The First Billions Years - Early Science from the NIRSpec GTO observations

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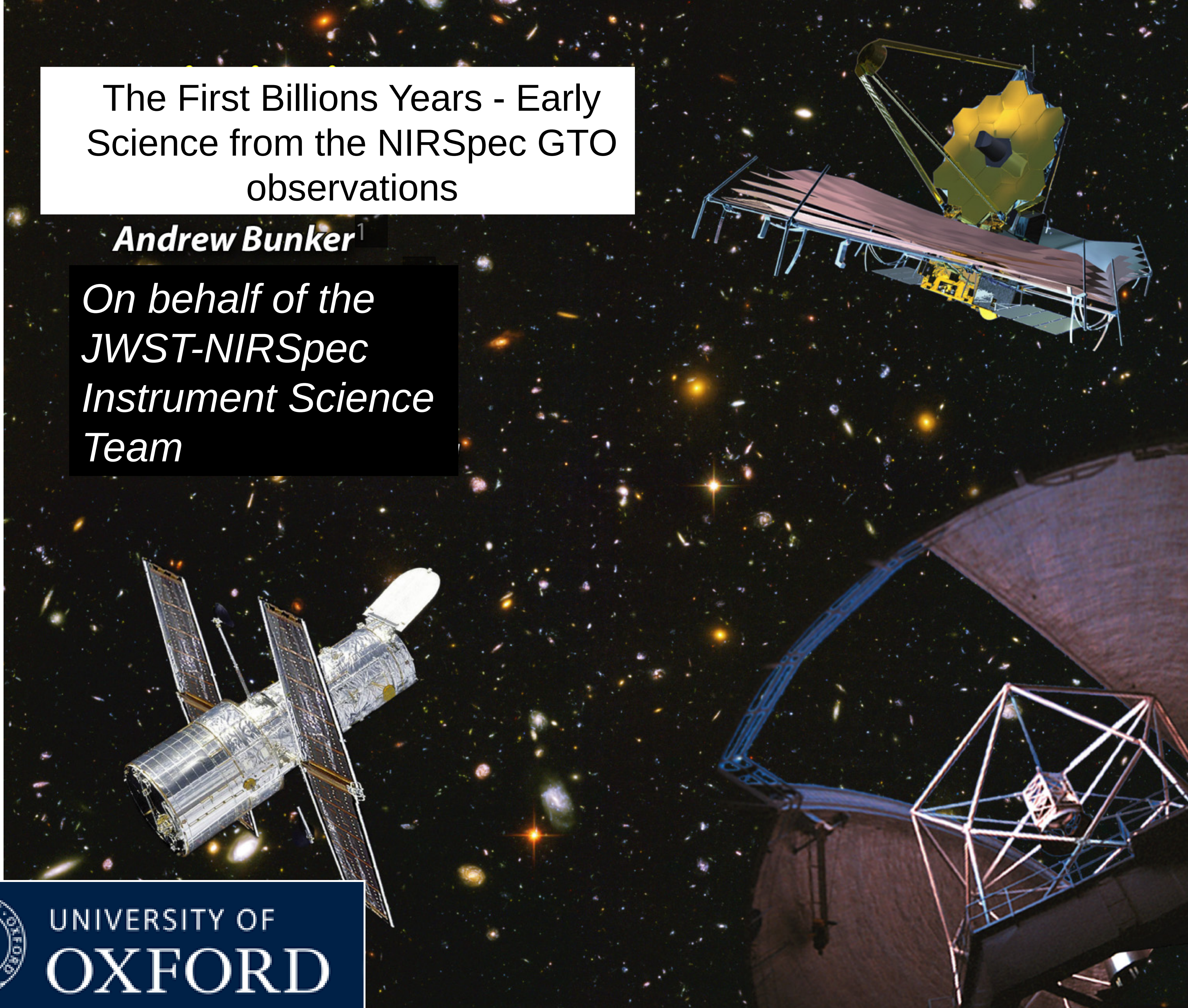
On behalf of the JWST-NIRSpec Instrument Science Team



UNIVERSITY OF OXFORD

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?

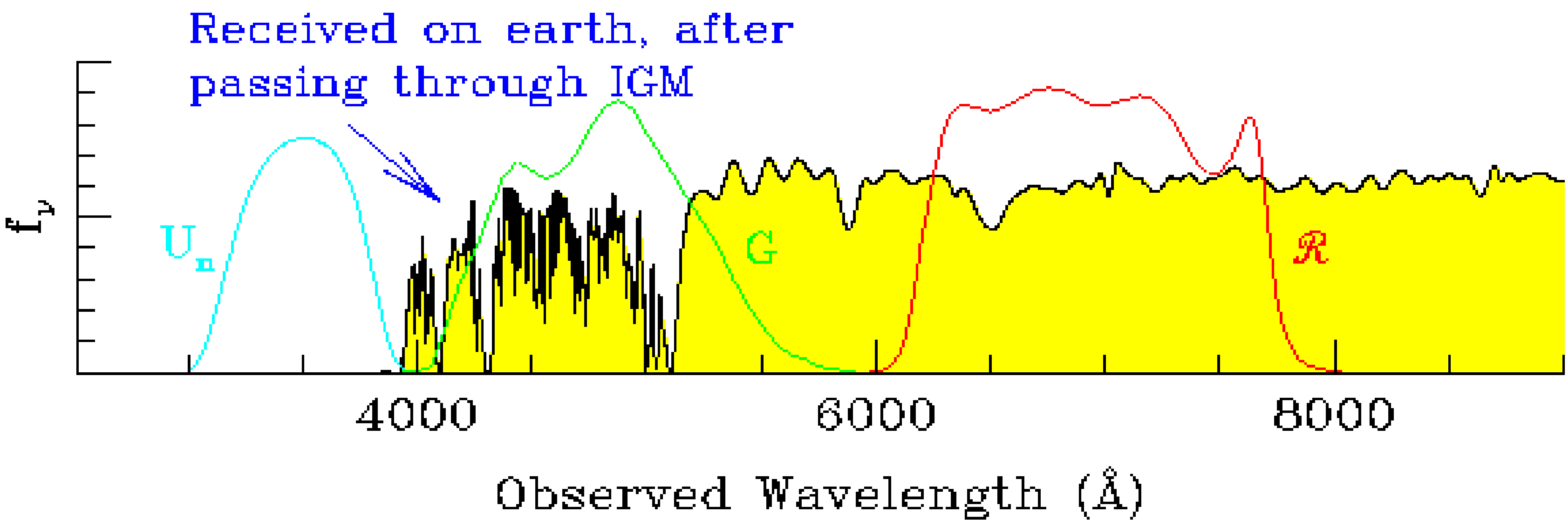
2) How is this star formation divided up among galaxies of different masses/environments as a function of cosmic time (“downsizing” etc).

3) Can we find the first generation of metal-free Population-III stars?

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)?

