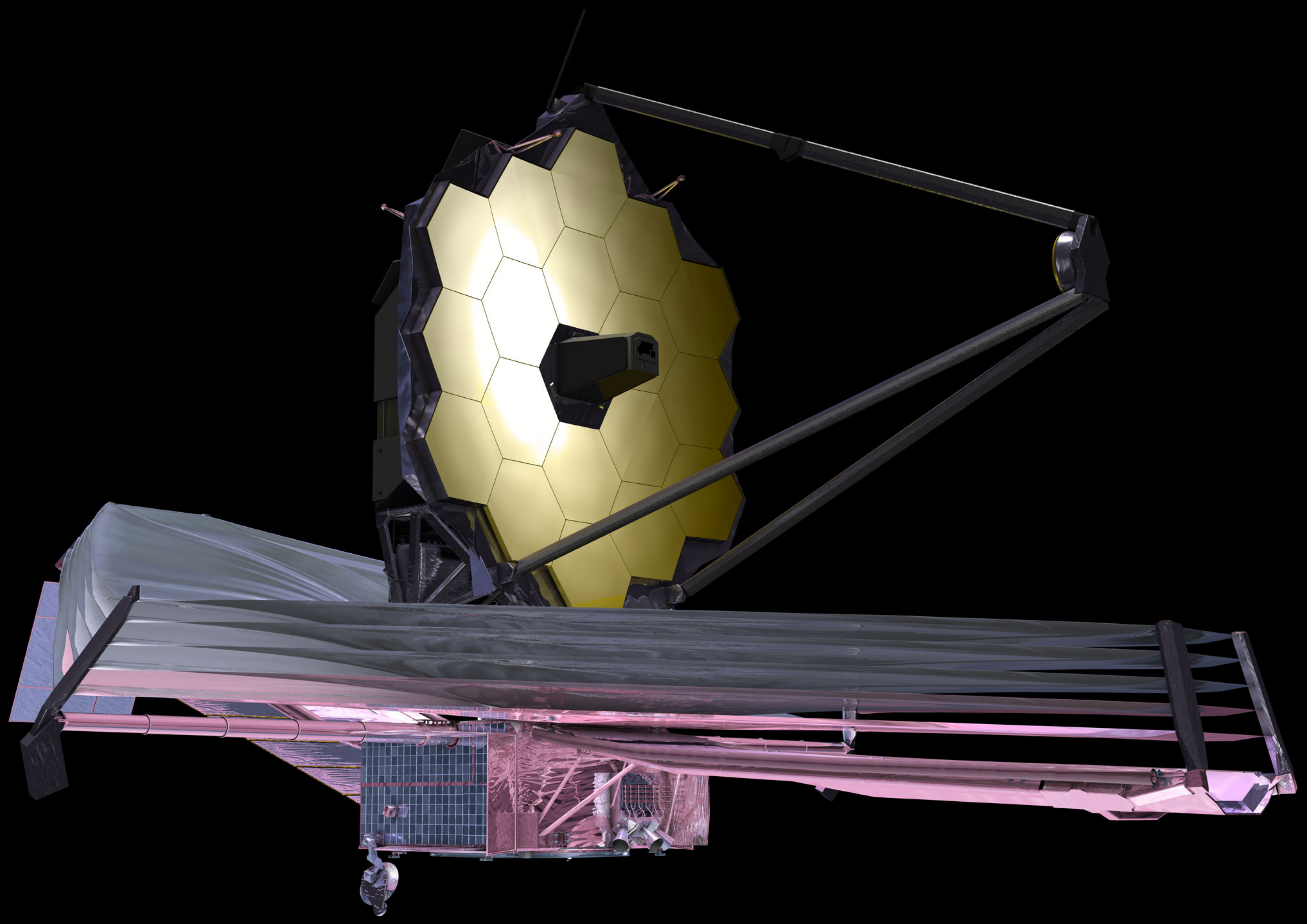


Distant Galaxies with JWST

Emma Curtis-Lake
STFC Webb Fellow
Banyuls
July 2025

Introducing myself

- STFC (UK-based funding agency) Webb fellow - doing science with JWST, supporting the community in using the telescope, and taking the public along for the incredible journey.

- PI of NIRSpec side of the JADES Survey (since June) - largest survey with JWST in first two years of operations.

- Currently lead developer of BEAGLE and BEAGLE-AGN and complete SED fitting geek!

- Things I love (random order!) - Statistics, galaxies, my family, gardening, reading, travelling, talking to the public about JWST, working with students, the early Universe

Talk outline

- Galaxy evolution - broad brush-strokes and some pre-JWST results
- Inferring galaxy properties of distant galaxies Pre-JWST
- Now - NIRCam, the power of medium bands, MIRI, spectroscopy
- Introduction to SED fitting
- Early galaxy evolution should be easy with JWST now, right?
- Summary

Galaxy evolution & some results pre-JWST

Galaxy evolution

Credit:NAOJ

Galaxy evolution

What might we expect to be evolving?

- Build up in numbers of galaxies over time
- Galaxies likely getting more massive
- Building up more metals in the ISM
- Depletion in gas reservoirs
- Prevalence of AGN
- ...?

Credit:NAOJ

Galaxy evolution

How do we study galaxy evolution?

- Often, we look at some properties of the galaxy population (e.g. brightness, mass, amount of metals), sometimes multiple at once (e.g. mass-metallicity, mass-sfr relations) and trace the evolution over cosmic time.
- We then compare to galaxy simulations, or if we can link our galaxy populations to their underlying dark matter halo properties

Credit:NAOJ

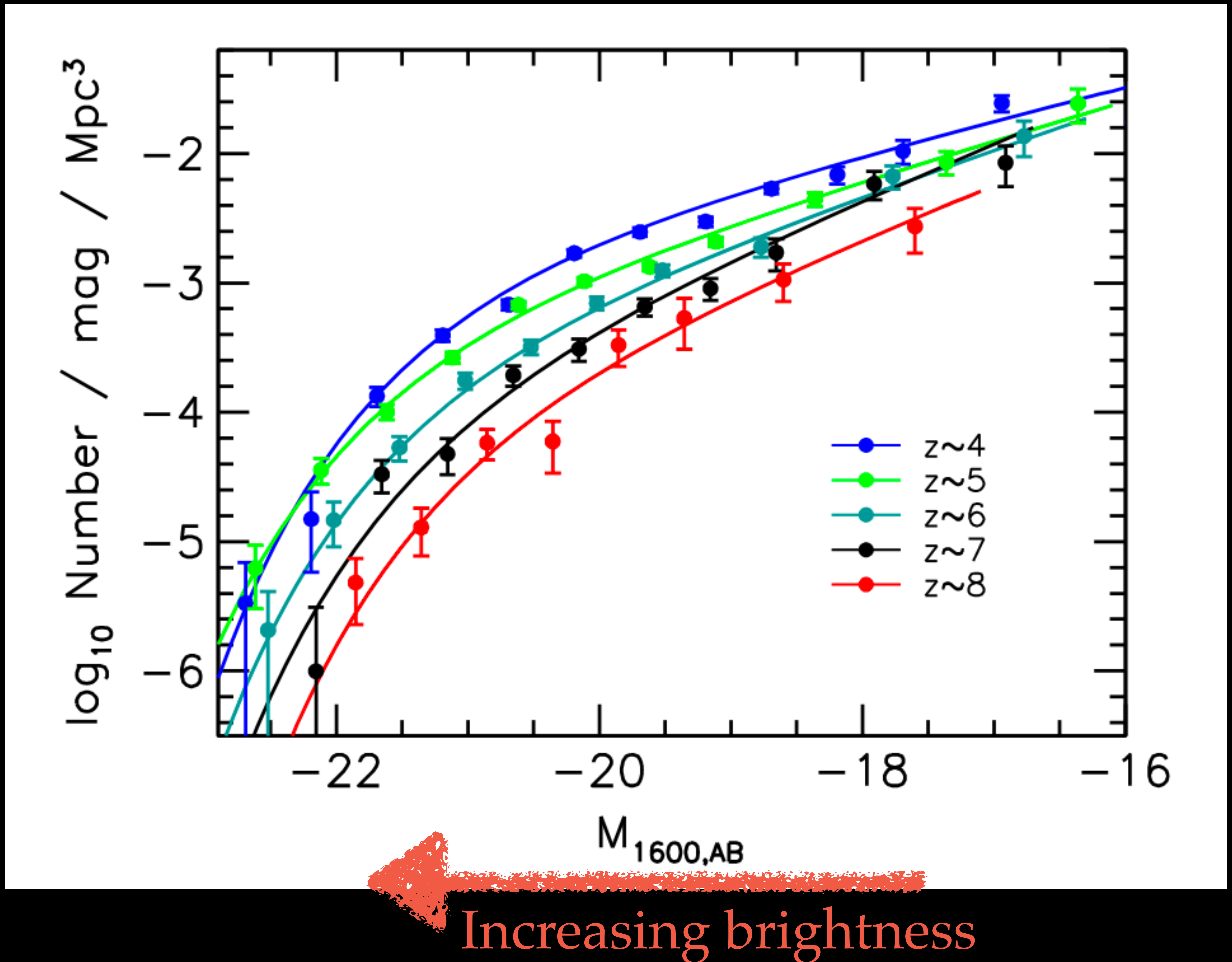
Cosmic star formation rate density
billion
1 billion
4 billion
8 billion
13.8 billion
Formation of the first astronomical objects
Present day

Galaxy evolution

What might we expect to be evolving?

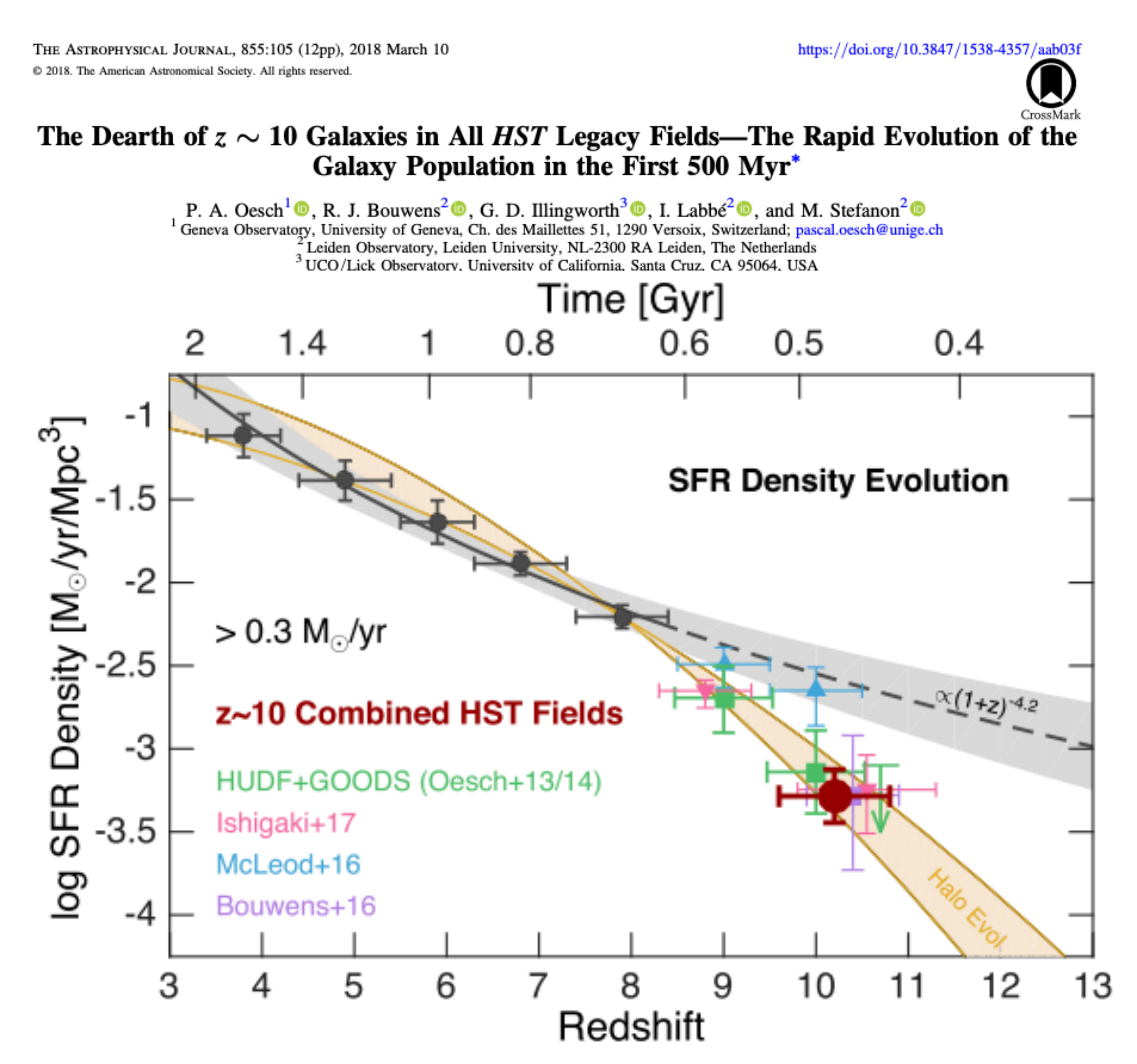
- Build up in numbers of galaxies over time

Bouwens+ 2015.ApJ.803



Luminosity functions:
'Count' numbers of galaxies
of given brightness
within survey volume

Pre-JWST, some disagreements


THE ASTROPHYSICAL JOURNAL, 855:105 (12pp), 2018 March 10 https://doi.org/10.3847/1538-4357/aab03f
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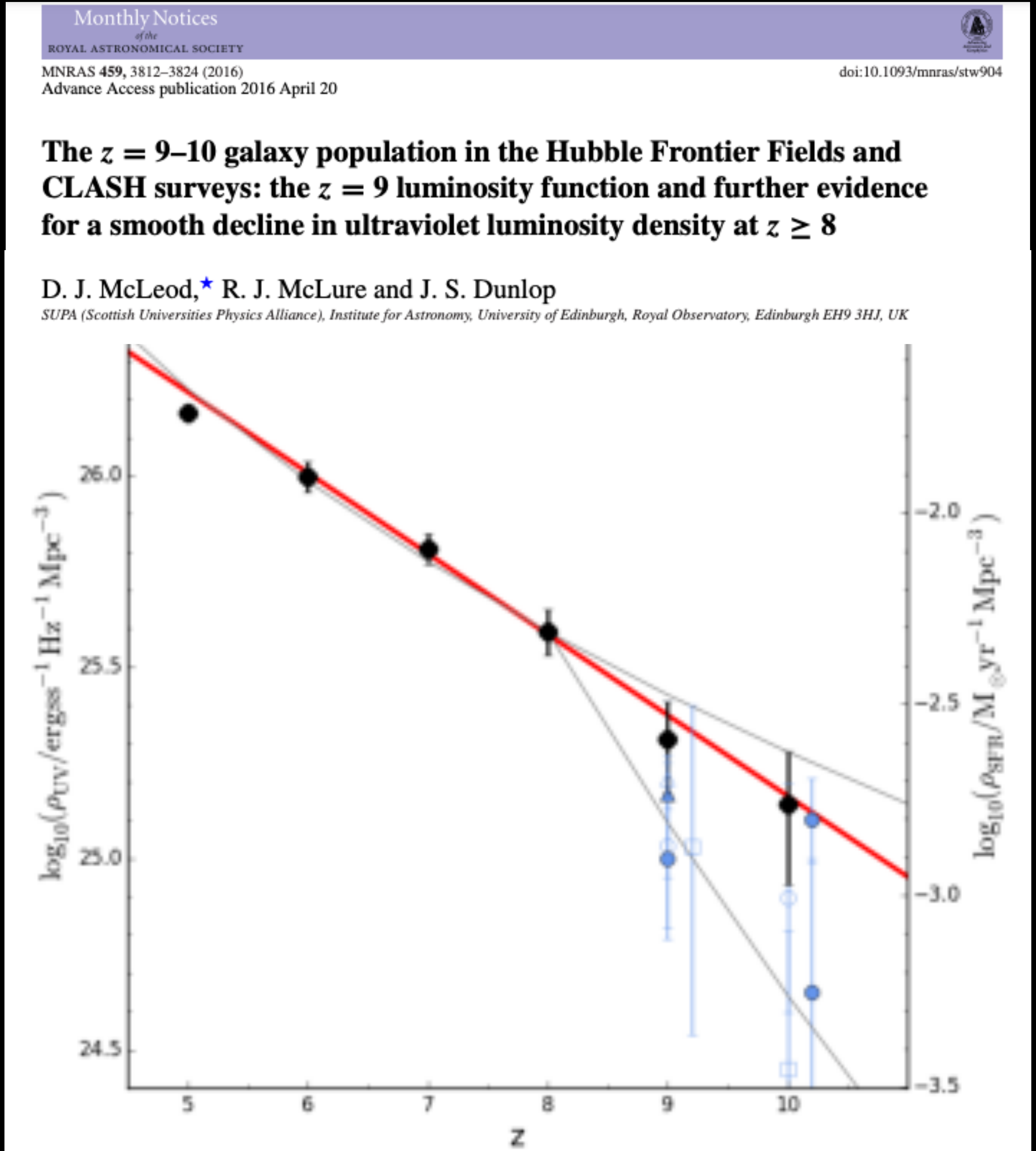
The Dearth of $z \sim 10$ Galaxies in All *HST* Legacy Fields—The Rapid Evolution of the Galaxy Population in the First 500 Myr*

P. A. Oesch[1], R. J. Bouwens[2], G. D. Illingworth[3], I. Labbé[2], and M. Stefanon[2]
[1] Geneva Observatory, University of Geneva, Ch. des Maillettes 51, 1290 Versoix, Switzerland; pascal.oesch@unige.ch
[2] Leiden Observatory, Leiden University, NL-2300 RA Leiden, The Netherlands
[3] UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA


Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 459, 3812–3824 (2016) doi:10.1093/mnras/stw904
Advance Access publication 2016 April 20

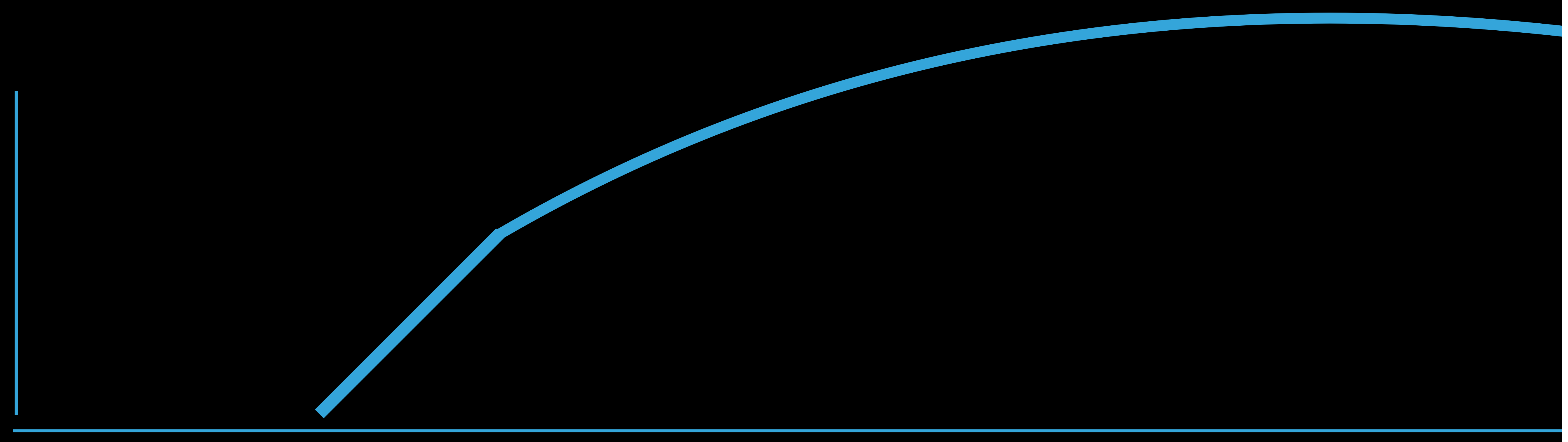
The $z = 9$–10 galaxy population in the Hubble Frontier Fields and CLASH surveys: the $z = 9$ luminosity function and further evidence for a smooth decline in ultraviolet luminosity density at $z \geq 8$

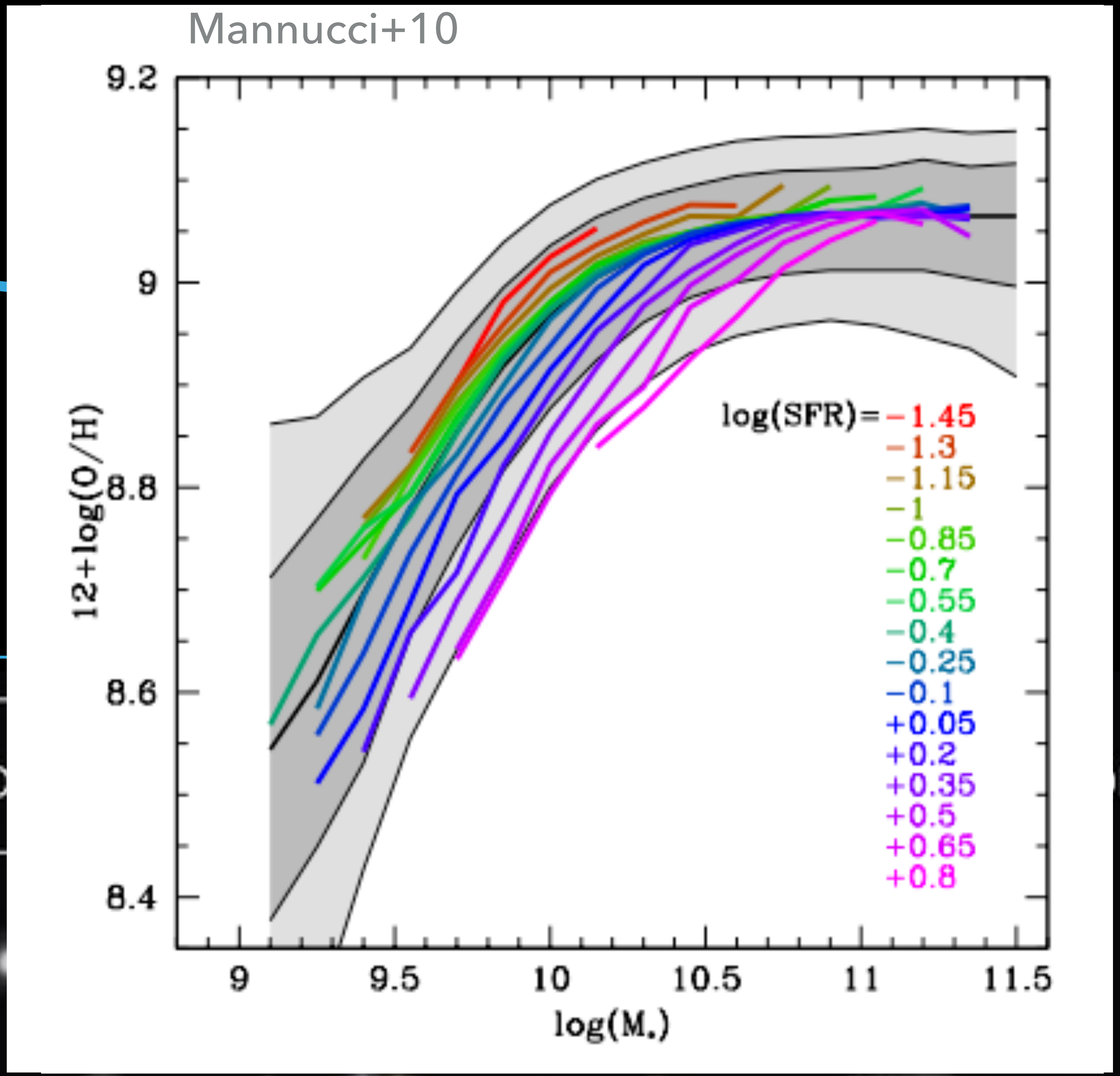
D. J. McLeod,* R. J. McLure and J. S. Dunlop
SUPA (Scottish Universities Physics Alliance), Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK

These show the cosmic star formation rate density at early times, but WARNING, x-axis is flipped

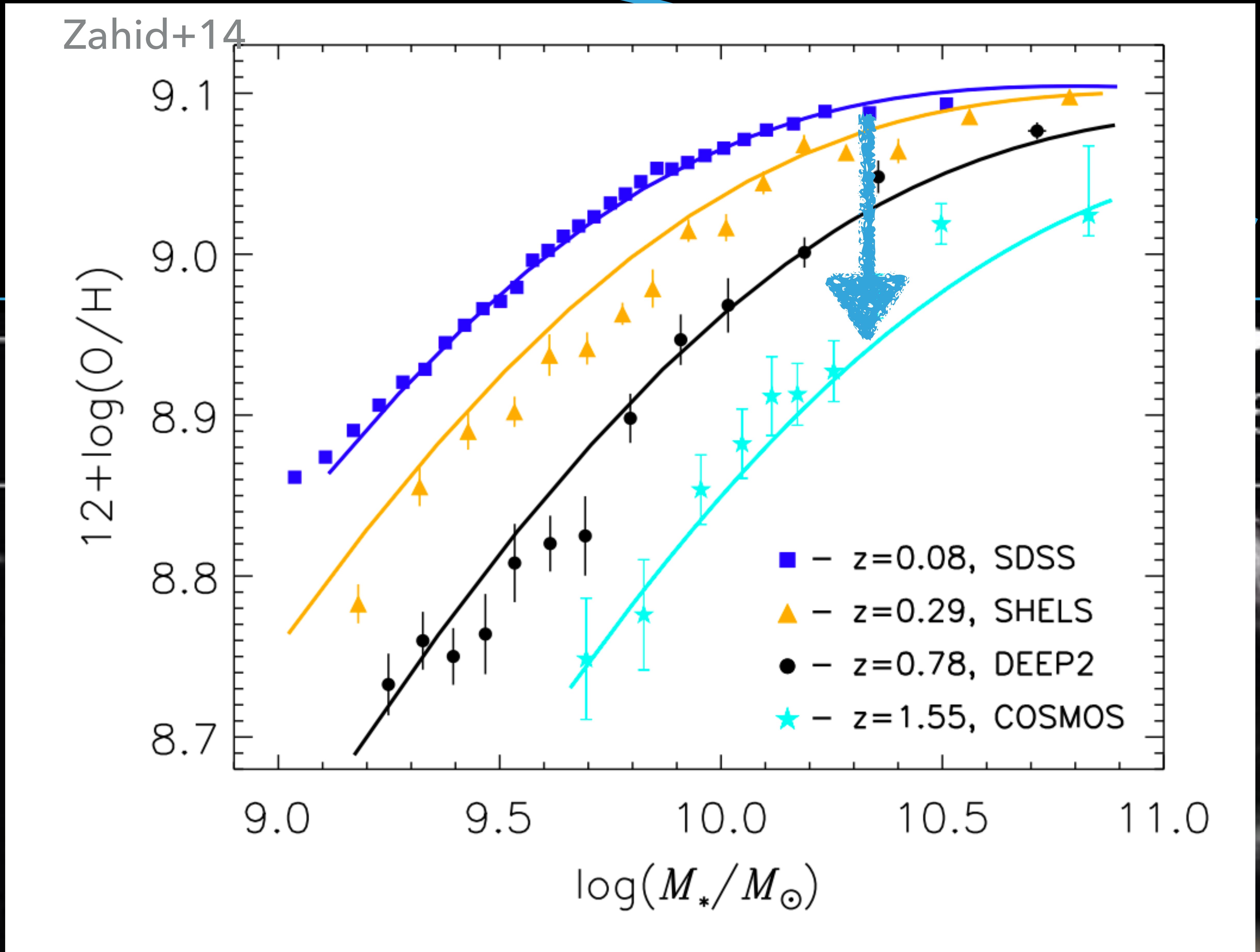
Cosmic star formation rate density
Hubble could see to within ~400 Million years of the Big Bang
but JWST can see further
1 billion
4 billion
8 billion
13.8 billion
Formation of the first astronomical objects
Present day
Credit:NAOJ

Cosmic star formation rate density





Impossible to extend this work to high redshifts with ground-based facilities because of the atmosphere.



Credit:NAOJ

Cosmic star formation rate density
billion
1 billion
4 billion
8 billion
13.8 billion
Formation of the first astronomical objects
Present day
Credit:NAOJ

Inferring galaxy properties of distant galaxies Pre-JWST

Studying the high-redshift Universe pre-JWST - Timeline

- 1996 - Steidel et al. give spectroscopic confirmation of objects $3<z<3.5$ selected using the Lyman-break Technique (Steidel & Hamilton 1992, 1993, Steidel, Pettini & Hamilton I, II and III 1995)

- 2002 - Beginning of the GOODS (Great Observatories Origins Deep Survey) with Hubble imaging across two fields that become known as GOODS-South and GOODS-North - in the North there was the Hubble Deep Field North and in the south was deep Chandra (X-ray) imaging.

- Sept 2003- Jan 2004 - Data for the Hubble Ultra-deep Field (HUDF) taken -this plus GOODS provide fruitful datasets to probe up to z~7

- 2009 - Hubble upgraded with more sensitive IR-camera WFC3 - another boon for the high-redshift community and high competition to identify high-redshift candidates. HUDF09 campaign. Now pushing up to z~11-12!

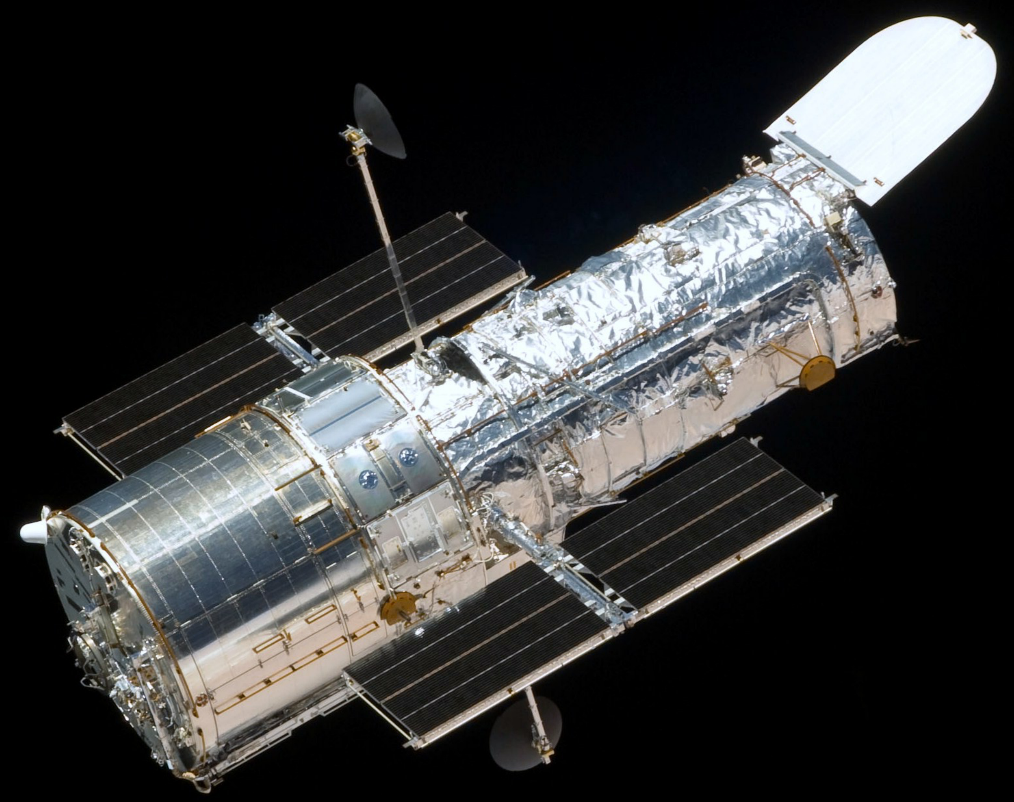
- 2012 - UDF12 campaign (Ellis+13) adds hundreds more hours to HUDF

- Progress since …. Spitzer giving rest-frame optical imaging - ALMA helping with spectroscopic confirmations - some ground based surveys covering wider areas up to z~10-11 (e.g. COSMOS, Hyper Suprime-CAM).

Credit: NASA

Inferring galaxy properties Pre-JWST

First we have to find them.....

