

THE BLUETIDES SIMULATION

US
UNIVERSITY
OF SUSSEX

**Carnegie
Mellon
University**

STEPHEN M. WILKINS
YU FENG, TIZIANA DI MATTEO, RUPERT CROFT,
CHRIS LOVELL, DACEN WATERS

BLUETIDES

TALK OUTLINE

Motivation for **BlueTides**

Basic details of **BlueTides**

Basic physical properties of galaxies

SED modelling and photometric properties.

- Rest-frame UV - near-IR SED
 - Ionising production efficiency
 - UV - SFR calibration
 - UV continuum slope
- Including the effect of the assumed SPS model.*

Predictions for JWST

BLUETIDES

MOTIVATION AND REQUIREMENTS

The aim of BlueTides is to understand the physics of early galaxy formation and evolution by simulating the population of galaxies (including SMBHs) at high-redshift (EoR) observationally accessible to HST, JWST, WFIRST, and (perhaps) Herschel.

The aim is to simulate statistically useful samples of galaxies over a stellar-mass range of $10^{7.5} - 10^{10.5} M_{\odot}$ at $z \sim 6-8$.

BLUETIDES

SIMULATION

BlueTides is a very large cosmological hydrodynamical simulation of the high-redshift Universe run using the NCSA BlueWaters facility.

- It simulates down to $z=8$ (phase I, completed) and $z=6$ (phase II, ongoing)
- Simulates a volume $\sim 577^3 \text{ Mpc}^3$
 - Roughly 200 times larger than EAGLE and Illustris. 10,000 times that of a single NIRSspec pointing at $z=8-9$.
- $2 \times 7040^3 \sim 0.7$ trillion particles
- Mass/Spatial resolution is slightly worse than EAGLE and Illustris

See: Feng et al. [2015](#), [2016](#); Wilkins et al. [2016bcde](#); Waters et al. [2016ab](#); di Matteo et al. [2016](#); and others in the future

