Prospects for High Redshift Spectroscopic Studies with Upcoming Facilities

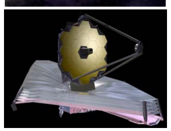
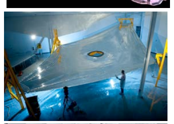
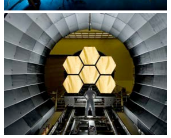
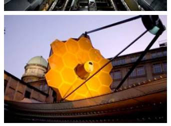
Andrew Bunker

On behalf of the NIRSpec Instrument Science Team

UNIVERSITY OF OXFORD

The JWST mission: status and overview

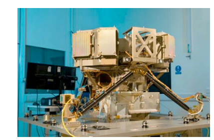
JAMES WEBB SPACE TELESCOPE

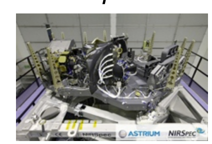
P. Ferruit

(ESA JWST project scientist)

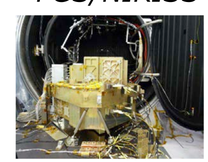
MIRI



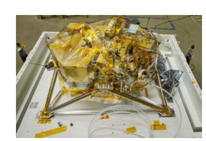
NIRSpec



FGS/NIRISS



NIRCam

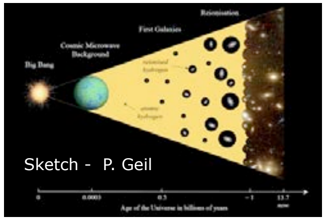


European Space Agency

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

JAMES WEBB SPACE TELESCOPE

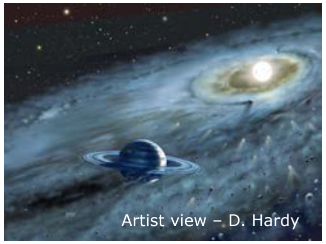
- **The end of the dark ages: first light and re-ionization.**


Sketch - P. Geil

- **The assembly of galaxies: the formation and evolution of galaxies.**


Hubble Ultra-deep Field

- **The birth of stars and proto-planetary systems.**


Artist view – D. Hardy

- **Planetary systems (including our solar system and exoplanets) and the origin of life.**


Artist view – R. Hurt

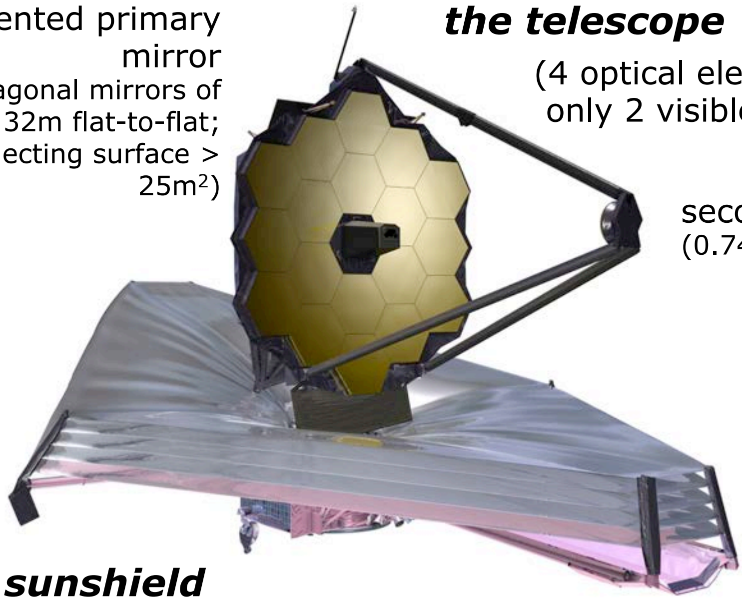
And a wealth of other scientific programs as JWST will be a general observatory.

See Gardner et al., 2006, Space Science Reviews, 123, 485

European Space Agency

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

JAMES WEBB SPACE TELESCOPE



segmented primary mirror
(18 hexagonal mirrors of 1.32m flat-to-flat; collecting surface > 25m^2)

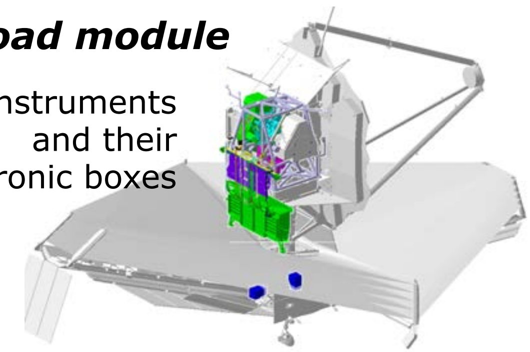
the telescope

(4 optical elements, only 2 visible here)

secondary mirror
(0.74m diameter)

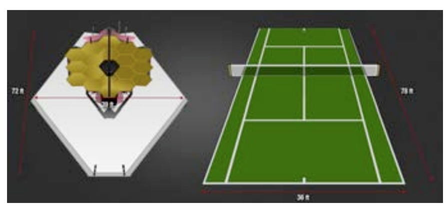
payload module

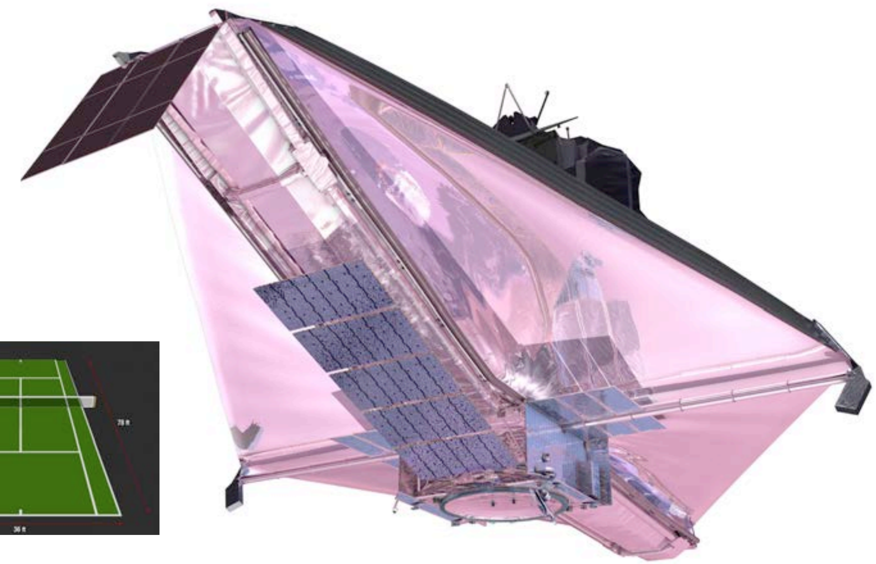
the 4 instruments and their electronic boxes



the sunshield

5 membranes of Kapton foil allowing **passive cooling of the telescope and the instruments down to ~40K**
the size of a tennis court

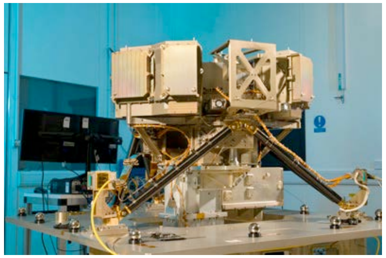




the spacecraft bus and solar panels

Note that a cryogenic cooler is used to cool JWST's mid-infrared instrument (MIRI) down to 6-7K.

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



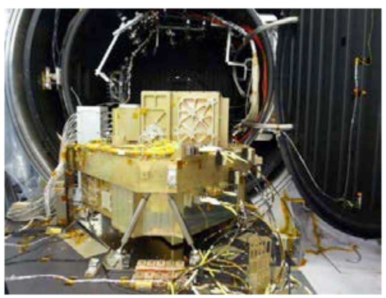
MIRI = Mid-InfraRed Instrument

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.

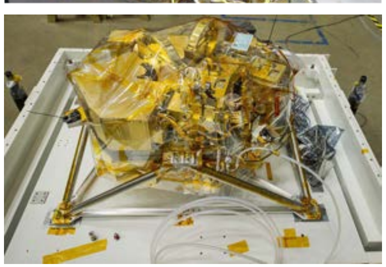


NIRISS = Near-infrared Imager and Slit-less Spectrograph

FGS = Fine Guidance Sensor

Provided by the Canadian Space Agency.

PIs: R. Doyon & C. Willott



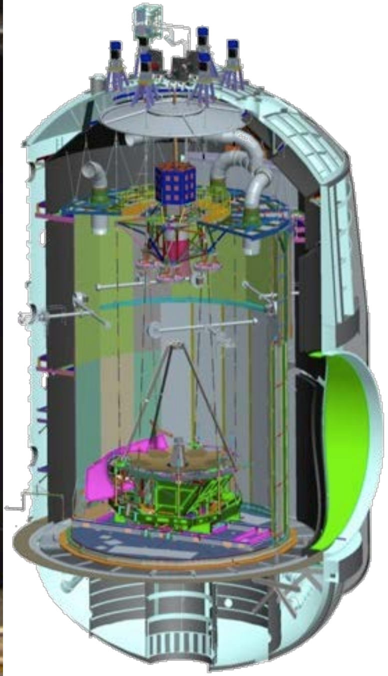
NIRCam = Near-InfraRed Camera

Developed under the responsibility of the University of Arizona.

PI: M. Rieke

JWST's instruments

JWST – From now to launch.



First half of 2017: testing of the telescope and the instruments together at the Johnson Space Center.

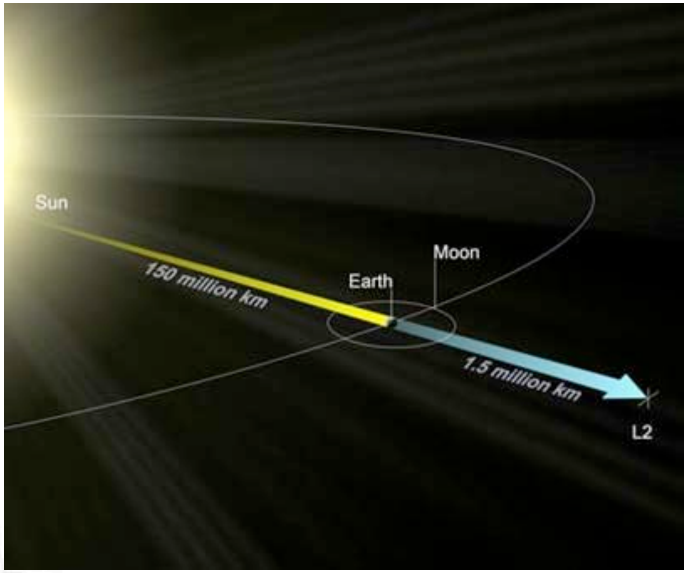
JWST – What happens next?

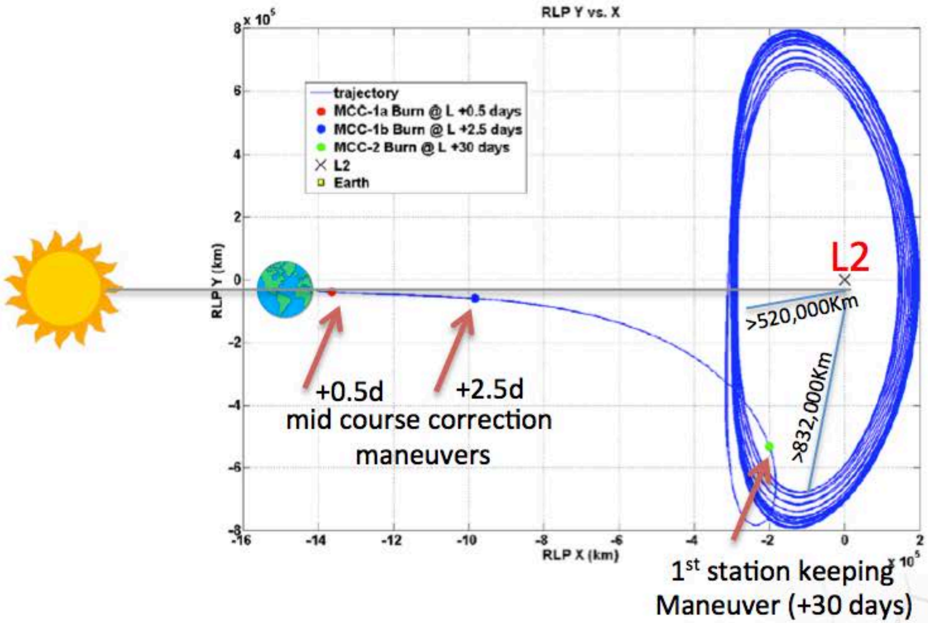
And in October 2018…
… LAUNCH!

But this will only be the beginning of the story for the scientific life of JWST!

JWST - Orbit and field-of-regard

L2 "halo" orbit. Keeping the Sun, the Earth and the Moon on the same side of the sunshield.