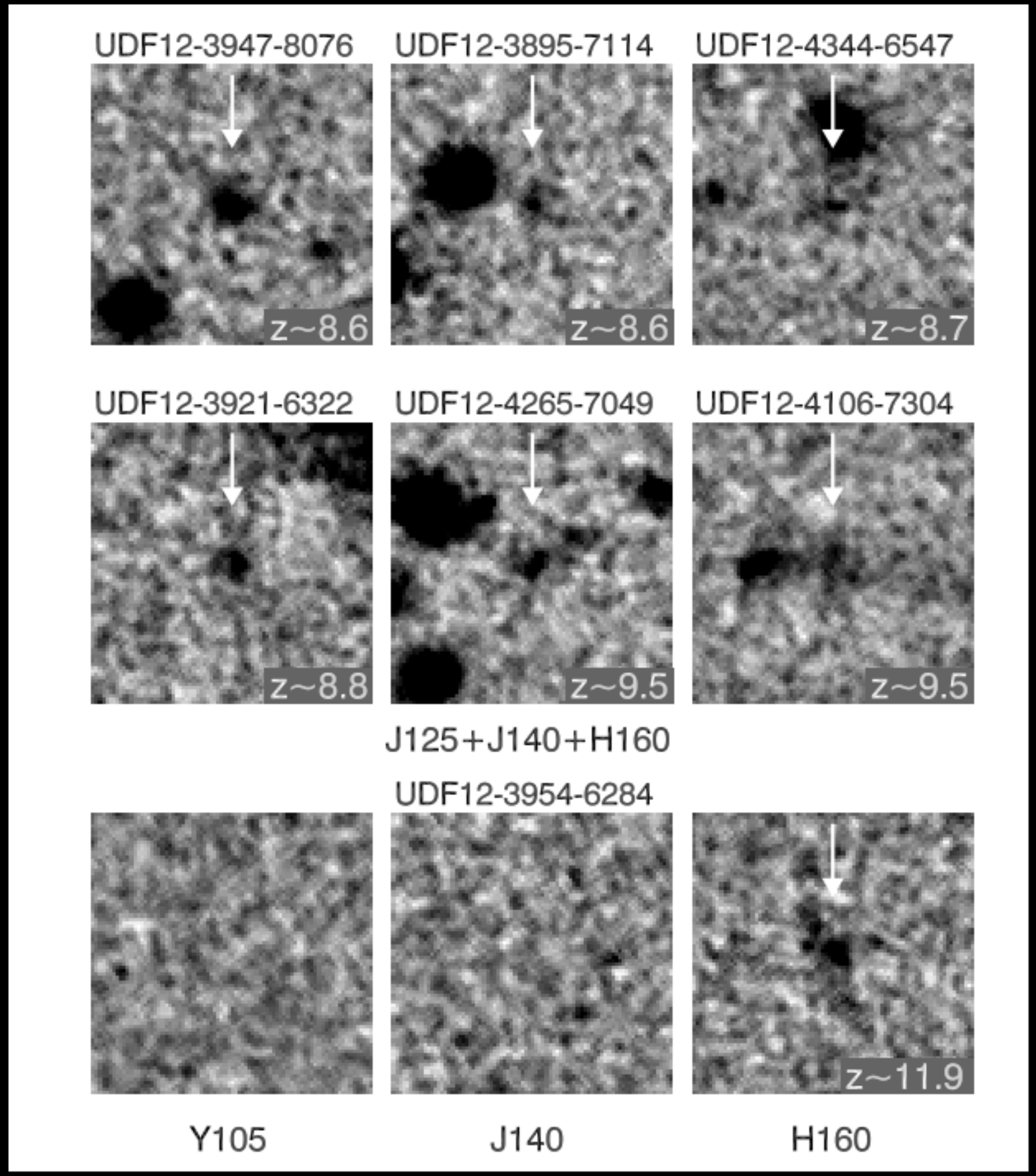


Hubble eXtreme Deep Field (XDF)
Hubble Space Telescope • ACS/WFC • WFC3/IR

NASA and ESA

STScI-PRC12-37

Inferring galaxy properties Pre-JWST



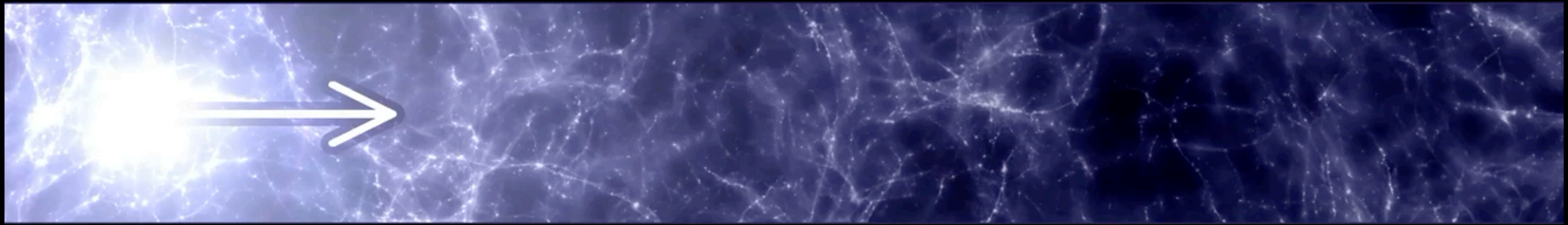
Ellis et al. 2013, ApJ, 763

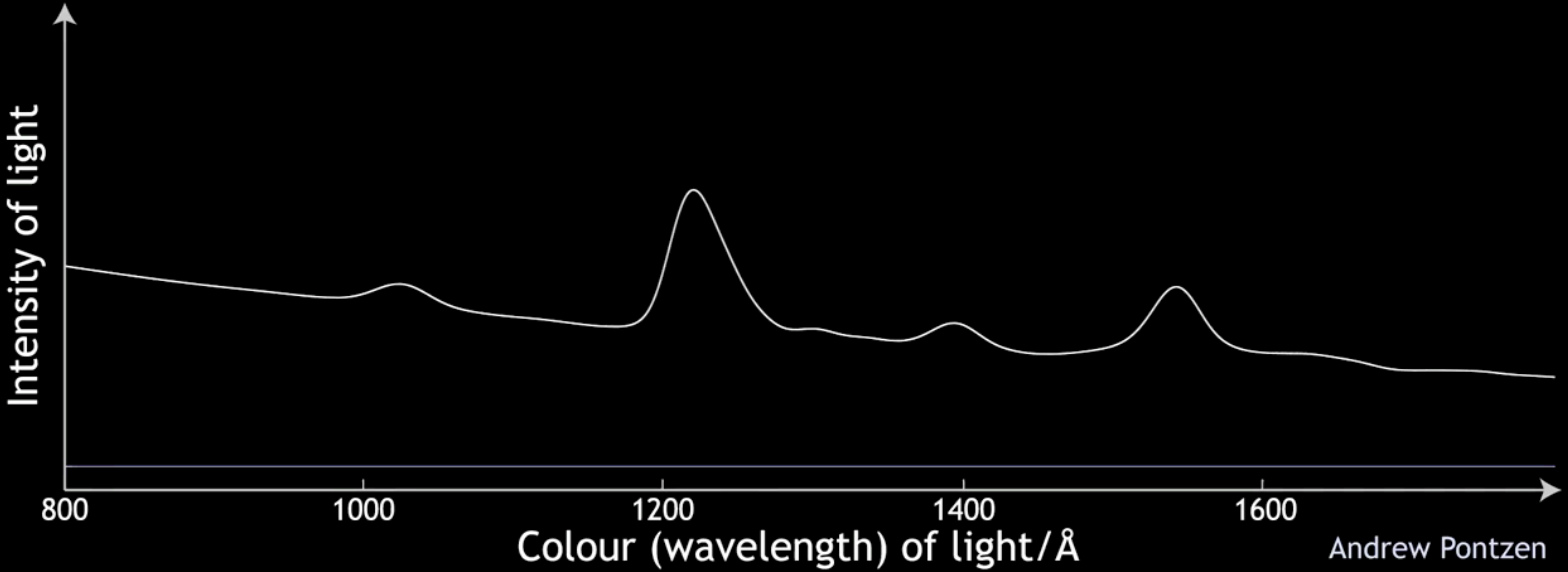
Hubble eXtreme Deep Field (XDF)
Hubble Space Telescope • ACS/WFC • WFC3/IR

NASA and ESA

STScI-PRC12-37

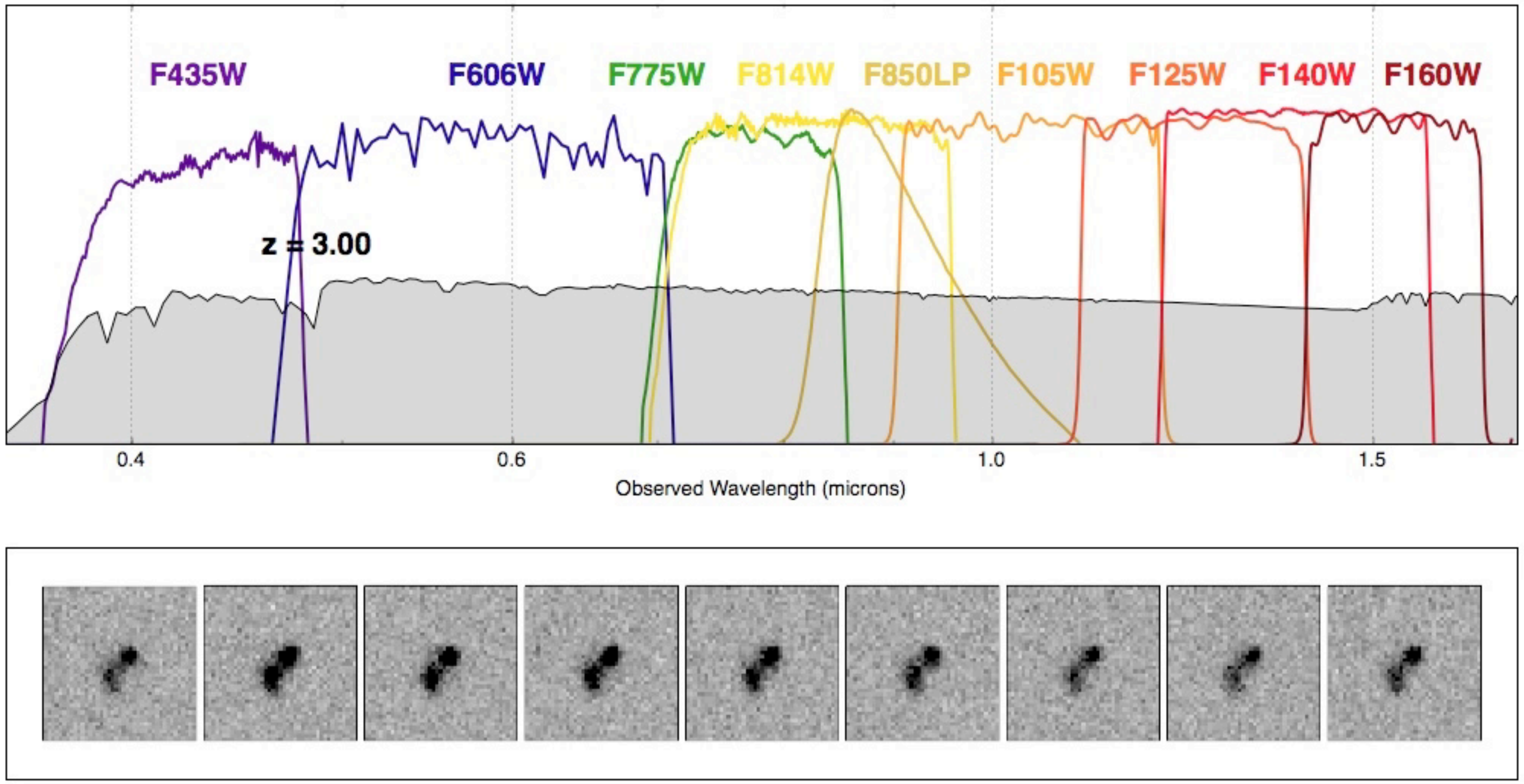
Inferring galaxy properties Pre-JWST





Inferring galaxy properties Pre-JWST

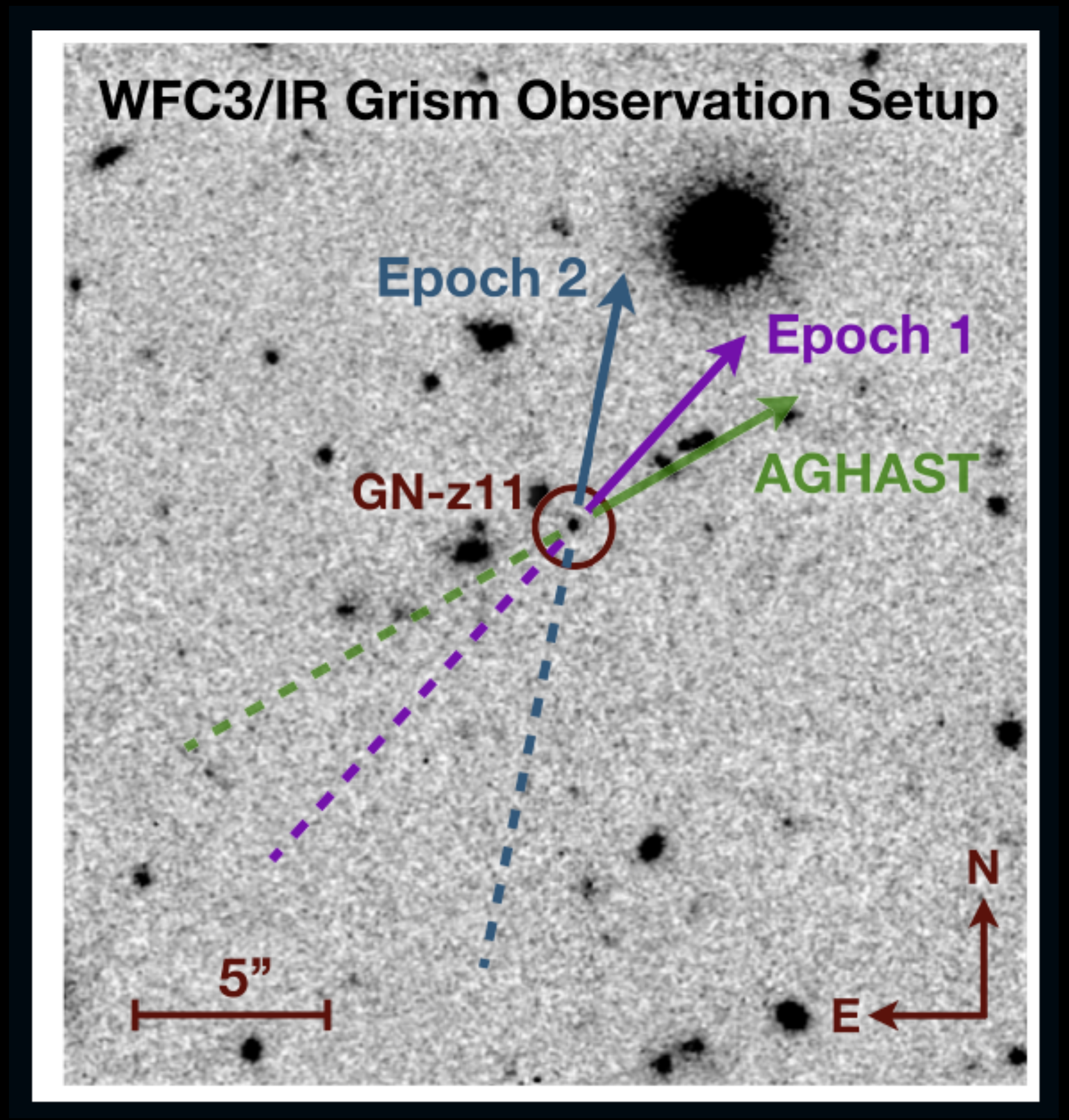
Huge samples at z>3.5 selected from the rest-frame UV via Lyman break

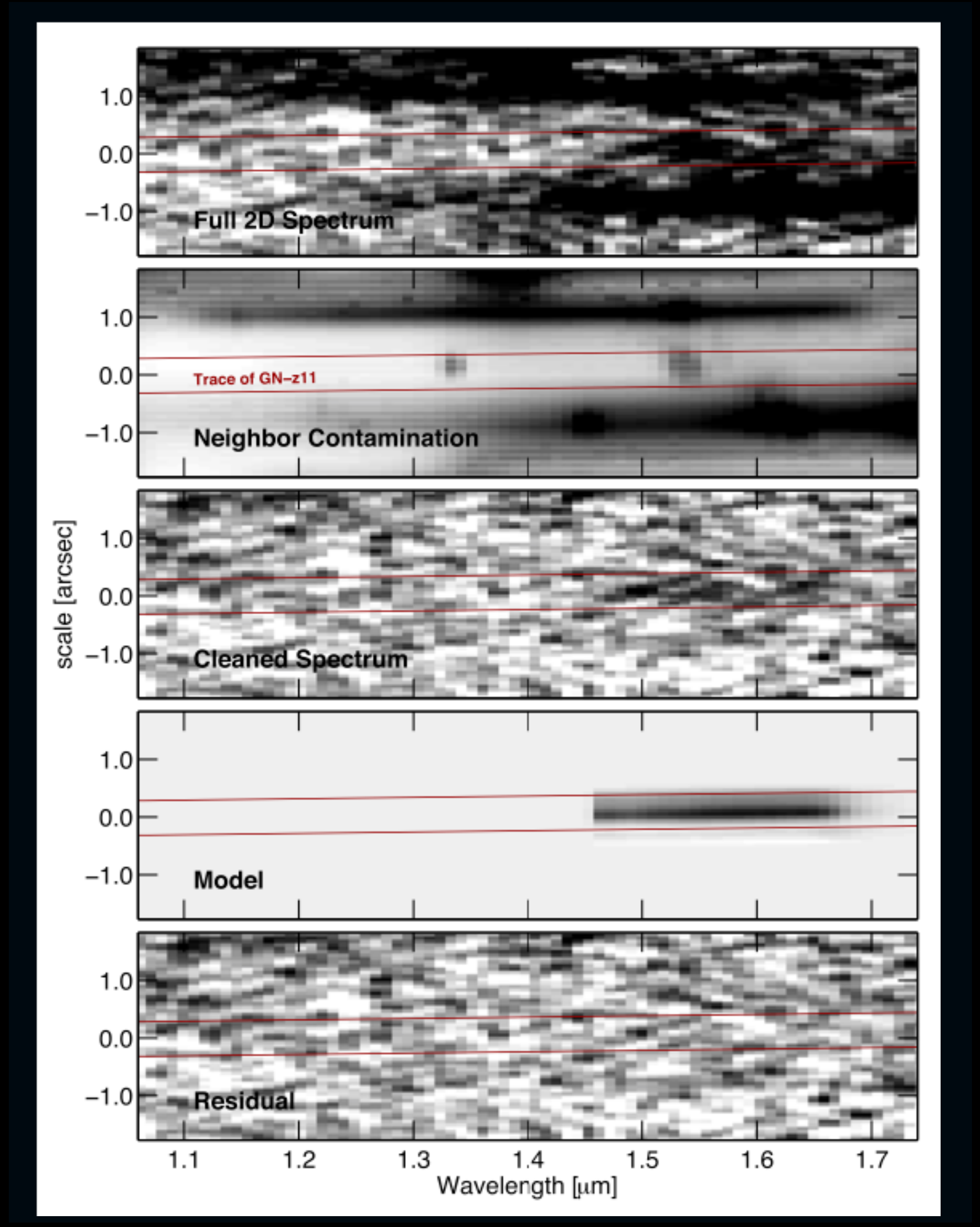


Credit - XDF team

Inferring galaxy properties Pre-JWST

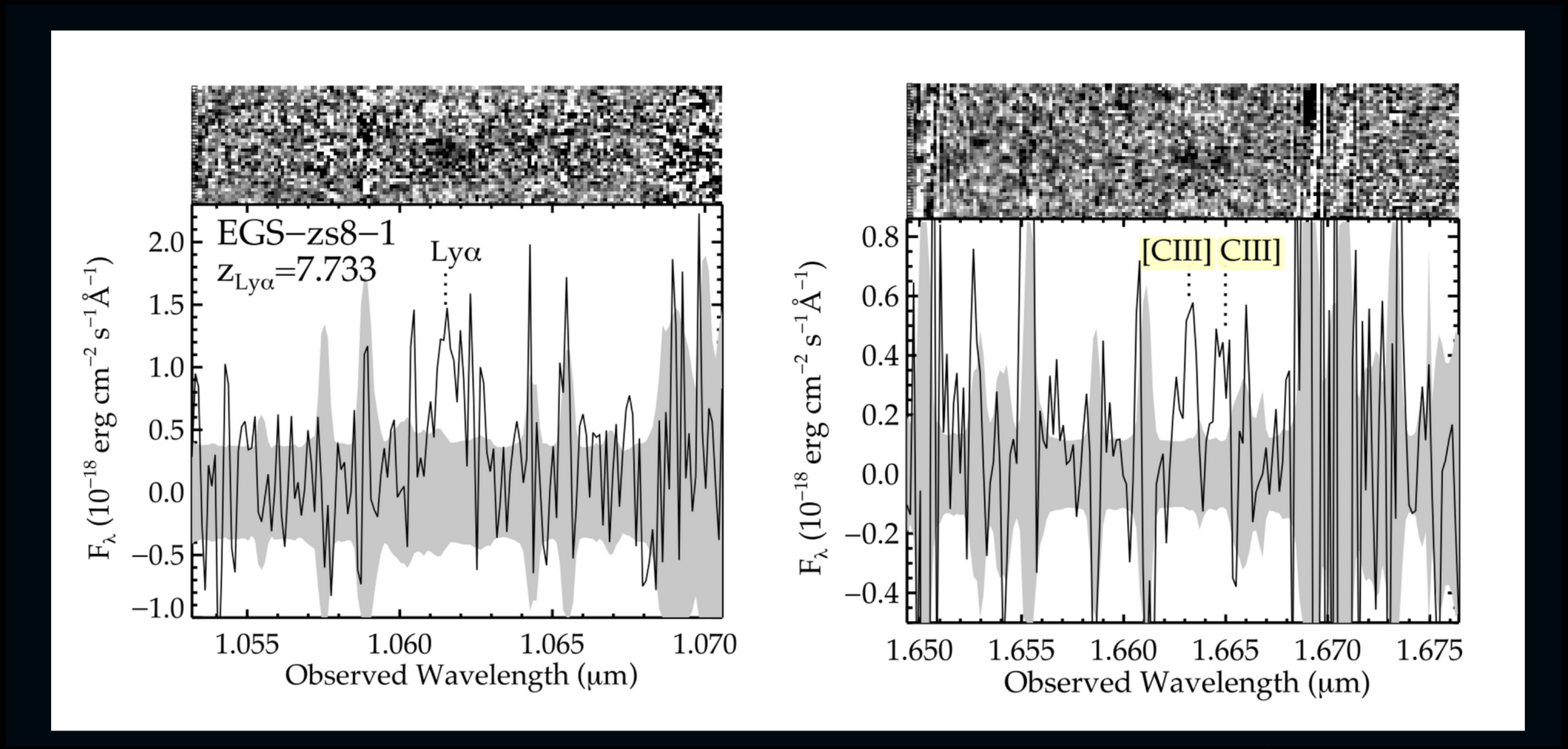
These were the spectra that got me excited pre-JWST!





Oesch+16

GN-z11 - most distant spectroscopically confirmed galaxy pre-JWST. z~11.1 from initial analysis, later updated to 10.957 from emission line detections in Jiang+21



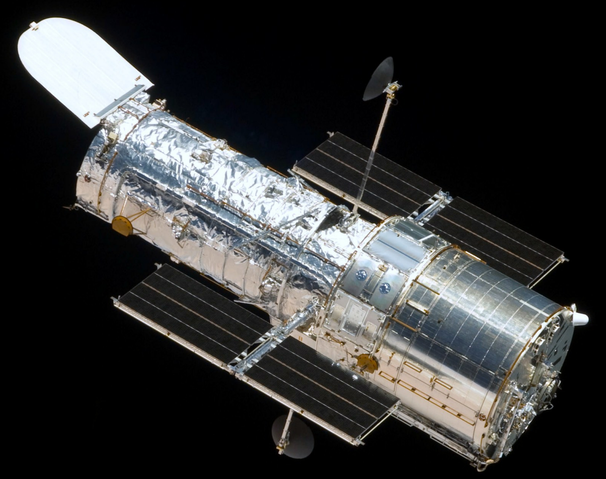
Stark+16 - highest redshift (z=7.73) detection of emission line other than Hydrogen in a normal star forming galaxy before ALMA

On the whole any spectroscopic confirmation very challenging.

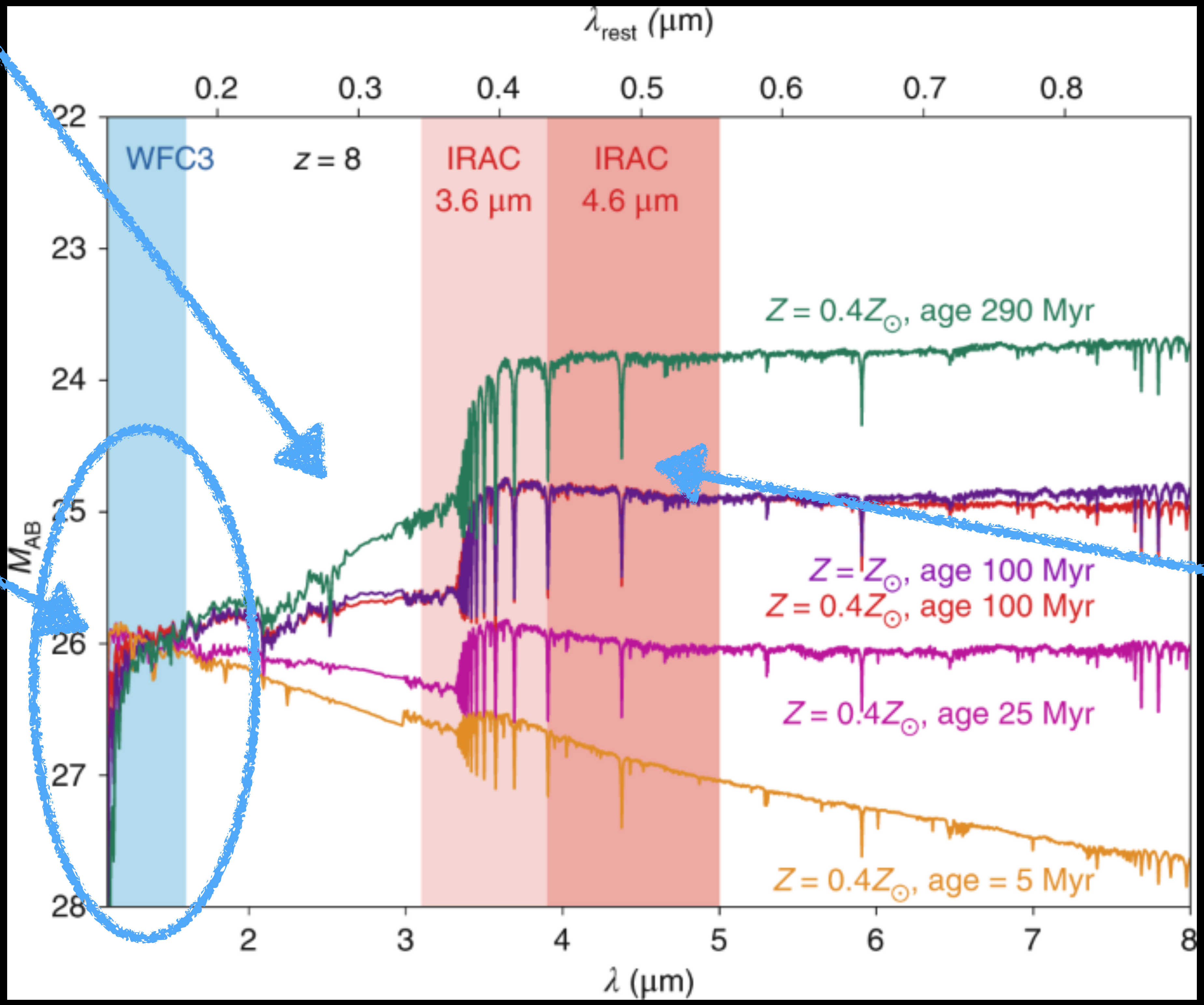
Distances predominantly inferred from photometry using the Lyman break.
Called photometric redshifts