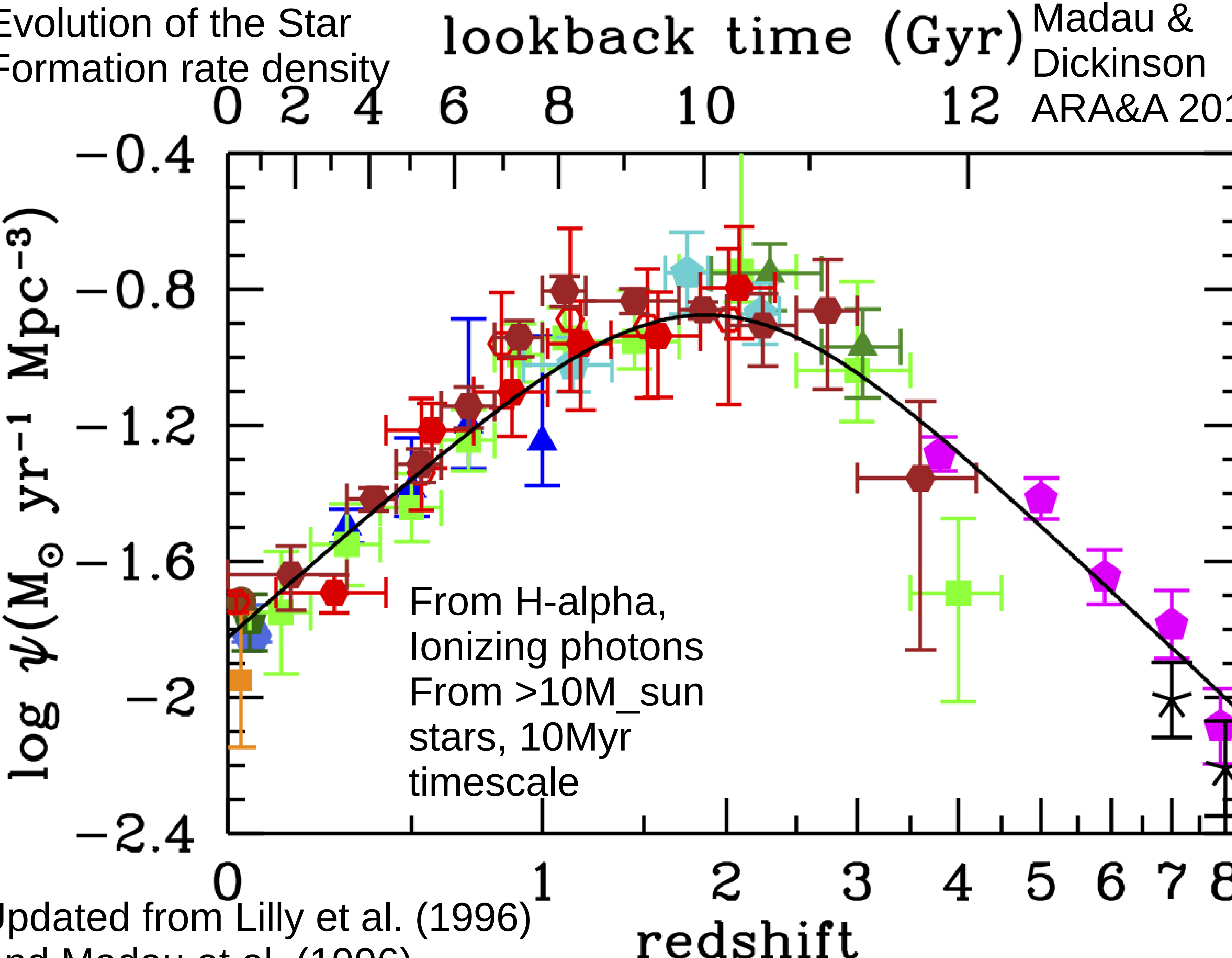
6) What is the co-evolution of supermassive black holes and galaxies, and how do we form SMBHs at $z>7$?



"Lyman break technique" - sharp drop in flux at λ below Ly-α. First done by Steidel et al. have >1000 z~3 objects, "drop" in U-band. Now with HST/WFC3 in the near-IR pushing "optical dropout" galaxies at z~6-12. At z>6 almost complete Gunn-Peterson absorption below Lyman-alpha (Universe mostly neutral at z>8-9)

Evolution of the Star Formation rate density

Madau & Dickinson ARA&A 2014



Updated from Lilly et al. (1996)
And Madau et al. (1996)

Evolution of the Star Formation rate density

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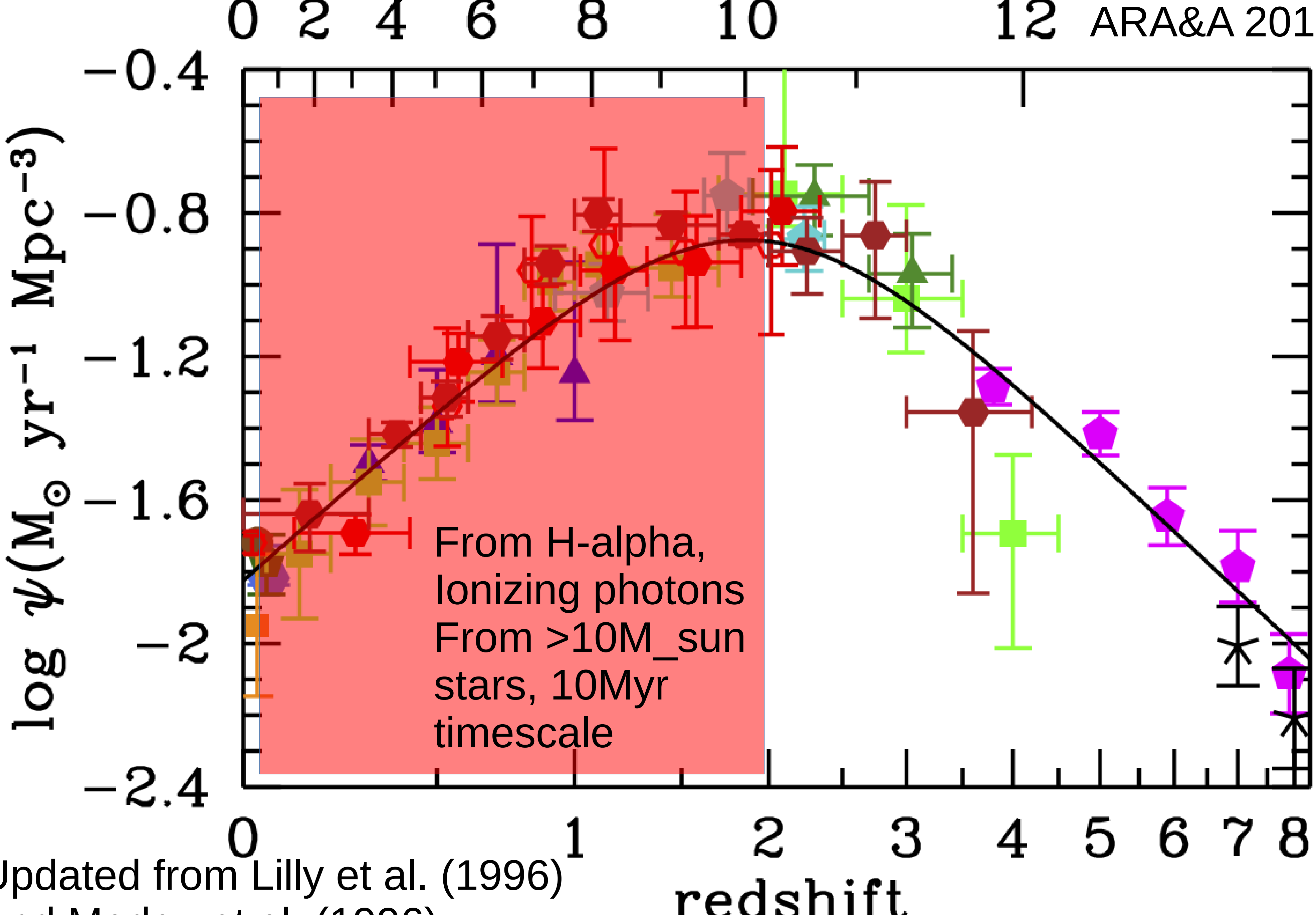