BLUETIDES

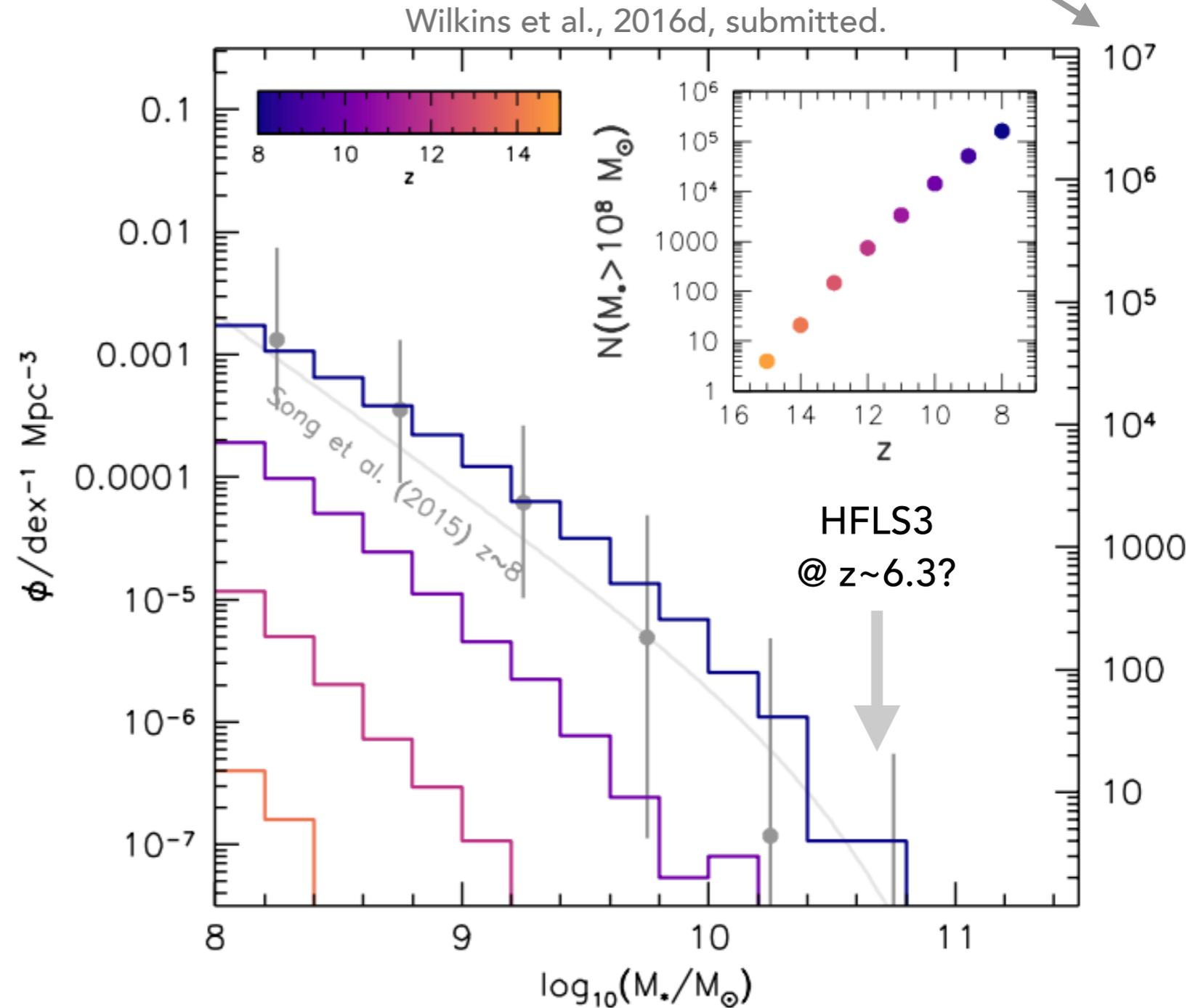
GALAXY STELLAR MASS FUNCTION

BlueTides reproduces observational constraints on the GSMF at $z \sim 8$.

It simulates sufficient volume to include the most massive galaxies identified at high-redshift.

Observations from Song et al. (2015). Note: observational estimates of the GSMF at high-redshift are highly uncertain, with significant variation between different studies.

number of galaxies in each mass bin in BLUETIDES.