Inferring galaxy properties Pre-JWST

Ground-based
K-band



Hubble

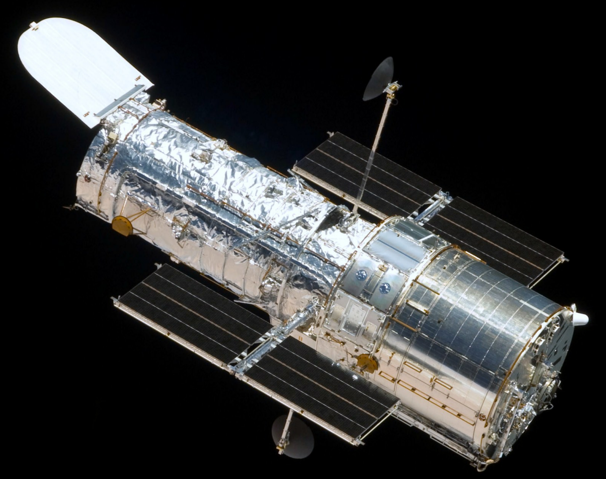


Spitzer

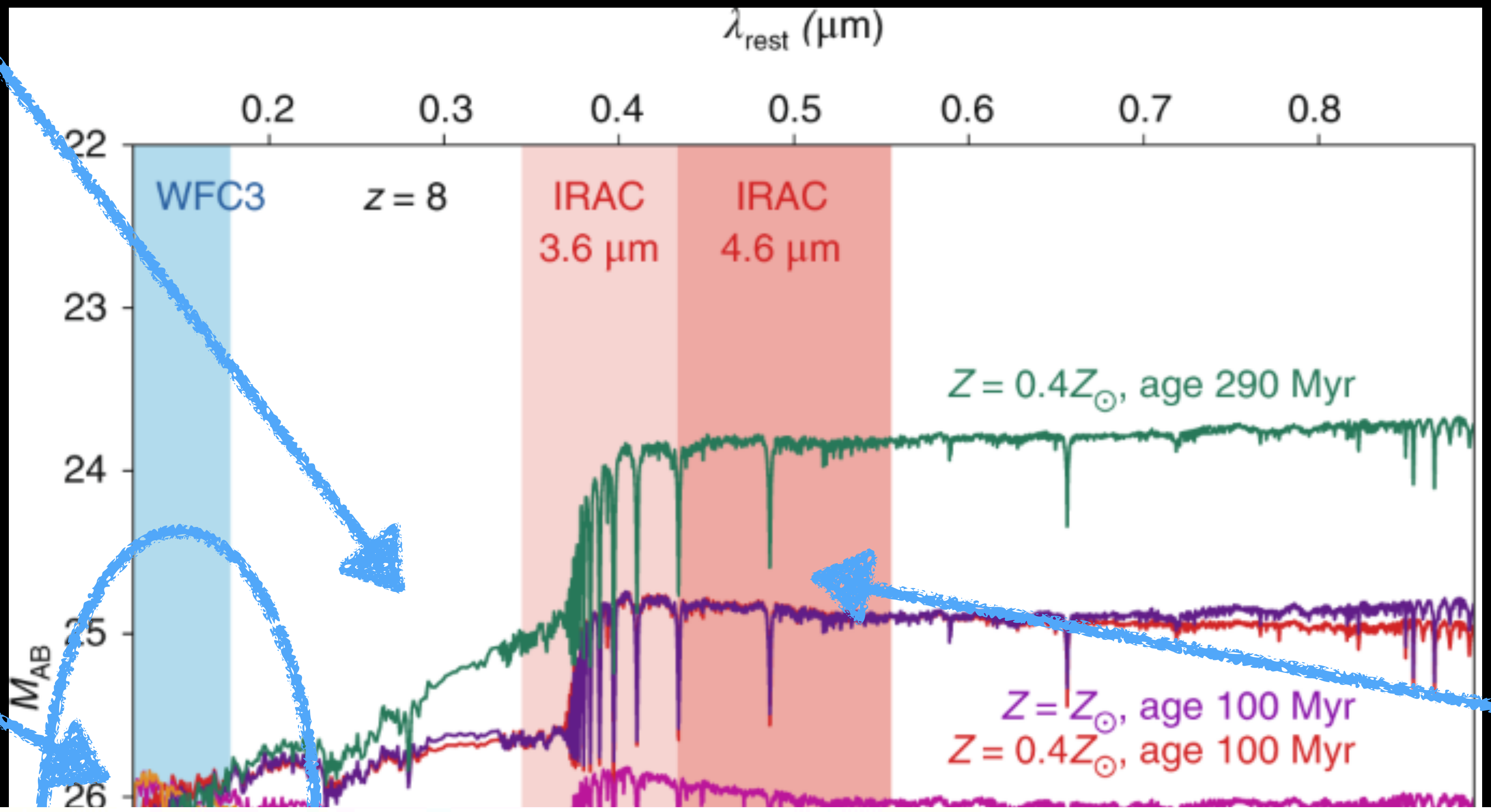
Bradač+ 2020NatAs…4..478B

Inferring galaxy properties Pre-JWST

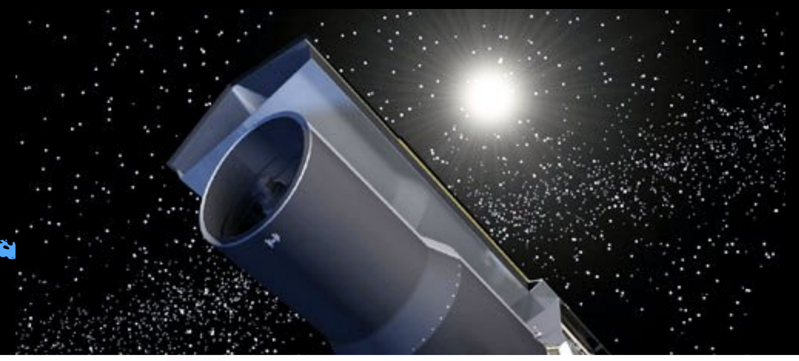
Ground-based K-band

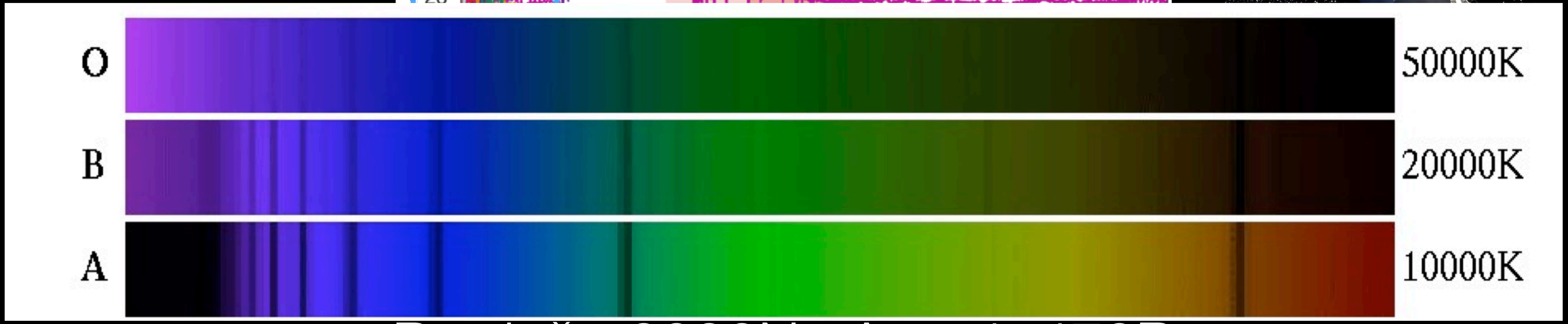


Hubble



Spitzer

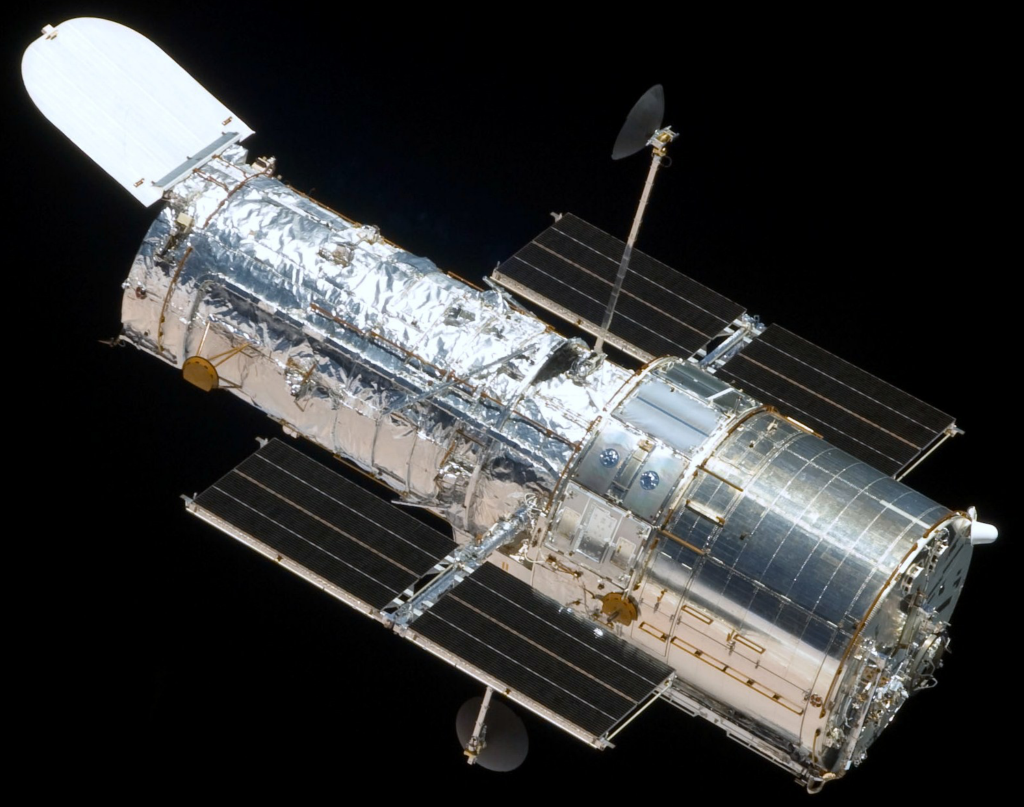


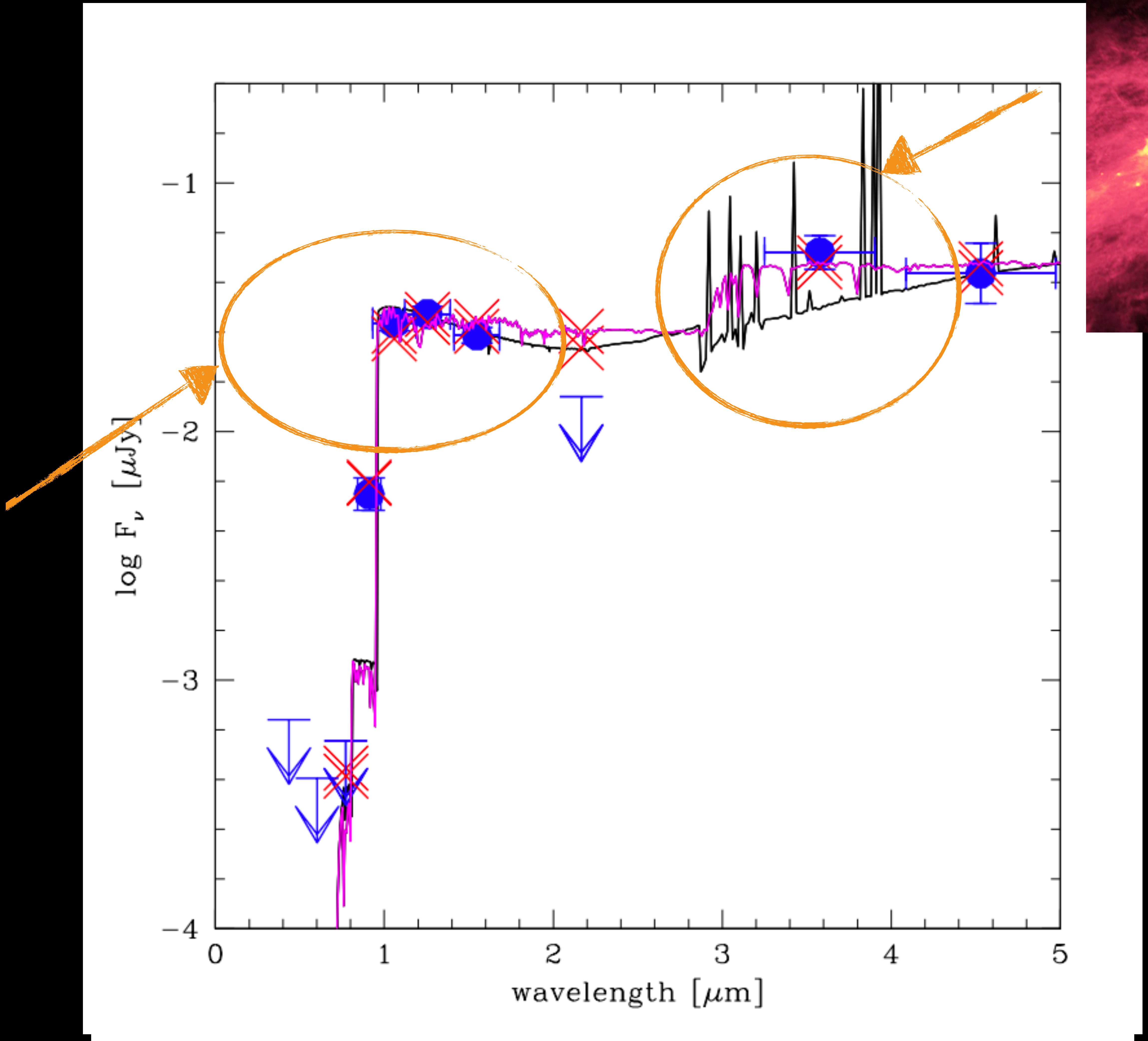


Bradač+ 2020NatAs…4..478B

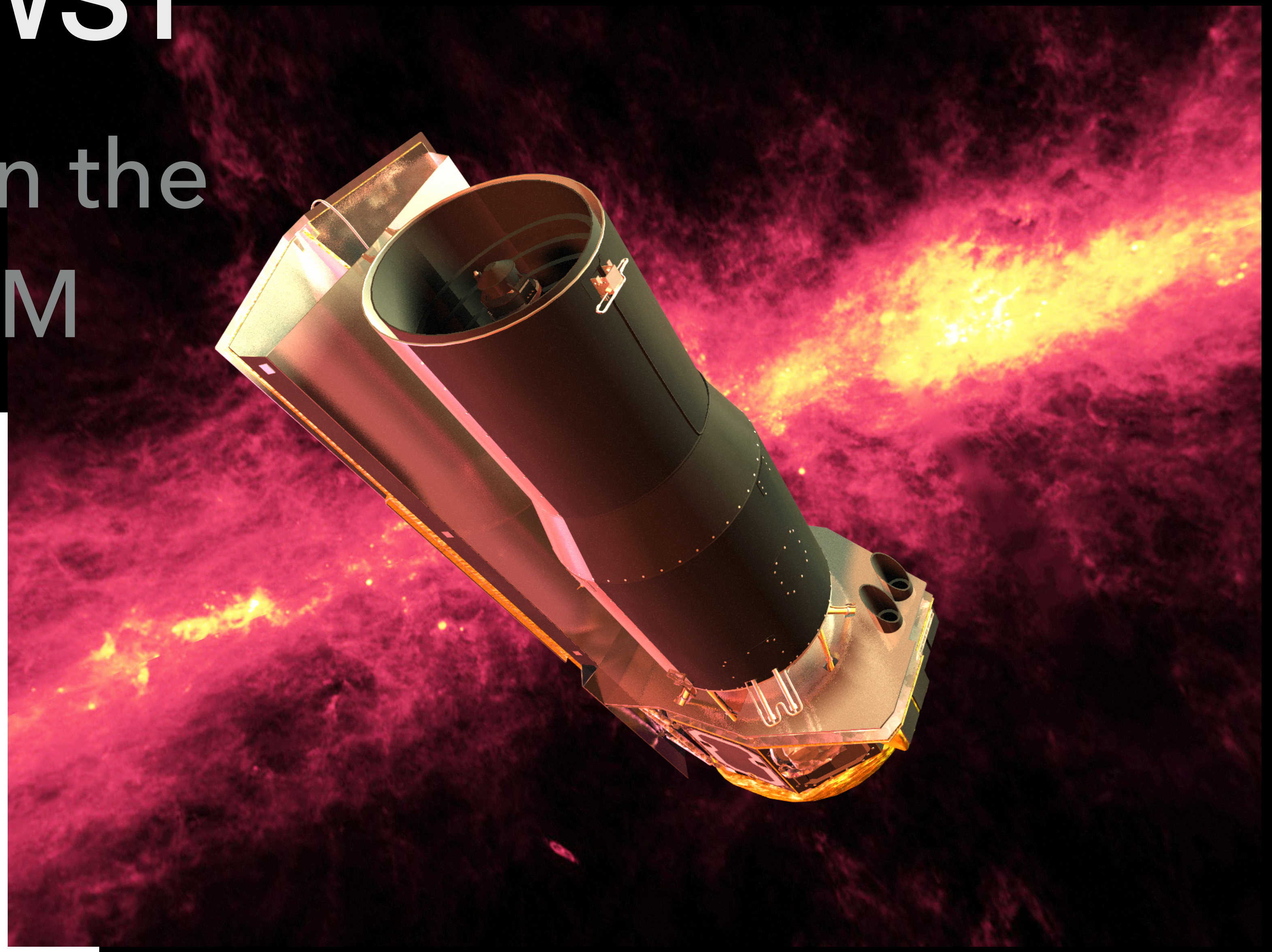
Inferring galaxy properties Pre-JWST

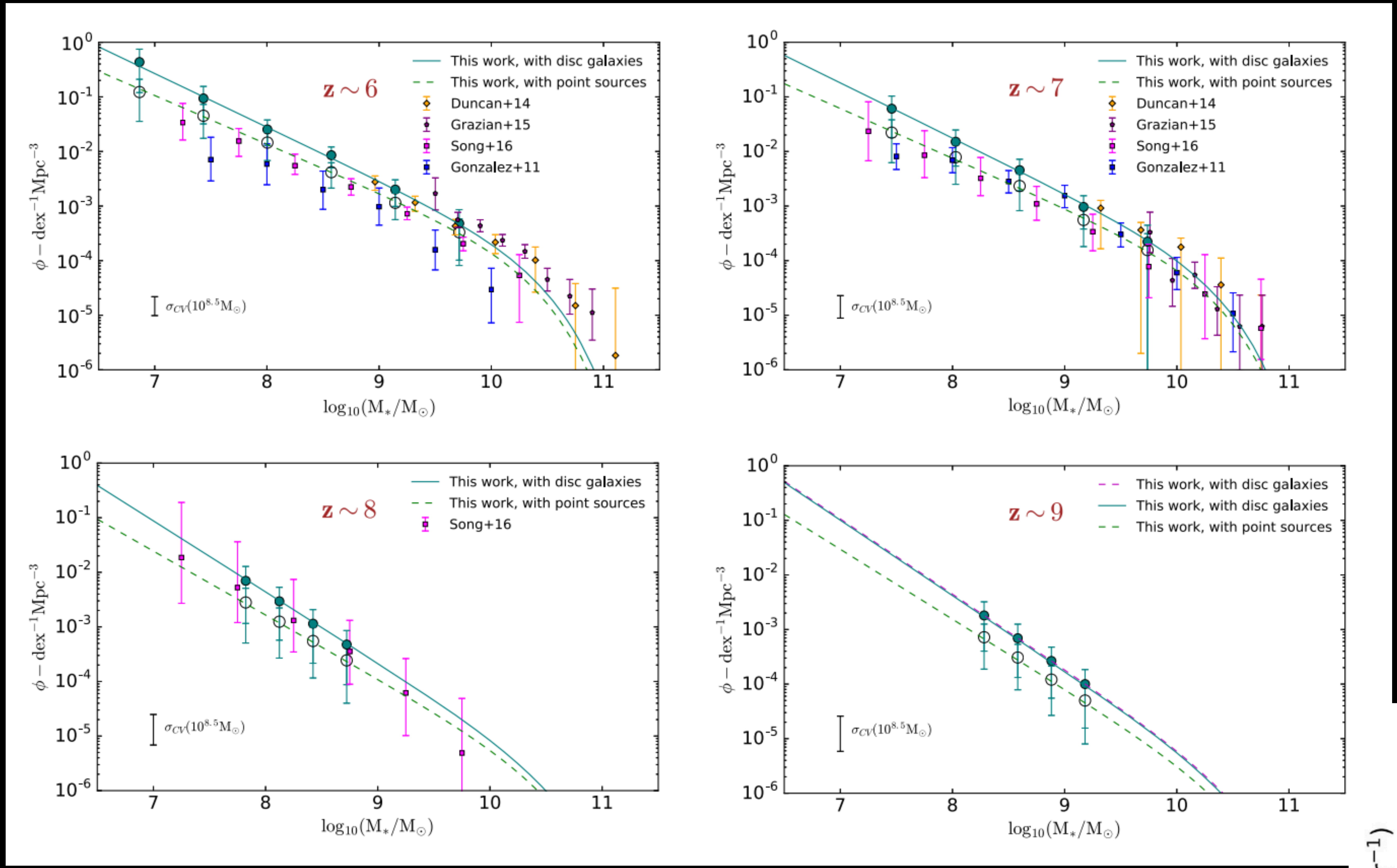
But it isn't only stars that emit light in the rest-frame optical! - BIG PROBLEM



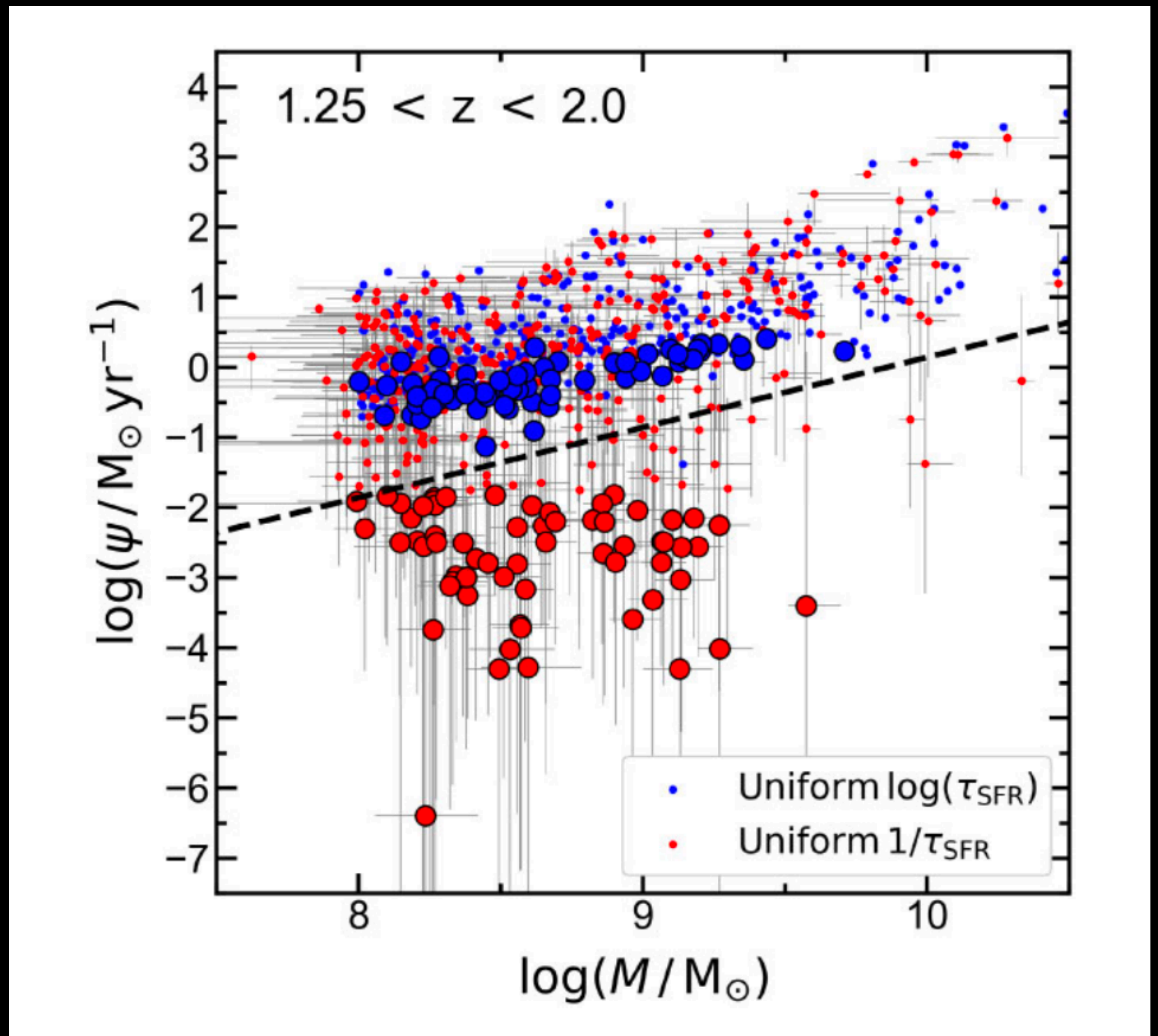


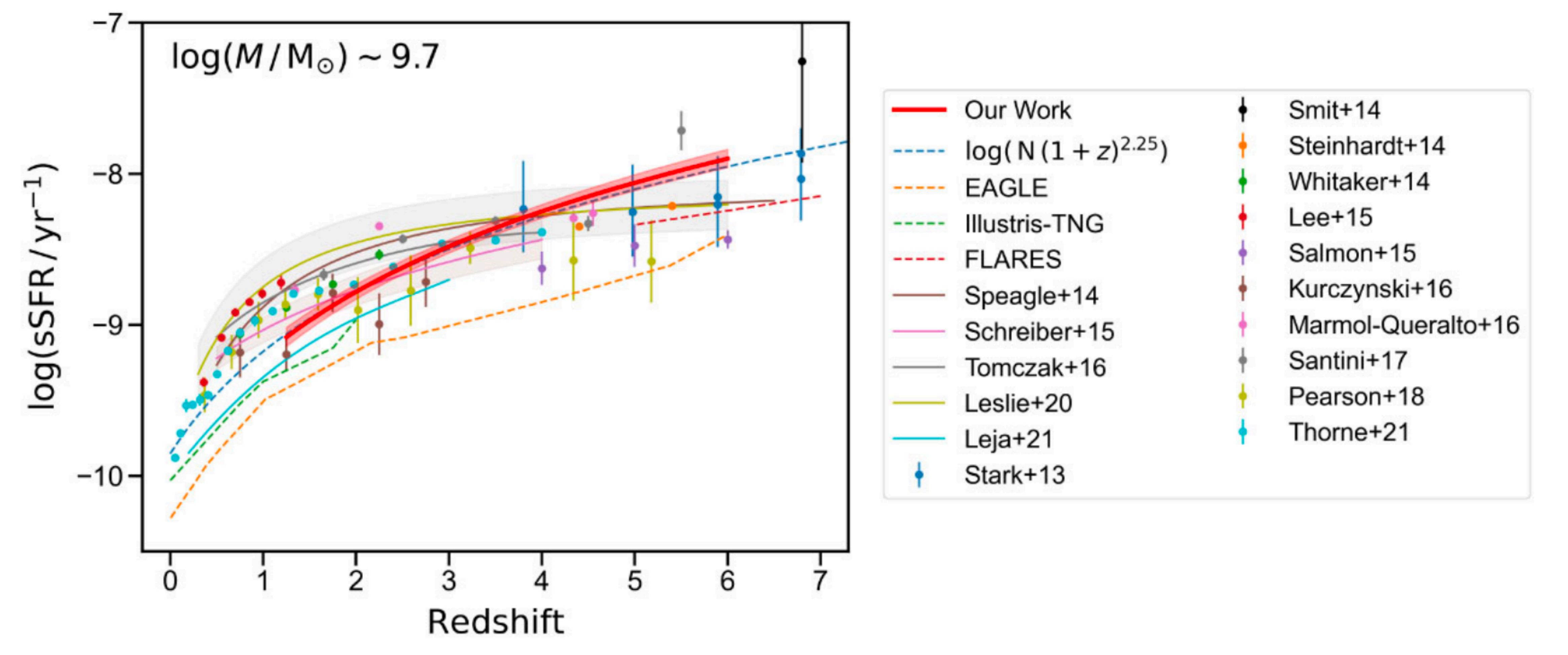
Schaerer & De Barros, 2010, A&A, 515





Bhatawdekar+ 2019MNRAS.486.3805B



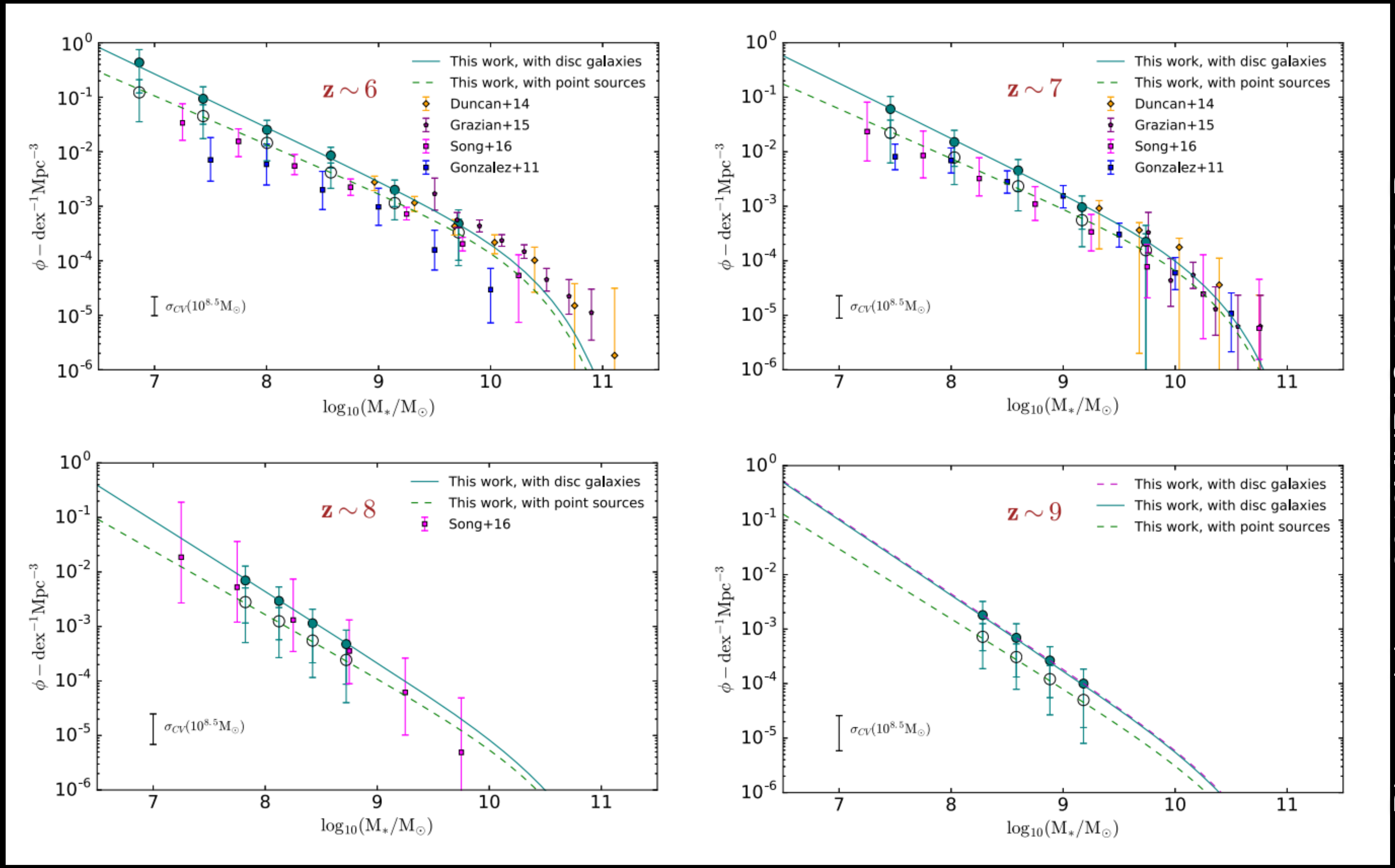


Sandles+ 2022MNRAS.515.2951S

Thanks to rest-optical coverage with Spitzer (often only 2 filters!), people would estimate stellar masses etc. with SED fitting.

Thanks to rest-optical coverage with Spitzer (often only 2 filters!), people could estimate stellar masses etc. with SED fitting.

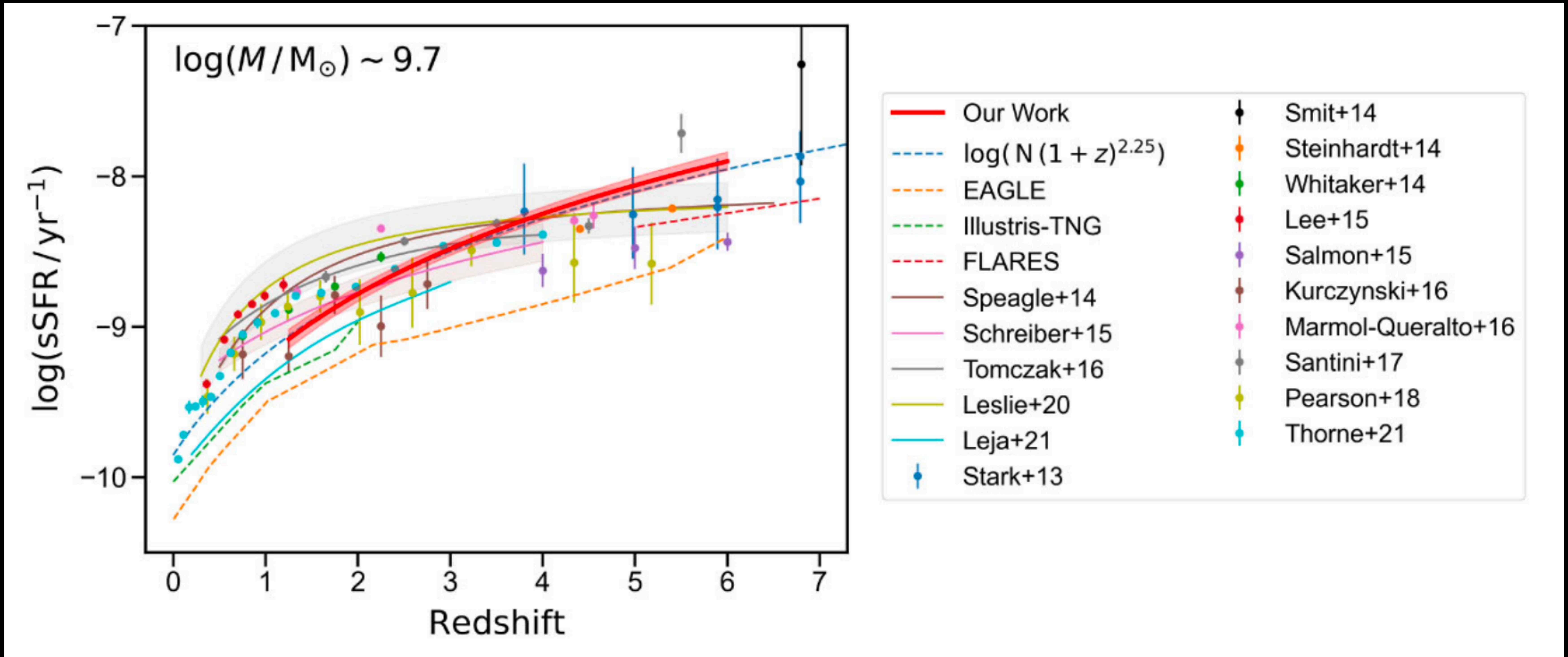
Number of objects/
Stellar mass bin/
Co-moving
Mpc^3



log(Stellar mass)

Bhatawdekar+ 2019MNRAS.486.3805B

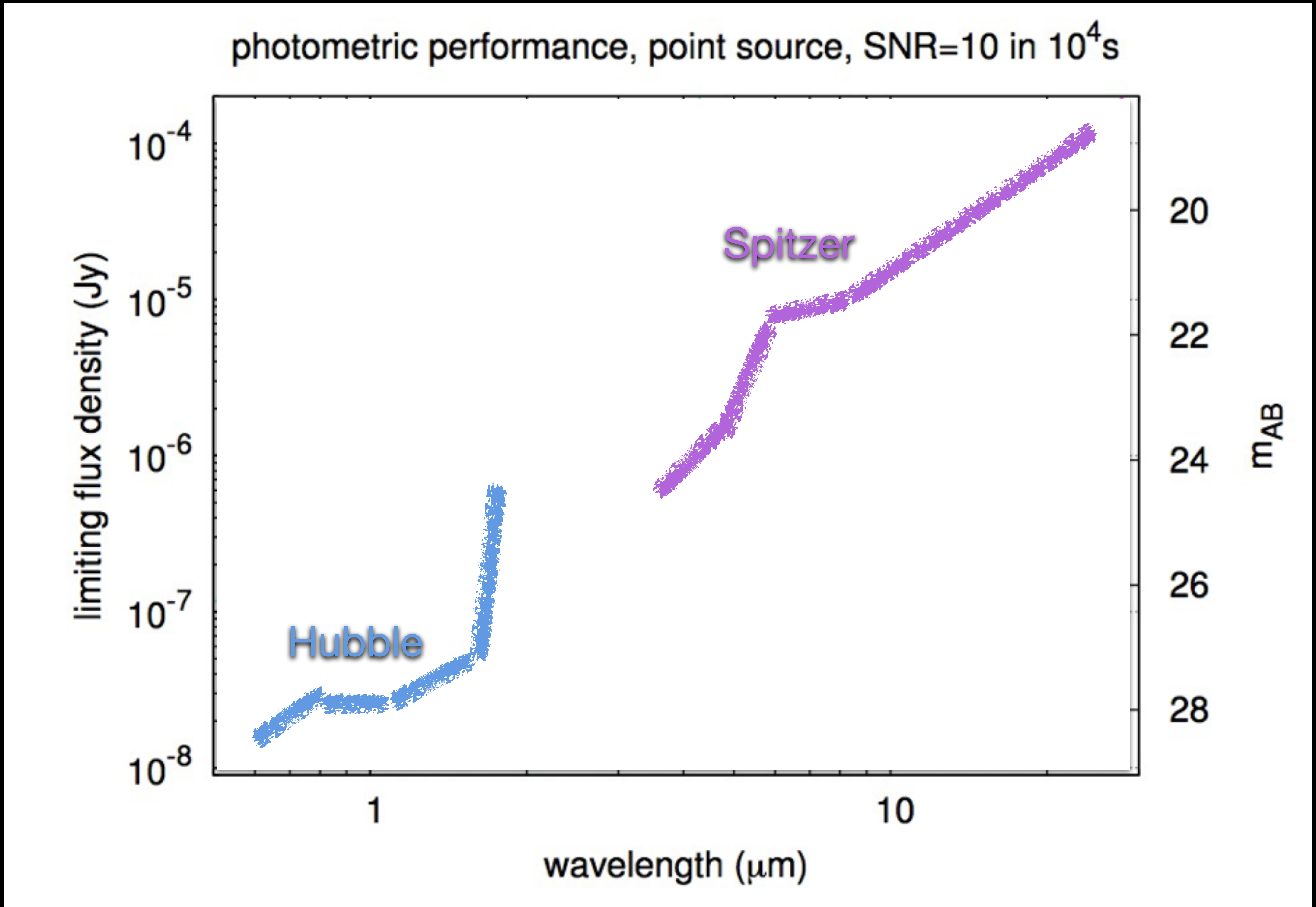
Thanks to rest-optical coverage with Spitzer (often only 2 filters!), people could estimate stellar masses etc. with SED fitting.



Sandles+ 2022MNRAS.515.2951S

Specific SFR = SFR/stellar mass - higher star formation rate than past integrated star formation rate to higher redshifts, potentially higher gas fractions (more fuel) -> higher SFR

Huge difference in sensitivity between Hubble and Spitzer

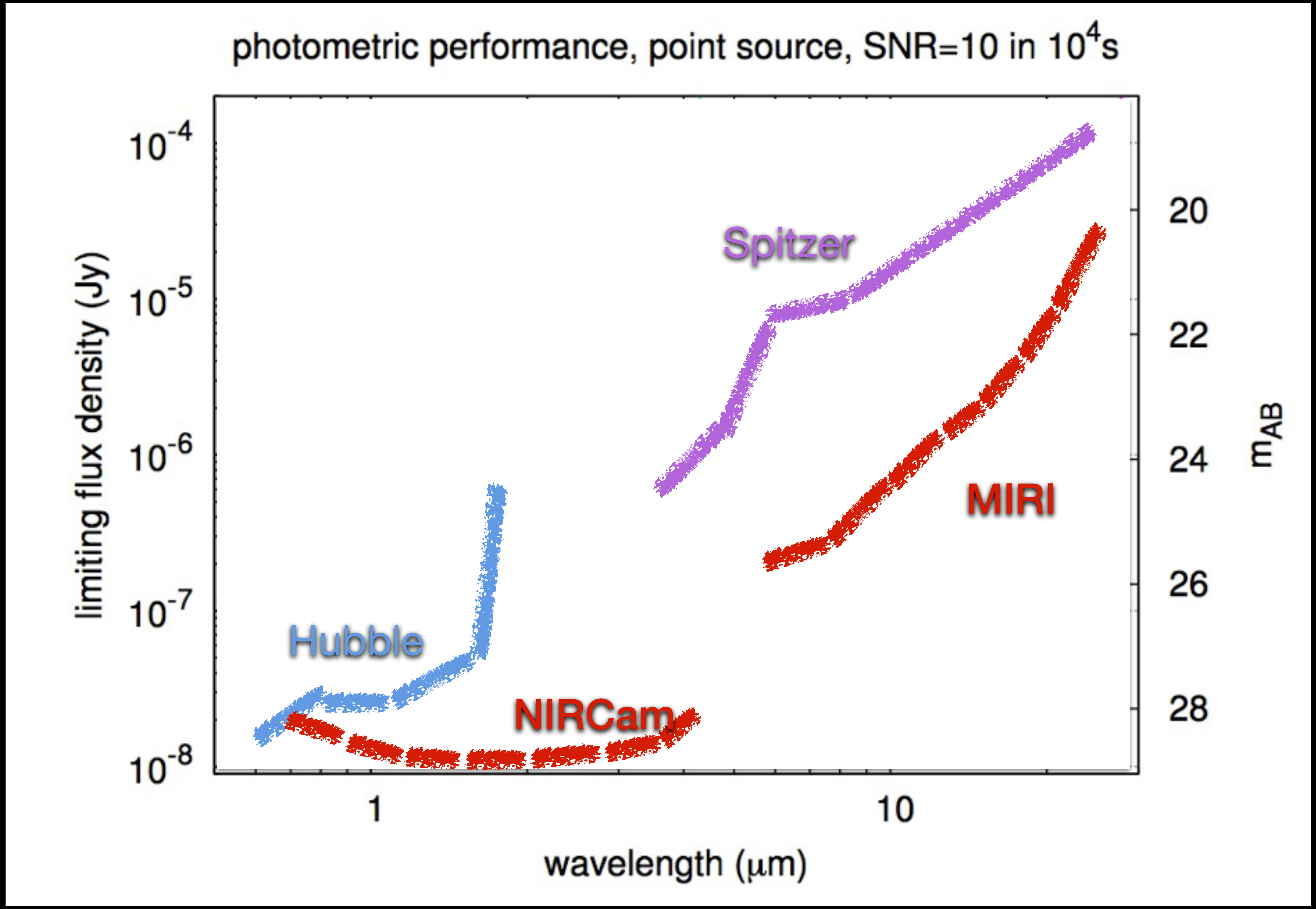


Credit:Rigby

And Spitzer had very low spatial resolution -> we only really had rest-optical information for the brighter galaxies at high redshift.