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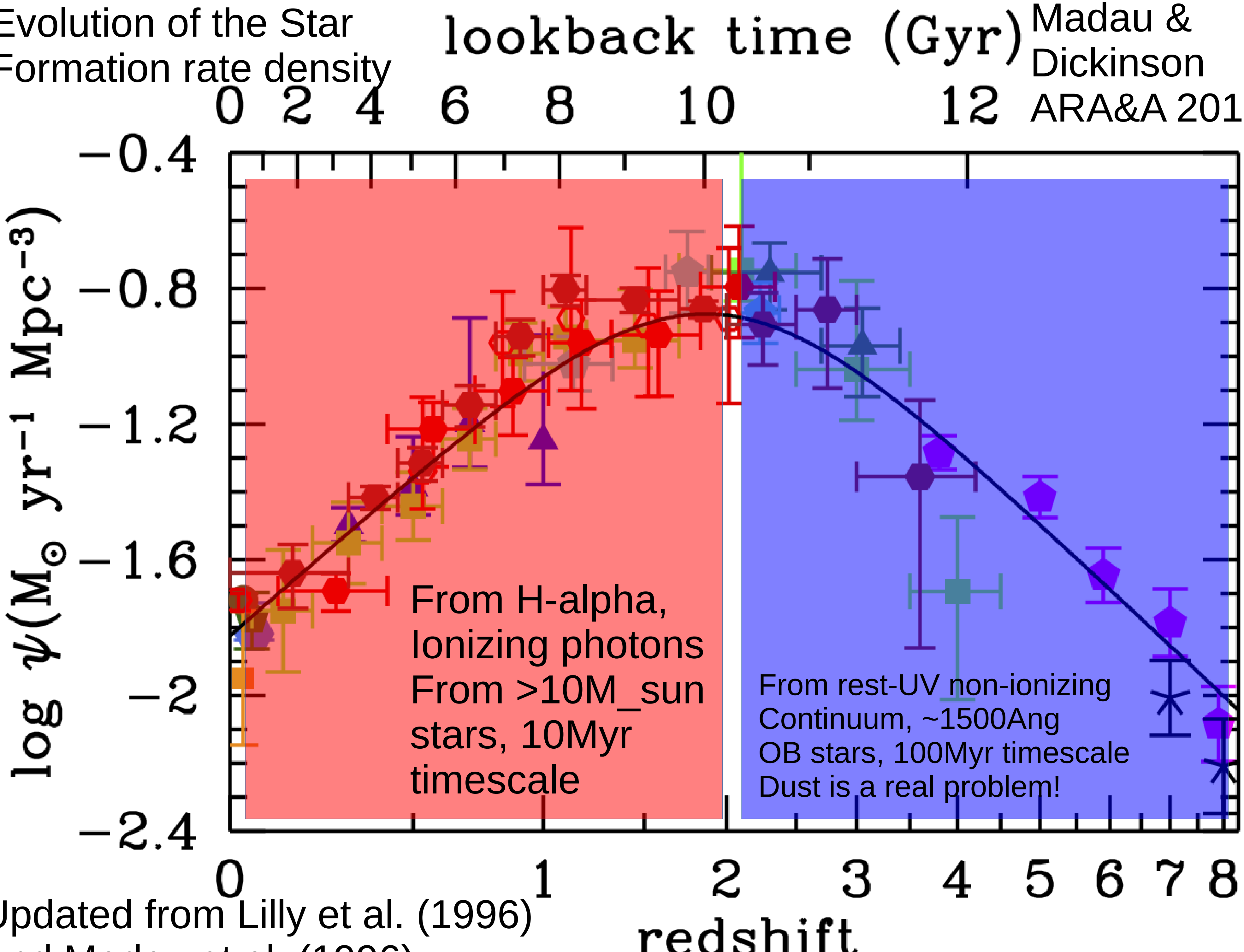

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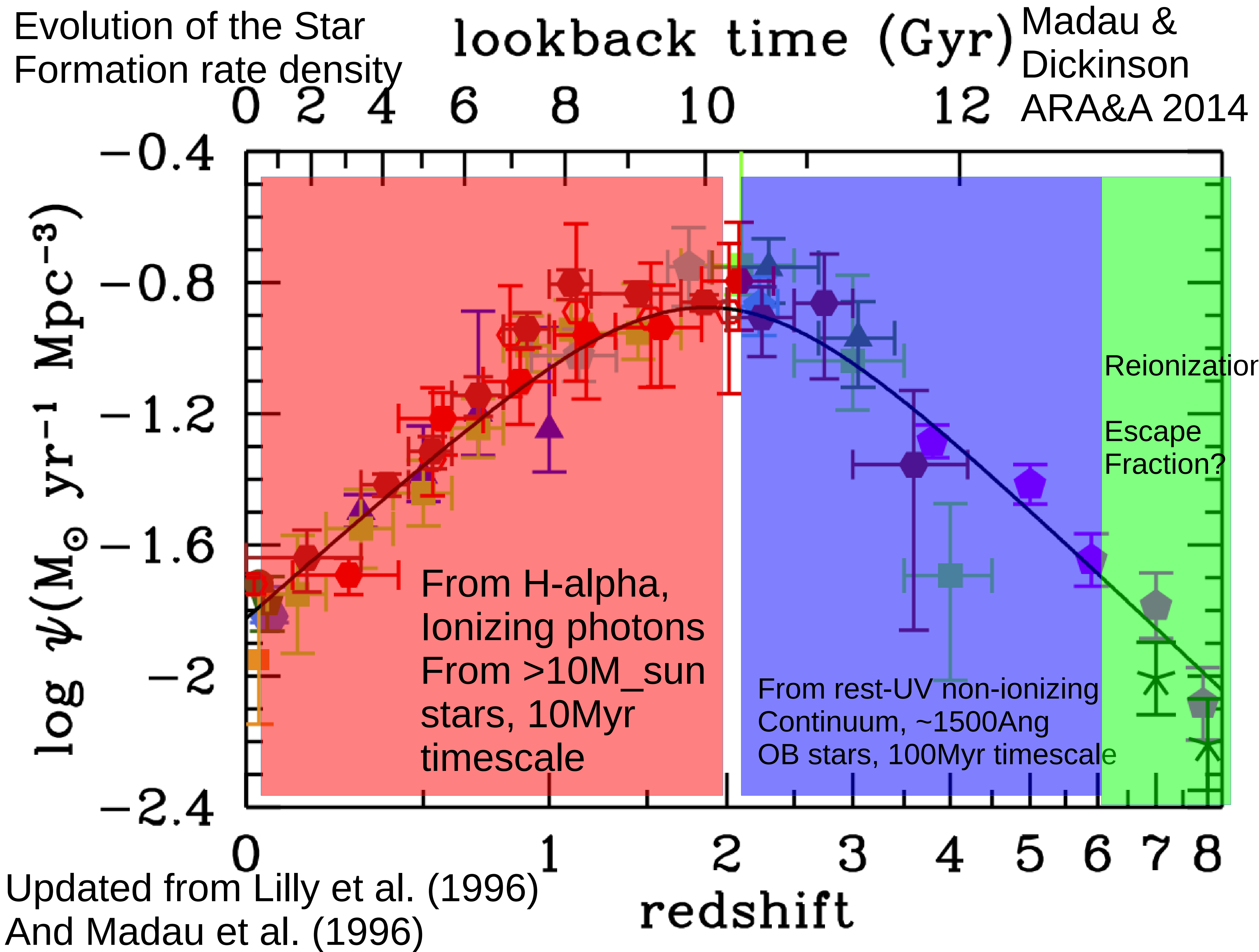
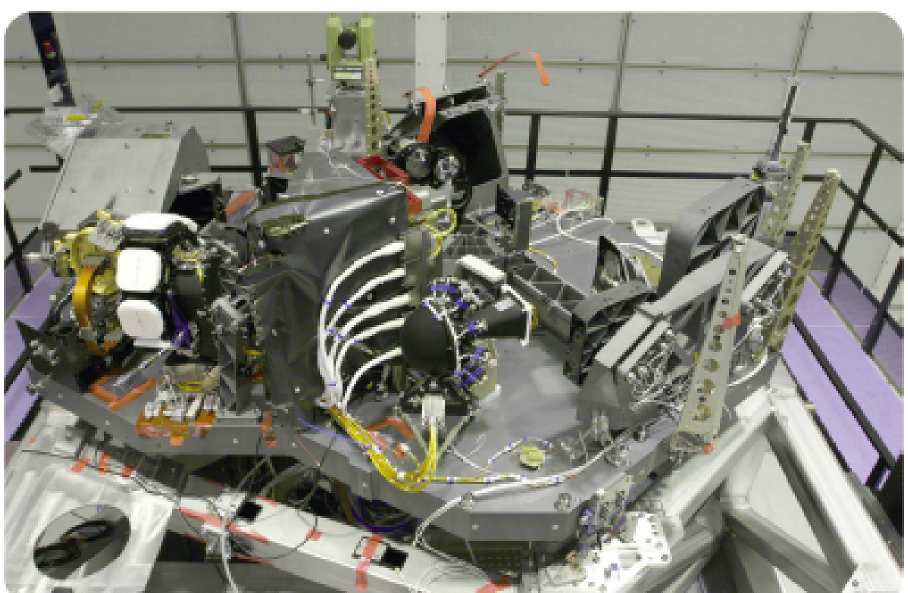