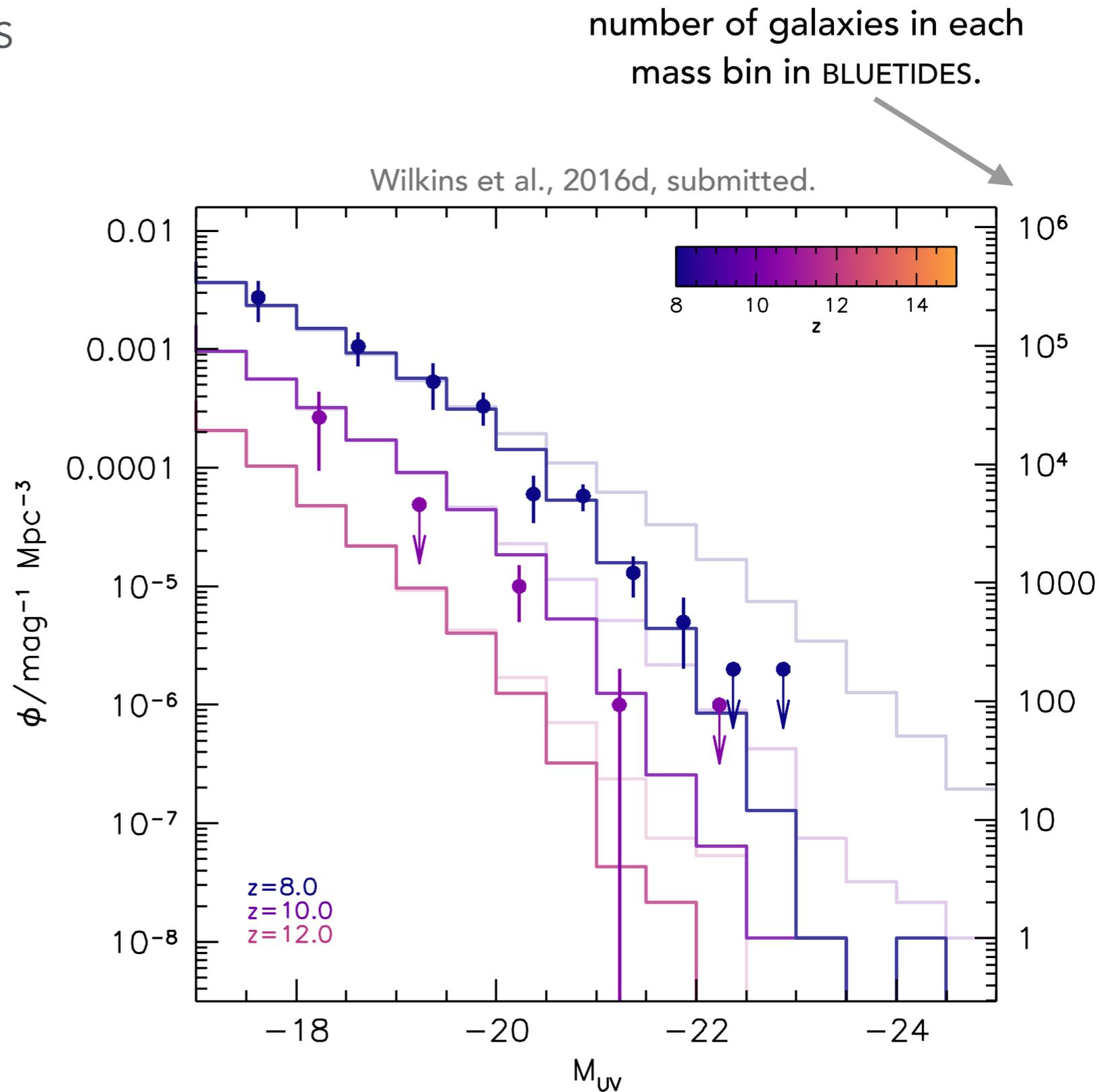
BLUETIDES

GALAXY STELLAR MASS FUNCTION

BlueTides reproduces observational constraints on the UVLF at $z \sim 8$ and 10.

(More on dust in a second)

Observations from Bouwens et al. (2015). Note: faint-lines show the intrinsic luminosity function.