Now, thanks to JWST!

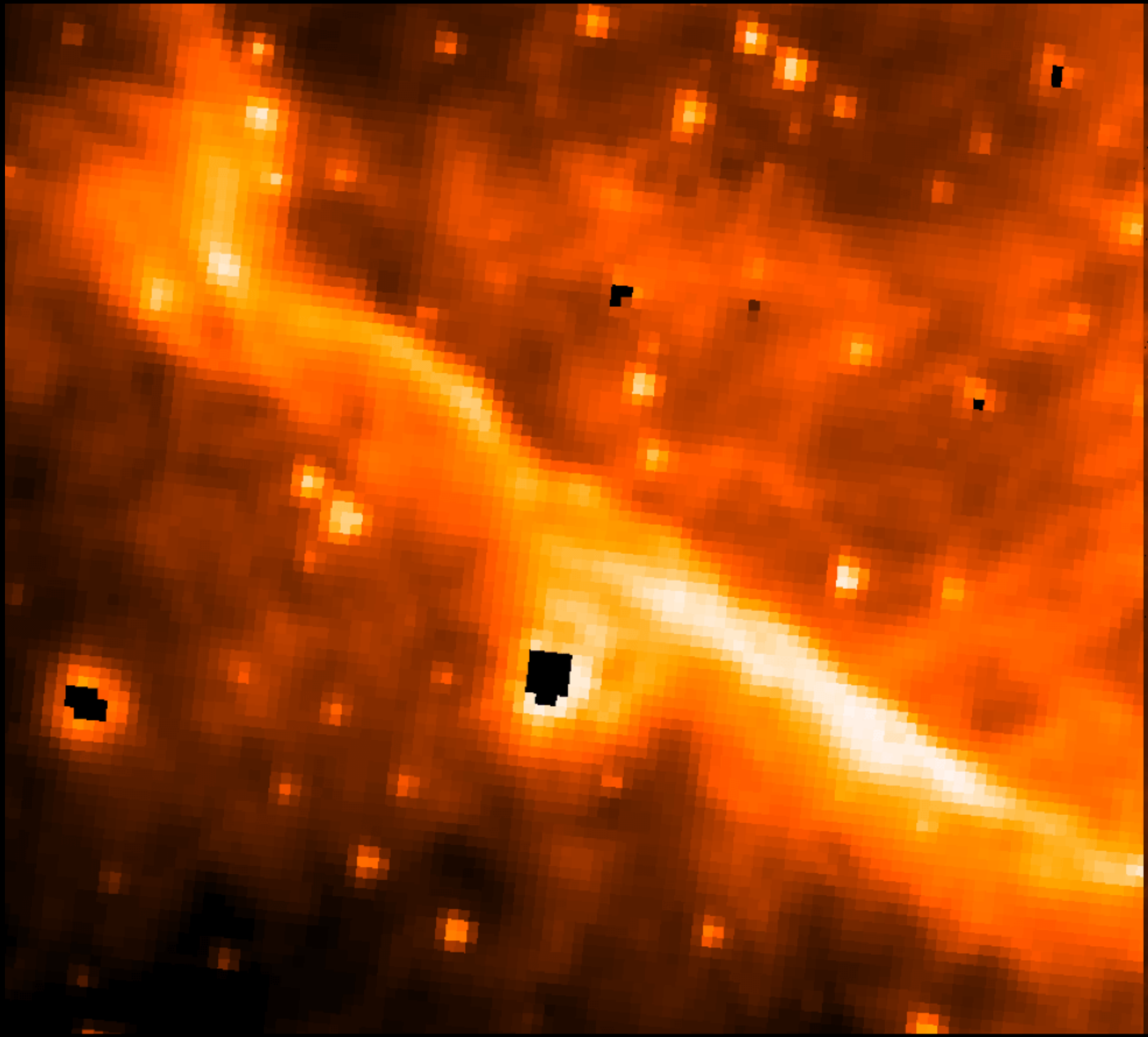
Huge improvement in sensitivity compared to first 2 Spitzer filters, and MIRI extends to longer wavelengths.



Credit:Rigby

Now, thanks to JWST!

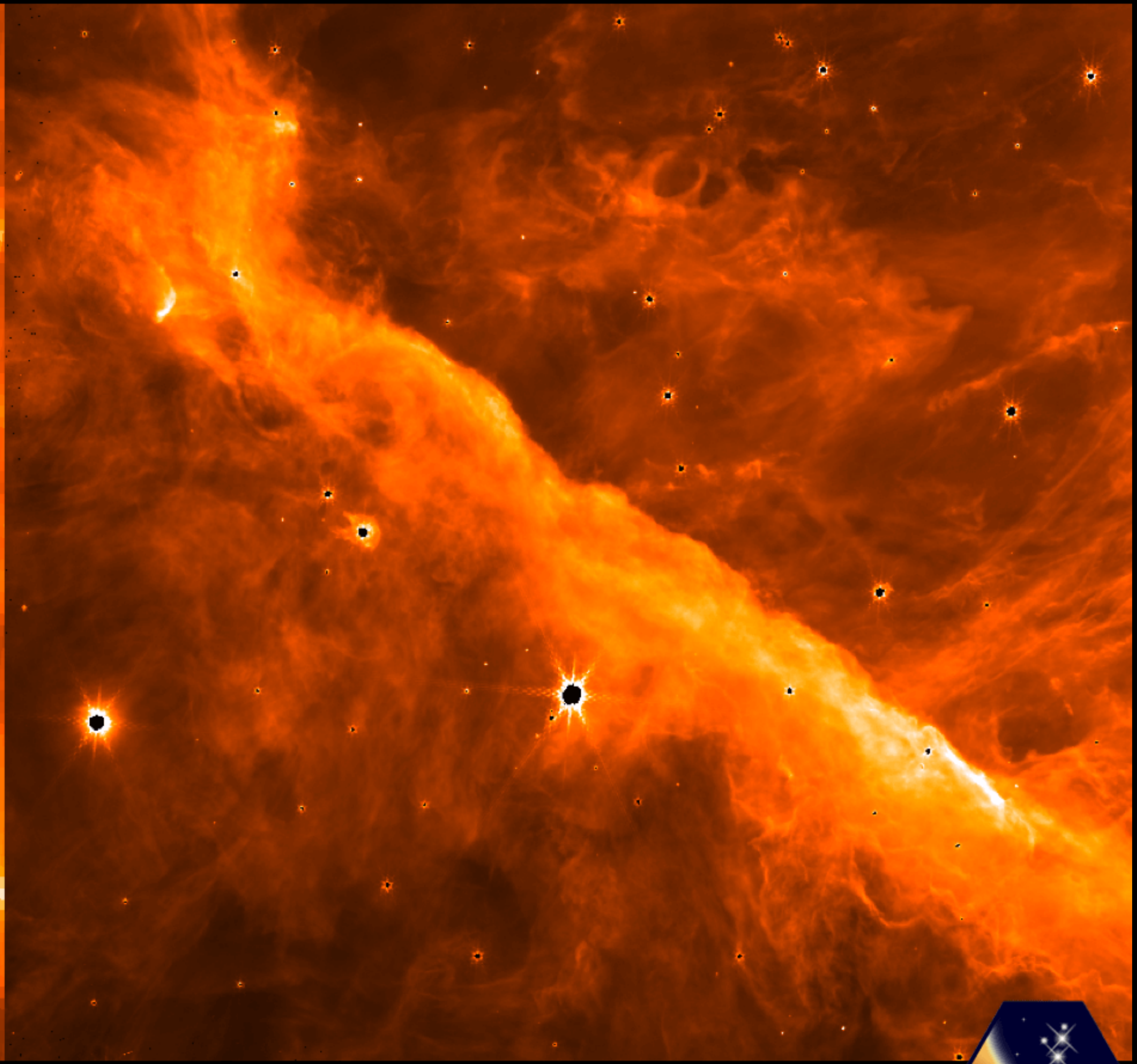
Spitzer



Credits : NASA / JPL-Caltech/S.T. Megeath

IRAC / 3.6 µm

JWST



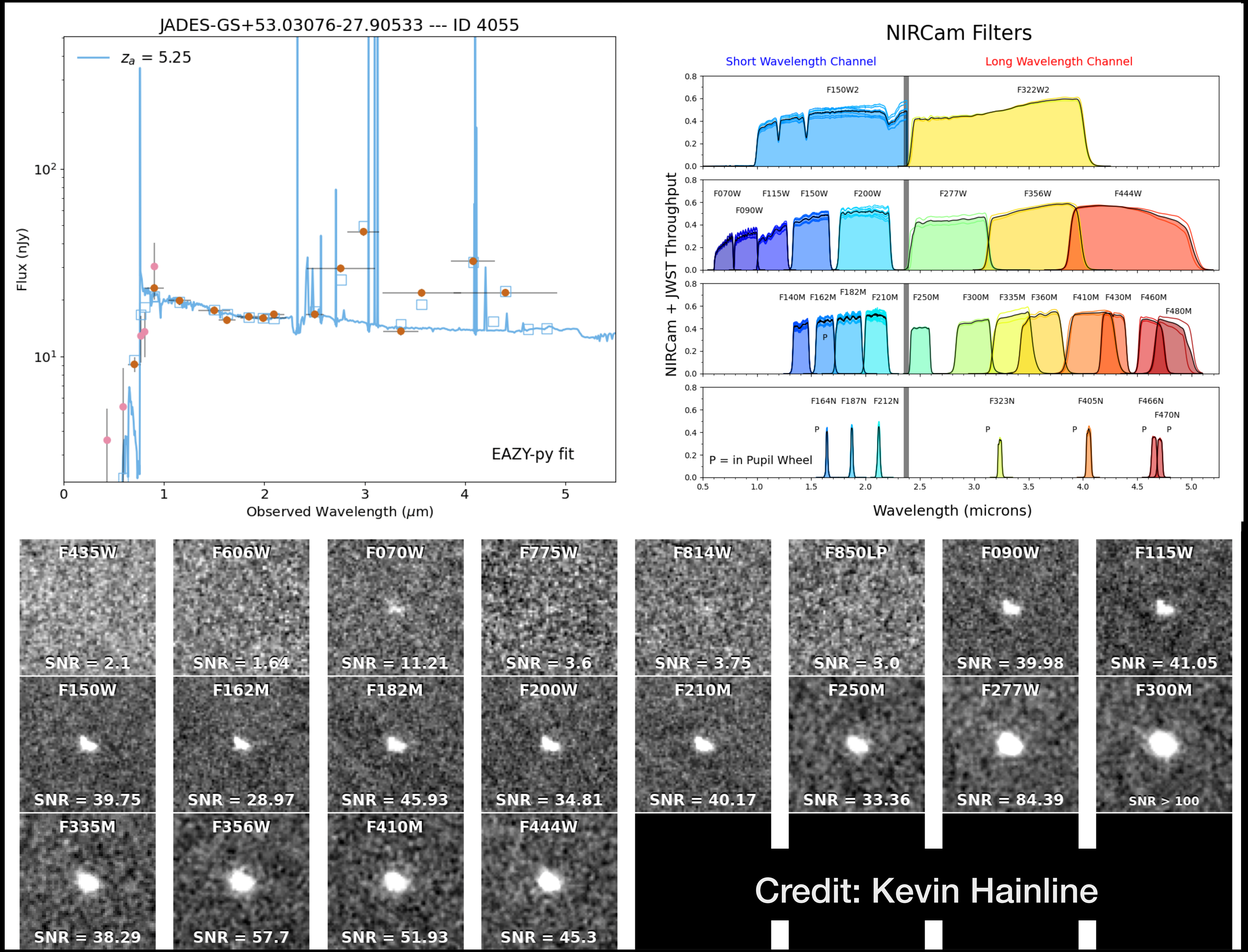
Credits : NASA / ESA / CSA and PDRs4All team

NIRCam / 3.35 µm

Amazing spatial resolution

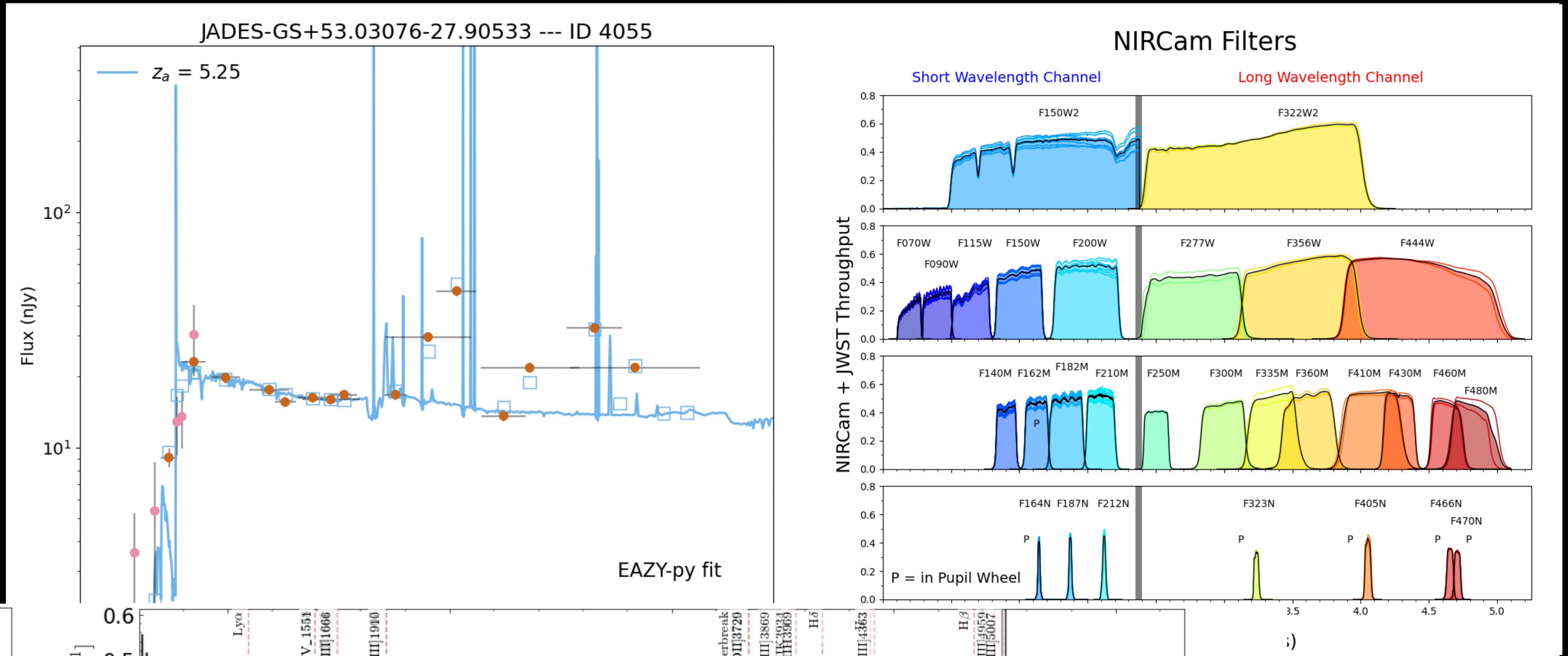
Now, thanks to JWST!

A 'sweetie' box of filter choice disentangling emission line contribution to different filters.

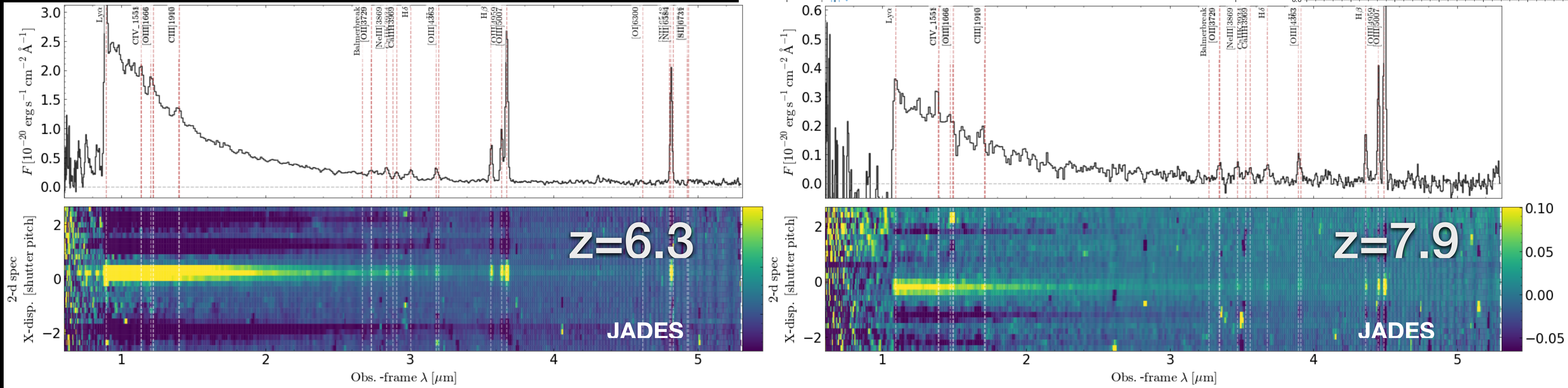


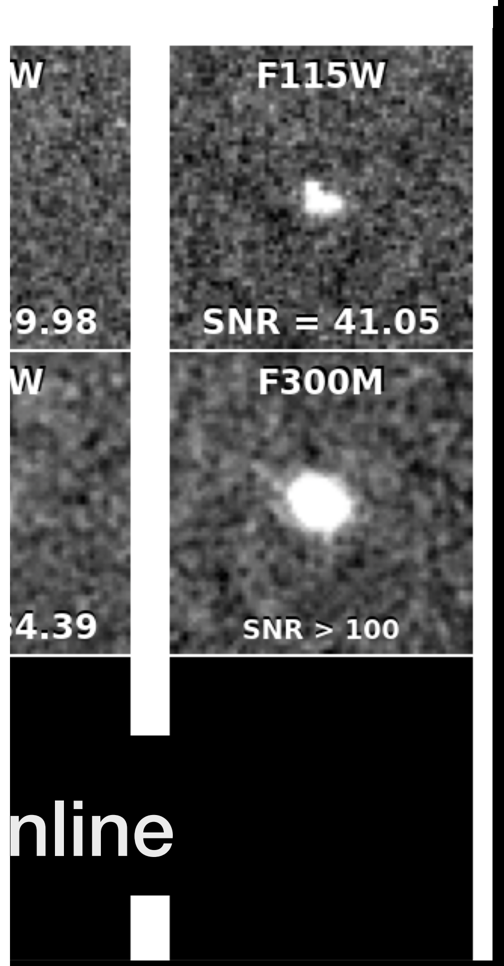
Credit: Kevin Hainline

Now, thanks to JWST!



And beautiful spectra!





Analysing this rich dataset

Emission line fluxes and ratios, can infer:

- SFRs (~10Myr timescales)
- Dust attenuation
- Likely ionising source
- ISM metallicities, densities, chemical abundances (see Danielle's talk)

But if we go down the SED modelling route, we can potentially infer all the above (depending on model complexity - a major caveat) as well as:

- Stellar masses
- SFRs over longer timescales - useful for assessing stochasticity of star formation and physical processes at play with galaxy evolution on different timescales.

Introduction to SED fitting
Comparing models to data to infer physical properties

Chevallard+2016

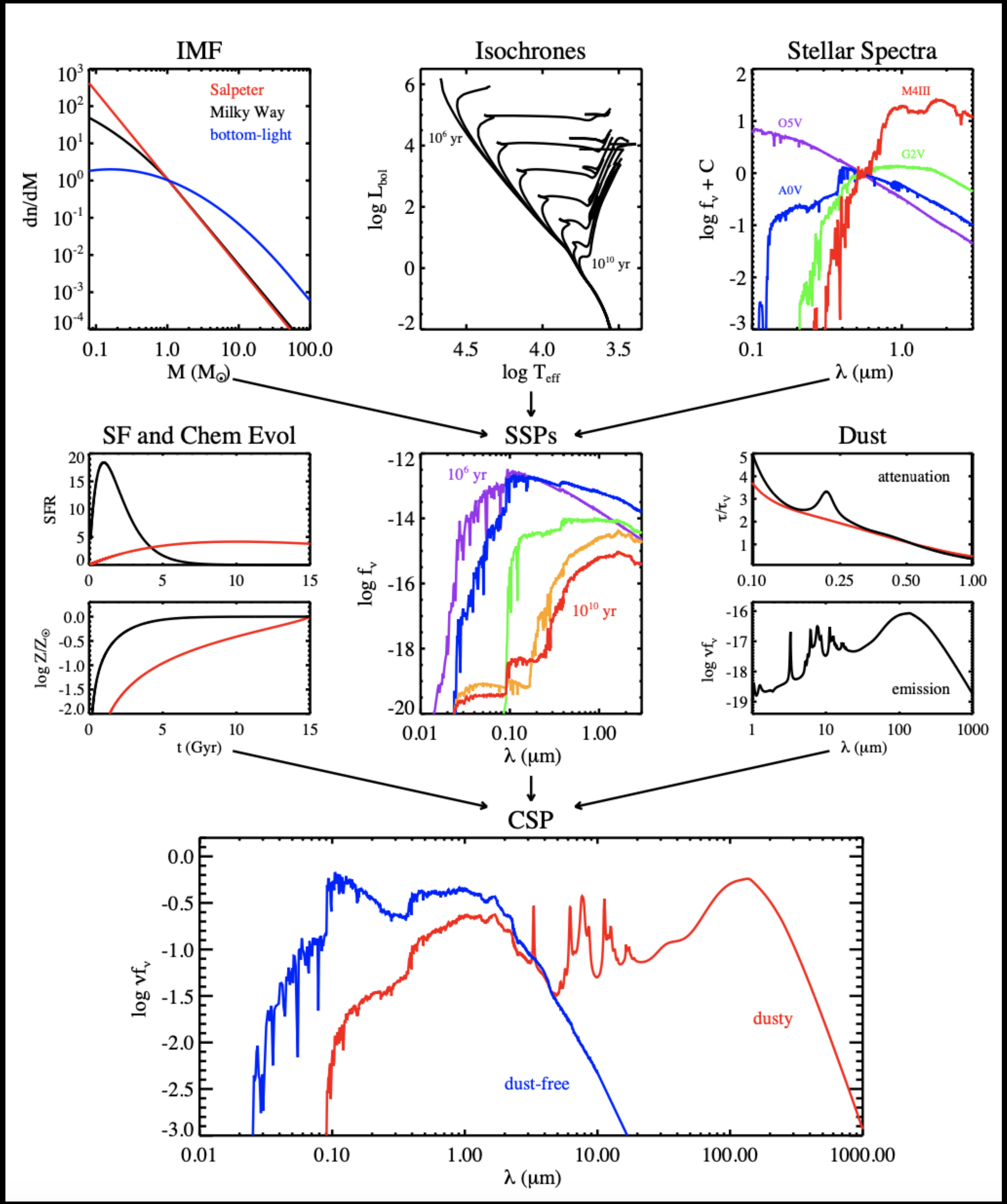
2021ApJS..254...