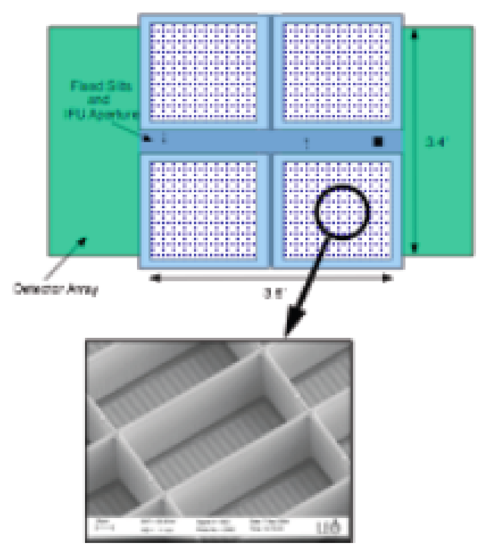
Evolution of the Star Formation rate density
Madau & Dickinson ARA&A 2014
lookback time (Gyr)
0 2 4 6 8 10 12
log ψ(M⊙ yr⁻¹ Mpc⁻³)
−0.4
−0.8
−1.2
−1.6
−2
−2.4
From H-alpha, Ionizing photons From >10M_sun stars, 10Myr timescale
From rest-UV non-ionizing Continuum, ~1500Ang OB stars, 100Myr timescale
Reionization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

NIRSpec

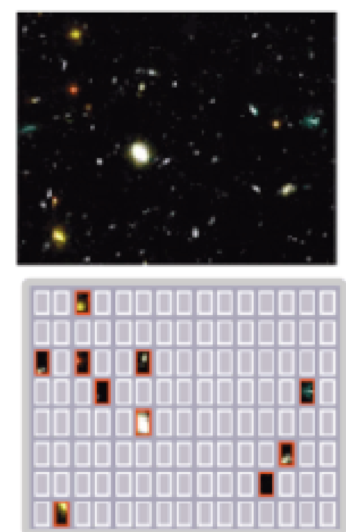
- Developed by the European Space Agency with Astrium GmbH and GSFC
  - ➡ Operating wavelength: 0.6 – 5.0 µm
  - ➡ Spectral resolution: 100, 1000, 3000
  - ➡ Field of view: 3.4 x 3.4 arc minutes
  - ➡ Aperture control: programmable micro-shutters, 250,000 pixels
  - ➡ Angular resolution: shutter open area 203 x 463 mas, pitch 267 x 528 mas
  - ➡ Detector type: HgCdTe, 2048 x 2048 pixel, 2 detectors, T_{op} = 37K (passive)
  - ➡ Reflective optics, SiC structure and optics



Microshutters



Multiple Objects
≤ 100 objects

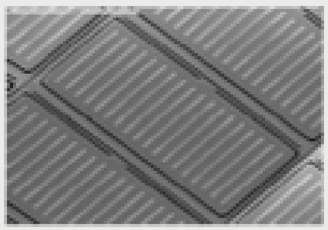


JWST/NIRSpec
Multi-object spectroscopy (MOS)

- **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.

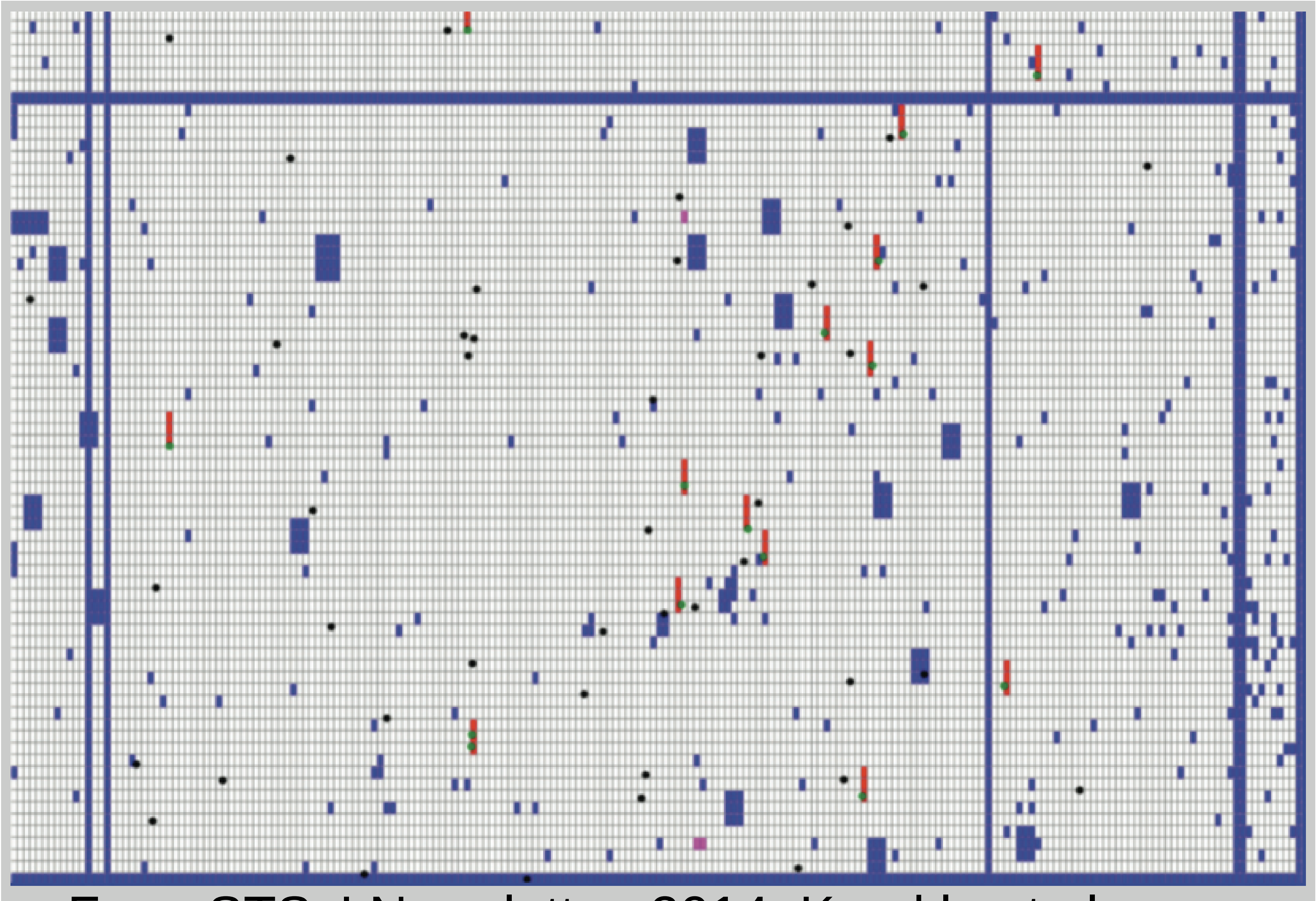
This gives us a total of almost **250 000** small apertures that can be individually opened/closed