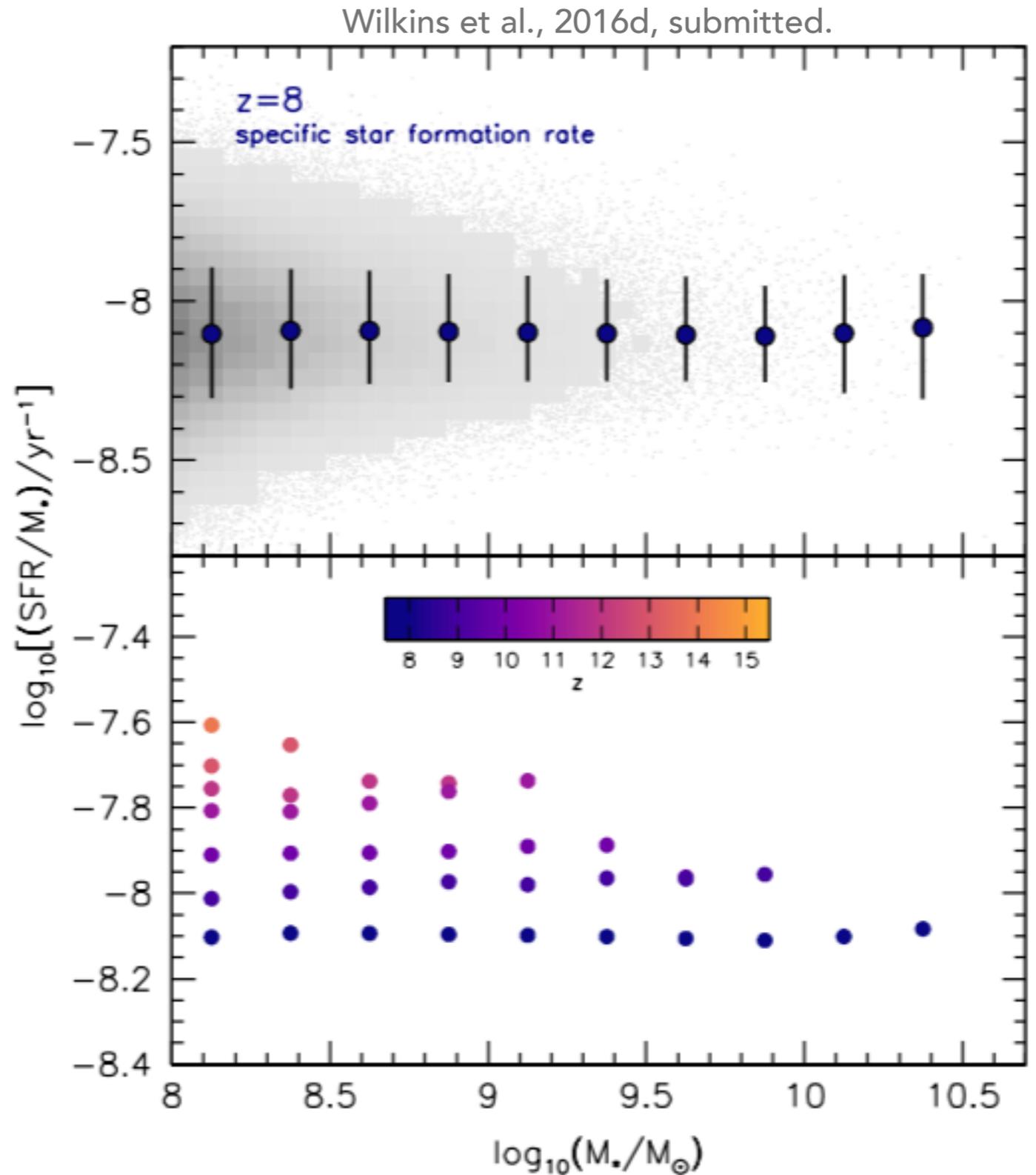


Wilkins et al., 2016d, submitted.

BLUETIDES

PHYSICAL PROPERTIES

The average shape of the SFH (and therefore average age and specific SFR) shows virtually no variation with mass though does evolve strongly with redshift.