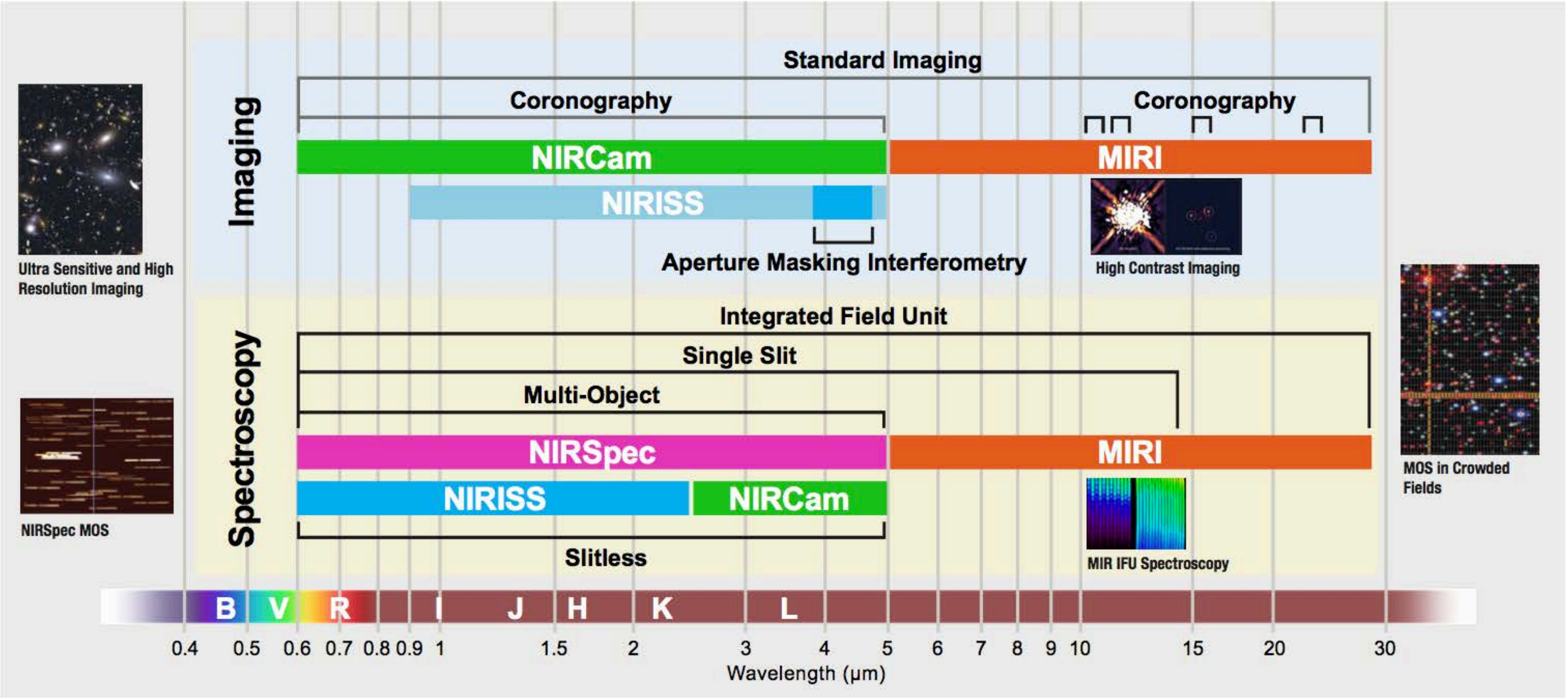




Halo orbit period is ~ 6 months

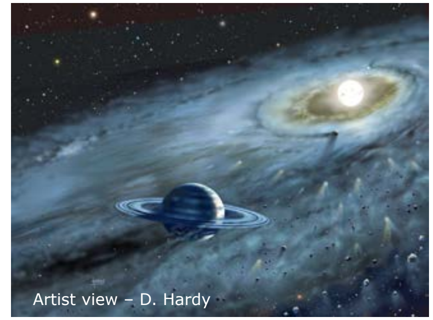
Final details on the orbit depend on launch window

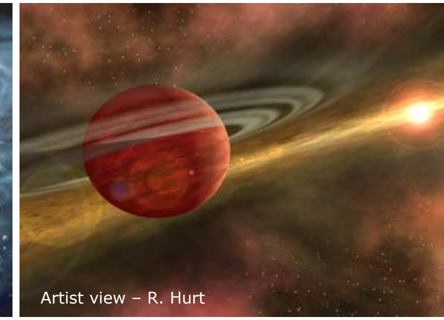
JWST capabilities



Credit: STScI

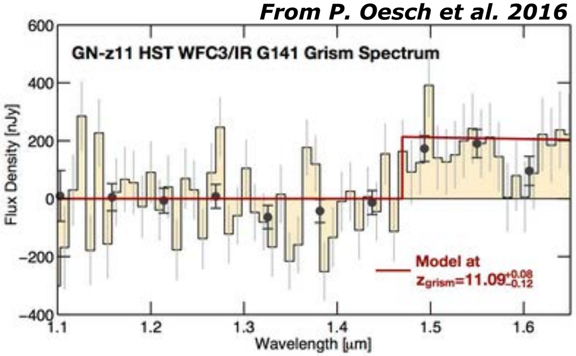
JWST/NIRSpec – The origin…



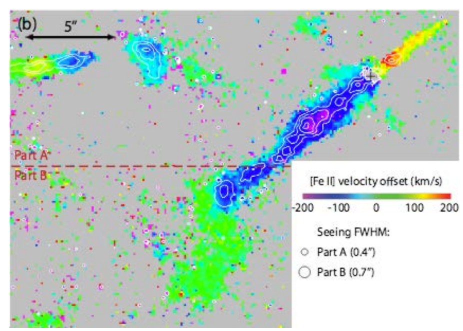


JWST will be one of the major space-based observatories of the next decade and its science goals encompass a very broad set of topics.

From P. Oesch et al. 2016

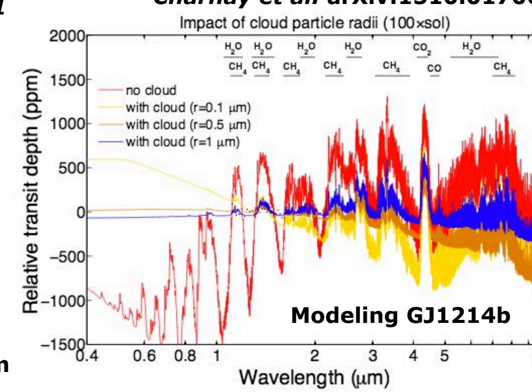


From Ellerbroek et al. 201



3D spectroscopy – YSO disk-jet system

***Charnay et al.* arXiv:1510.01706**



Spectroscopy will be a key tool to achieve JWST science goals.

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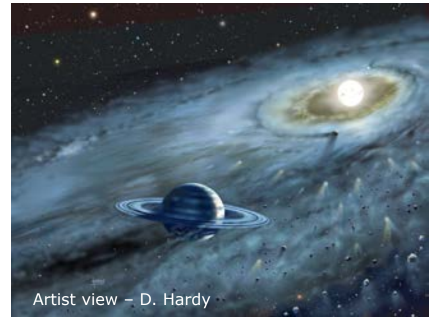
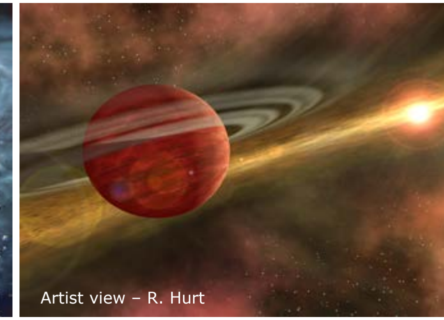
European Space Agency

JWST/NIRSpec – The origin…





To achieve JWST science goals a near-infrared spectrograph was needed in the instrument suite. It should be capable of:

- **Deep multi-object spectroscopy at low, medium (around 1000) resolution over a "wide" field of view.**
- **Spatially-resolved, single-object spectroscopy at "high" (a few thousands) spectral resolution over a "small" (a few arc seconds) field of view.**
- **High-contrast slit spectroscopy at various spectral resolutions, including an aperture for extra-solar planet transit observations.**

JWST NIRSpec – The instrument

- **Yes this is a NIRSpec presentation but do not forget that in JWST, spectroscopy comes in many flavors.**
  - Always take a careful look and pick the instrument and the mode most suited to your science objectives.

Instrument	Type	Wavelength (microns)	Spectral resolution	Field of view
NIRISS	slitless	1.0-2.5	~150	2.2′ x 2.2′
NIRCam	slitless	2.4-5.0	~2000	2.2′ x 2.2′
NIRSpec	MOS	0.6-5.3	100/1000/[2700]	9 square arcmin.
NIRSpec	IFU	0.6-5.3	100/1000/2700	3″ x 3″
MIRI	IFU	5.0-28.8	2000-3500	>3″ x >3.9″
NIRSpec	SLIT	0.6-5.3	100/1000/2700	Single object
MIRI	SLIT	5.0-10.0	60-140	Single object
NIRSpec	Aperture	0.6-5.3	100/1000/2700	Single object
NIRISS	Aperture	0.6-2.5	700	Single object

Note: MIRI also has slitless spectroscopy capabilities over its imager field of view and over the 5.0-10.0 micron range.

JWST/NIRSpec – The instrument

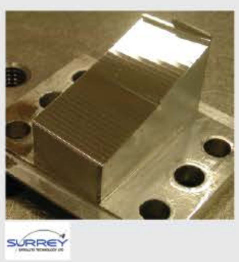
JWST/NIRSpec

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

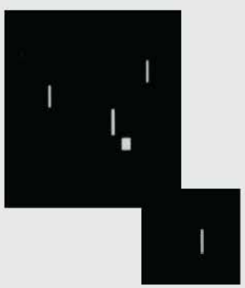


IFU spectroscopy with a 0.1″ sampling.

(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



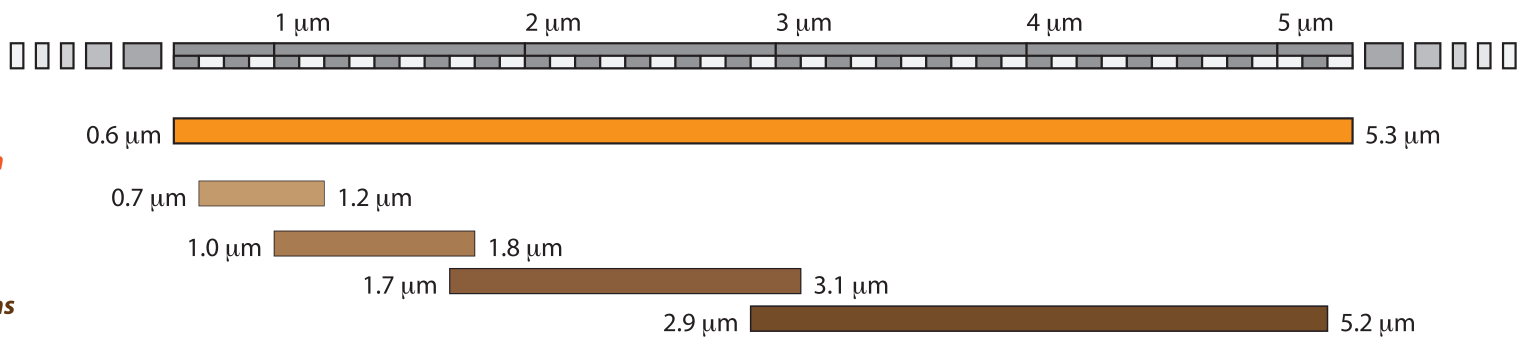
High-contrast slit spectroscopy.

(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.

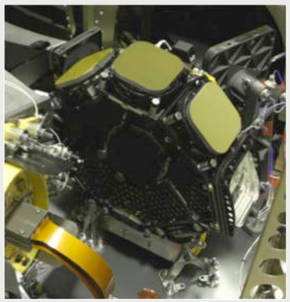
JWST/NIRSpec – The instrument

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.