Johnson+2021

Carnall+2018

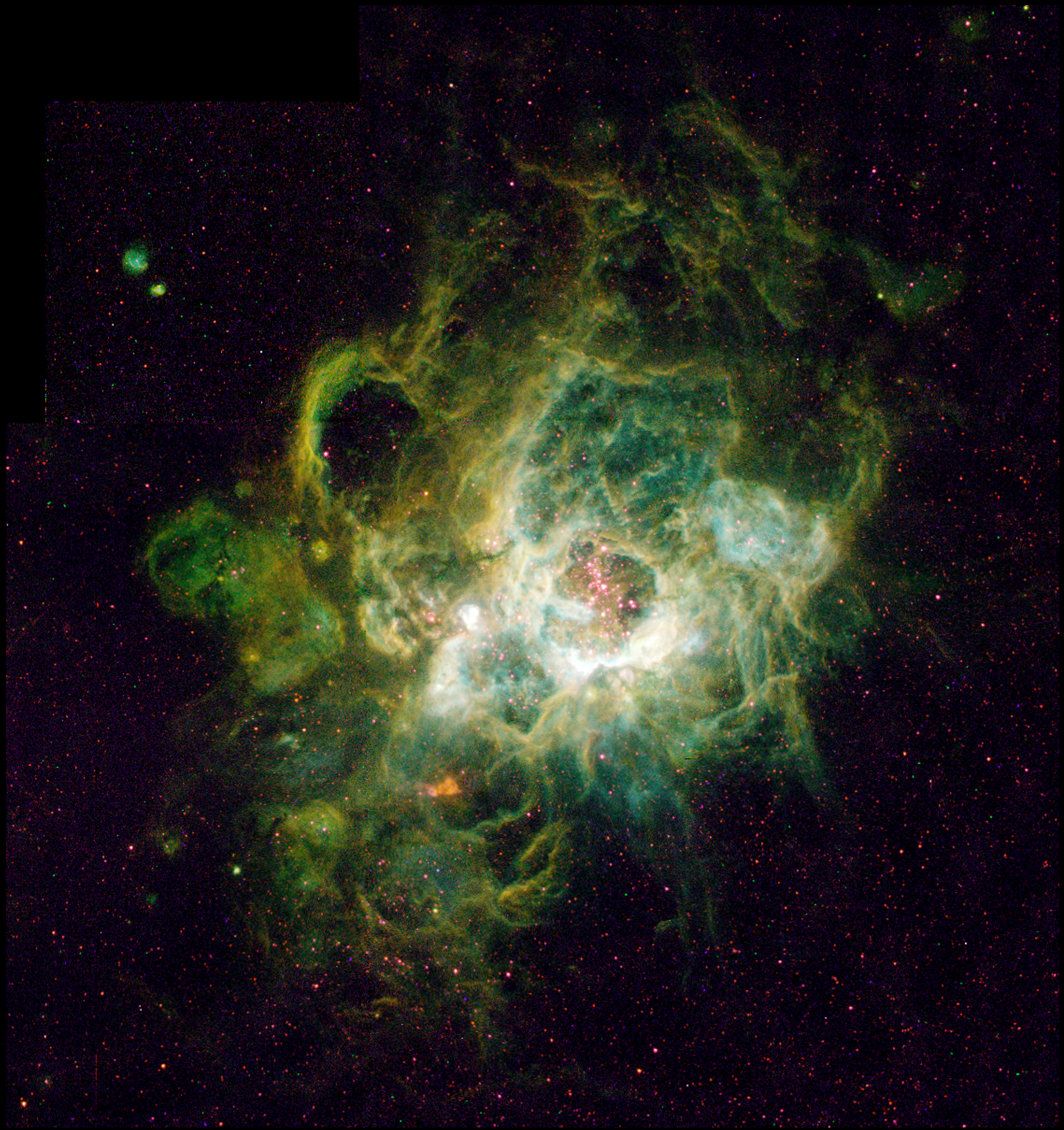
Boquien+2019 A&A…

SED fitting I - the models

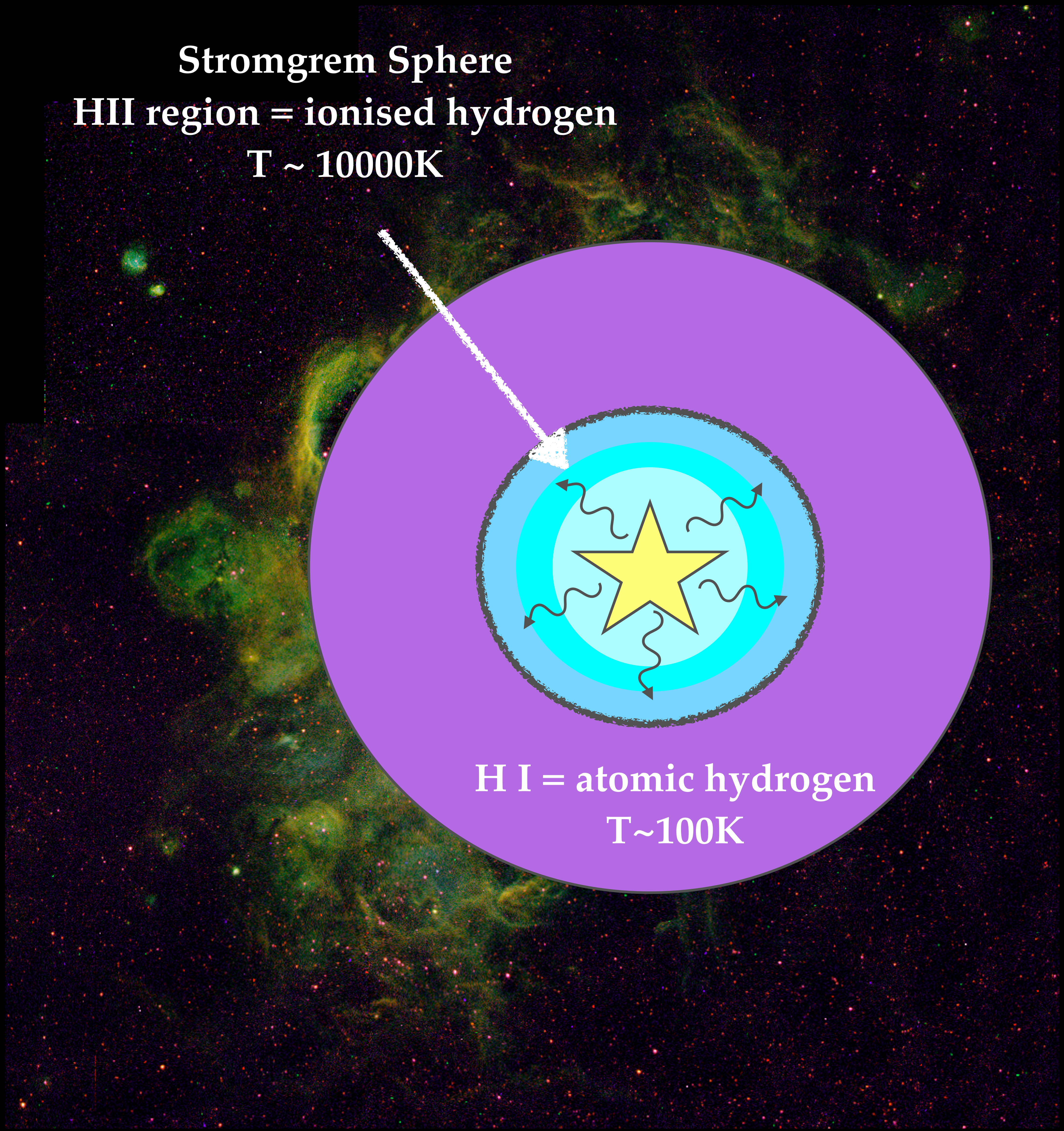


Conroy+ 2013ARA&A..51..393C

SED fitting I - the models
Nebular emission



SED fitting I - the models
Nebular emission



With large grids of physical parameters

SED fitting I - the models
Nebular emission

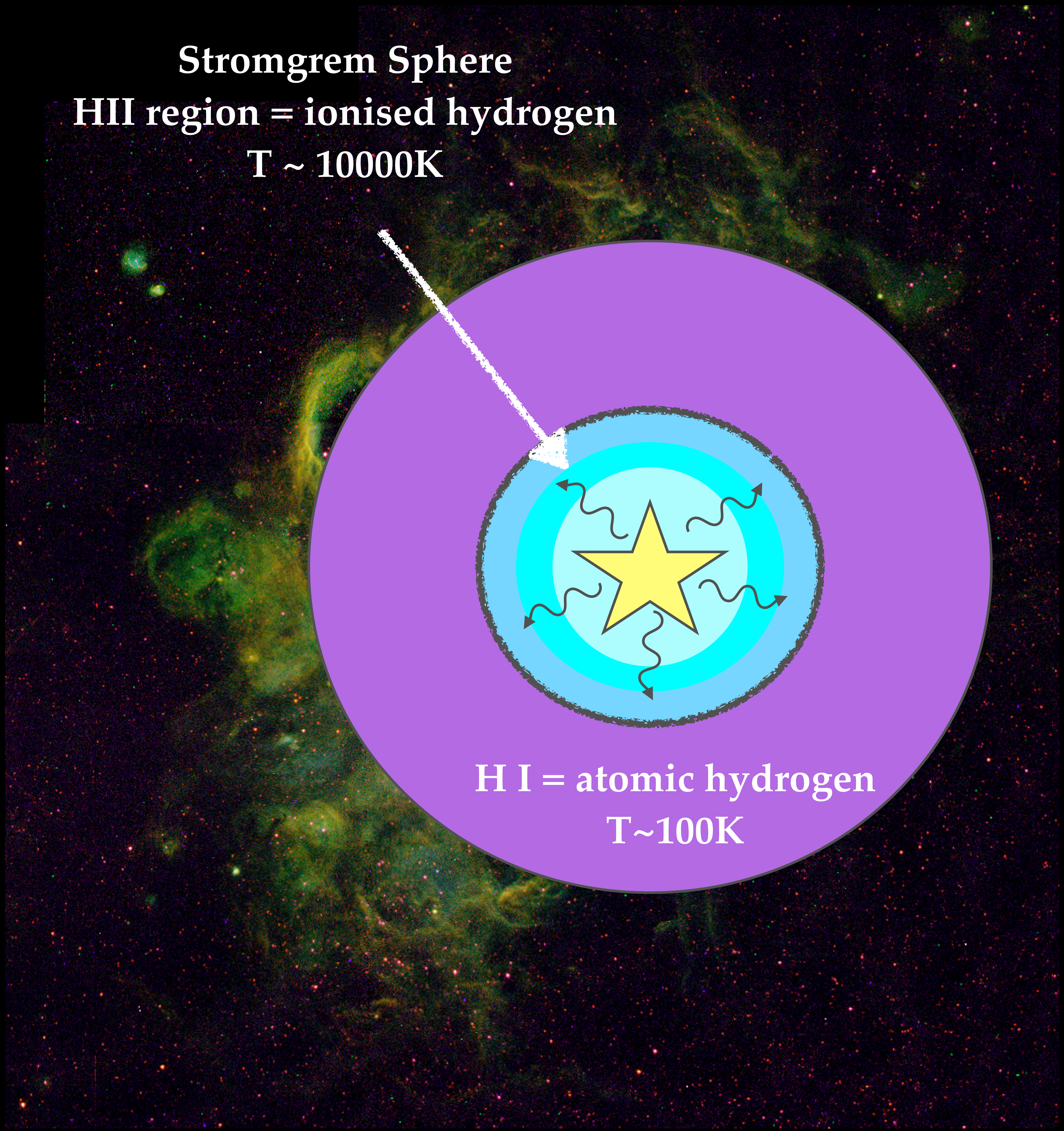
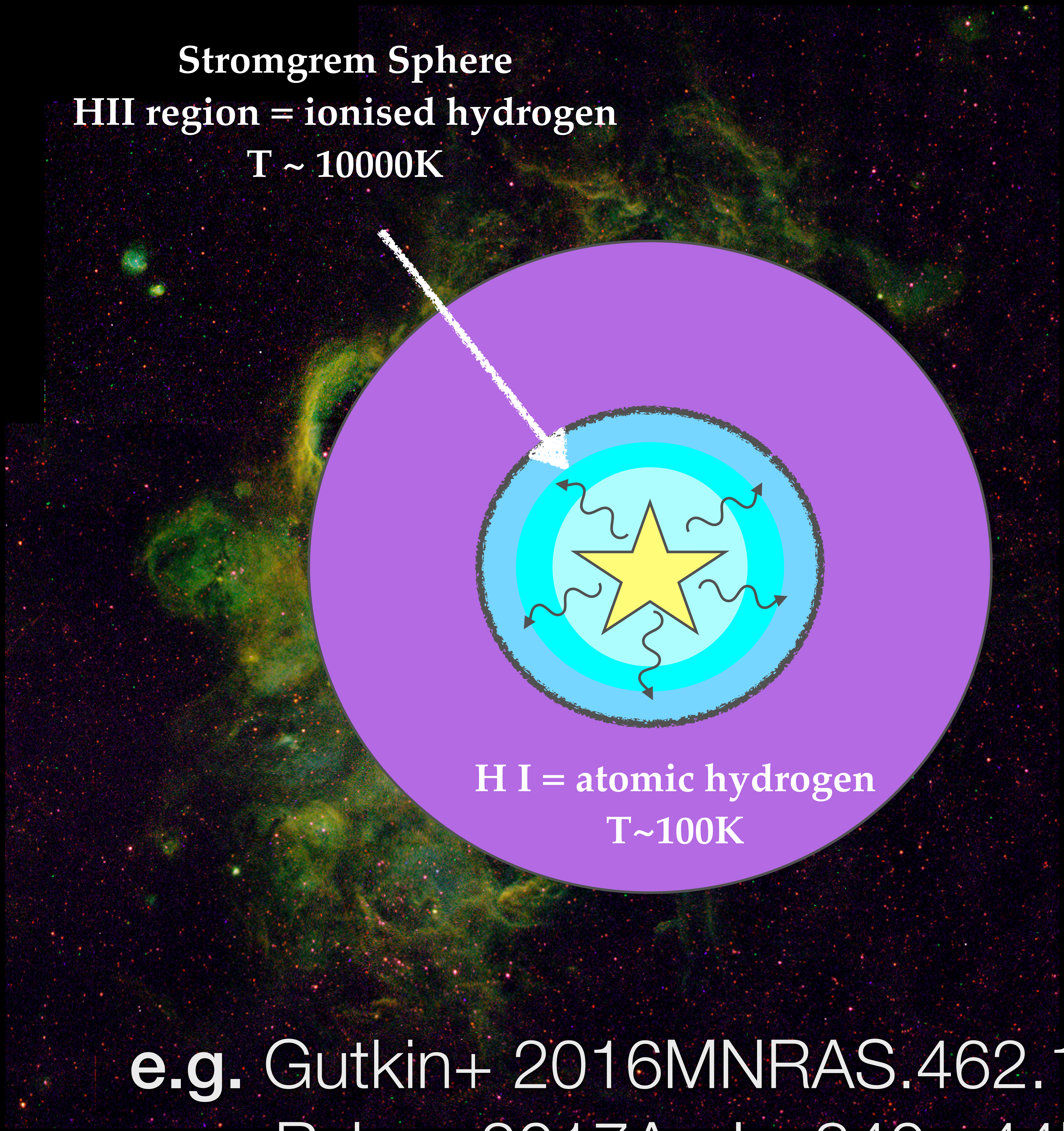
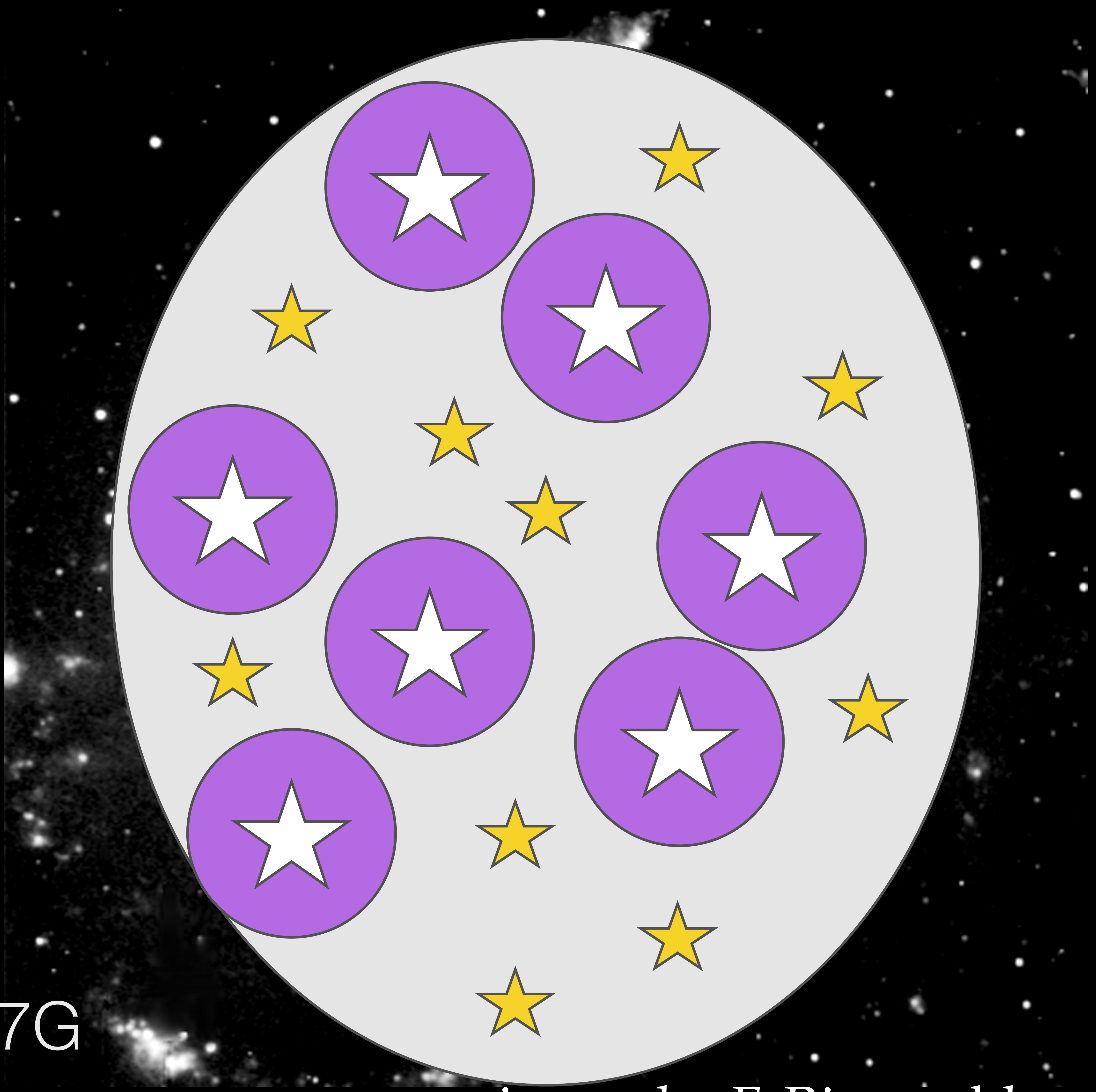


image by F. Ringwald

SED fitting I - the models
Nebular emission

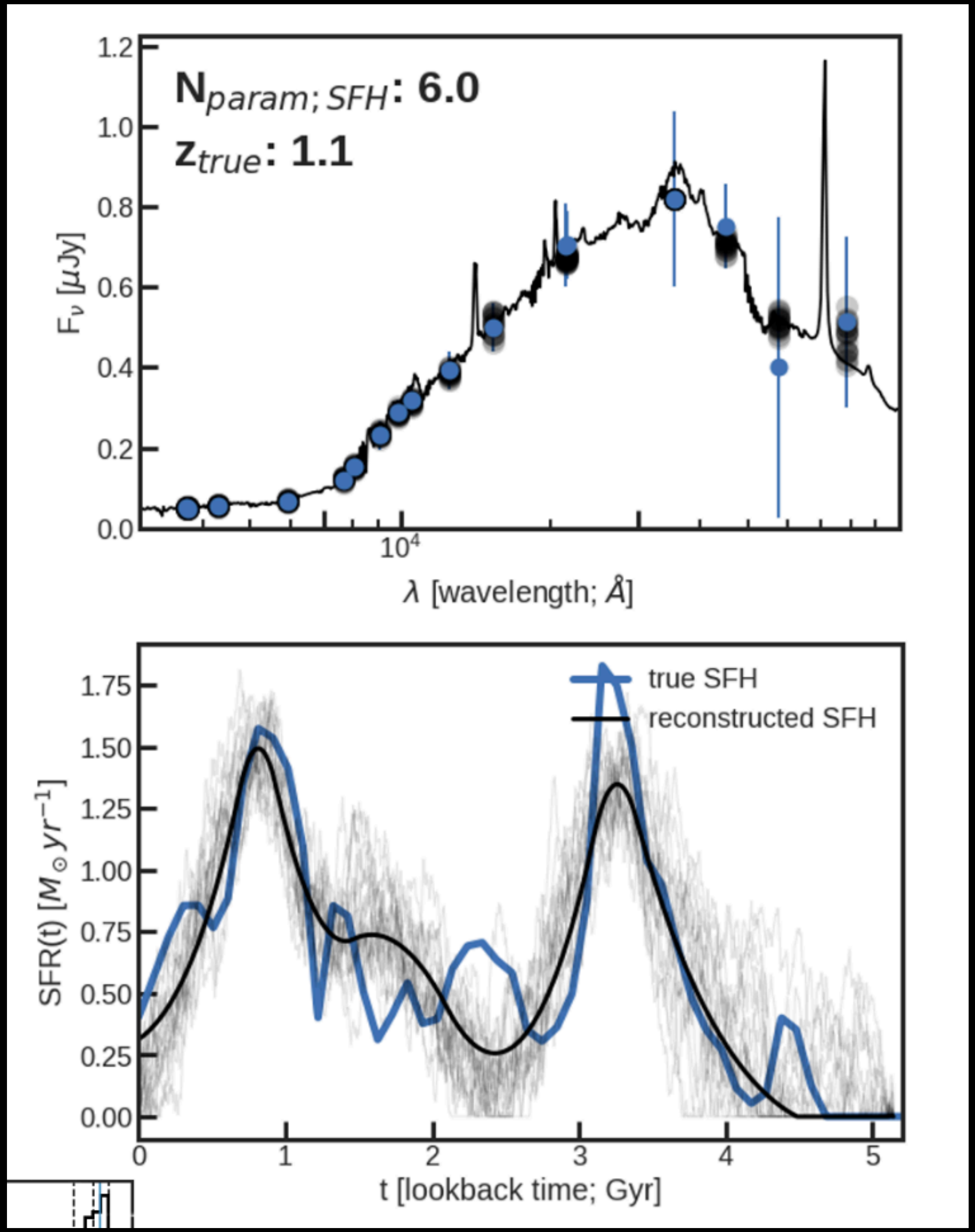




e.g. Gutkin+ 2016MNRAS.462.1757G
Byler+ 2017ApJ…840…44B

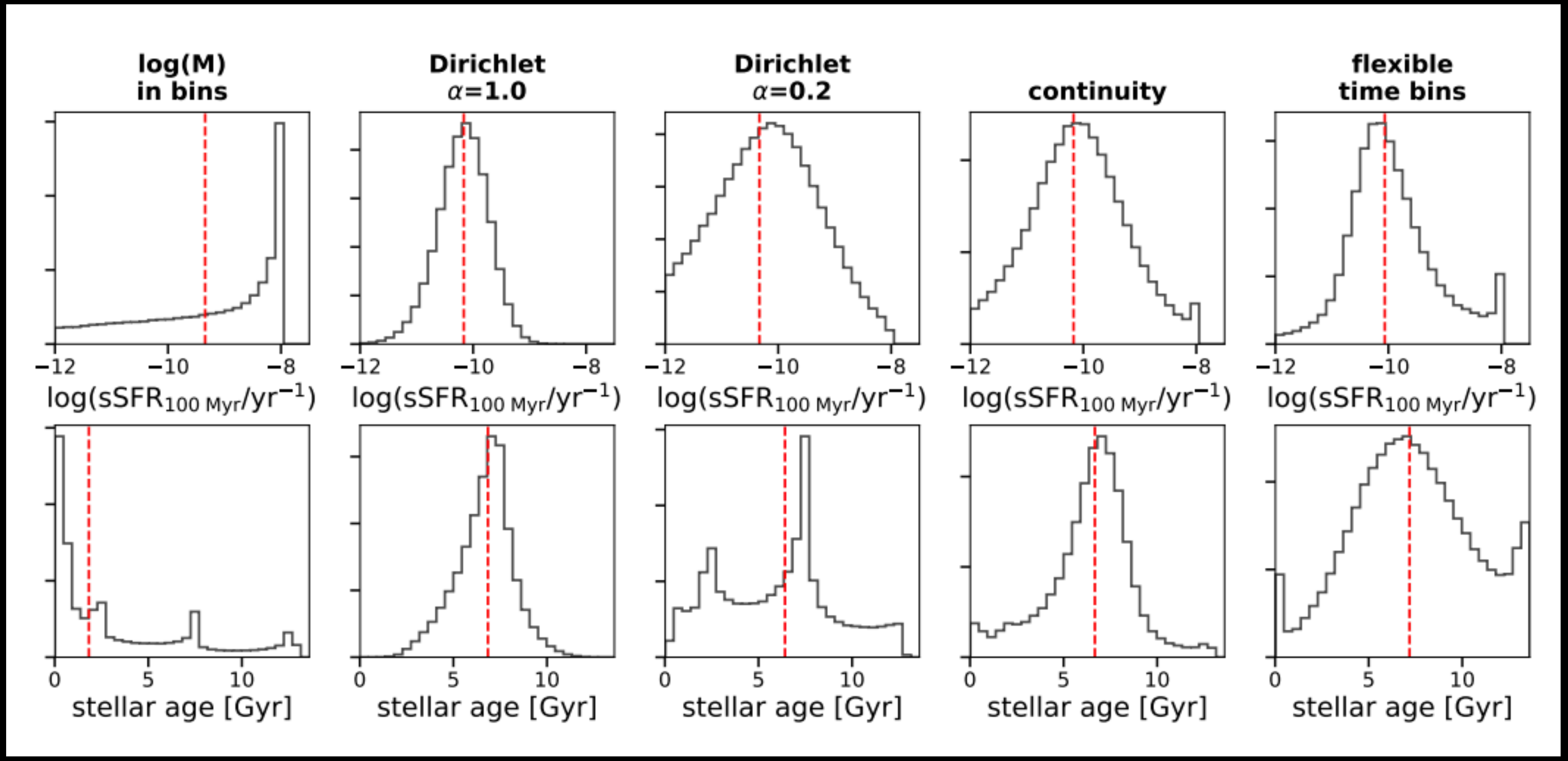
image by F. Ringwald

SED fitting I - the models
Star formation histories



Gaussian process/dense basis

Iyer+ 2019ApJ…879..116I



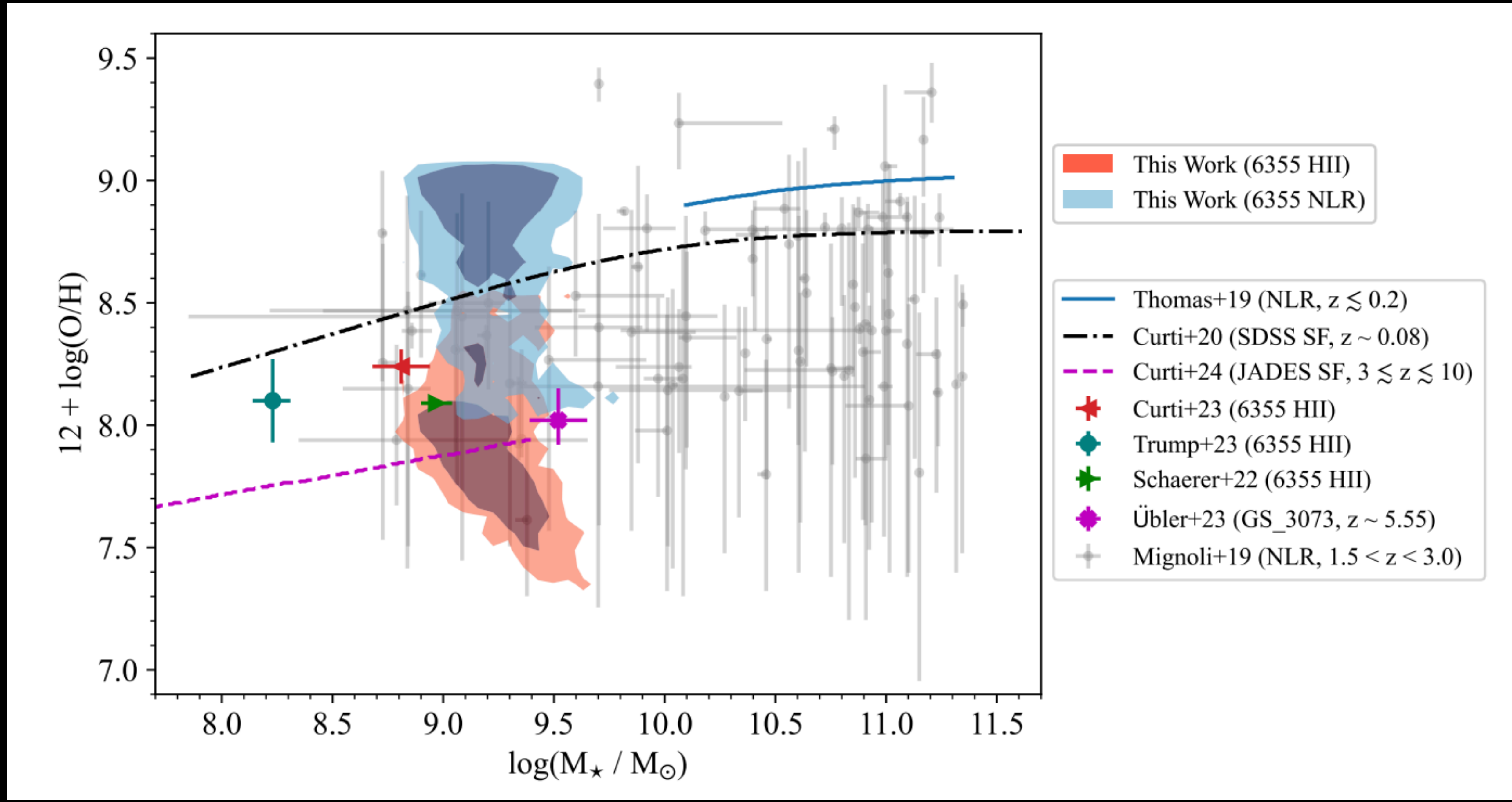
Prospector 'non-parametric'

Leja+ 2019ApJ…876….3L

Or stochastic prior e.g.

Tacchella+ 2022ApJ...927..170T

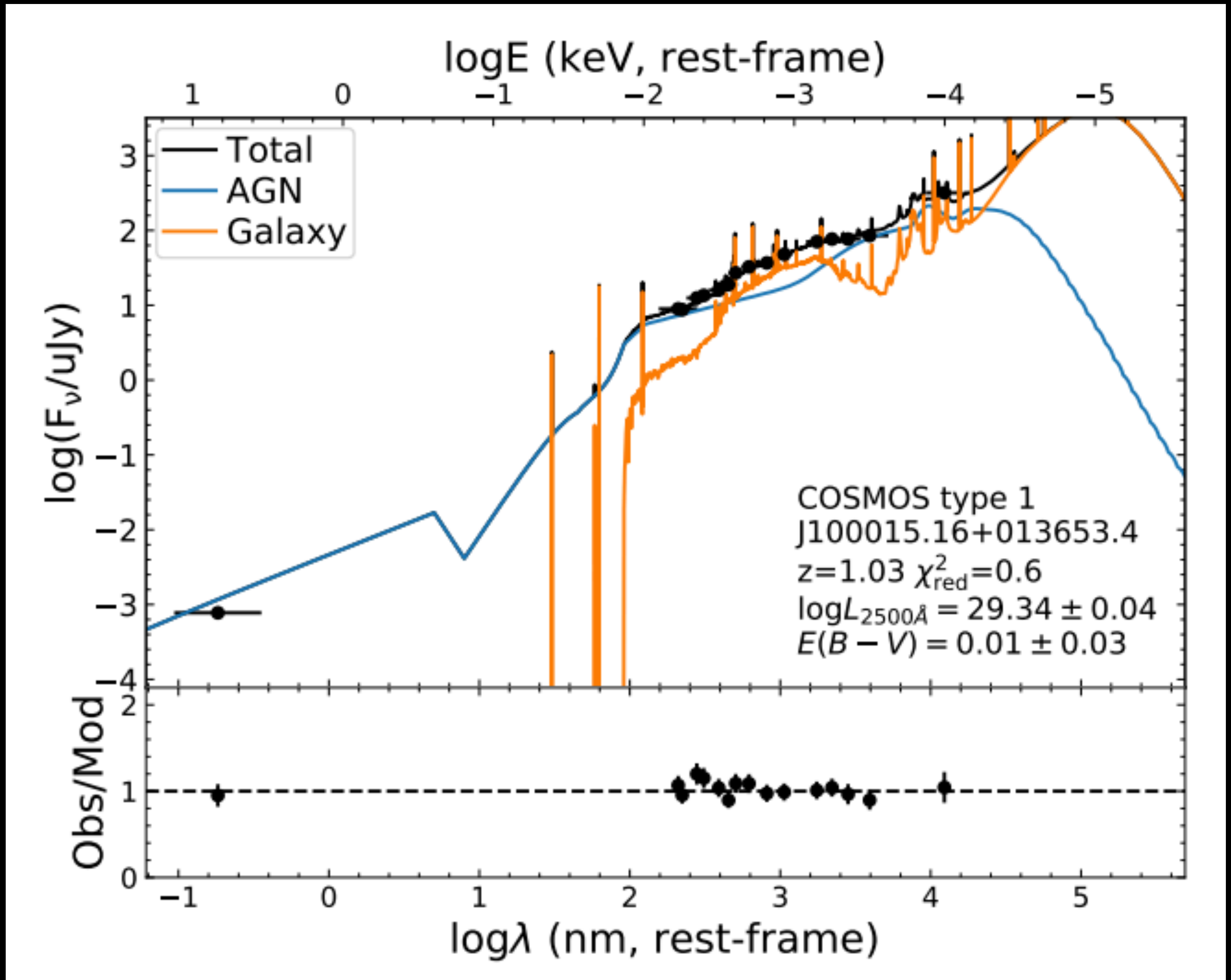
SED fitting I - the models
AGN



BEAGLE-AGN NLR modelling

Silcock+ arXiv.2410.18193

Vidal-Garcia, Plat, ECL+ 2024MNRAS.527.7217V



e.g. full SED X-CIGALE

Yang+ 2020MNRAS.491..740Y

SED fitting II - Inference, or inferring galaxy properties

Compare models to data quantitatively:

Minimising the chi2 is one method

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{f_{\mathrm{obs},i} - f_{\mathrm{model},i}}{\sigma_i} \right)^2$$

Where:

- $f_{\mathrm{obs},i}$ = the observed photometric flux (or magnitude) at the i-th data point
- $f_{\mathrm{model},i}$ = the model-predicted flux (or magnitude) at the same point
- σ_i = the uncertainty (error bar) on the observed point i
- N = number of photometric data points

SED fitting II - Inference, or inferring galaxy properties

Compare models to data quantitatively:

Or you can construct a likelihood to maximise. If you believe the errors on the data to be Gaussian distributed, you can construct a Gaussian likelihood

$$\mathcal{L} = \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(-\frac{(f_{\mathrm{obs},i} - f_{\mathrm{model},i})^2}{2\sigma_i^2}\right)$$

Where:

- $f_{\mathrm{obs},i}$: observed photometric flux (or magnitude) at band i
- $f_{\mathrm{model},i}$: model-predicted flux (or magnitude) at band i
- σ_i: uncertainty on the observed flux at band i
- N: number of photometric bands or data points

SED fitting II - Inference, or inferring galaxy properties

Compare models to data quantitatively:

Or you can construct a likelihood to maximise. If you believe the errors on the data to be Gaussian distributed, you can construct a Gaussian likelihood

$$\ln \mathcal{L} = -\frac{1}{2} \sum_{i=1}^{N} \left[\left(\frac{f_{\mathrm{obs},i} - f_{\mathrm{model},i}}{\sigma_i} \right)^2 + \ln(2\pi\sigma_i^2) \right]$$

Where:

- $f_{\mathrm{obs},i}$: observed photometric flux (or magnitude) at band i
- $f_{\mathrm{model},i}$: model-predicted flux (or magnitude) at band i
- σ_i: uncertainty on the observed flux at band i
- N: number of photometric bands or data points

SED fitting II - Inference, or inferring galaxy properties

With Bayesian statistics, you use the likelihood and the Bayes theorem:

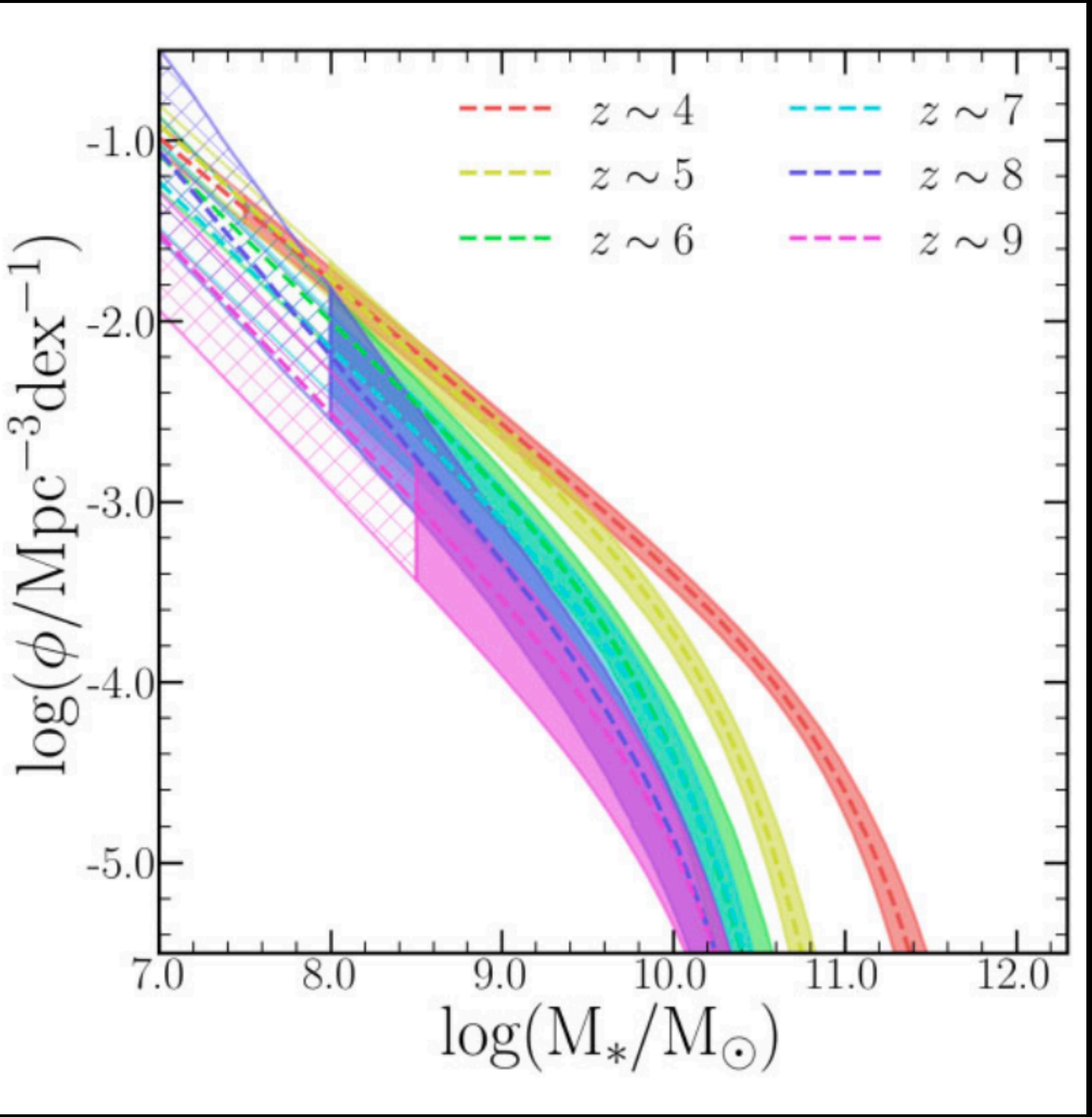
Posterior Likelihood x Prior

$$P(\text{model} \mid \text{data}) = \frac{P(\text{data} \mid \text{model})\, P(\text{model})}{P(\text{data})}$$

Evidence

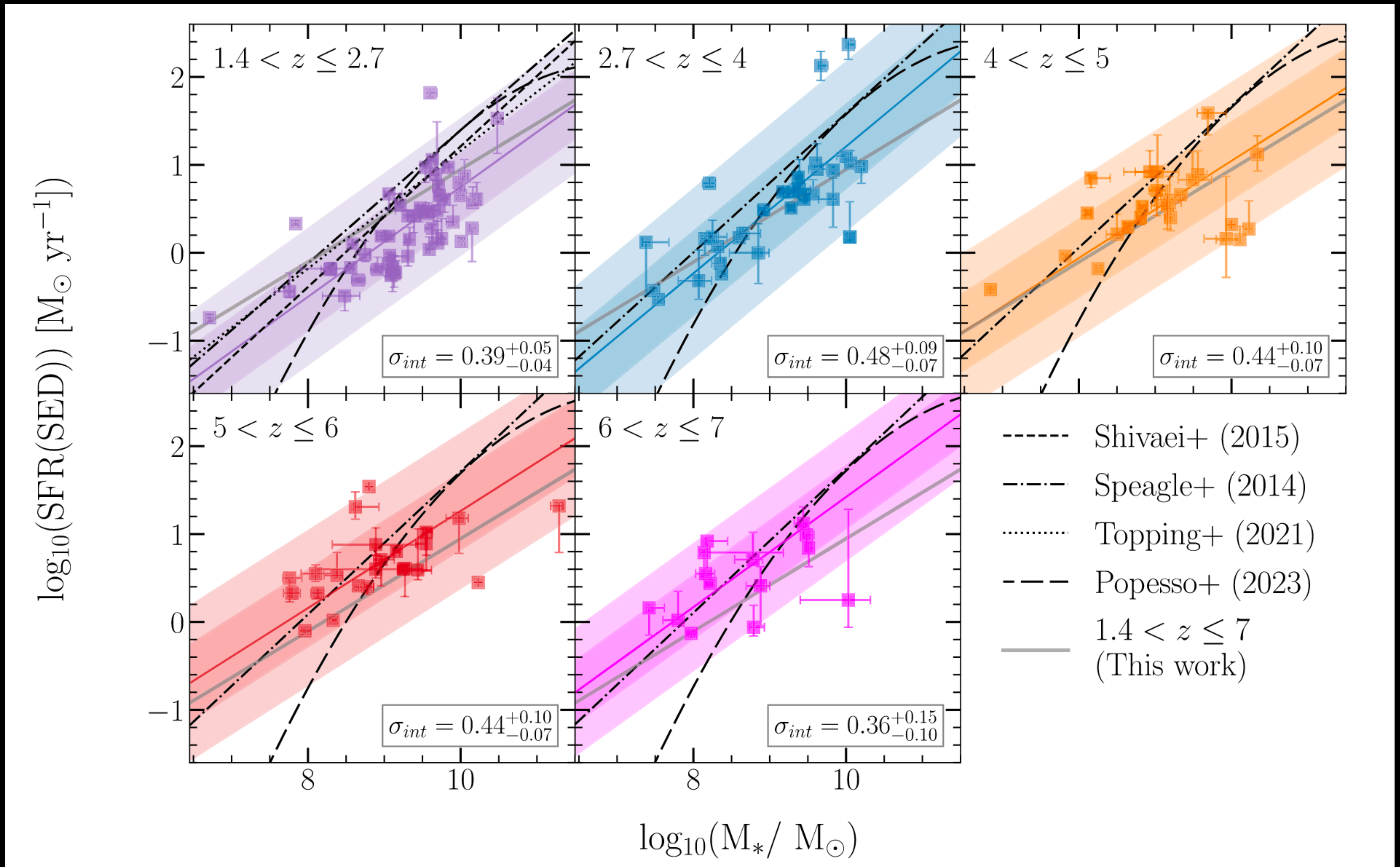
Galaxy evolution should be easy with JWST now, right?
(Results skewed towards those from JADES)