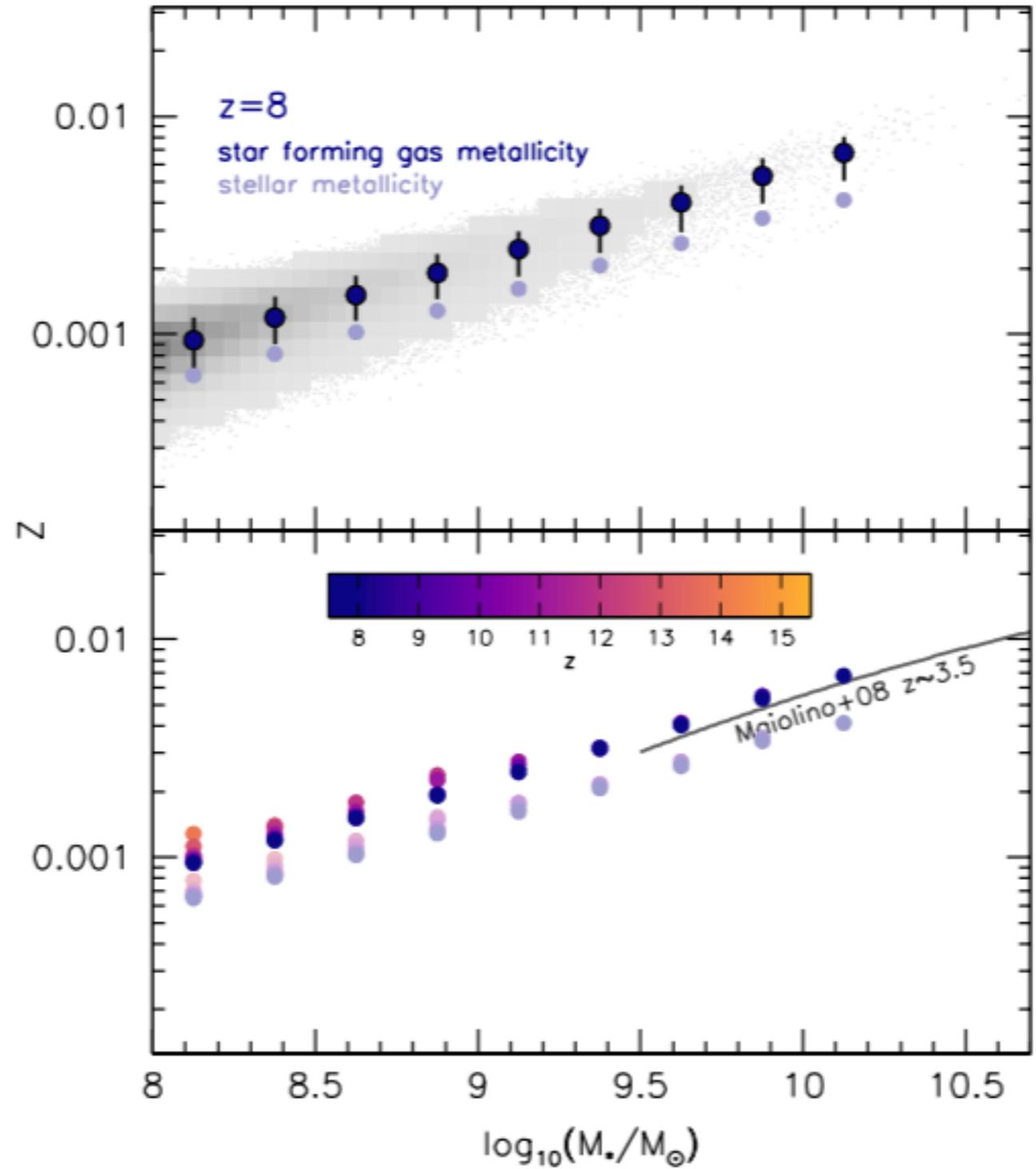
BLUETIDES

PHYSICAL PROPERTIES

There is a strong mass-metallicity relations in place.

Approaching ~50% solar at $10^{10} M_{\odot}$.
Overlaps observational constraints at $z \sim 3.5$.

Wilkins et al., 2016d, submitted.