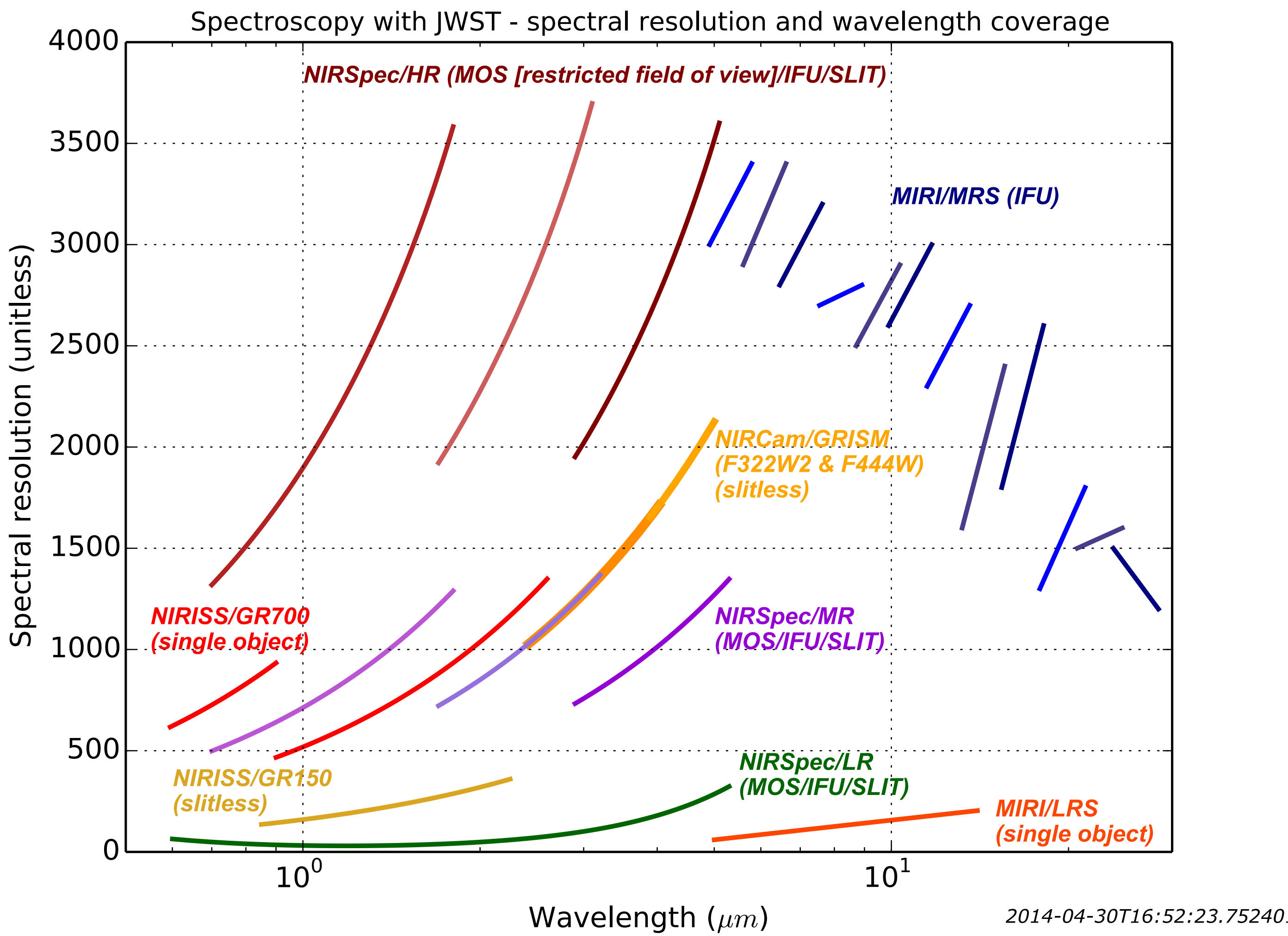
Configurations that can be obtained thanks to a combination of filters and dispersers installed on two wheels (FWA and GWA)



JWST/NIRSpec – The instrument

- **Again JWST offers a large variety of configurations.**

And NIRSpec proposes its share…



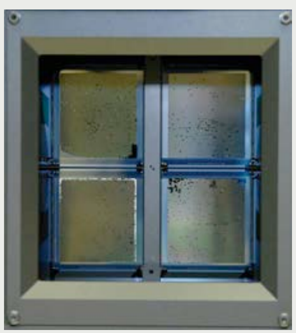
JWST/NIRSpec
Multi-object spectroscopy (MOS)

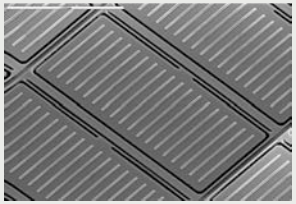
JAMES WEBB SPACE TELESCOPE

- **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.

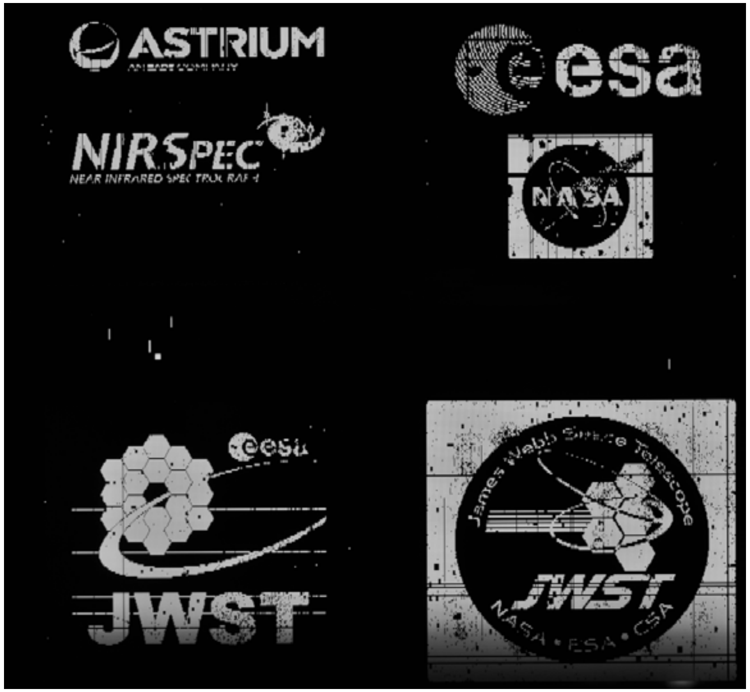
Using 4 arrays of 365x171 micro-shutters each, provided by NASA GSFC.

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



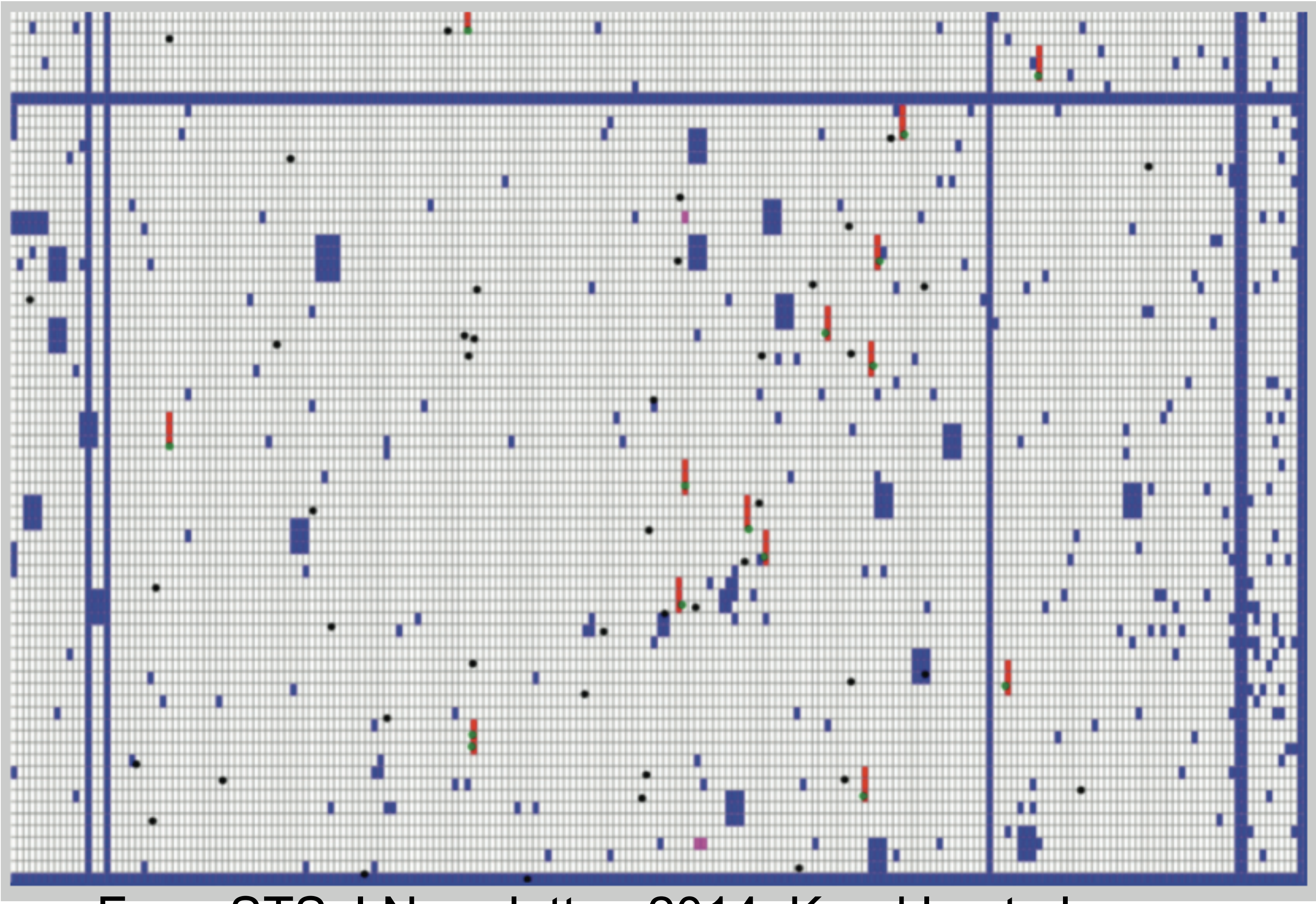


MEMS device – 105x204 micron shutters



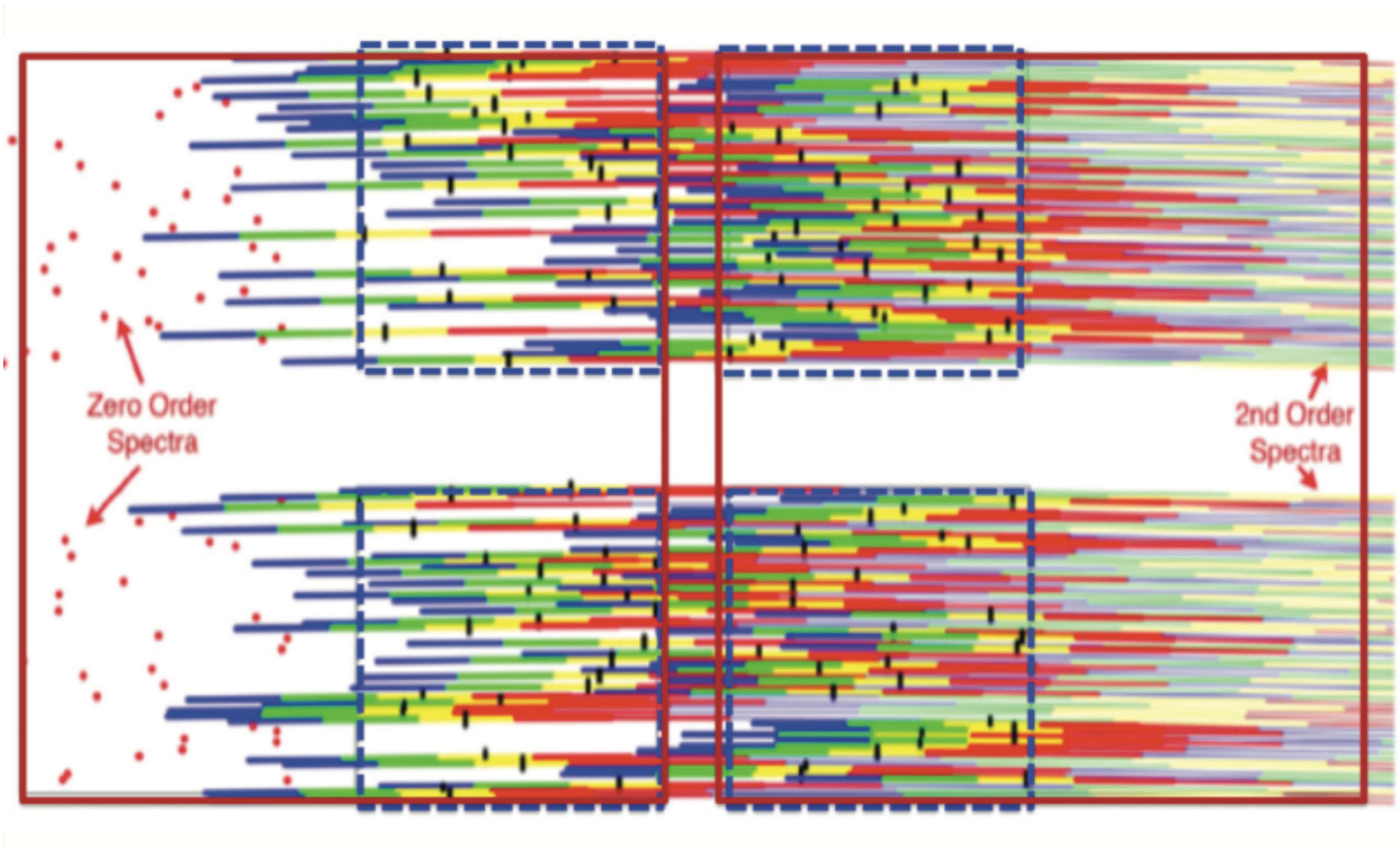
We typically need > 85-90 % of the shutters operable.

NIRSpec microshutters



From STScI Newsletter, 2014, Karakla et al.

Spectra from NIRSpec



From STScI Newsletter, 2014, Karakla et al.