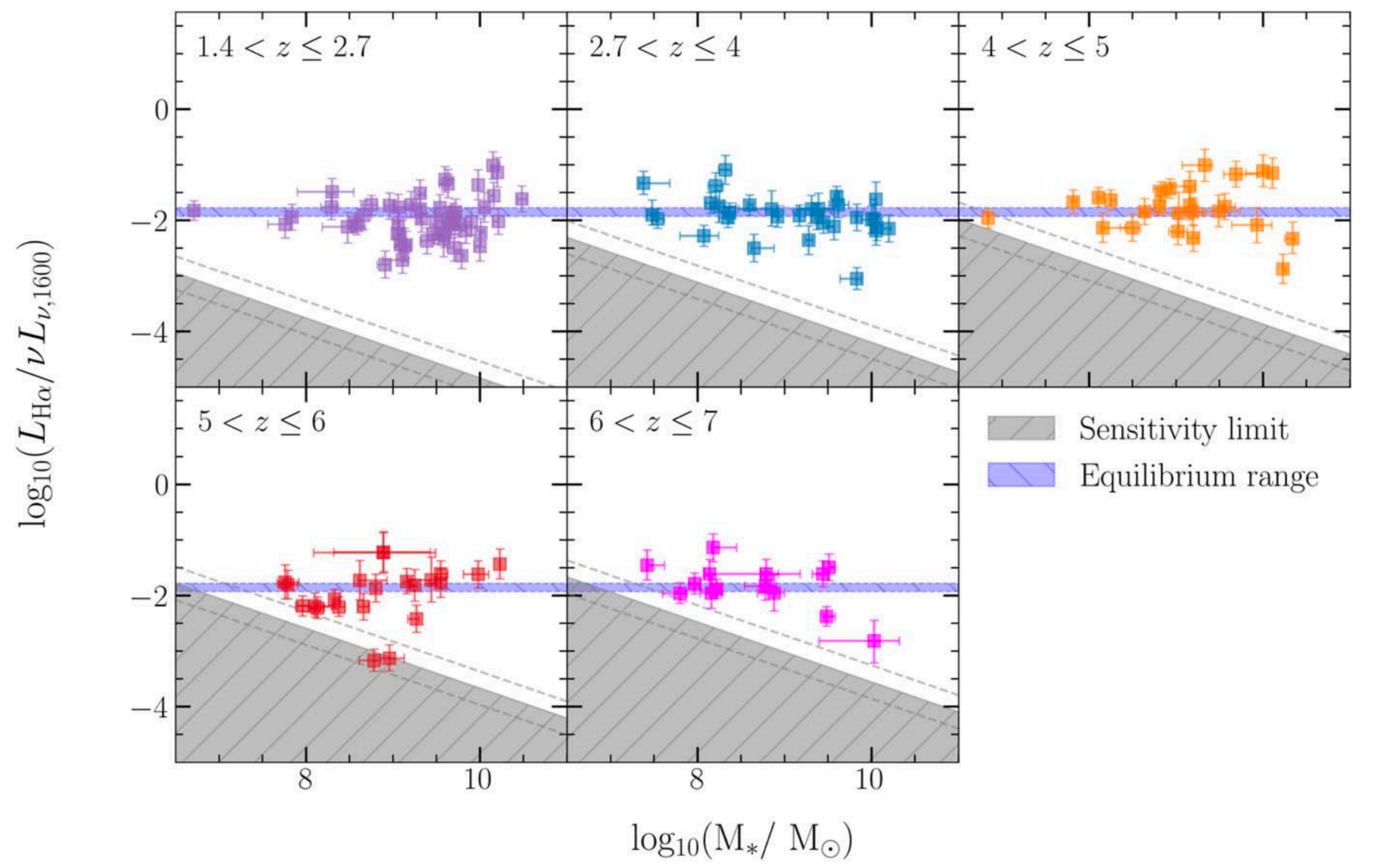
Pushing stellar mass functions to high redshifts with rest-optical NIRCam coverage



Weibel+ 2024MNRAS.533.1808W

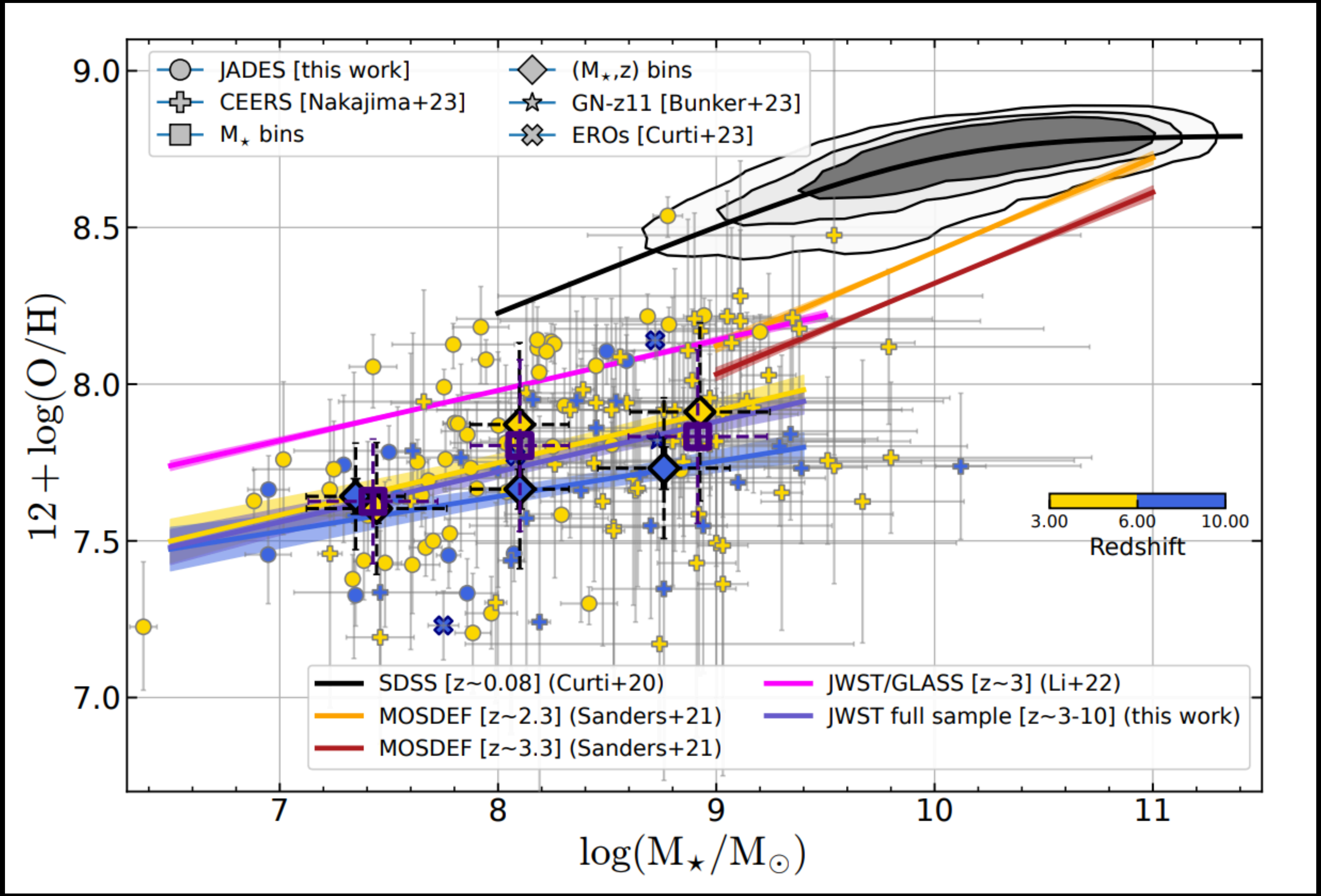
M*-SFR, these things should be easy now with NIRCam data, right?





Clark+ 2024ApJ...977..133C
(See also Rinaldi+ 24)

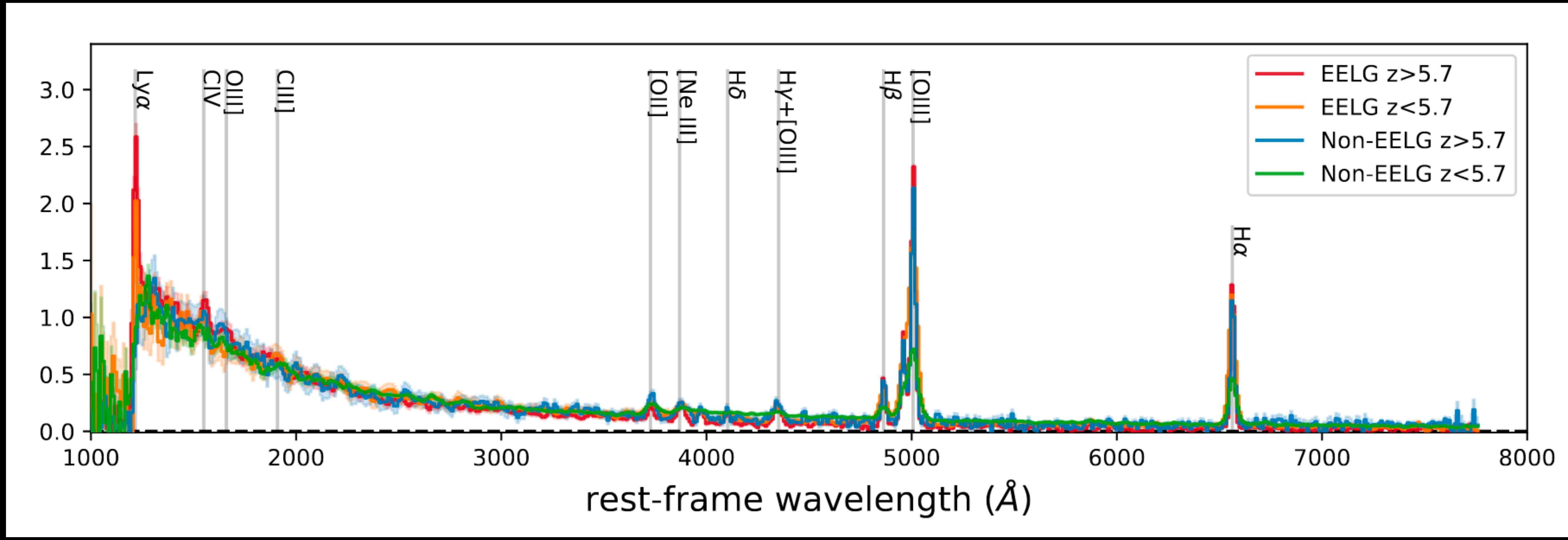
Generally lower metallicities



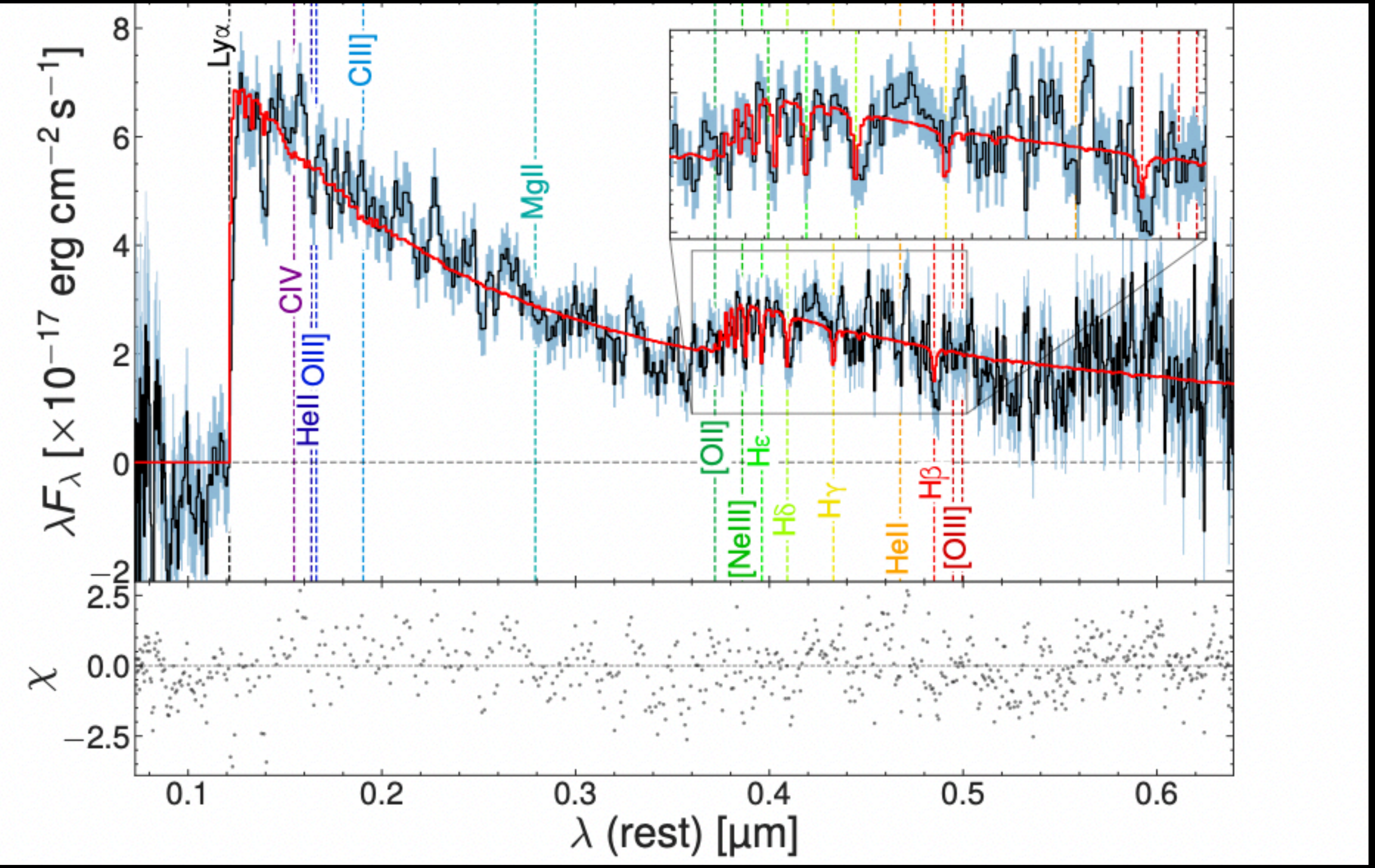
Shallower slope in mass-metallicity relation at low stellar masses with slope well reproduced by momentum-driven winds from supernovae. Decreasing metallicities to higher redshifts

Curti+24a

At first glimpse a diverse population of galaxies, indicative of stochastic star formation



From extreme equivalent width emission lines
e.g. Boyett+ 2024MNRAS.535.1796B



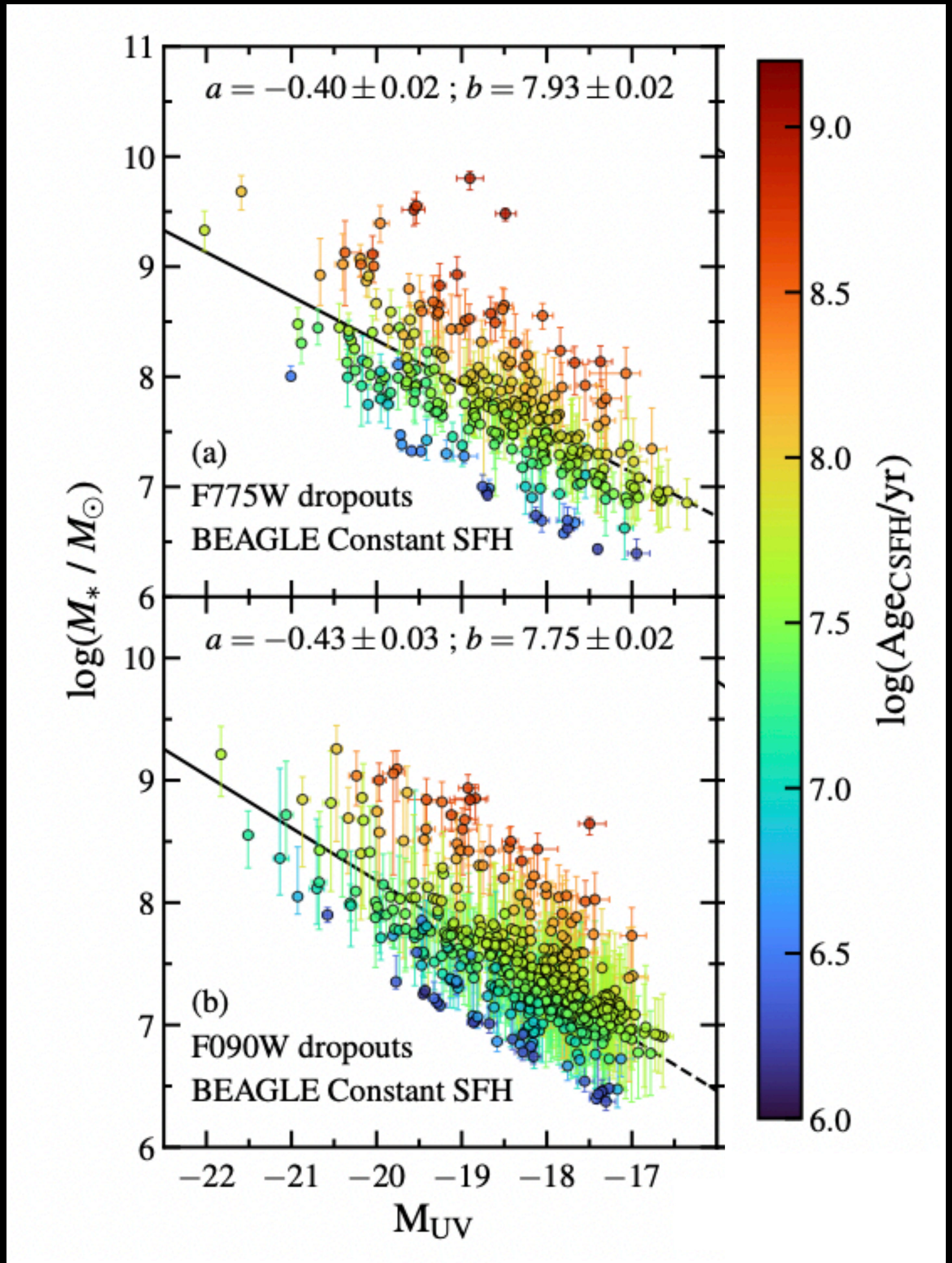
To napping galaxies
Looser+ 2024Natur.629…53L

See also:
Strait+ 2023ApJ...949L..23S,
Looser+ 2025A&A…697A..88L
+++

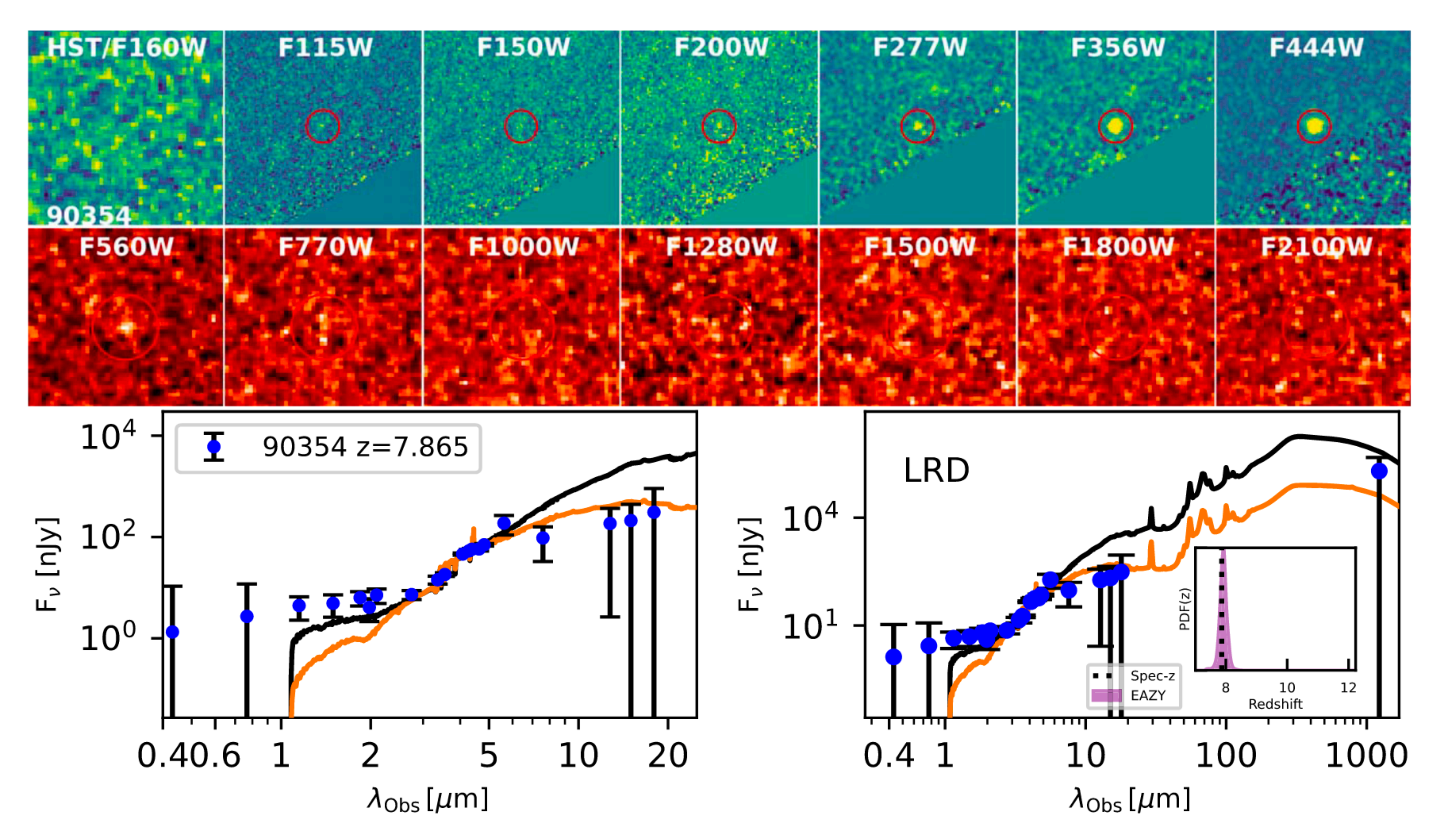
Many of the relationships we study have stellar mass as a baseline, but…

Stochastic SFHs mean our stellar masses are very dependent on prior/model assumed

Endsley+ 2024MNRAS.533.1111E



The addition of MIRI constraints can help!



Williams+ 2024ApJ...968...34W

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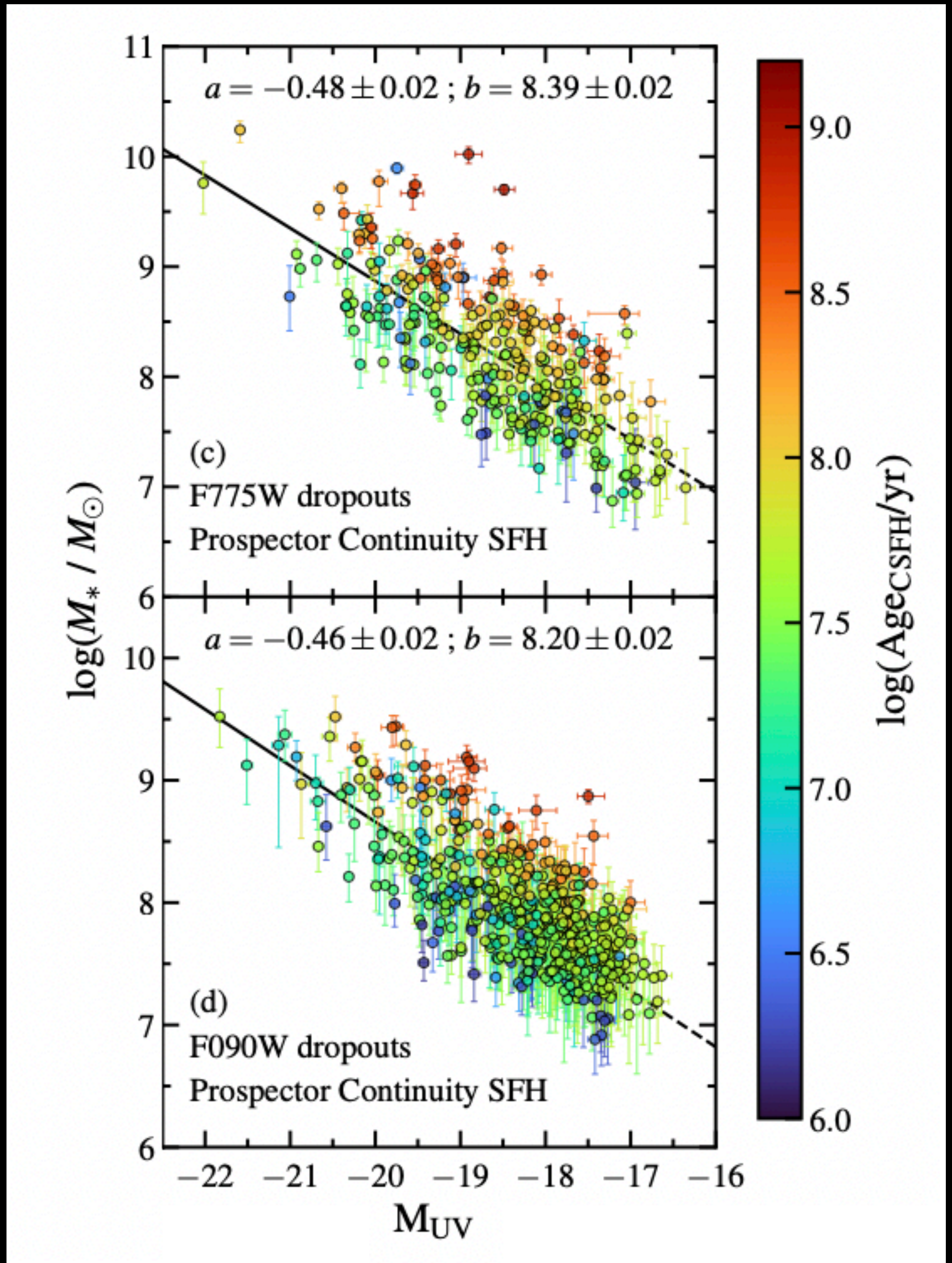

Endsley+ 2024MNRAS.533.1111E

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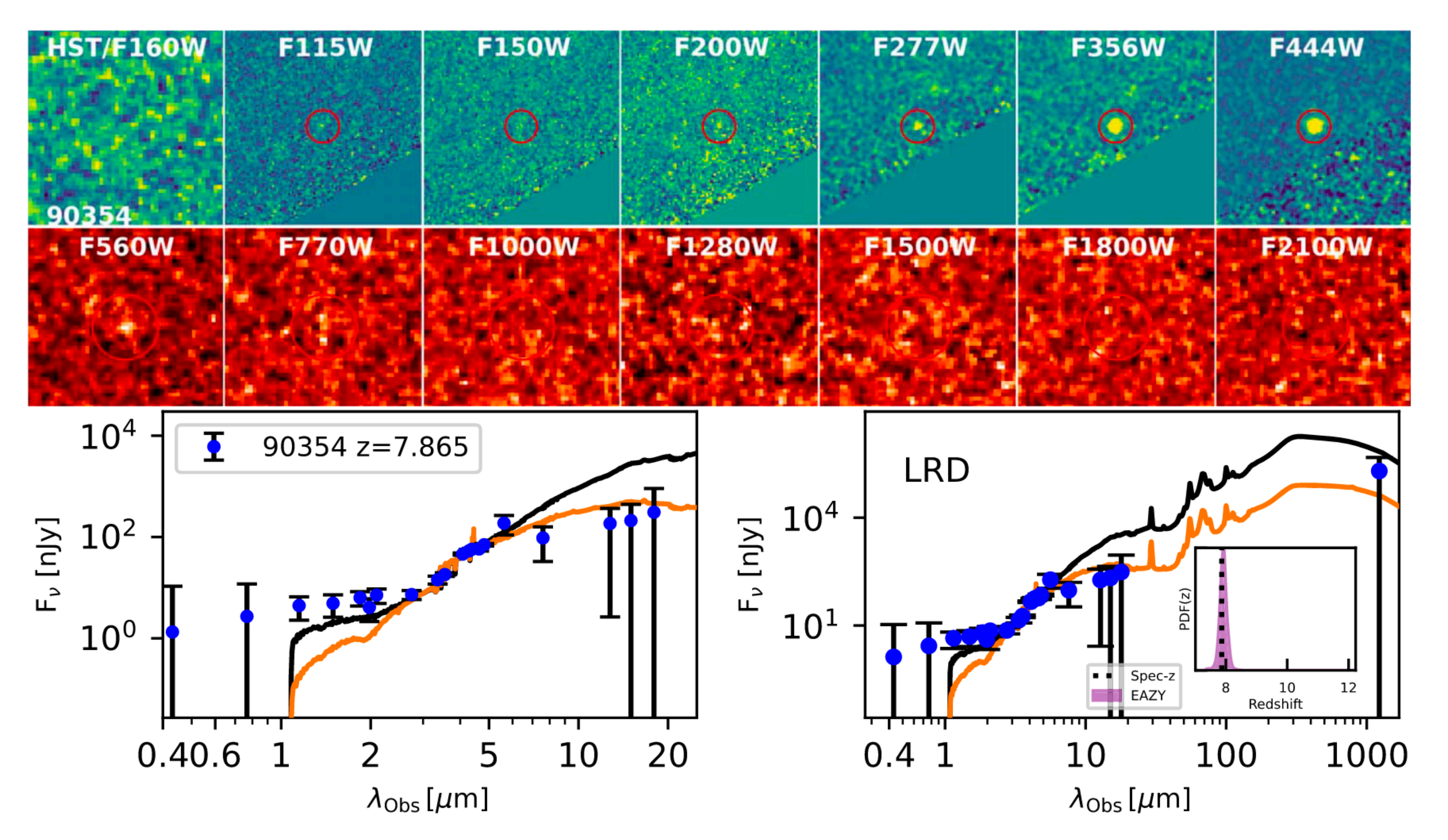
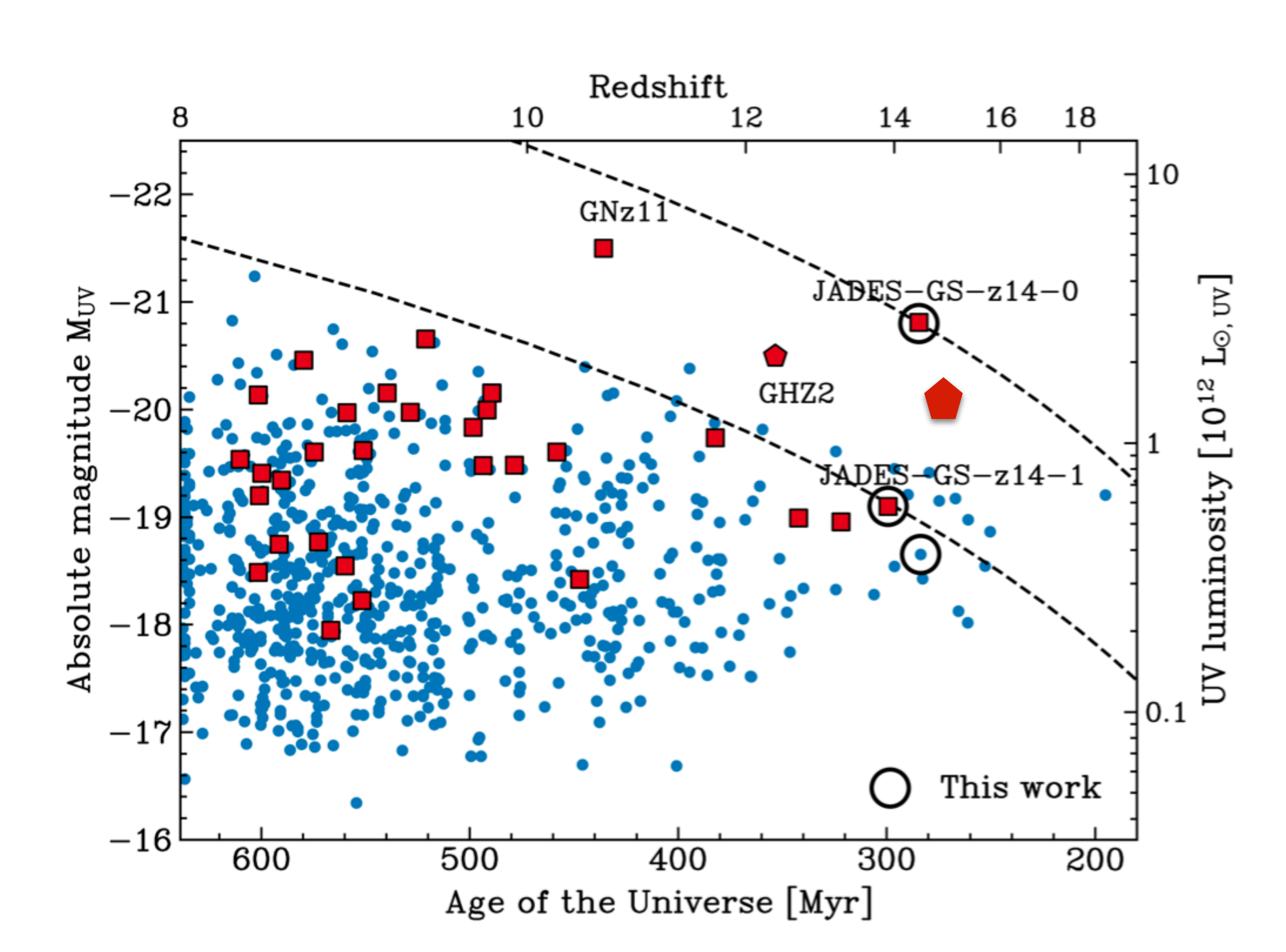