MEMS device – 105x204 micron shutters

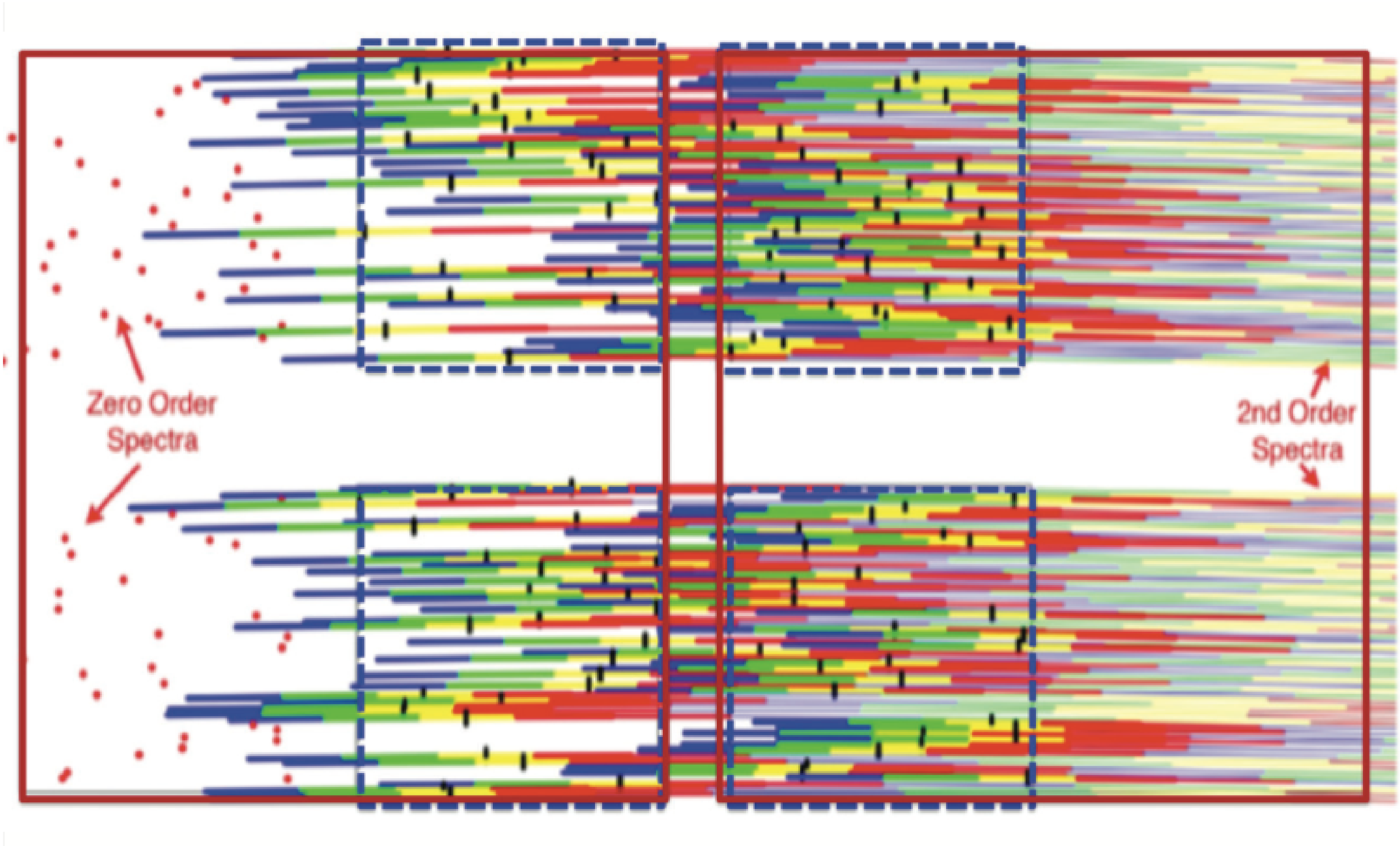
We typically need > 85-90 % of the shutters operable.

NIRSpec microshutters



From STScI Newsletter, 2014, Karakla et al.