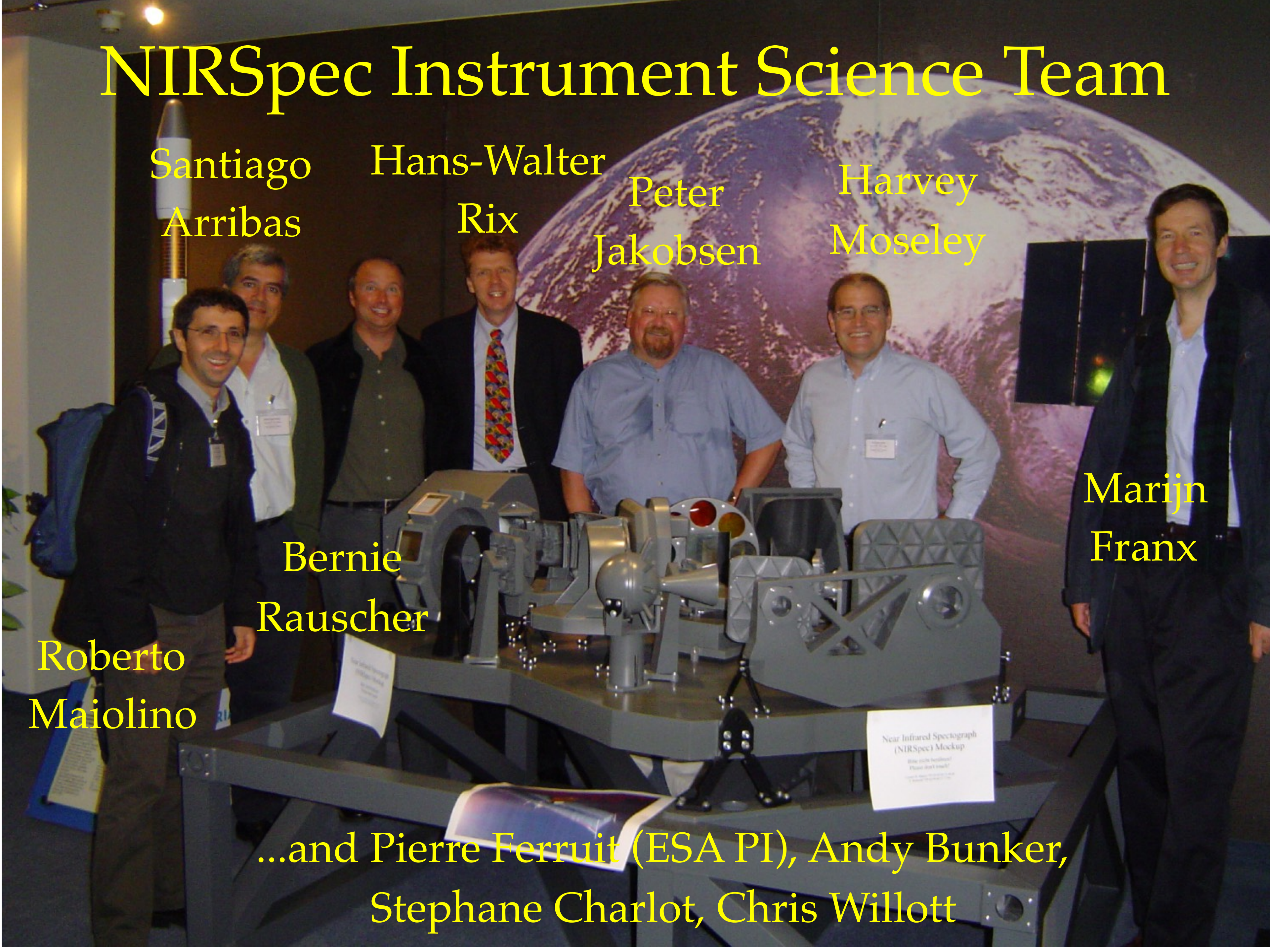
JWST – Science & timeline for scientific operation

Classes of Program

- Guest Observer (GO programs)
  - Open access for the community
  - ~80% of time in Cycles 1 through 5
- Guaranteed Time Observer (GTO) programs
  - 4020 hours allocated over first 30 months (i.e. Cycles 1 through 3)
  - NASA policy constraints on time/cycle
- Director's Discretionary Time (DD) programs
  - Up to 10%/cycle i.e. ≤877 hours
  - Rapid response observations & targeted science programs

includes ERS

Extracted from a presentation by N. Reid during the JWST2015 conference at ESA/ESTEC.


NIRSpec Instrument Science Team
Santiago Arribas
Hans-Walter Rix
Peter Jakobsen
Harvey Moseley
Bernie Rauscher
Marijn Franx
Roberto Maiolino
Near Infrared Spectograph (NIRSpec) Mockup
...and Pierre Ferruit (ESA PI), Andy Bunker,
Stephane Charlot, Chris Willott

NIRSpec Galaxy Assembly: An expanding team...

Santiago Arribas, Andy Bunker, Stéphane Charlot, Pierre Ferruit, Marijn Franx, Peter Jakobsen, **Roberto Maiolino**, Hans-Walter Rix, **Chris Willott**

Ricardo Amorin, Stefano Carniani, Jacopo Chevallard, **Emma Curtis-Lake**, Giovanna Giardino, Bernd Huseman, **Michael Maseda**, Tim Rawle, **Renske Smit**

ALSO WORKING WITH NIRCam IST/GTO
PI: Marcia Rieke
(including **Brant Robertson**, **Daniel Stark**)

Pierre Ferruit & the NIRSpec GTO team

http://www.cosmos.esa.int/web/jwst-nirspec-gto

NIRSpec GTO Plan

European Space Agency

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)?

NIRSpec GTO
MSA galaxy assembly program

Top priority science cases:

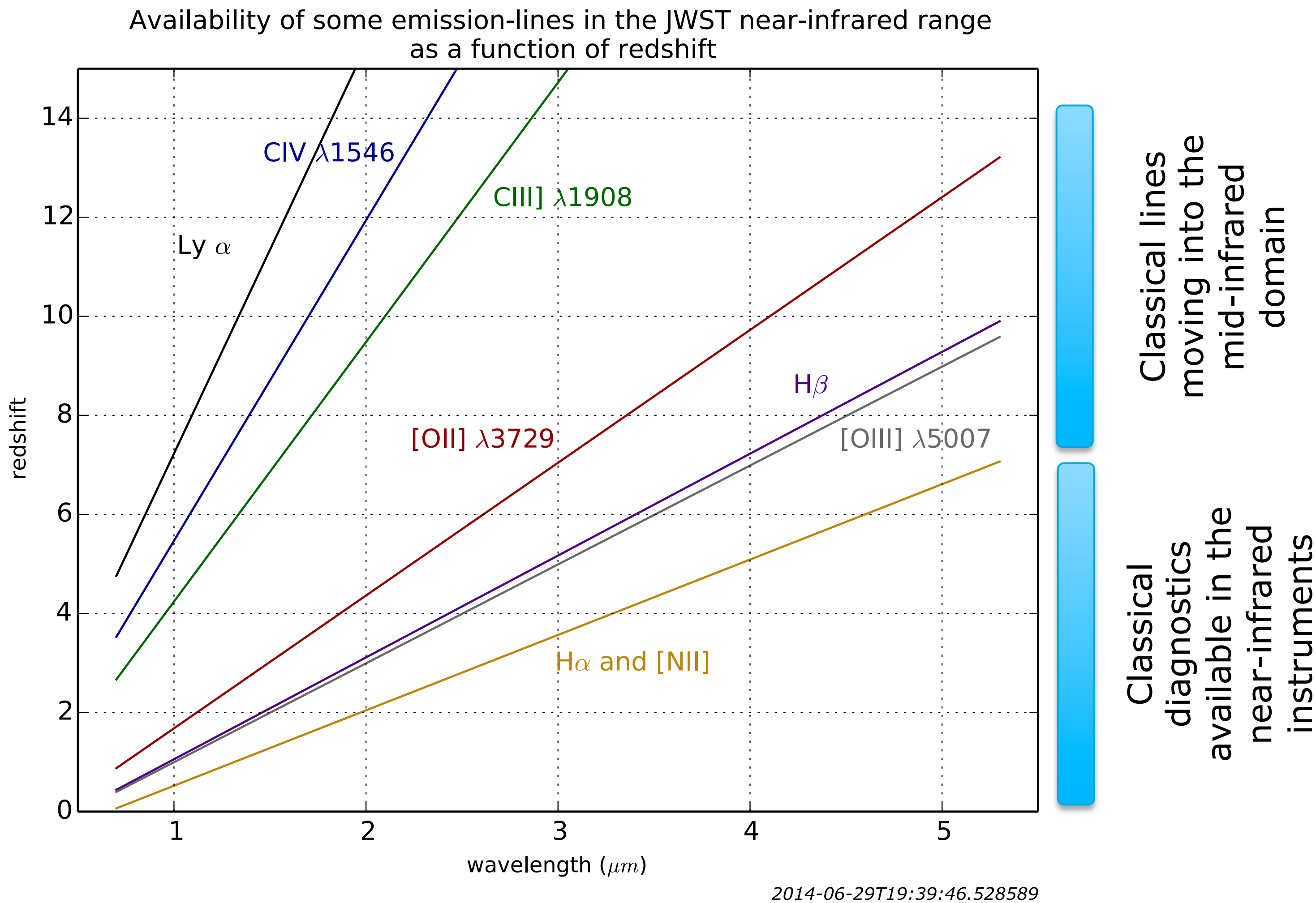
- Spectroscopic confirmation of the most distant galaxies
- Escape of Ly continuum and Lyα photons
- Stellar populations, kinematics and chemical enrichment
- PopIII
- AGNs and their host galaxies
- Large scale structure, environment

Summary table

Program	Lead(s)	Duration
The physics of galaxy assembly - the NIRSpec GTO spectroscopic survey	NIRSpec instrument science team	724 hours (+21 hours of contingency)
DEEP MOS survey		148 hours
MEDIUM MOS survey		200 hours
WIDE MOS survey		106 hours
IFU survey		270 hours
Cosmic reionization and metal enrichment from quasar spectroscopy	C. Willott & P. Jakobsen	42 hours
Resolved structure and kinematics of the nuclear regions of nearby galaxies	T. Böker	16 hours
Transiting exoplanet characterization with JWST/NIRSpec	S. Birkmann & J. Valenti	50 hours
Direct spectroscopy of an exoplanet with the JWST/NIRSpec IFU	S. Birkmann	6 hours
Star formation in the local group	G. de Marchi	15 hours
The physics of brown dwarfs	C. Alves de Oliveira	17 hours
Surface composition of mid-sized TNOs: searching for ammonia	A. Guilbert-Lepoutre	9 hours
	Total	**900 hours**

JWST/NIRSpec – The instrument

- **Nice emission-line diagnostics for galaxy assembly fans…**



Overall NIRSpec Galaxy Assembly Plan

a wedding cake survey at R=100 and R=1000, about 500hours

- 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
- Medium, 12 paintings 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/cm2/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

Confirmation Highest redshift sources (1)

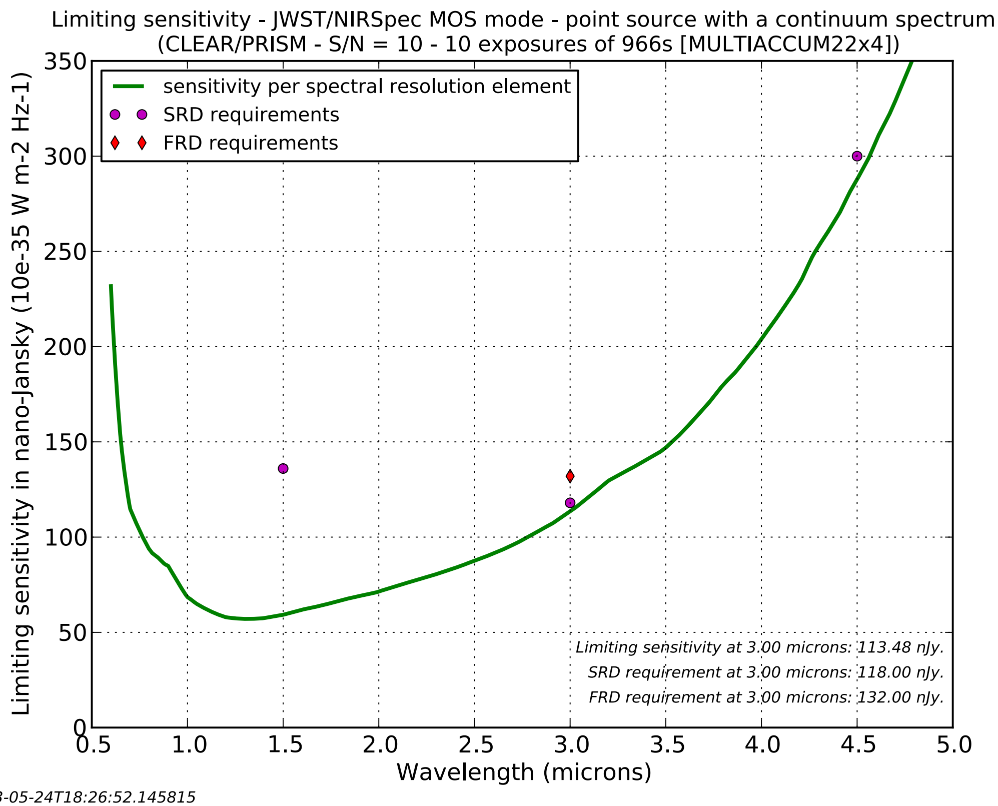
- **Science Objectives**
  - Get spectroscopic redshifts at $z>7$
  - Initial characterization of spectra

- **Methods**
  - Measure redshift from emission line/continuum features
  - Simple modelling of the spectra (potentially pop III, continuum UV slopes, etc)

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); HeII-1640 for pop III?