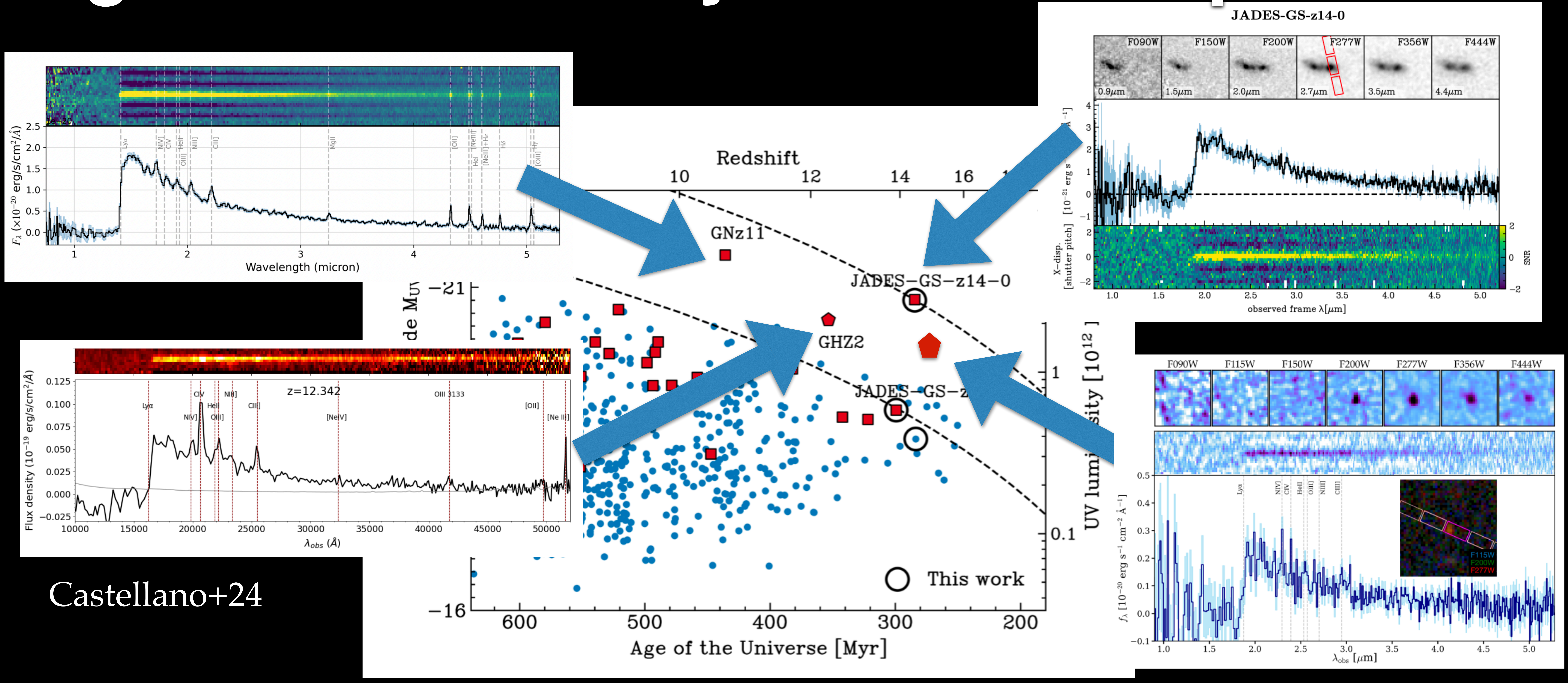
Williams+ 2024ApJ...968...34W

Highest redshift objects have us puzzled



Some of the most distant galaxies identified (current record z=14.44) are incredibly luminous, and also show diversity in emission line properties

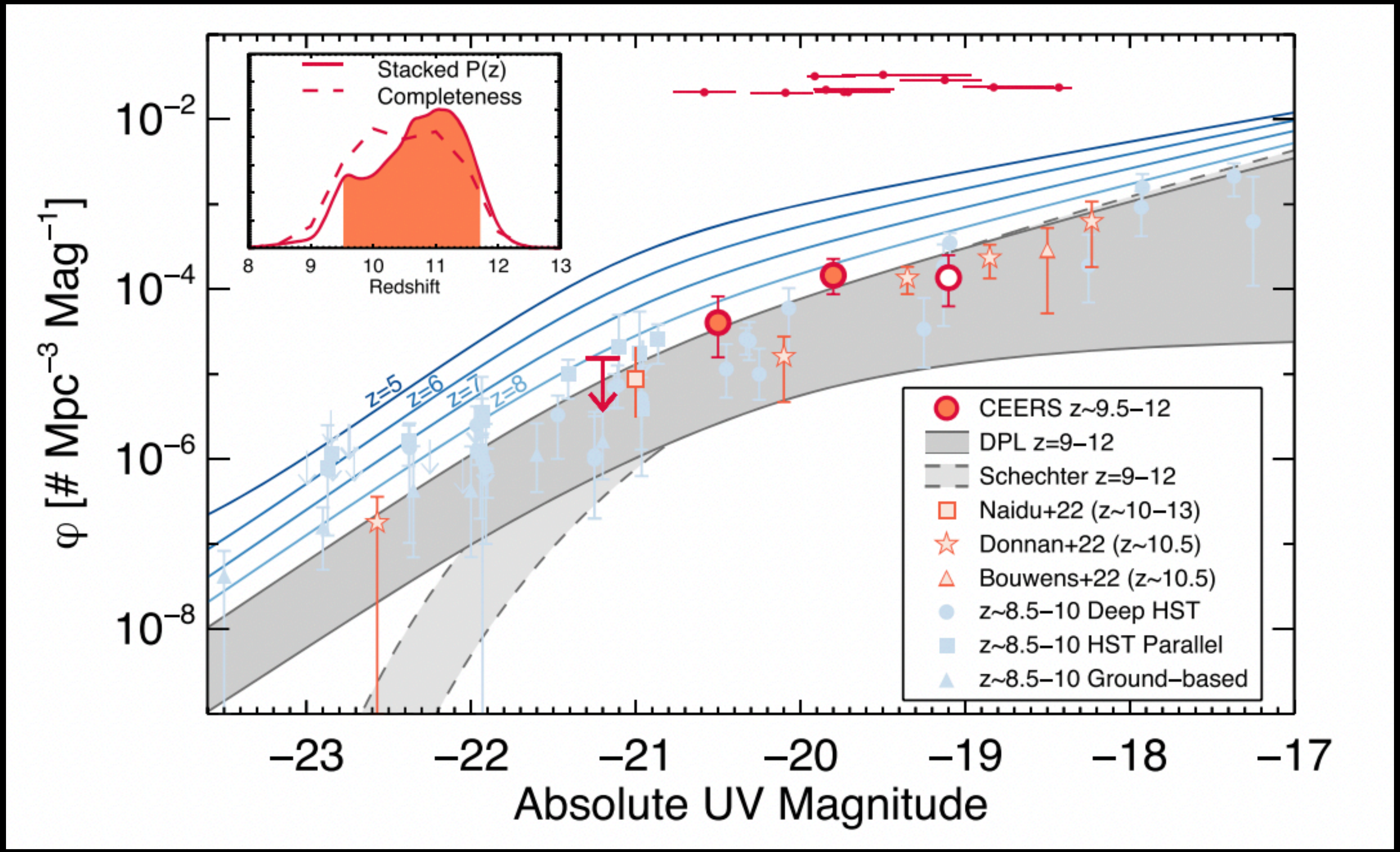
Highest redshift objects have us puzzled



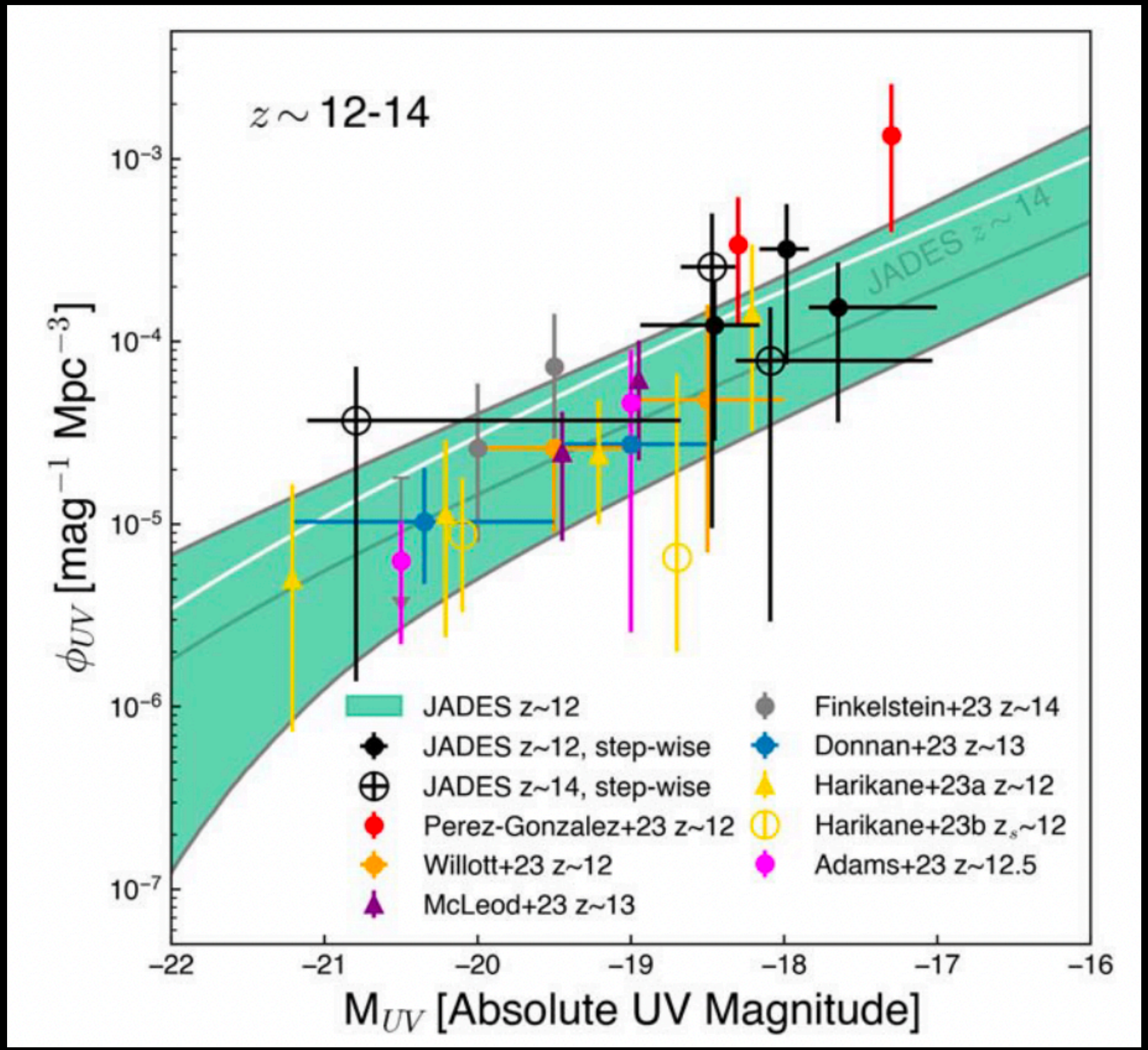
Some of the most distant galaxies identified (current record z=14.44) are incredibly luminous, and also show diversity in emission line properties

Highest redshift objects have us puzzled

- JADES confirming a result from the first months of JWST operations, less evolution in number densities of bright galaxies at the highest redshifts than was expected pre-JWST (i.e. more luminous galaxies than we were expecting)

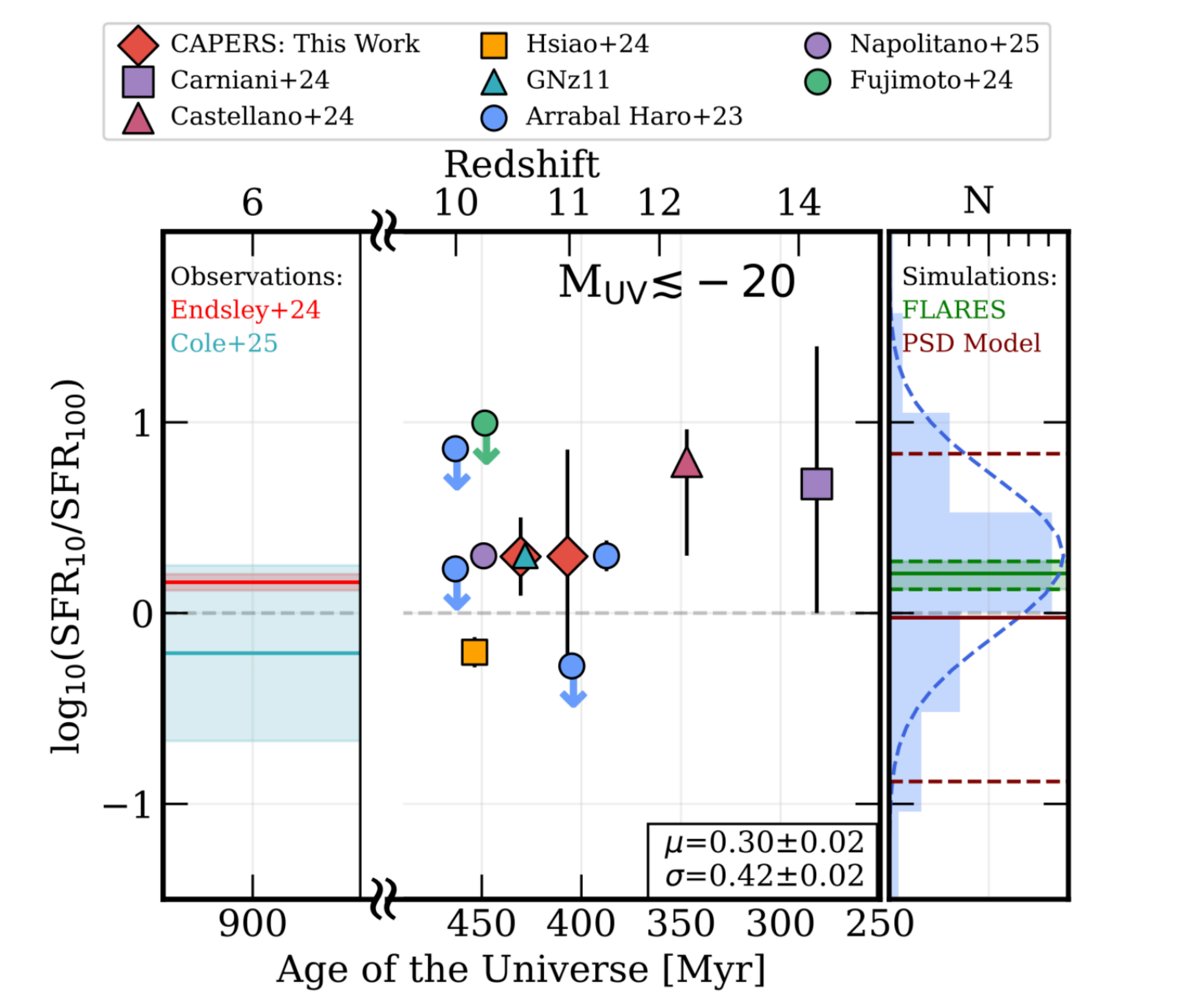


Finkelstein+22



See also: Adams+23, Harikane+23a,b,24, Donnan+23,24 + many others

Robertson+24

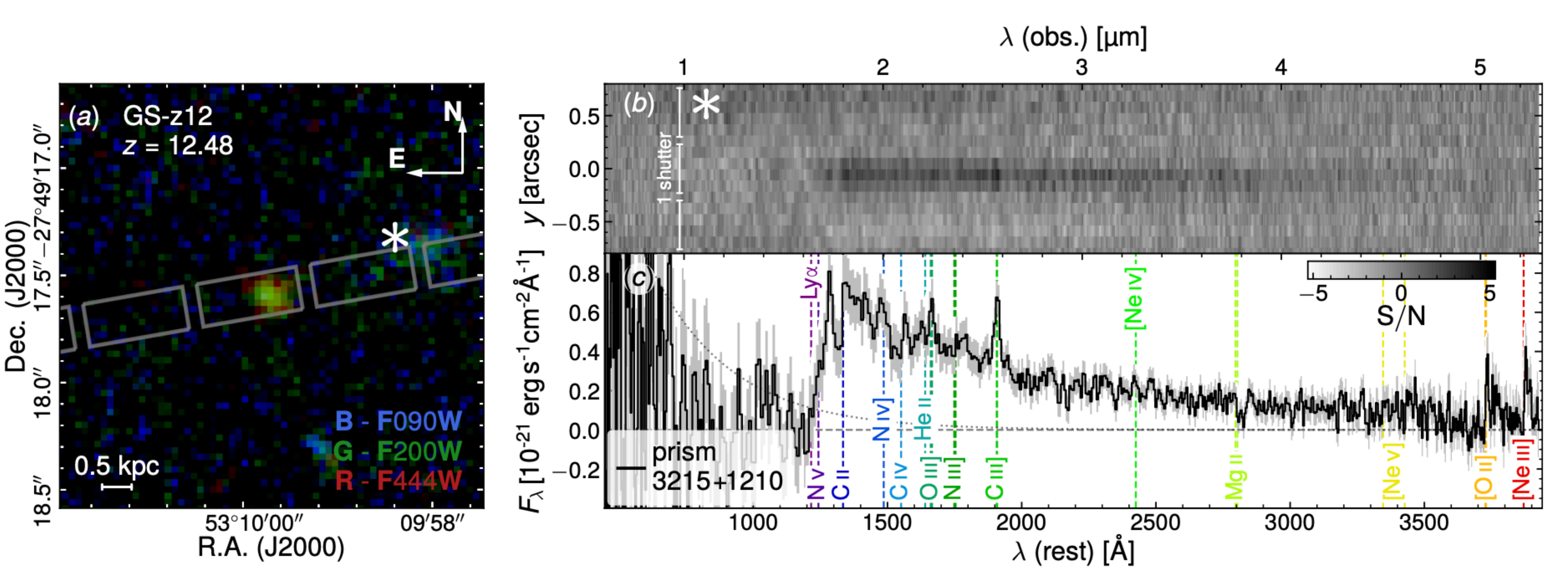


One of the (numerous) suggestions to explain UV luminous population at high-z is that they must be in bursting phase.

Kokorev+25, arXiv.2504.12504

Can we learn about early stellar populations from chemical abundance patterns? GS-z12

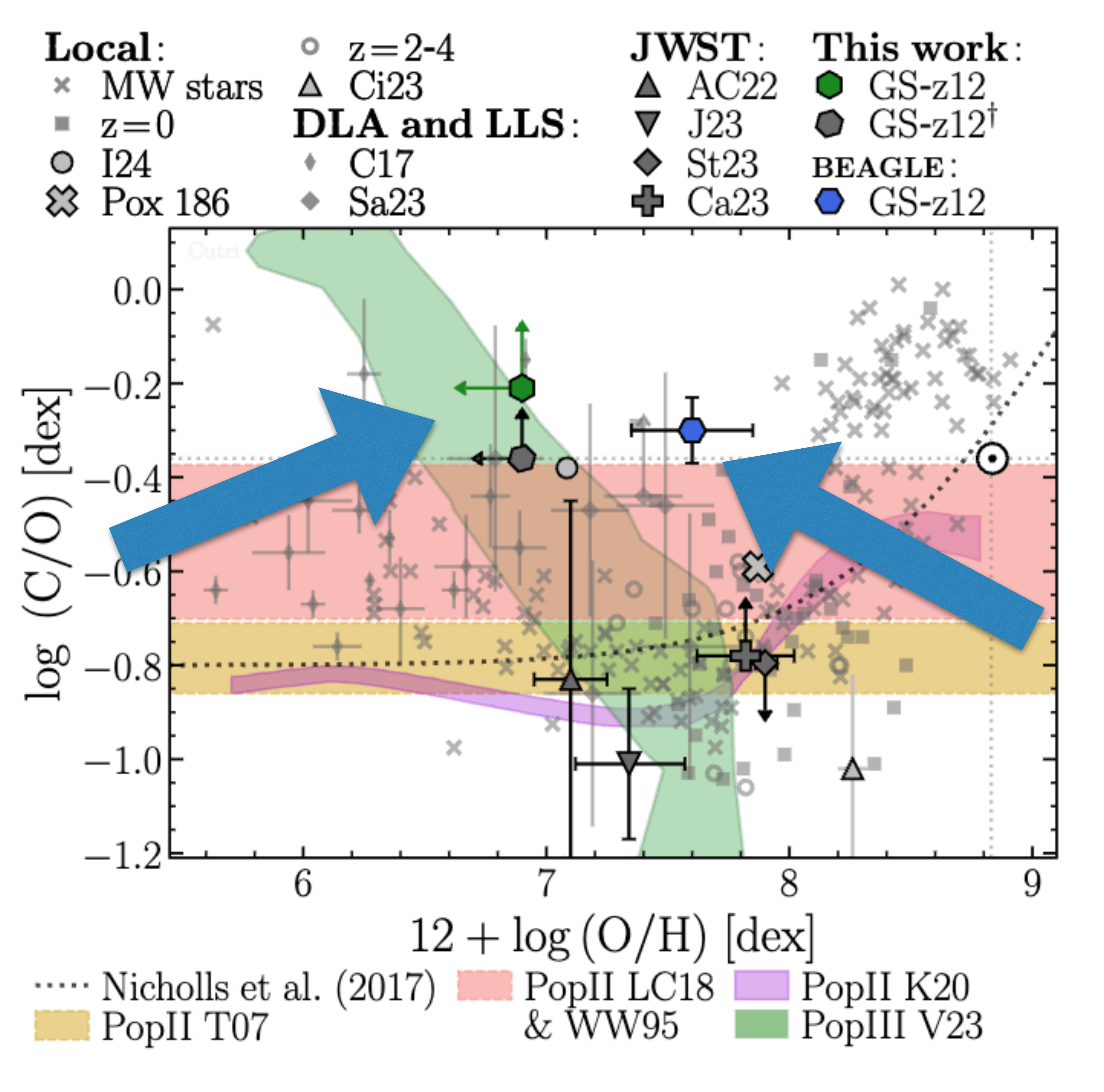
D'Eugenio+23



This was not one of the super-luminous galaxies, but a deep spectrum showed very strong carbon emission lines

Can we learn about early stellar populations from chemical abundance patterns? GS-z12

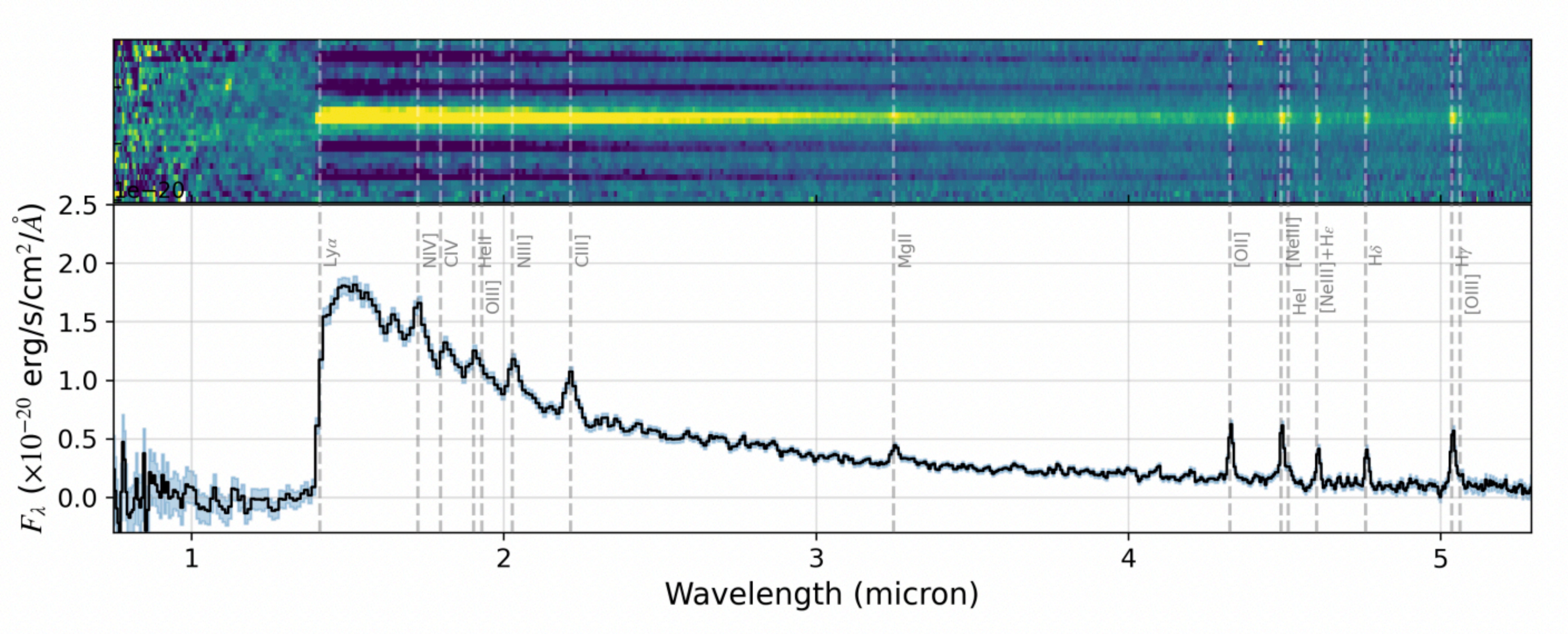
These C/O estimates directly from emission line fluxes/ratios



This estimate from SED-fitting with BEAGLE while varying C/O

D'Eugenio+23

A most surprising spectrum



Bunker+23

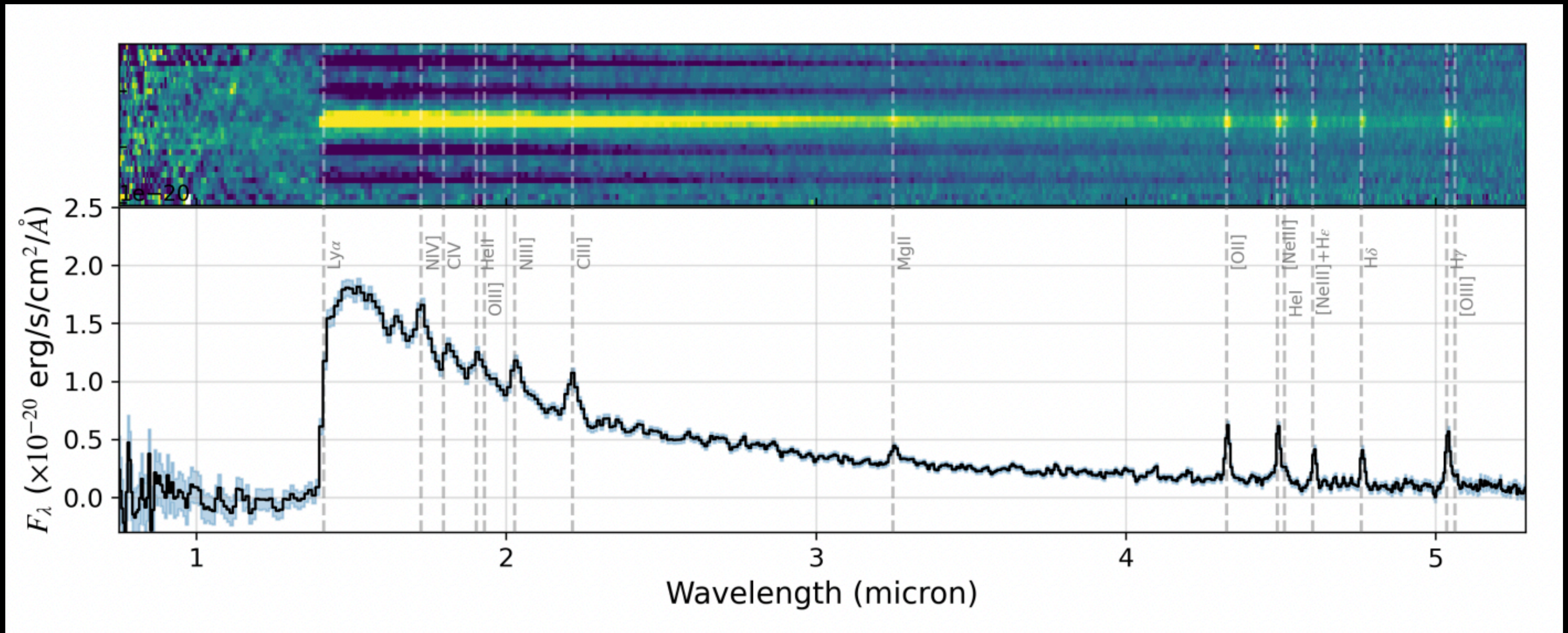
GN-z11 has very strong Nitrogen and Carbon lines in the UV and was the most luminous high-redshift galaxy identified with Hubble

A most surprising spectrum

- Evidence for the highest redshift black hole?

A small and vigorous black hole in the early Universe

Roberto Maiolino[1,2,3*], Jan Scholtz[1,2], Joris Witstok[1,2], Stefano Carniani[4], Francesco D'Eugenio[1,2], Anna de Graaff[5], Hannah Übler[1,2], Sandro Tacchella[1,2], Emma Curtis-Lake[6], Santiago Arribas[7], Andrew Bunker[8], Stéphane Charlot[9], Jacopo Chevallard[8], Mirko Curti[10], Tobias J. Looser[1,2], Michael V. Maseda[11], Tim Rawle[12], Bruno Rodríguez Del Pino[7], Chris J. Willott[13], Eiichi Egami[14], Daniel Eisenstein[15], Kevin Hainline[14], Brant Robertson[16], Christina C. Williams[17], Christopher N. A. Willmer[14], William M. Baker[1,2], Kristan Boyett[18,19], Christa DeCoursey[14], Andrew C. Fabian[20], Jakob M. Helton[14], Zhiyuan Ji[14], Gareth C. Jones[8], Nimisha Kumari[21], Nicolas Laporte[1,2], Erica Nelson[22], Michele Perna[7], Lester Sandles[1,2], Irene Shivaei[14] and Fengwu Sun[14]



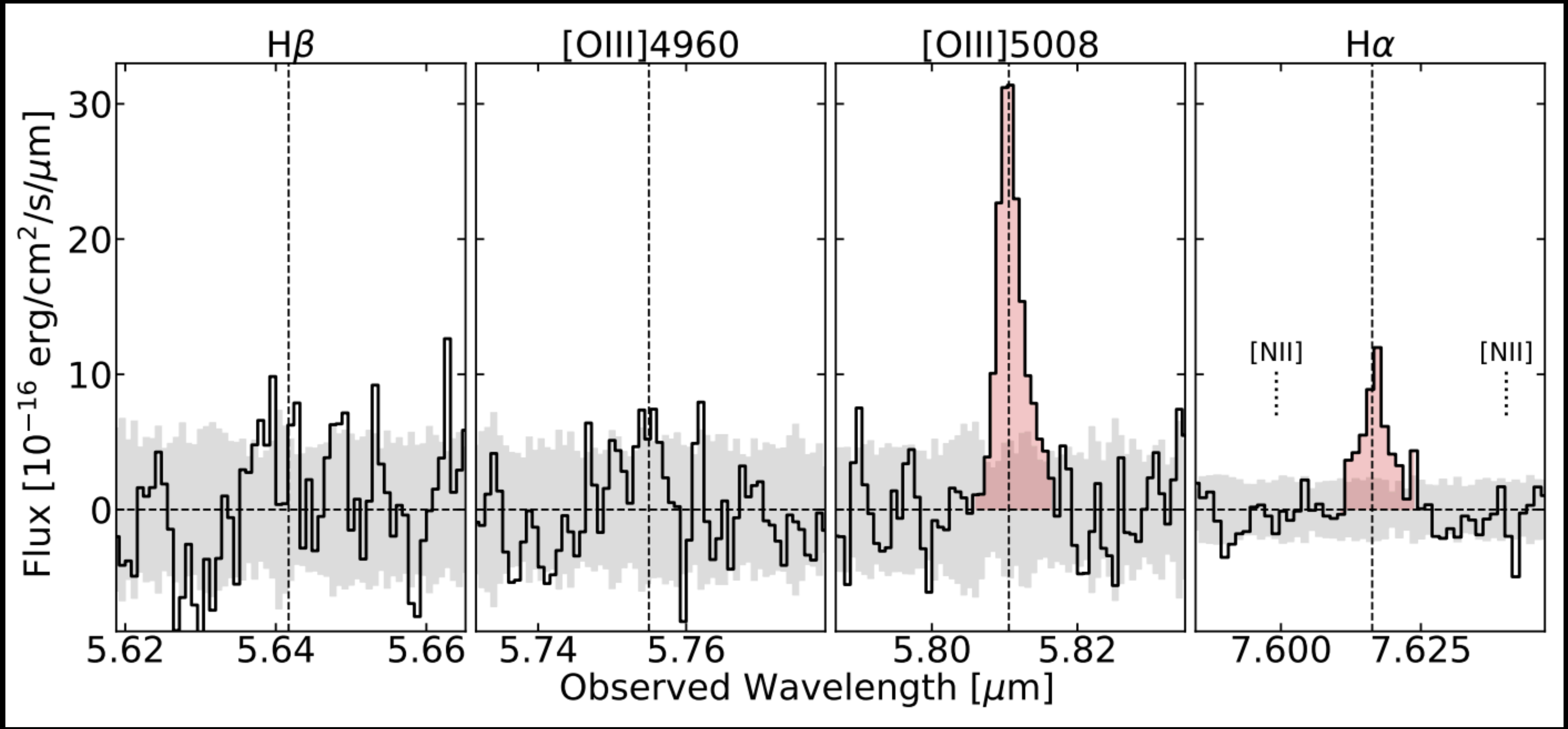
Bunker+23a arXiv:2302.07256

Maiolino+24, Nature

Although see Senchyna+23 and Cameron+23 for Wolf-Rayet star interpretation

A most surprising spectrum

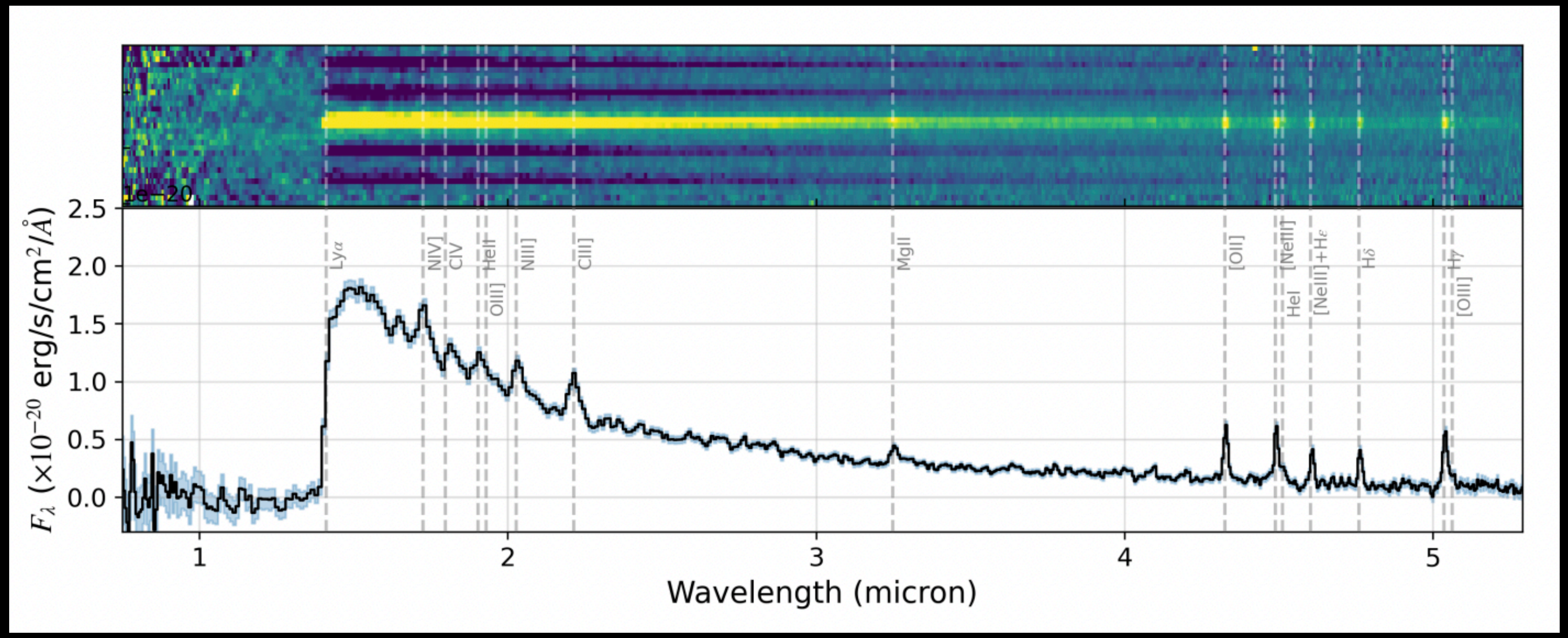
- Evidence for the highest redshift black hole?