Spectra from NIRSpec



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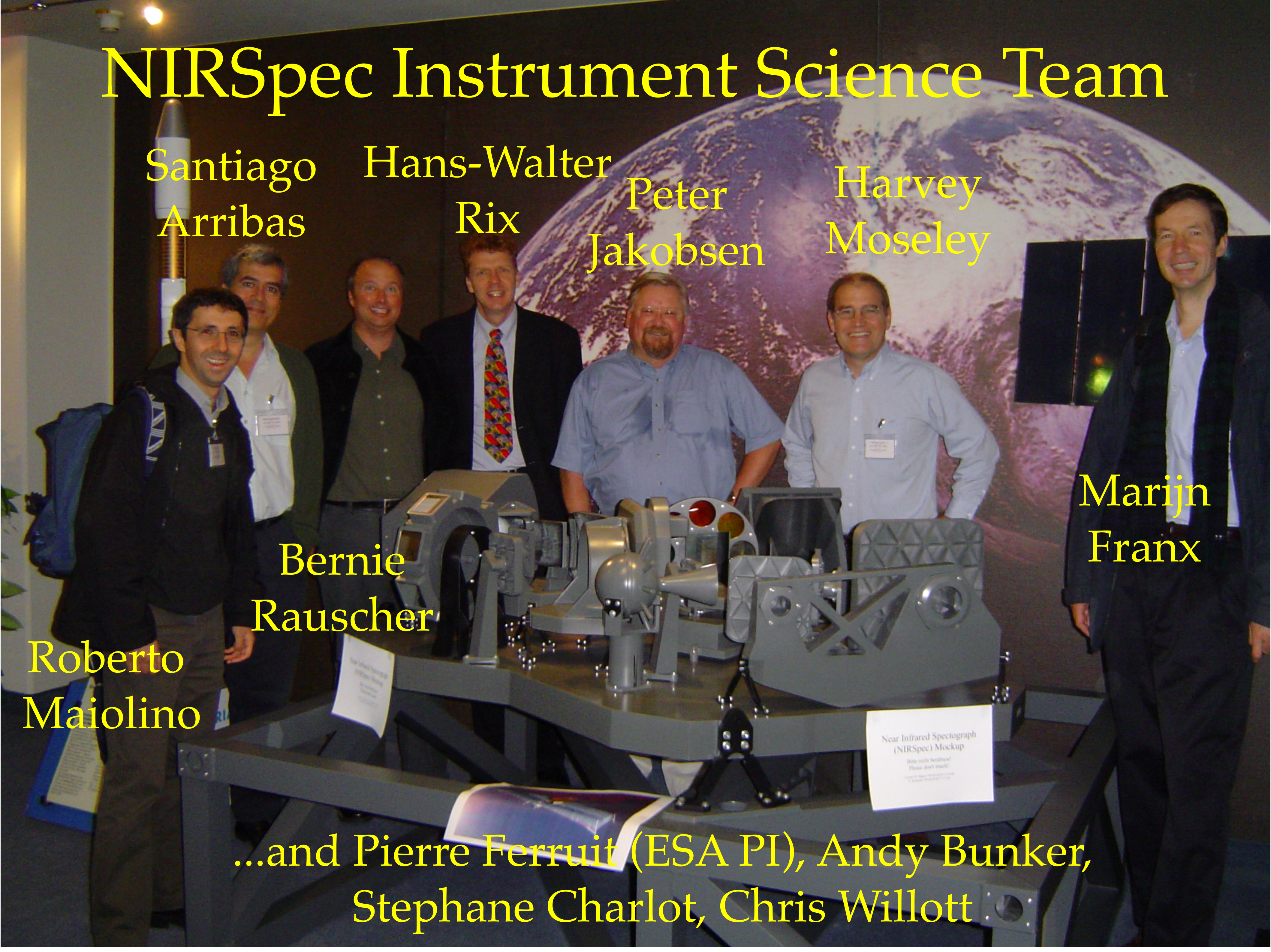

NIRSpec Instrument Science Team
Santiago Arribas
Hans-Walter Rix
Peter Jakobsen
Harvey Moseley
Marijn Franx
Bernie Rauscher
Roberto Maiolino
Near Infrared Spectograph
(NIRSpec) Mockup
...and Pierre Ferruit (ESA PI), Andy Bunker,
Stephane Charlot, Chris Willott

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

The GTO Galaxy Assembly Time

Targetting well-studied fields (want Hubble data at optical wavelengths to select Lyman breaks at z<7, and complementary UV/radio/sub-mm/X-ray etc. data)

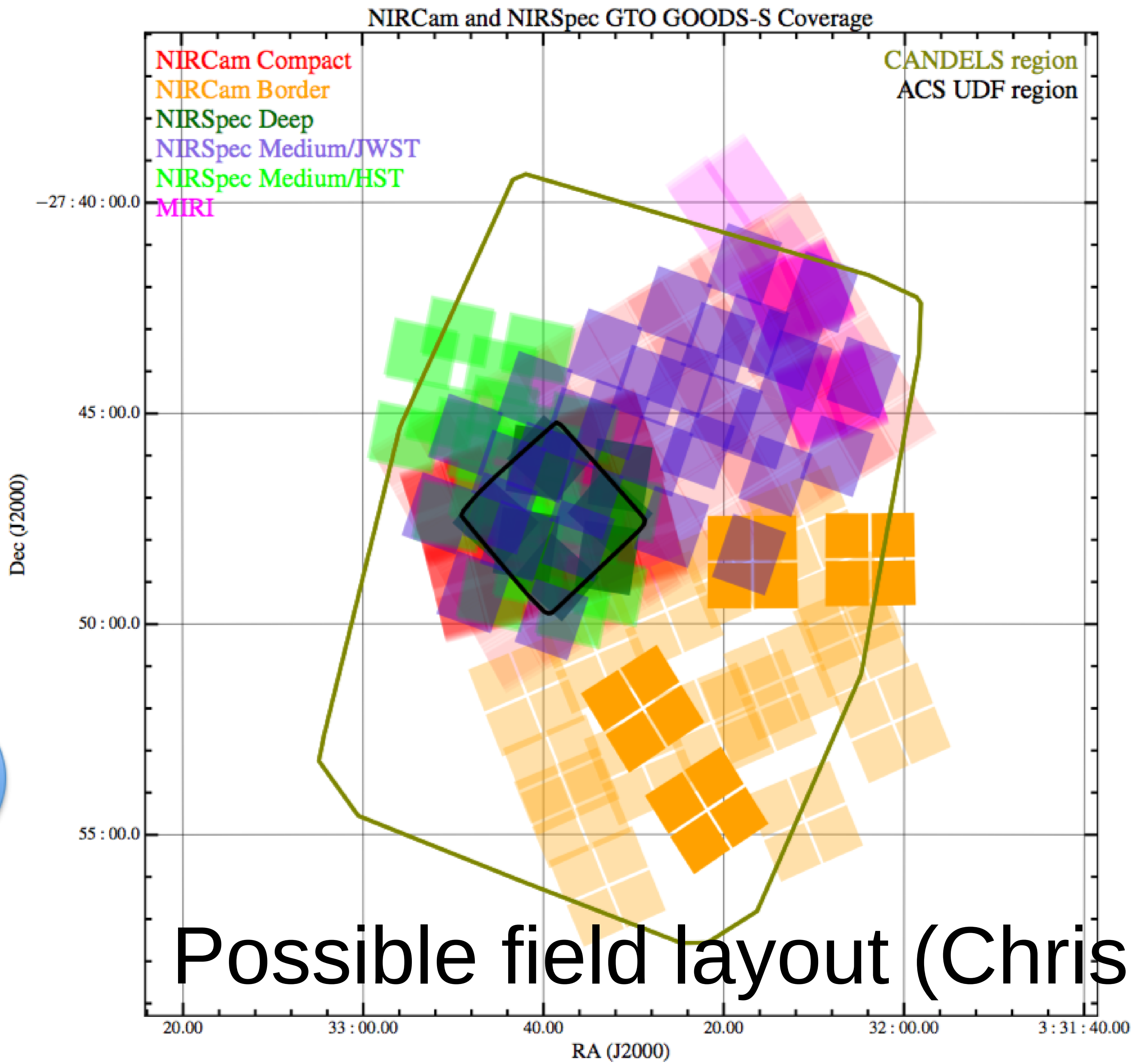
Using CANDELS fields, in particular GOODS-North and GOODS-South (which includes the Hubble Ultra Deep Field, HUDF).