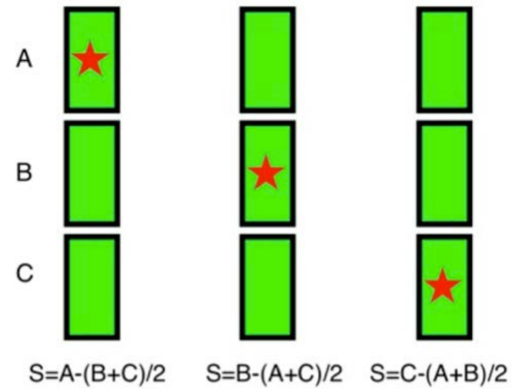
JWST/NIRSpec
Multi-object spectroscopy

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

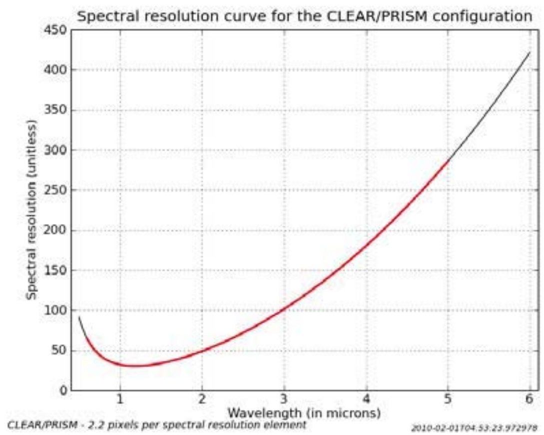


100 nJy = 1e-30 erg s-1 cm-2 Hz-1 = 1e-33 W m-2 Hz-1 = 26.4 AB mag = 24.3 K-band mag

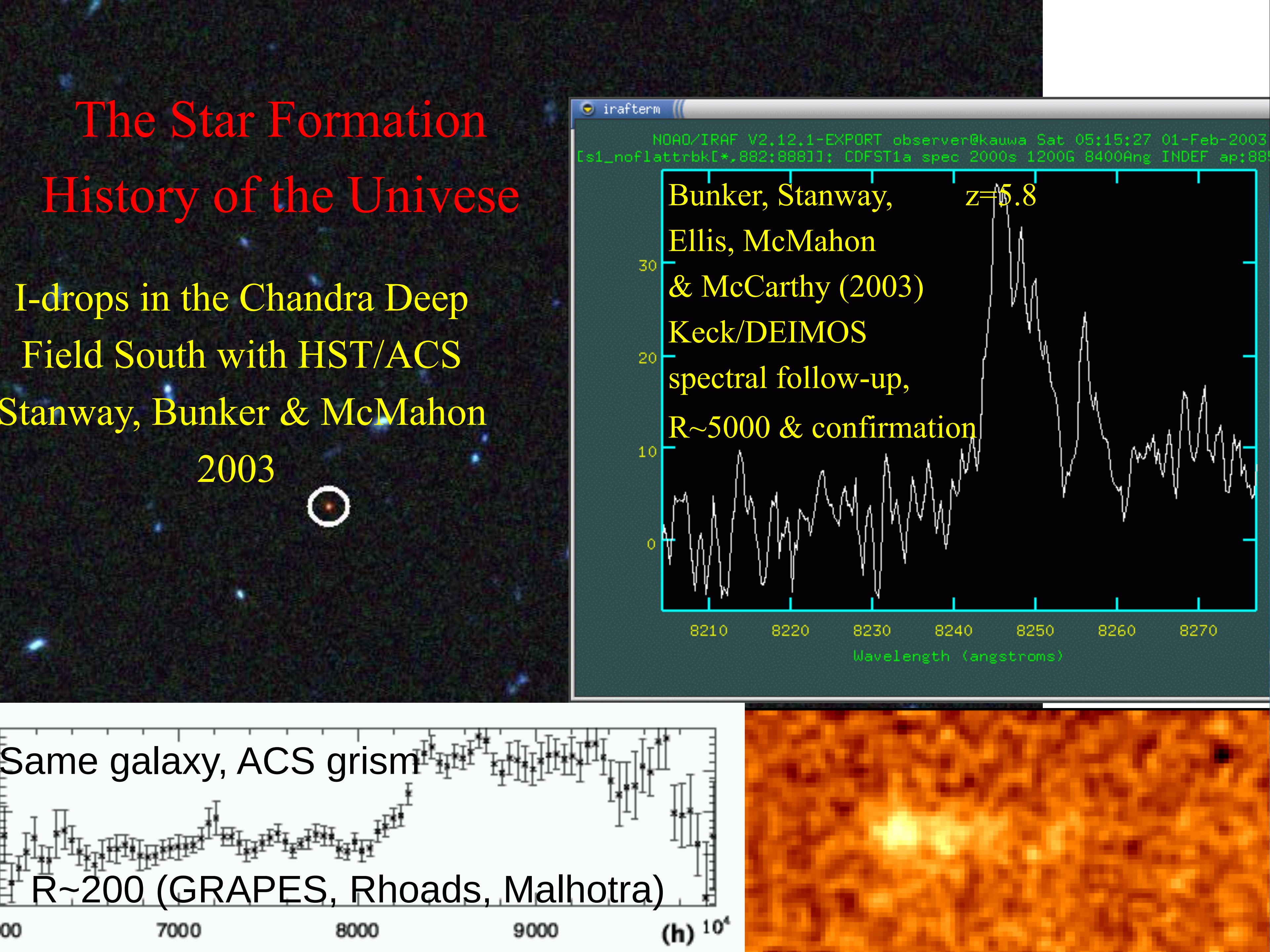
Note the gaps between the shutters are real (pitch = 202 microns, aperture = 175 microns, 14% relative bar size)



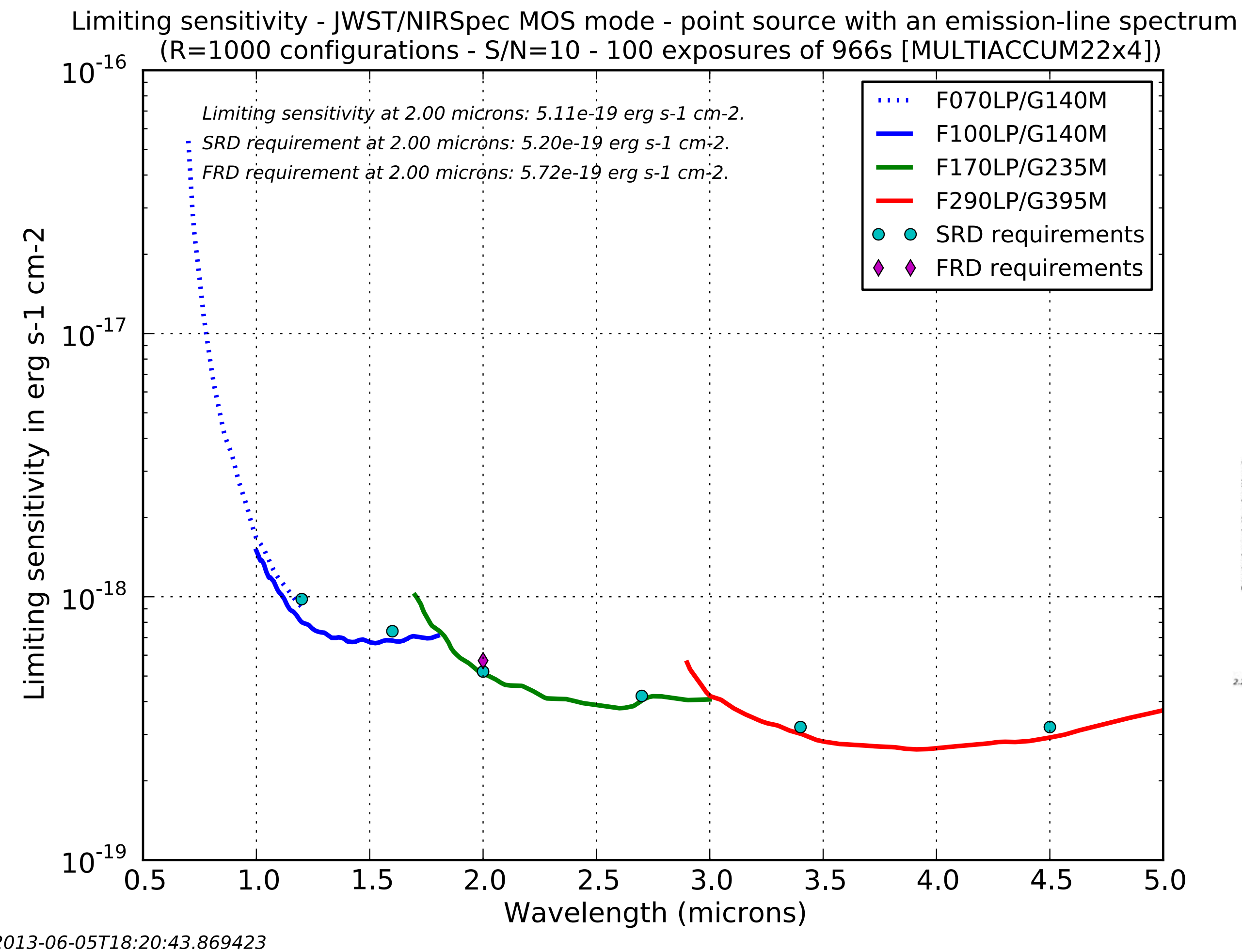
- Low spectral resolution



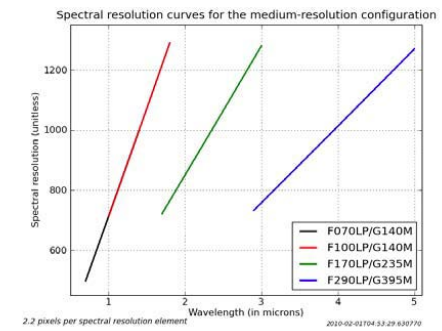
European Space Agency


The Star Formation
History of the Univese
I-drops in the Chandra Deep
Field South with HST/ACS
Stanway, Bunker & McMahon
2003
irafterm
NOAO/IRAF V2.12.1-EXPORT observer@kauwa Sat 05:15:27 01-Feb-2003
[s1_noflattrbk[*,882:888]]: CDFST1a spec 2000s 1200G 8400Ang INDEF ap:88
Bunker, Stanway,
Ellis, McMahon
& McCarthy (2003)
Keck/DEIMOS
spectral follow-up,
R~5000 & confirmation
z=5.8
30
20
10
0
8210
8220
8230
8240
8250
8260
8270
Wavelength (angstroms)
Same galaxy, ACS grism
R~200 (GRAPES, Rhoads, Malhotra)
00
7000
8000
9000
(h)
10⁴

JWST/NIRSpec
Multi-object spectroscopy



- Medium spectral resolution

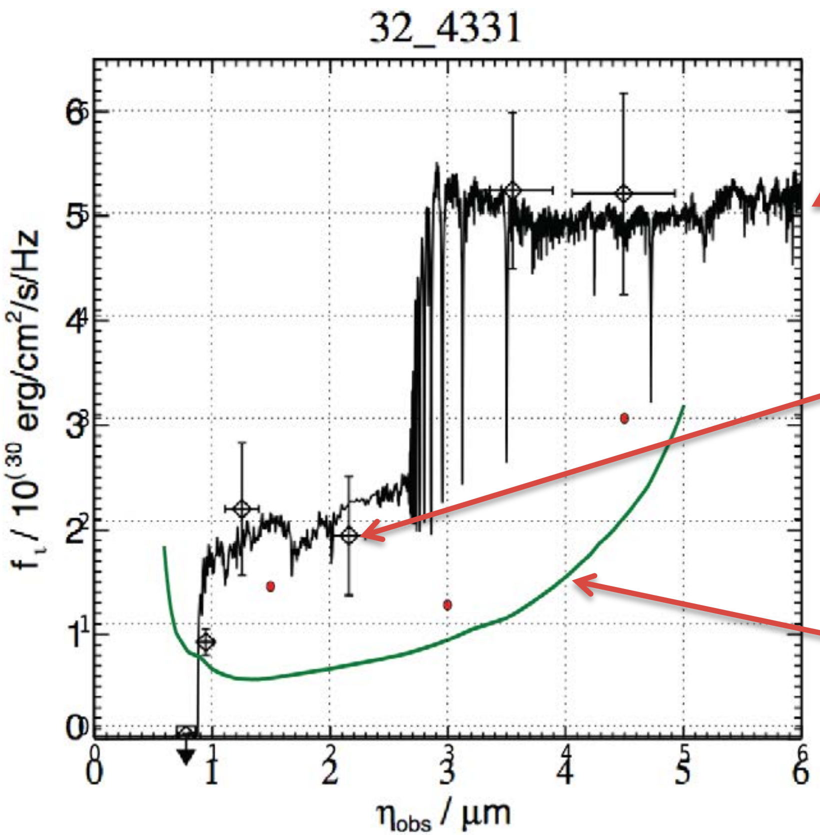


JAMES WEBB SPACE TELESCOPE

European Space Agency

JWST/NIRSpec
Multi-object spectroscopy – Example

- **Another way to illustrate the sensitivity of NIRSpec**
  - i' drop-out galaxies from Eyles et al. 2006 (GOODS + Spitzer IRAC imaging).