Álvarez-Márquez+25

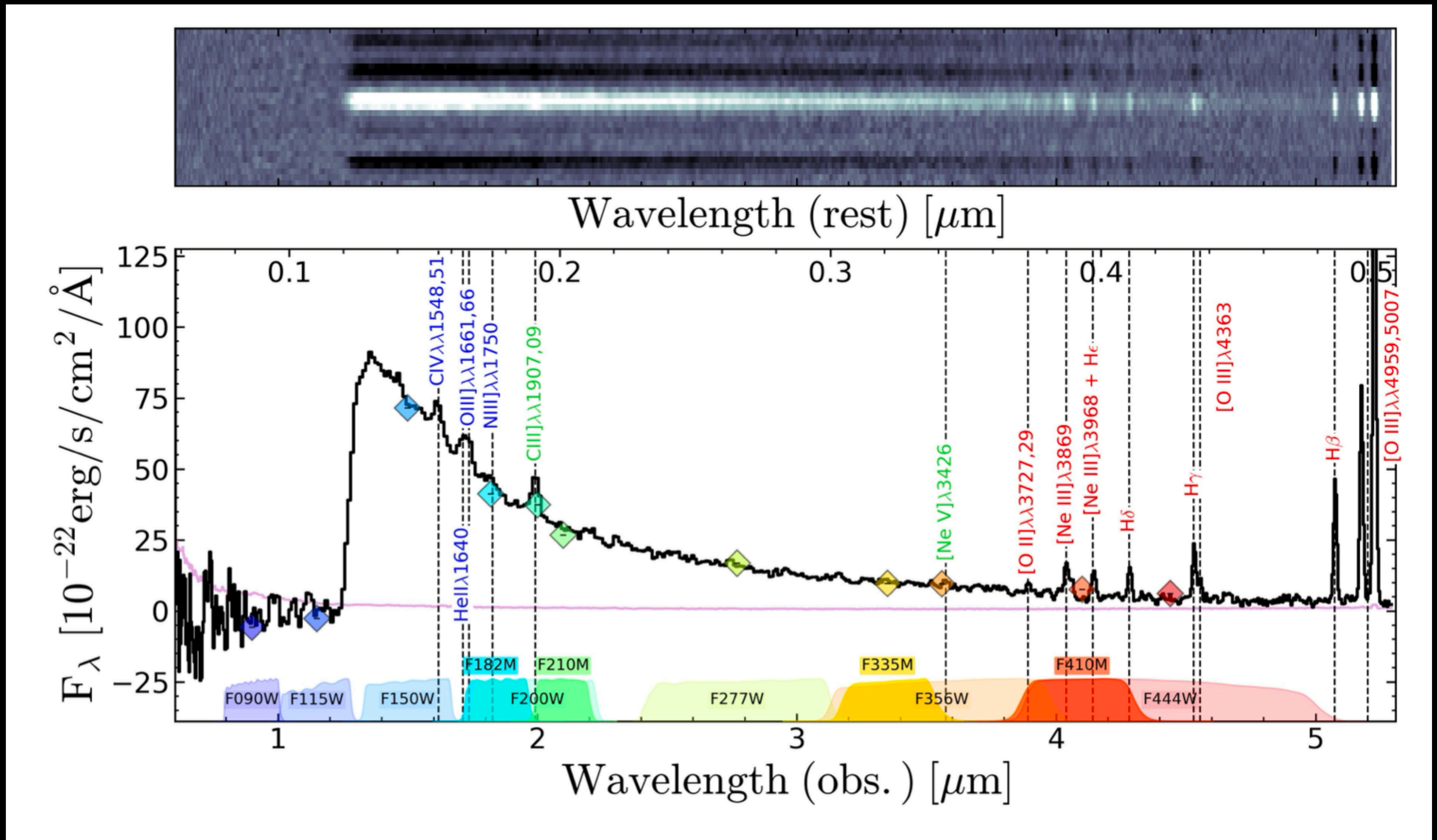
MIRI spectrum doesn't show a broad component in H-alpha

Unusual abundances revealed



Bunker+23

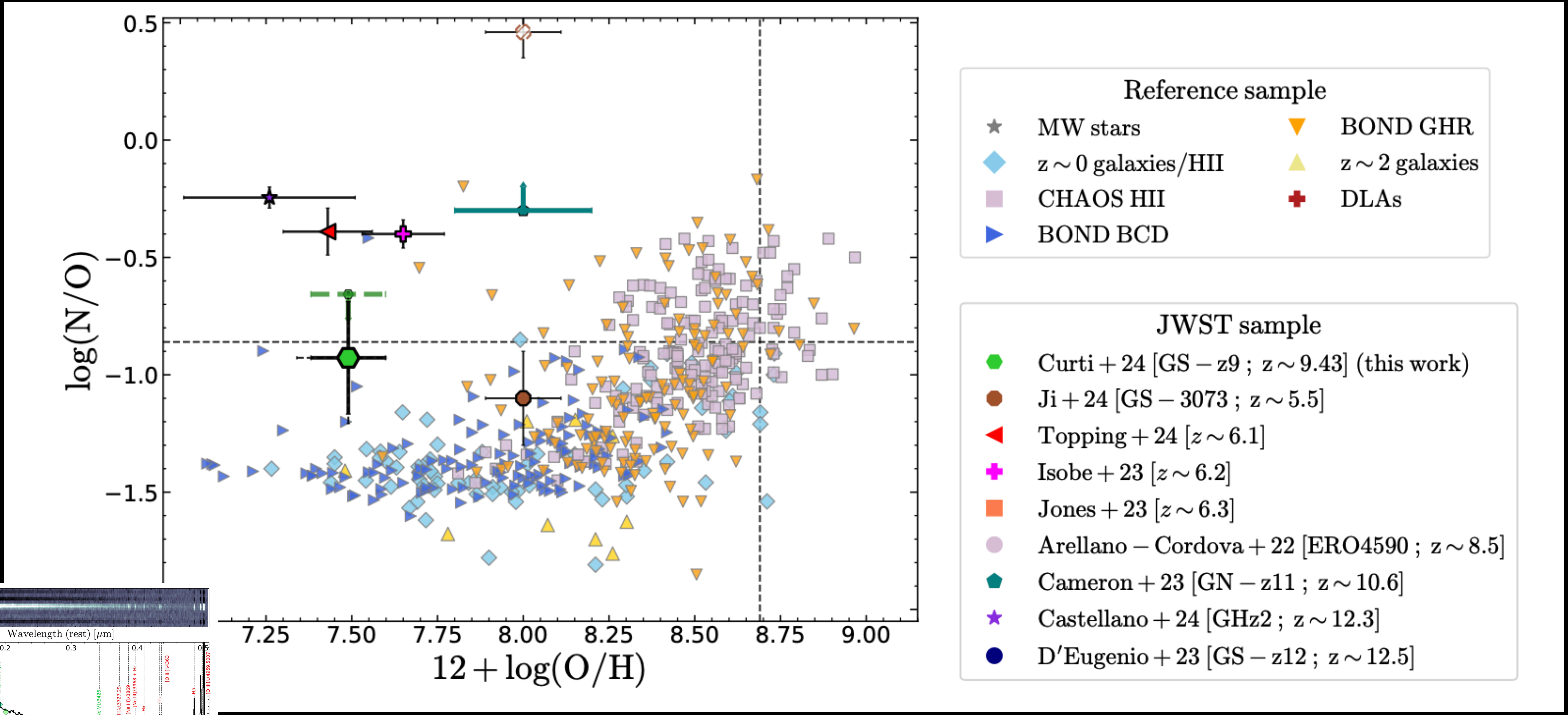
GNz11 - very strong Nitrogen lines/ high Nitrogen abundance (see Cameron+23) though may be only from central region if illuminated by ~10E6 M_o black hole (Maiolino+23). Abundances can be produced by Wolf-Rayet stars or tailored star formation history (Kobayashi, Ferrara 23)

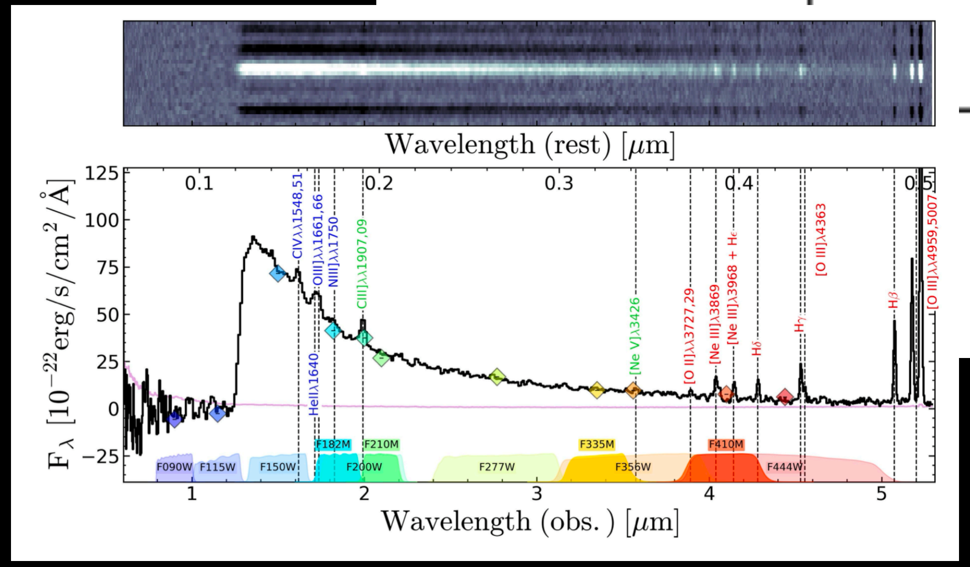


z~9.43 galaxy case study by Curti+24b
Lower C/O, high N/O
Presence of [Ne V] -> can't rule out AGN

See also GHZ2, Castellano+24

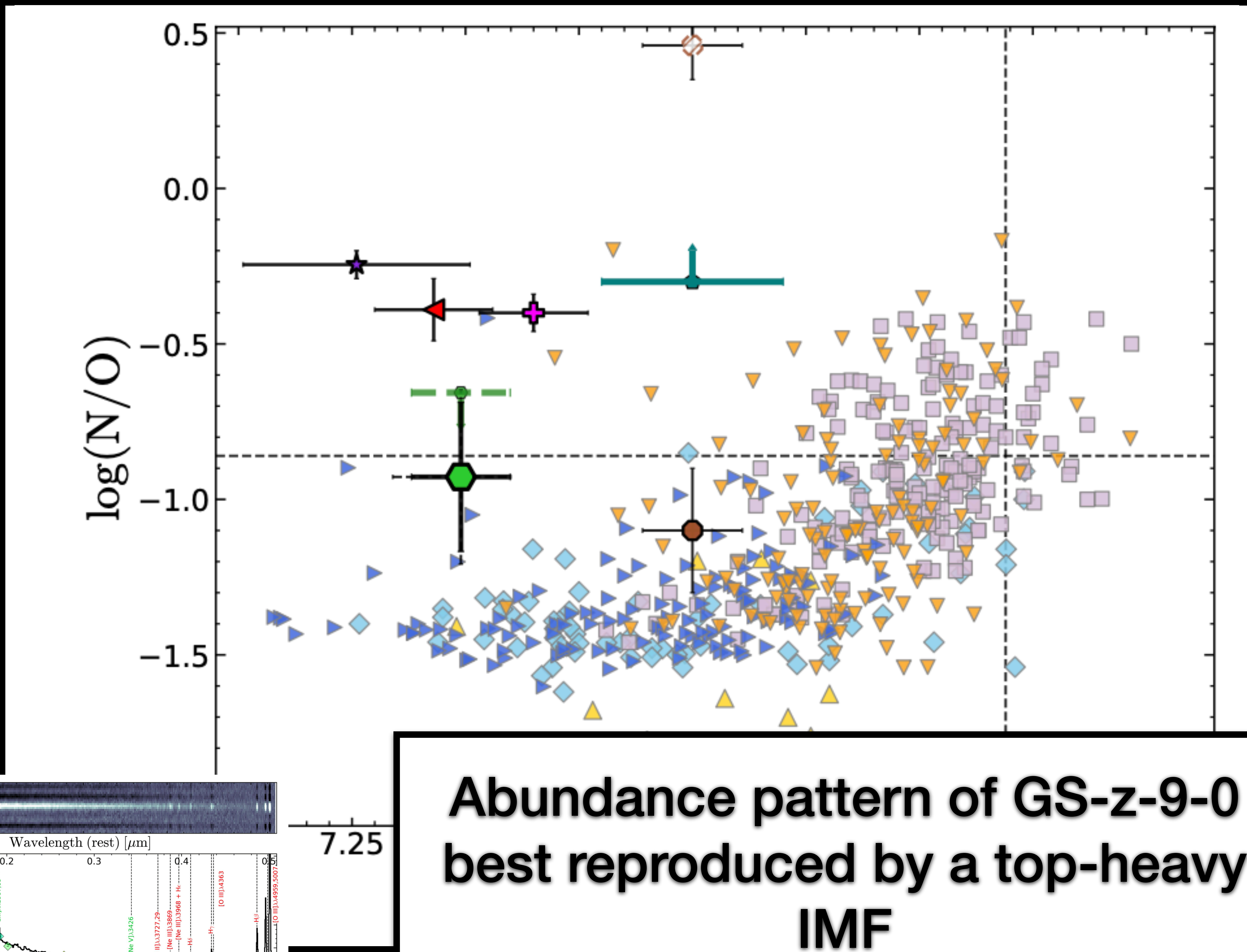
Unusual abundances revealed

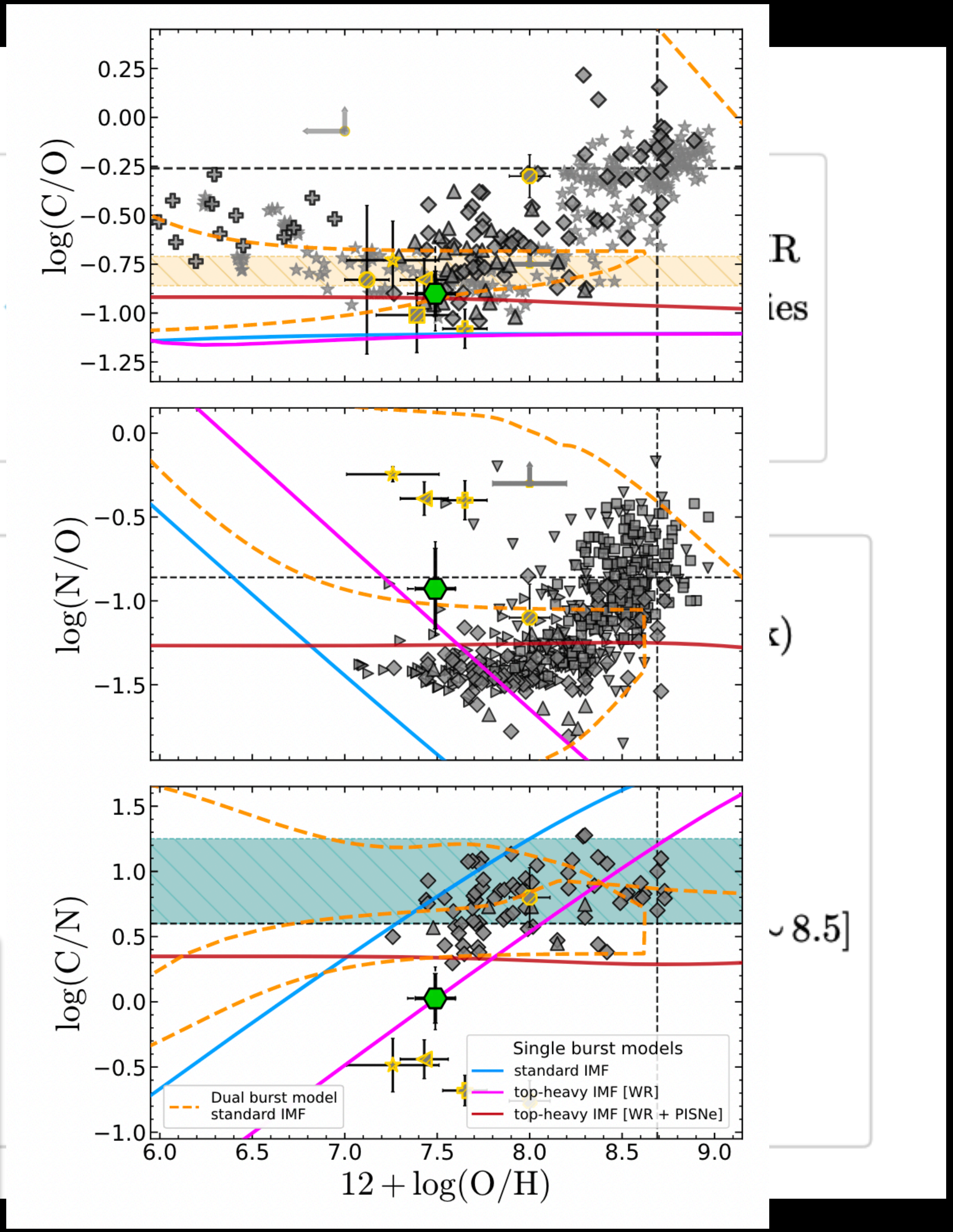


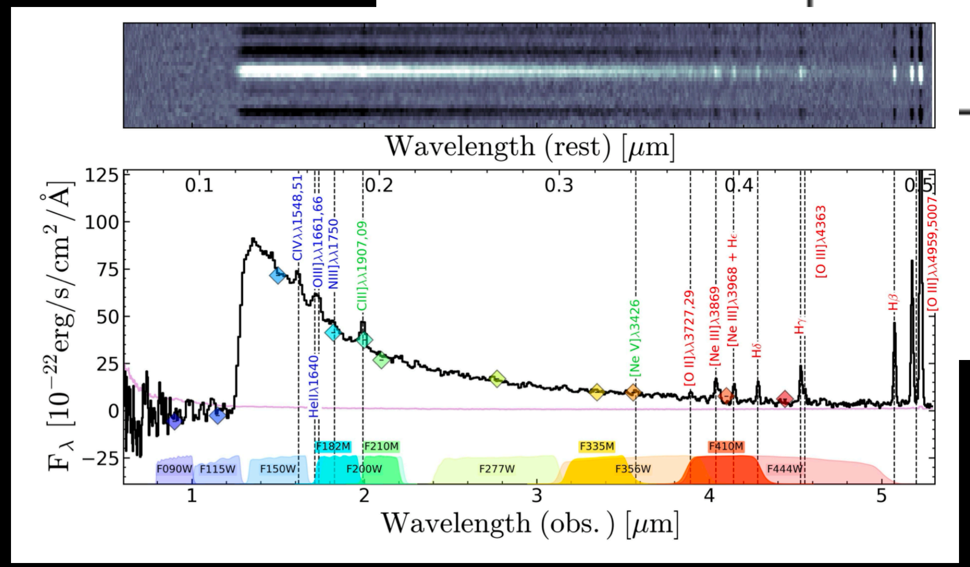


Curti+24b

Unusual abundances revealed



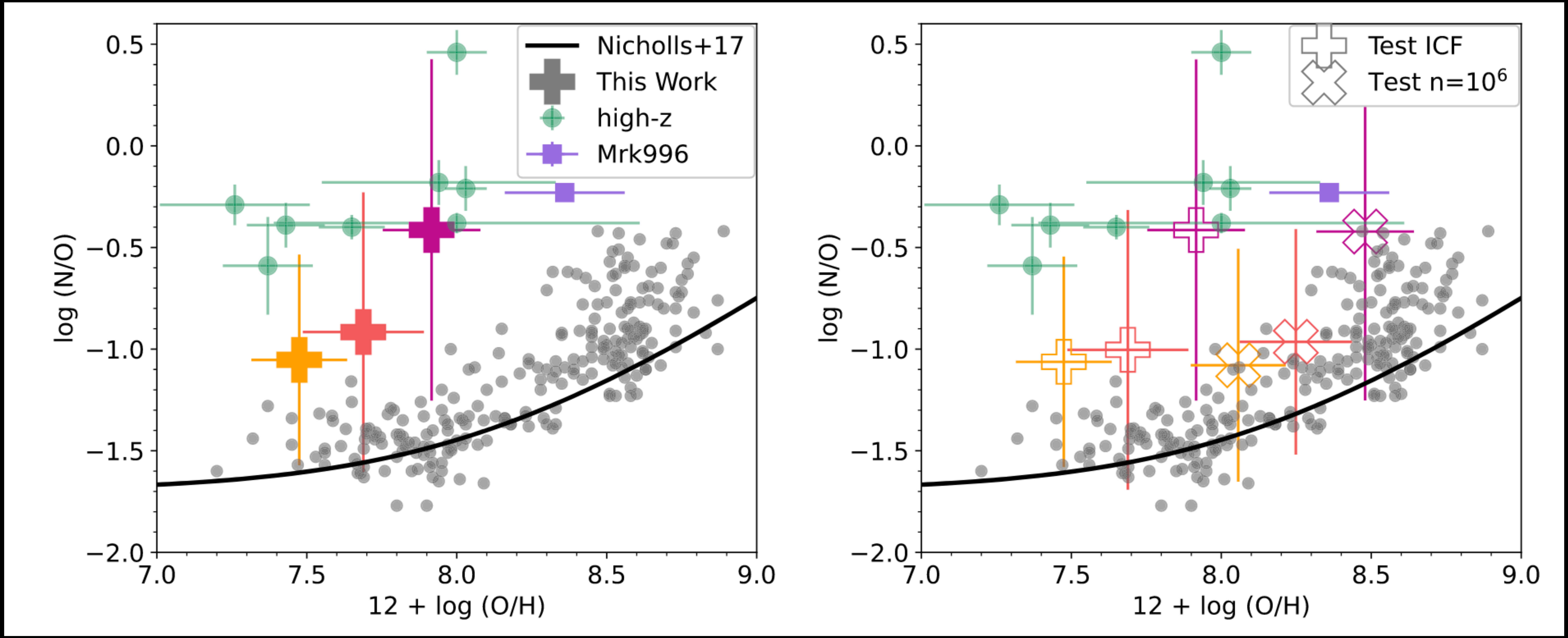




Abundance pattern of GS-z-9-0 best reproduced by a top-heavy IMF

Curti+24b

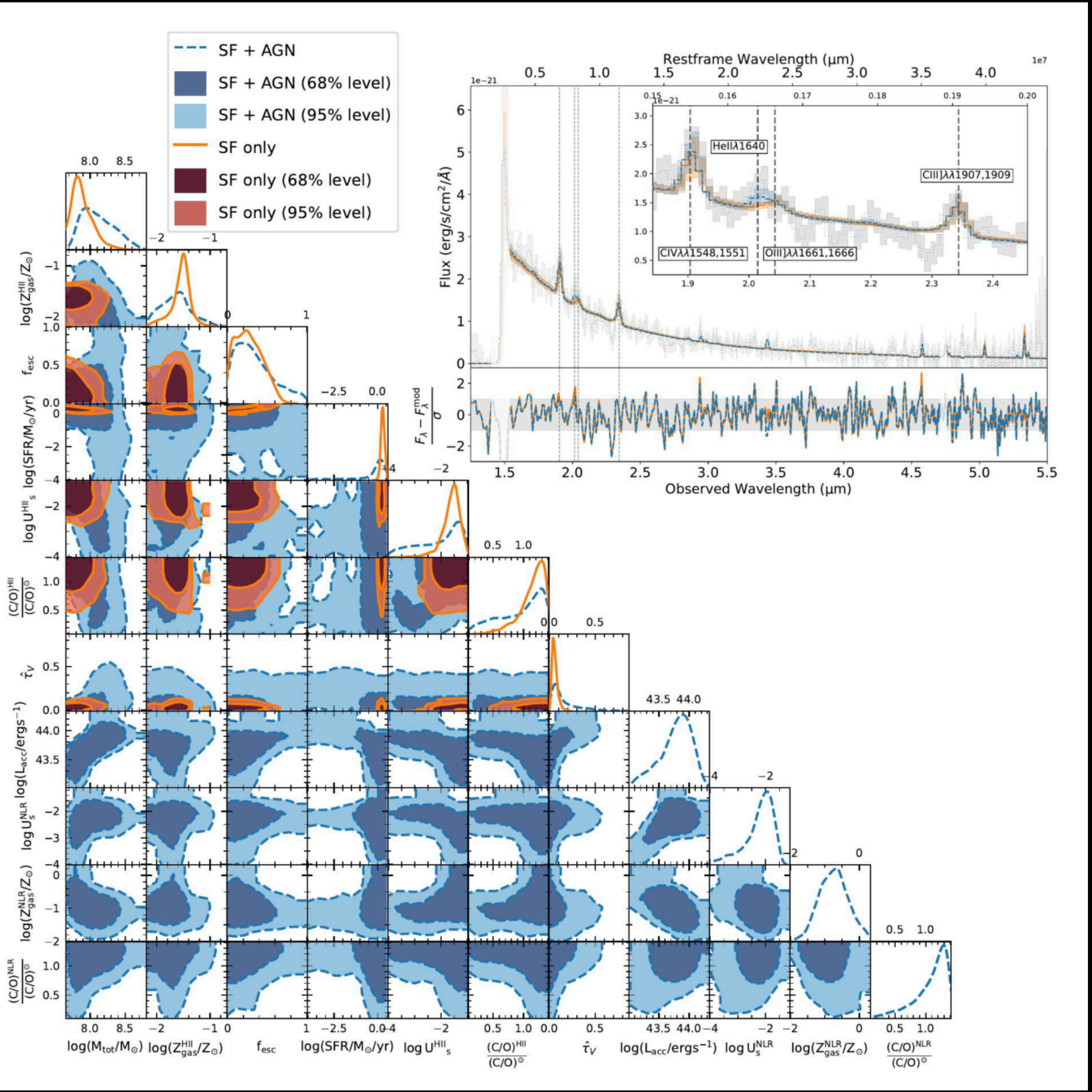
Unusual abundances revealed?



Hayes+25

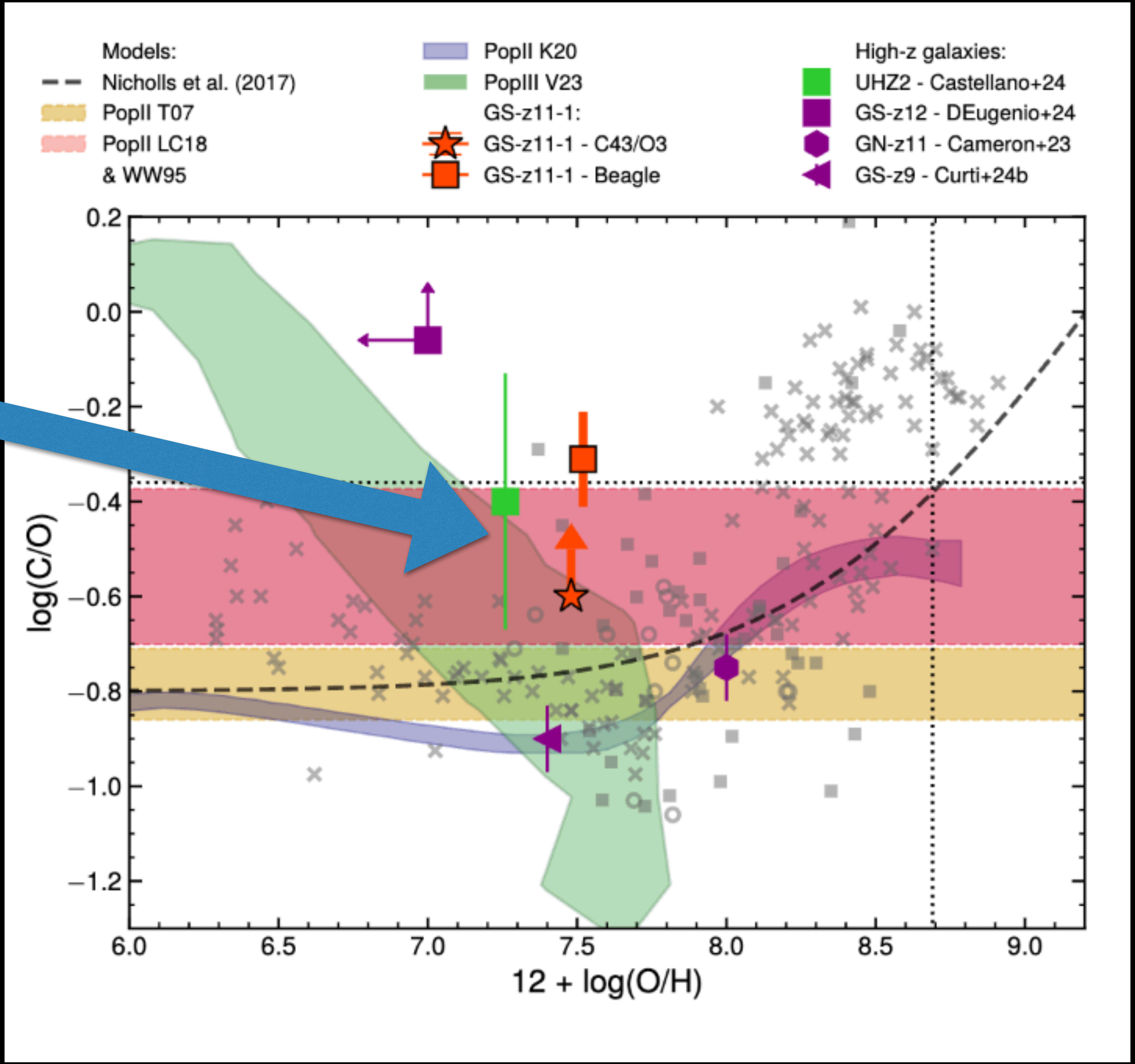
However, taking account of the higher densities experienced by gas emitting high ionisation lines in the rest-UV, maybe the abundances aren’t unusual?

GS-z11-1 also shows strong Carbon lines, hints of HeII. Fitting with BEAGLE with and without AGN NLR models indicate likely super-solar C/O abundance. This has also been tested for higher electron densities.



Scholtz, Silcock, ECL, in prep 2025

Consistent with PopII star yields?



Scholtz, Silcock, ECL, in prep 2025

Summary

How do we study galaxy evolution?

- Often, we look at some properties of the galaxy population (e.g. brightness, mass, amount of metals), sometimes multiple at once (e.g. mass-metallicity, mass-sfr relations) and trace the evolution over cosmic time.
- We then compare to galaxy simulations, or if we can link our galaxy populations to their underlying dark matter halo properties.
- JWST bringing dense SED sampling with deep imaging over many filters as well as spectroscopy should bring immediate gains

BUT… We are being challenged by the data currently -

- Stochastic SFHs make some basic physical property estimates challenging, e.g. stellar mass
- Basic observed properties are not reproduced by simulations e.g. most luminous galaxies at the highest redshifts.
- We are rushing to make sure that models/calibrations used to infer properties from emission lines are suited to the conditions at high redshifts, e.g. are we seeing unusual chemical abundances indicative of early stellar population yields, or are we seeing very dense ISM conditions?