Three tier survey - “wedding cake”

Will look at HUDF early in programme for part of 'deep' tier, target known high-z candidates from HST etc., high enough target density to use MSA effectively

Working with NIRCam team, will then follow-up NIRCam imaging (including another deep pointing, and several medium-depth fields)

Utilize parallels, mainly NIRCam and some MIRI



Possible field layout (Chris Willott)

The Three Tiers – 450 hours MSA

Deep (148 hours) - 100ks in CLEAR/PRISM for a set of ~150 objects; 4x25ks in F070LP/G140M, F170LP/G235M, F290LP/G395M and F290LP/G395H (25ks for each configuration) for the same set of objects (allowing spectra to overlap). Two fields, one HUDF HST-selected, the second (nearby) NIRCam-selected

Medium (200 hours) – 12 pointings targetting NIRCam, total of ~40ks of exposure time split between low (CLEAR/PRISM), medium (F070LP/G140M, F170LP/G235M and F290LP/G395M) and high (F290LP/G395H) resolution spectral configurations.
Another 8 pointings with shorter exposures targetting HST fields (all Medium Tier in GOODS-N & S)

Wide (106 hours) - about 35 pointings (~ 270 square arcminutes) across the CANDELS areas, with the low spectral resolution CLEAR/PRISM configuration (50 min) and two of the high-spectral resolution configurations, F170LP/G235H and F290LP/G395H (35 min each)

Confirmation Highest redshift sources

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) know the intergalactic medium of the Universe reionizes at $z>6$ (probably around $z=10-11$)

NIRSpec will get very accurate redshifts, and hence determine accurate rest-frame properties;

measure emission lines (Hα, Hβ, [OIII], [OII]), to constrain: attenuation by dust, star formation rate; ionization state and metallicity of the interstellar gas; presence of an AGN; HeII-1640 for pop III? Recent candidate (CR7, Sobral et al. 2015) now unlikely

Which Targets?

1) Set pointing to capture most “bright” $z>9$ candidates, new object classes

2) high S/N sources at $z > 6$ sufficient for line ratio work, add $z > 6$ AGN, ALMA sources (expect ~ 30)

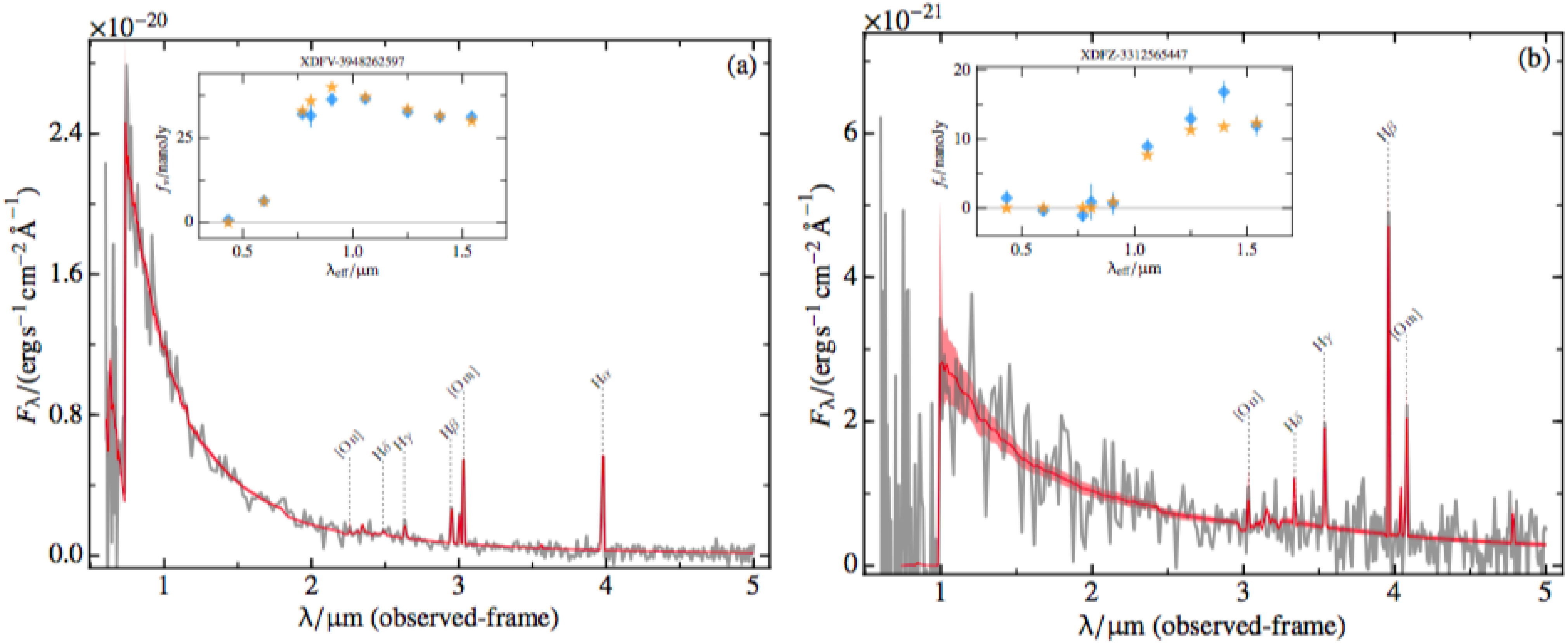
3) very rare sources at $z > 2$ for which we can high S/N spectroscopy at R~1000 on the continuum will be added (< 10 per MSA setting)

4) We use about 10 − 15% of remaining space for fainter galaxies at $z > 6$ (starting with the highest redshifts, working down). Science goal is redshifts and “simple” emission line diagnostics

5) Sources with “physics S/N ratio” will be selected at lower redshift (down to $z = 1.5$). Don't want to completely fill the masks with these – up to 20% remains available below. We divide these galaxies in bins of redshift, mass, star formation rate. This will encompass candidate passive galaxies at high redshift.

6) other types of sources (at the level of 20% or so) including “census sources” i.e. selected in a very simple way, e.g. 4.5 micron limited

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



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

Conclusions

- Have found star-forming galaxies at z=6-10 (Lyman breaks), limited spectroscopic confirmation at z~6; not much Ly-alpha emission beyond z~7 (due to Gunn-Peterson absorption?)

- NIRSpec Instrument Science Team investing most of our Guaranteed Time Observations into galaxy evolution (including half of 900hours on MSA survey, and about 1/3rd of the time on Integral Field Spectroscopy – see talk by Santiago Arribas)

- Working with NIRCam Instrument Science Team in combined survey of GOODS-North & South