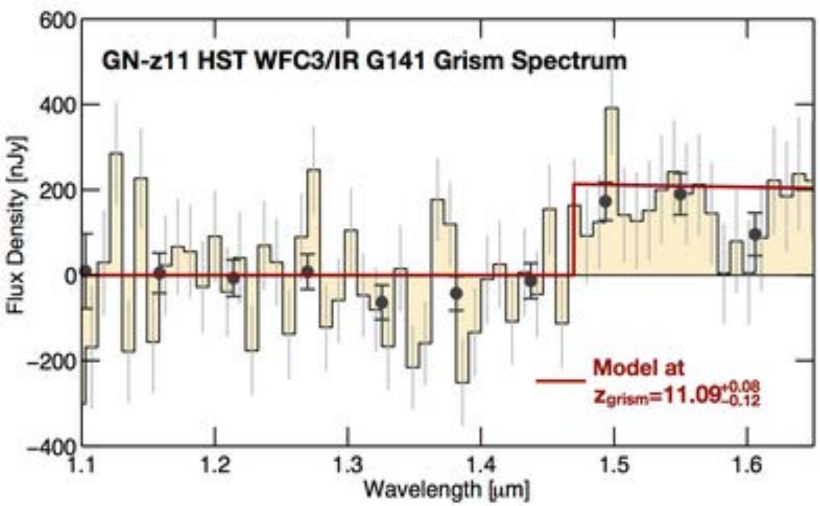
Best fit SED (few 10^{10} solar masses, current SFR of 9 solar masses per year; fairly evolved population)

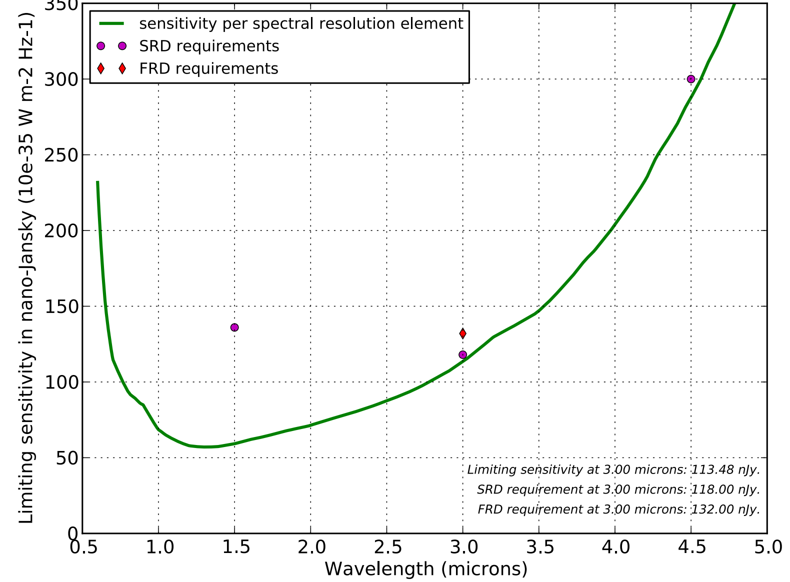
Photometry data points (Eyles et al. 2006)

JWST/NIRSpec limiting sensitivity in 10,000 s at low spectral resolution. Impact of detector cosmetics not included.

JWST/NIRSpec
Multi-object spectroscopy – Example

From P. Oesch et al. 2016





2013-05-24T18:26:52.145815

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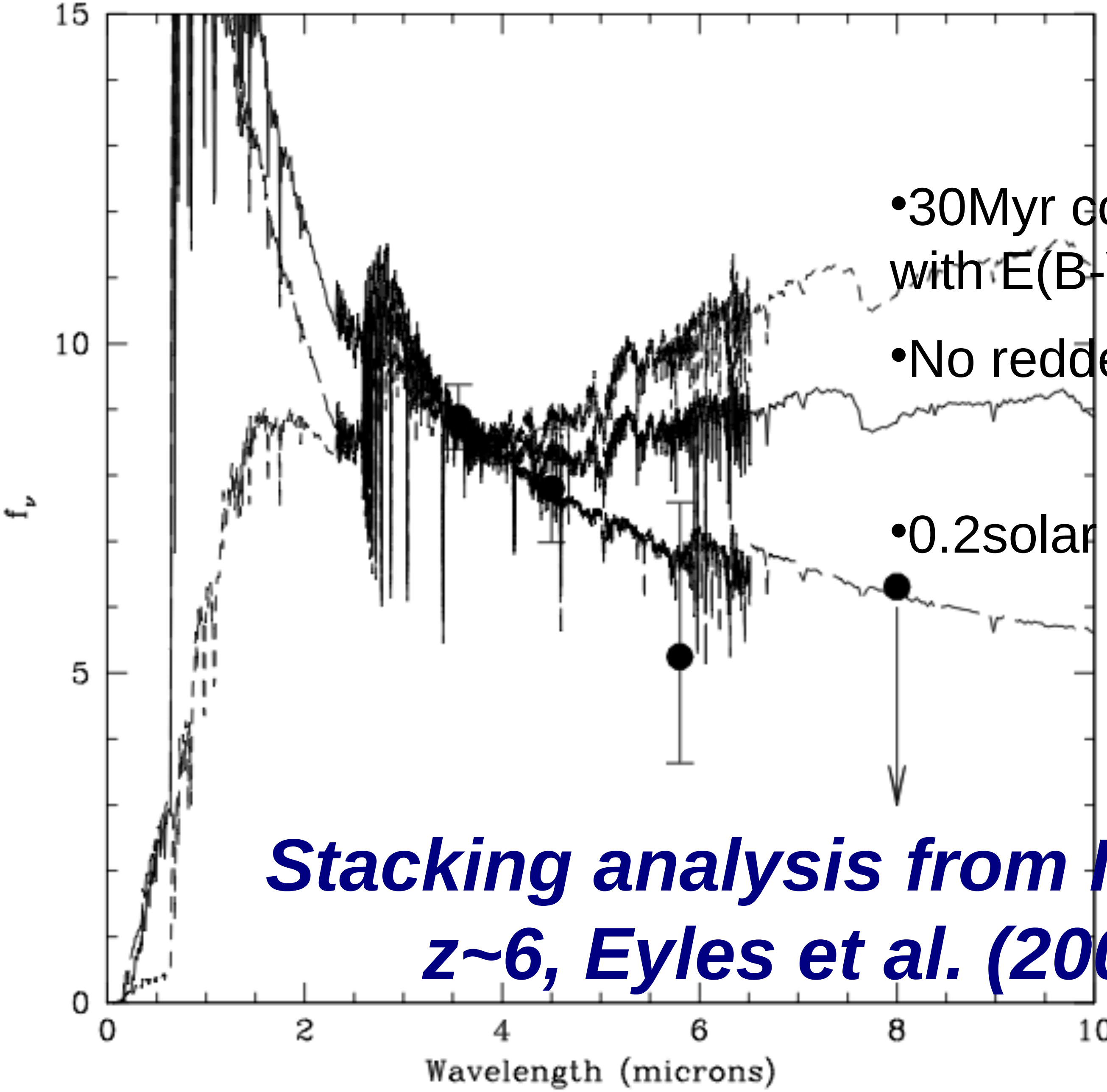


- 30Myr const SFR with E(B-V)=0.1
- No reddening
- 0.2solar metallicity

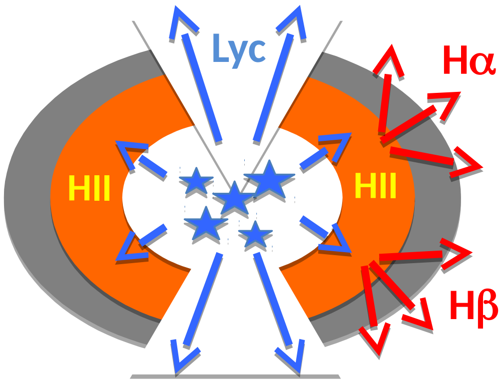
Stacking analysis from IRAC at z~6, Eyles et al. (2007)

Confirmation of highest redshift (2)

- **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?**
- **Link to the program at large**
  - part of Deep UDF, Deep, Medium, Shallow;
  - R=100 and R=1000 to get emission lines

- **Ancillary Data:** HST UDF, NIRCam imaging
  - Target selection (based on SED (photo-z), dropout, etc, magnitude, size)
  - Morphological information (sizes)
  - photometry for accurate SED

The Lyman continuum escape fraction (1)

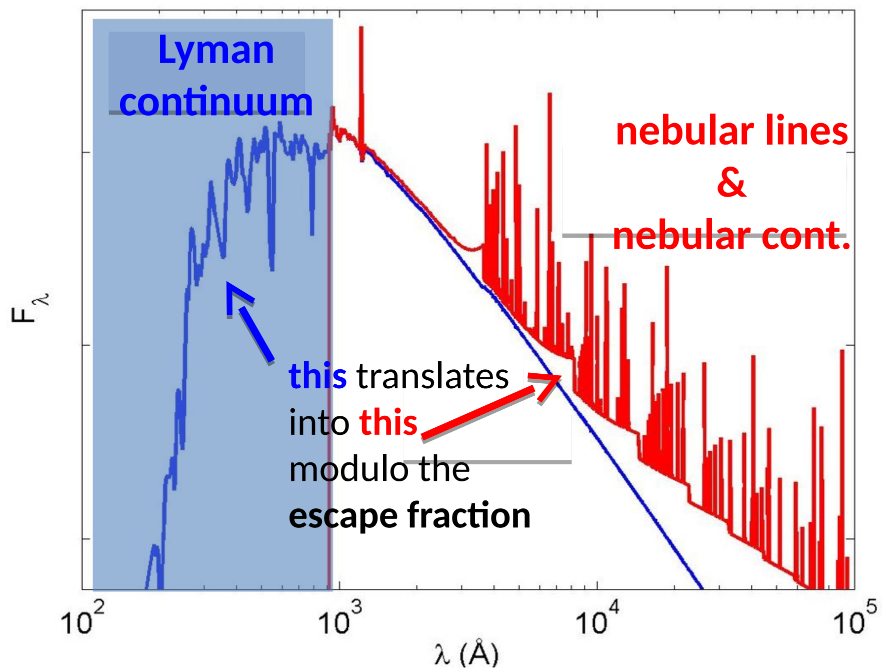


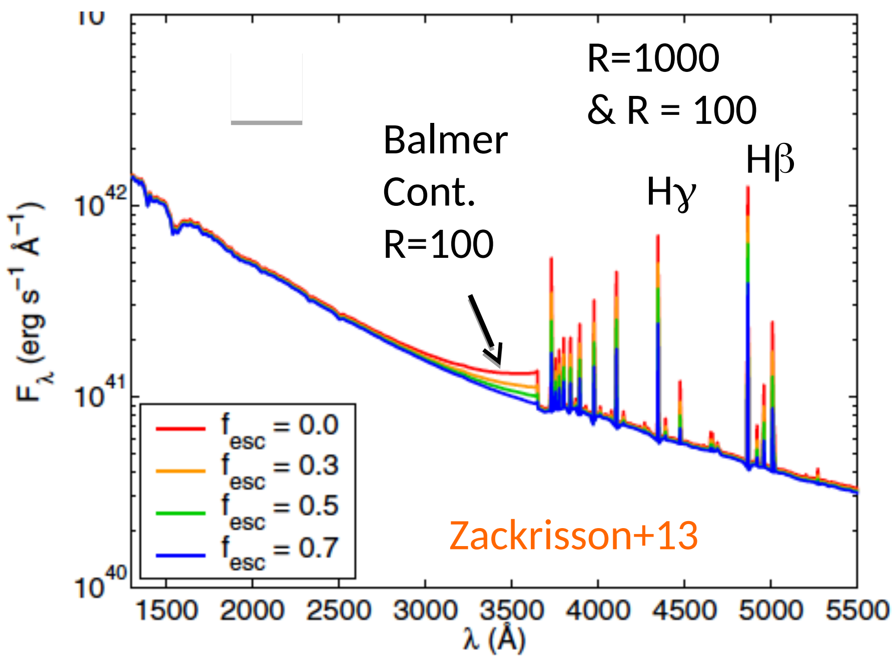
Science goals

- 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)





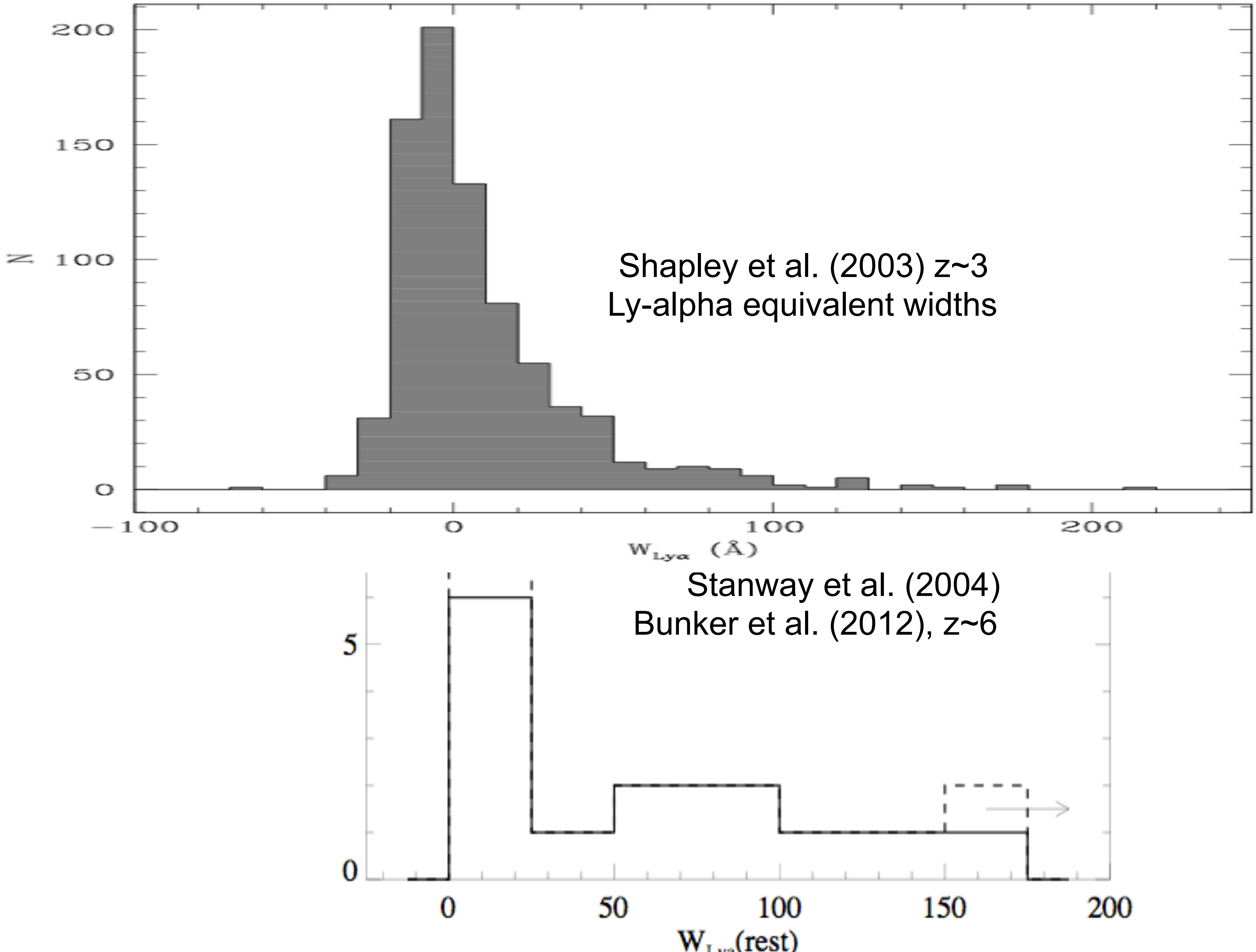
JWST-NIRSpec – Escape Fraction and Reionization

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

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.

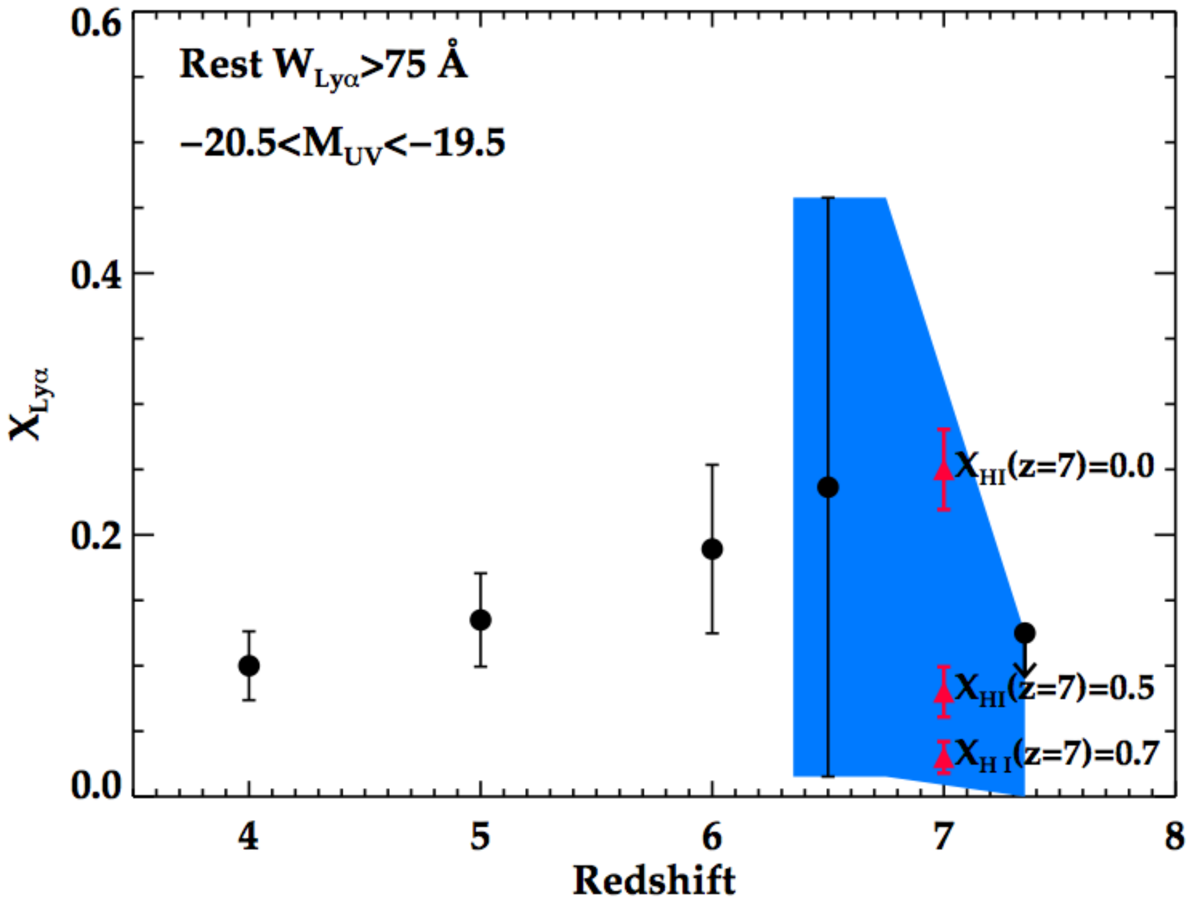
[Modulo the UV extrapolation beyond Lyman-alpha, which may be model dependent, but can be constrained by the HeI/H ratio, or even HeII/HeI/H.]

Also: searches for PopIII – HeII 1640Ang

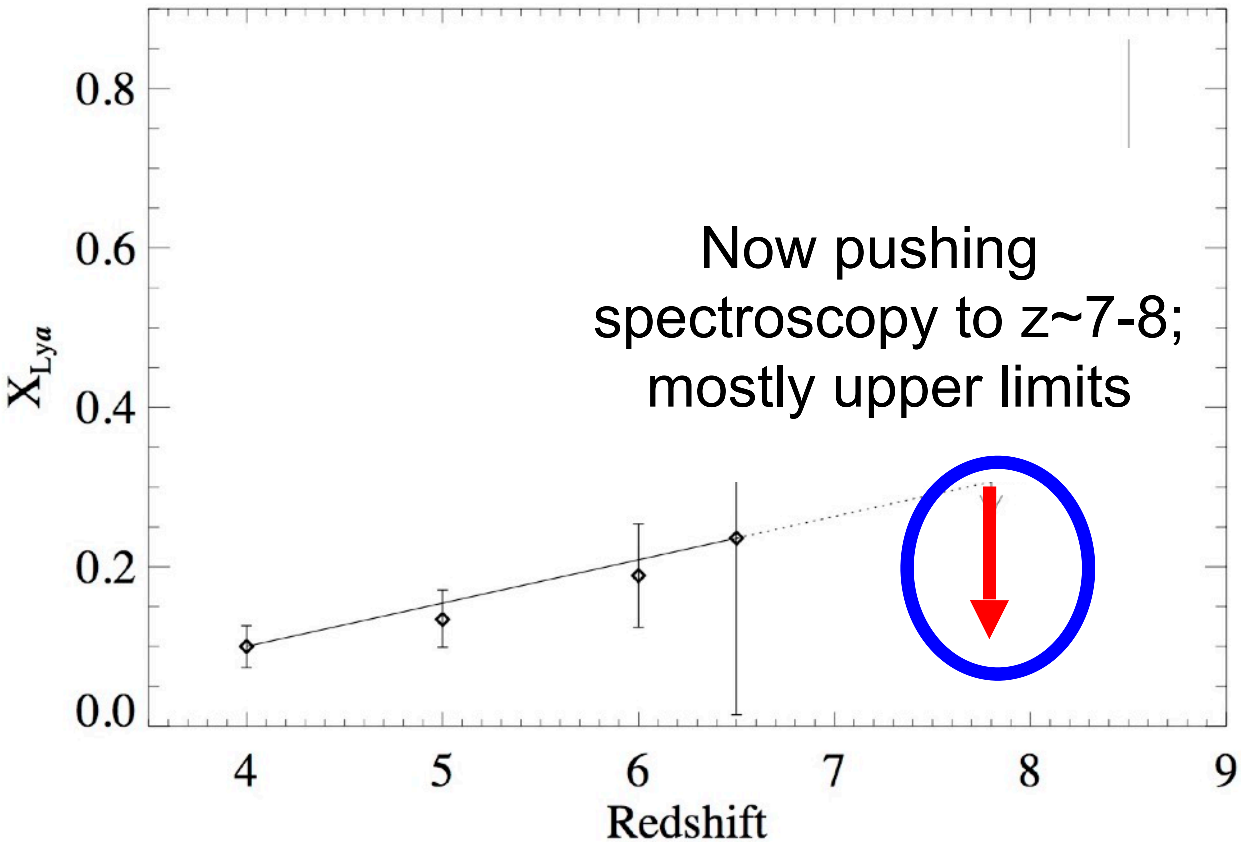


Shapley et al. (2003) z~3
Ly-alpha equivalent widths
N
$W_{Ly\alpha}$ (Å)
Stanway et al. (2004)
Bunker et al. (2012), z~6
$W_{Ly\alpha}$(rest)

Ly-alpha fraction (Stark et al. 2010)



Lyman alpha equivalent width distribution as a function of redshift for patchy or not reionization scenarios. Also, measuring Lyman alpha line shape evolution into the reionization epoch with systemic redshifts determined from nebular lines.



Stark et al. (2010) Caruana et al. (2012, 2014). Ly-alpha suppressed in mostly-neutral IGM

Quantities to be measured:

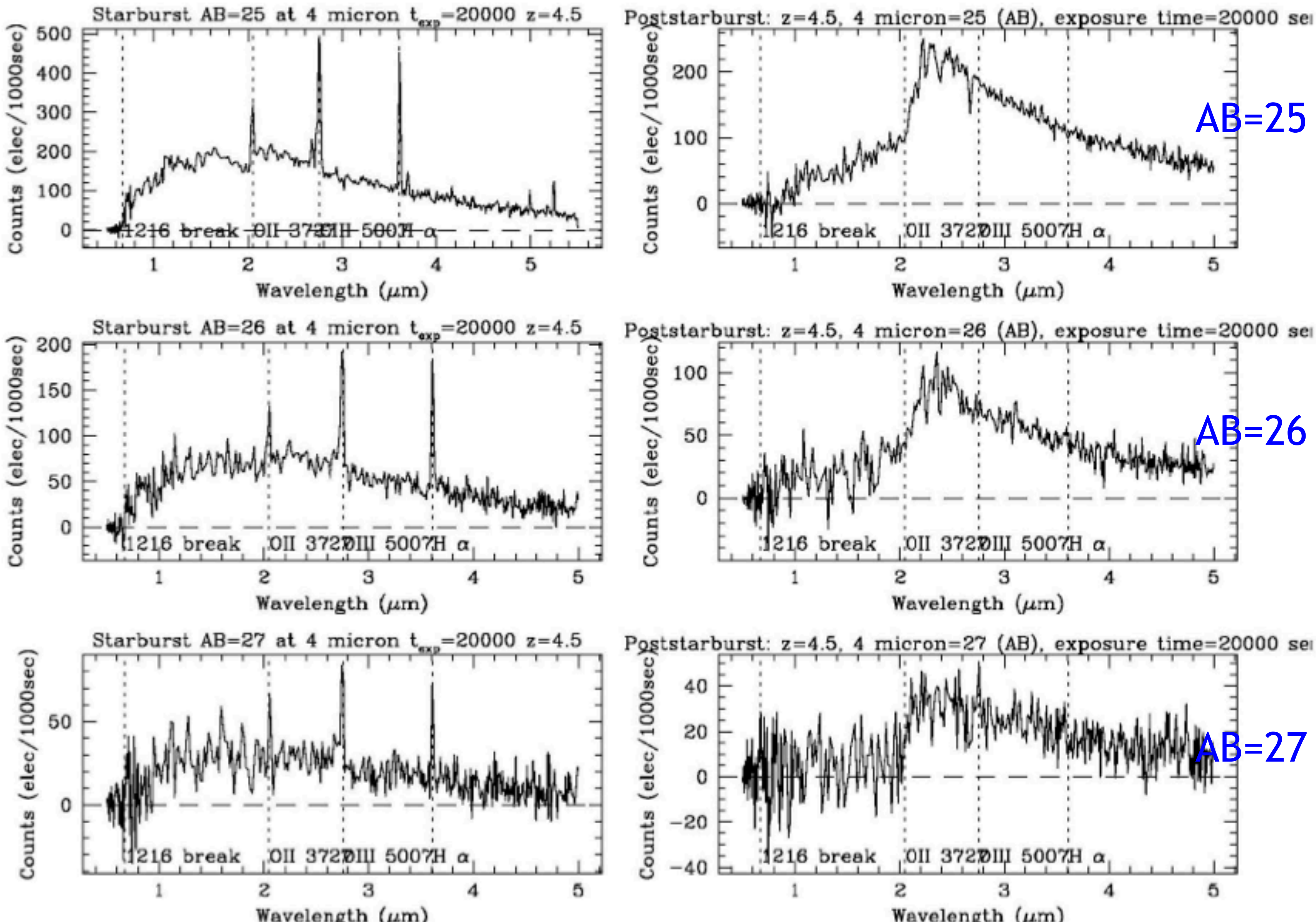
- Stellar mass
- Galaxy age and star formation history
- Star Formation Rate
- Stellar metallicity
- Gas metallicity
- Attenuation by dust
- Presence and power of AGN
- Black hole masses
- Presence of shocks
- Outflows
- Dynamics

Evolution of mass-metallicity relation (FMR?)
Increase in ionisation parameter with redshift?