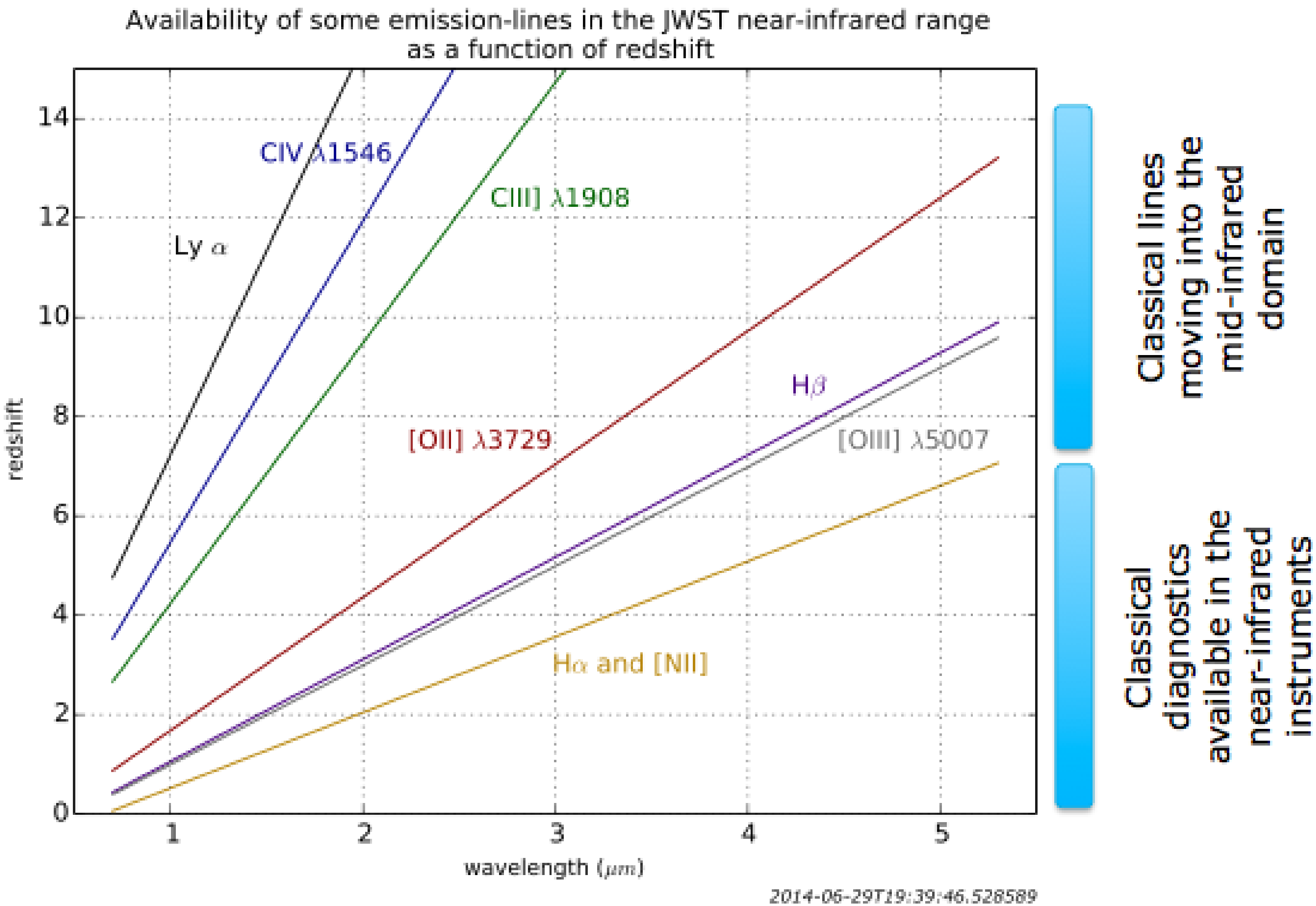
- JWST spectroscopy will get Hα, Hβ, [OIII], [OII] to high redshift,
Getting REAL redshifts for luminosity functions

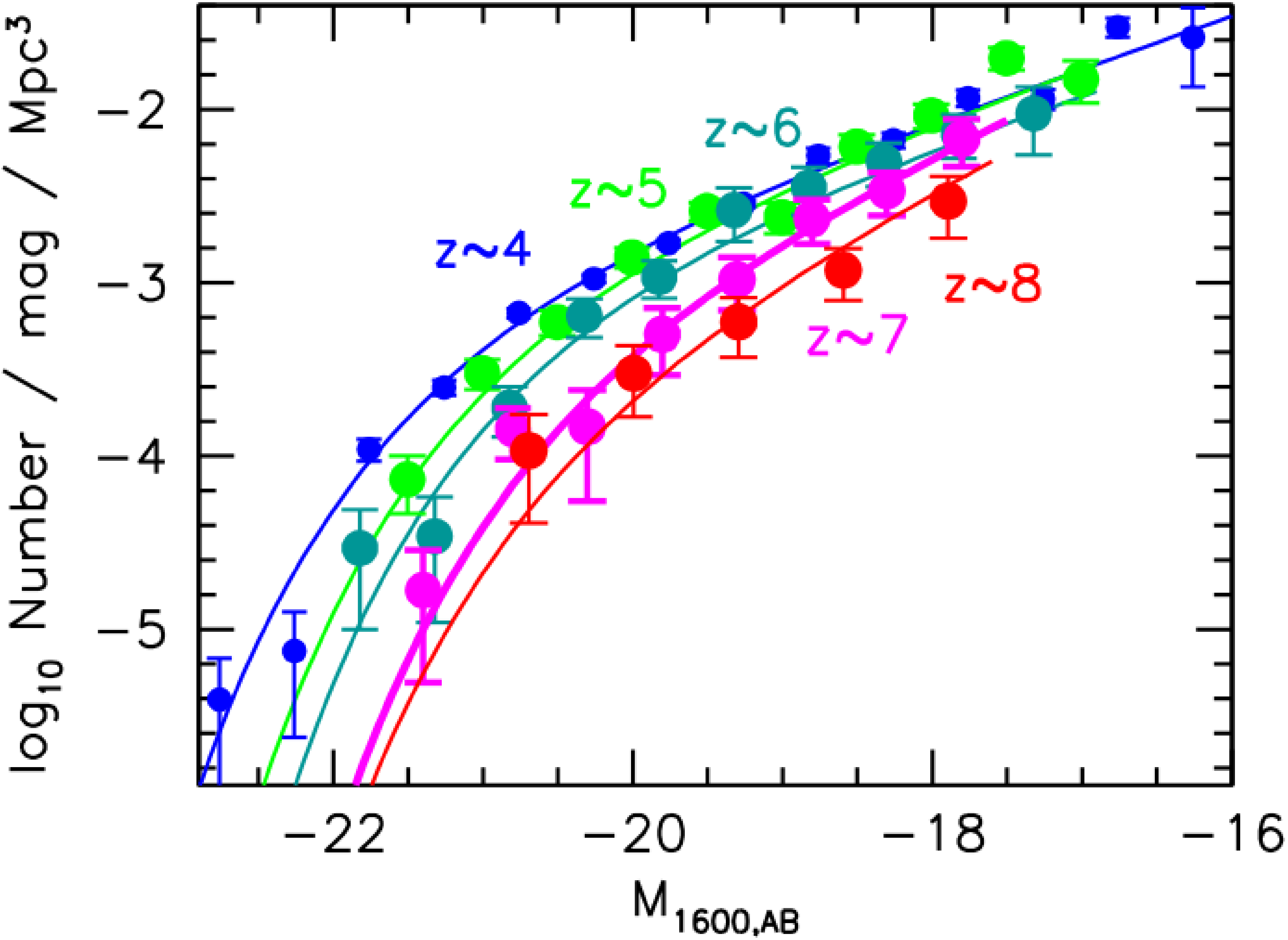
- will determine escape fractions, star formation rates, metallicities (Pop-III ?)

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

JWST/NIRSpec – The instrument

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





Evolution of the restframe UV luminosity function
From Bouwens et al. (2011)

The Key Problem

We know the intergalactic medium of the Universe reionizes at z>6
(probably around z=8-9 from Planck CMB)
What is the source of the UV photons to do this?
AGN are under-abundant at these high redshifts
Can star formation do it? Or is it something else?
Have been successful in recent years in finding star-forming galaxies at z=6 and beyond
Insufficient photon density from the high redshift luminous galaxies we have found so far

Can a different IMF (perhaps associated with Pop III) produce more ionizing photons (below 912Ang) than we infer from observations above Lyman-alpha (1216Ang)?

Is it the unobserved faint end of the luminosity function?

What is the escape fraction of ionizing photons?

Ly-alpha fraction (Stark et al. 2010)