NIRSpec MSA simulations; T_exp = 20,000 sec z=4.5 with R100

NIRSpec team (Franx, Bunker, Ferruit, Maiolino, Arribas, Charlot, Rix, Willot, Jakobsen)

Starburst Post-starburst



widely-used indicator for the O/H abundance has been "R23" (Pagel et al. 1979), uses [OII], [OIII] and Hβ - reasonably close in wavelength (minimizes the effect of differential dust extinction) and accounts to first order for ionization by using two species of oxygen (also updated O/H method of Curti et al. 2017).

Can determine R23 out to z~9 with JWST. However, there is a well known "double fork" in the plot of R23 against metallicity, but the [NII]/H-alpha line ratio can be used to break the degeneracy and determine if a galaxy lies on the upper or lower branch. With NIRSpec, we can track [NII]6583Å out to a redshift of z~7, much further than the current z~2.5 limit.

not just one "number" which describes the chemical enrichment of an individual galaxy, and we can improve on the simplistic R23 metallicity by measuring abundances of different elements.

Abundance ratios provides strong constraints on galaxy evolution, and in particular the relative contribution to chemical enrichment from core-collapse supernovae and asymptotic giant branch stars, which have different timescales and hence the abundance patterns should evolve strongly with redshift.

The N/O ratio can be determined using the [SII], [NII], Hβ and [OIII] lines to constrain the ionization parameter (Dopita et al. 2016), and similarly the CIII]1909 and CIV lines provide the carbon abundance (Amorin et al. 2017).

Among AGB stars, nitrogen is produced from relatively massive stars (~5M_sun), while carbon is produced by the low-mass end (1-3M_sun) with longer lifetimes. Oxygen is produced very promptly from core-collapase supernovae (with >8M_sun progenitors). Hence the relative abundances probed by JWST tell us about the galactic archeology, and potentially any evolution of the stellar initial mass function.

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)

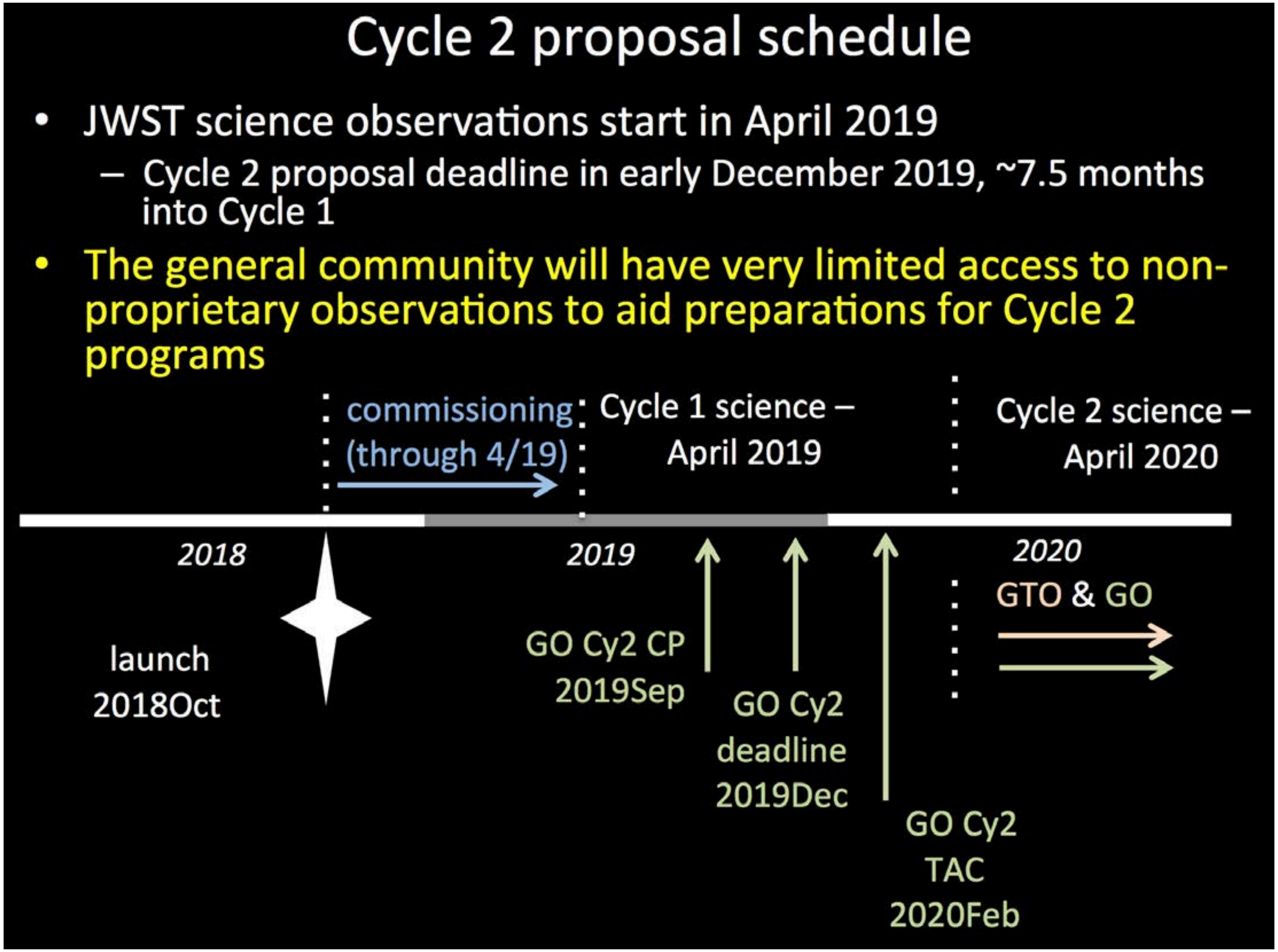
MIRI:

- 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)

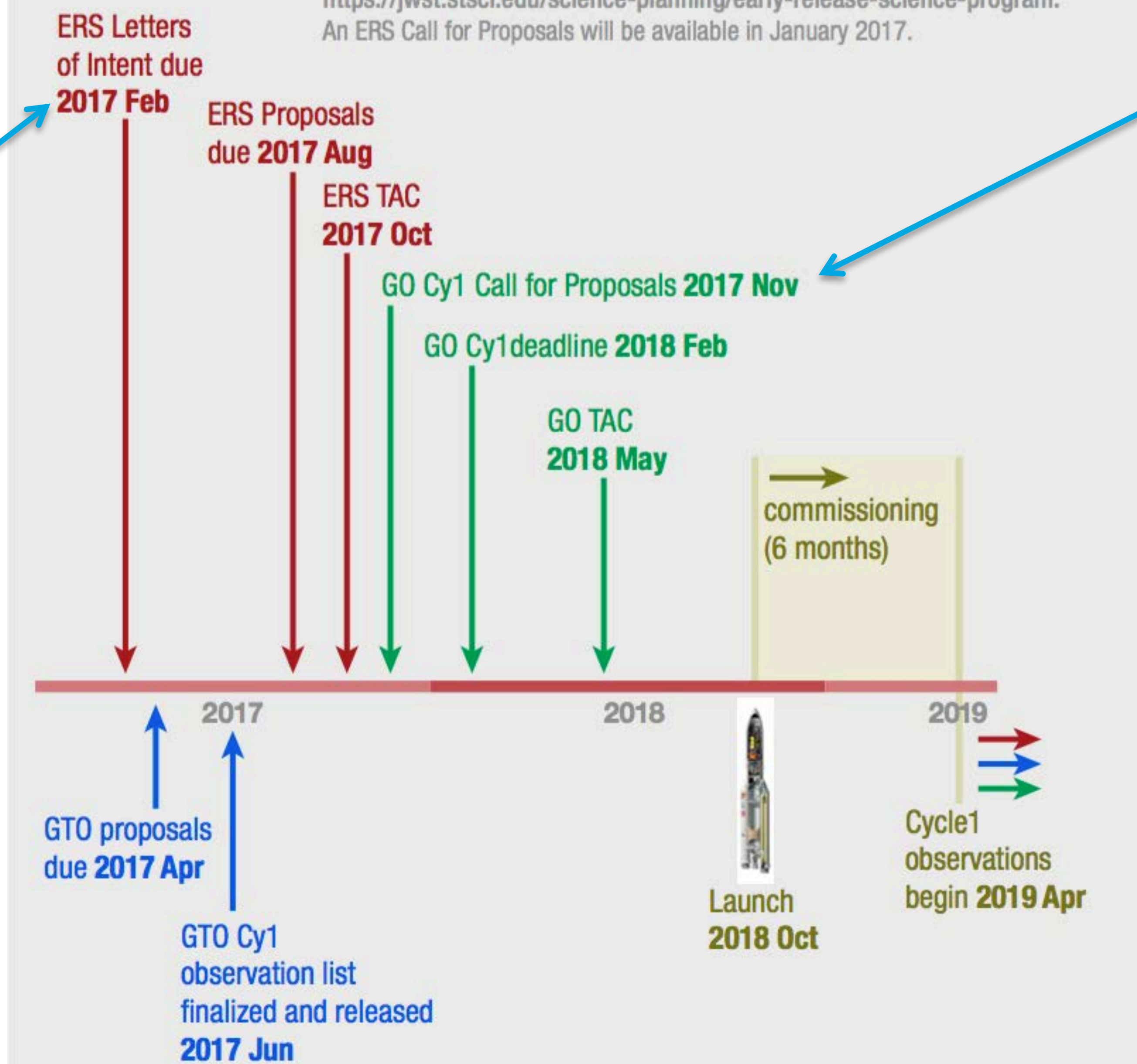
JWST – Science & timeline for scientific operation



Extracted from a presentation by N. Reid during the JWST2015 conference at ESA/ESTEC.

JWST Science Timeline

Updates on the ERS program will be provided at:
https://jwst.stsci.edu/science-planning/early-release-science-program.
An ERS Call for Proposals will be available in January 2017.



Conclusions

- Have found star-forming galaxies at z=6-10 (Lyman breaks), and spectroscopic confirmation at z~6; not much Ly-alpha emission beyond z~7 (due to Gunn-Peterson absorption?)
- However, z>7 number counts from HST/WFC3 imply the newly-discovered galaxies would struggle to reionize the IGM
- Many of these have very blue rest-UV spectral slopes
- High escape fraction/Steep faint end slope/low metallicity/smooth IGM?
- JWST spectroscopy will get Hα, Hβ, [OIII], [OII] to high redshift, Getting REAL redshifts for luminosity functions
- will determine escape fractions, star formation rates, metallicities...

Program plan – Medium Survey (100-200 sq. arcmin)

- 9 NIRSpec pointings x 2 fields (test cosmic variance)
- (9arcmin x 9arcmin per field; possible fields include
- GOODS/CANDELS, Frontier Fields –
- complementary data, X-ray, UV, sub-mm....)
- ~3000 galaxies at 2<z<6 (150 galaxies per pointing)
- AB < 27
- R=100: 20ksec per pointing (continuum)
- R=1000: 10ksec per pointing in each of three bands
    - (emission lines)
- total of ~ 230 hours

- Shallow survey (200-400 sq. arcmin, 48 pointings)

- AB<25, 7000+ galaxies, R=100 for 1000s
- R=1000 at 2-5microns for 1000s (2 settings)
- Total of ~50 hours