BLUETIDES

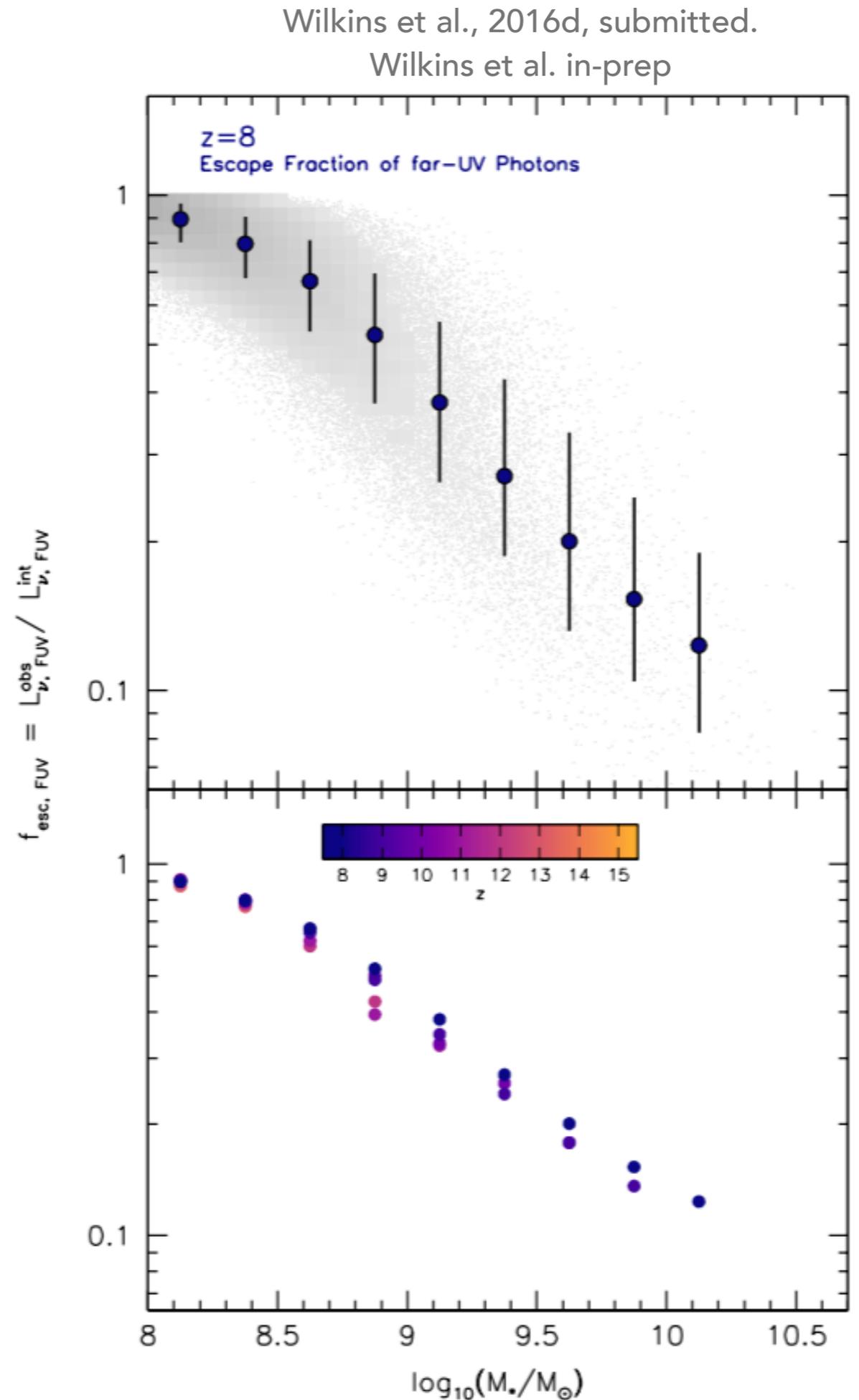
PHYSICAL PROPERTIES

Explored several different dust models.

This model simply links the integrated line-of-sight surface density of metals to the dust optical depth for each star particle.

The result is a strong correlation between stellar-mass ($M^* > 10^8 M_\odot$) and the attenuation. Galaxies at $M^* \sim 10^{10} M_\odot$ have a UV attenuation of $A \sim 2.5$.

far-UV (150nm) escape fraction
[dust attenuation]



BLUETIDES

PHYSICAL PROPERTIES

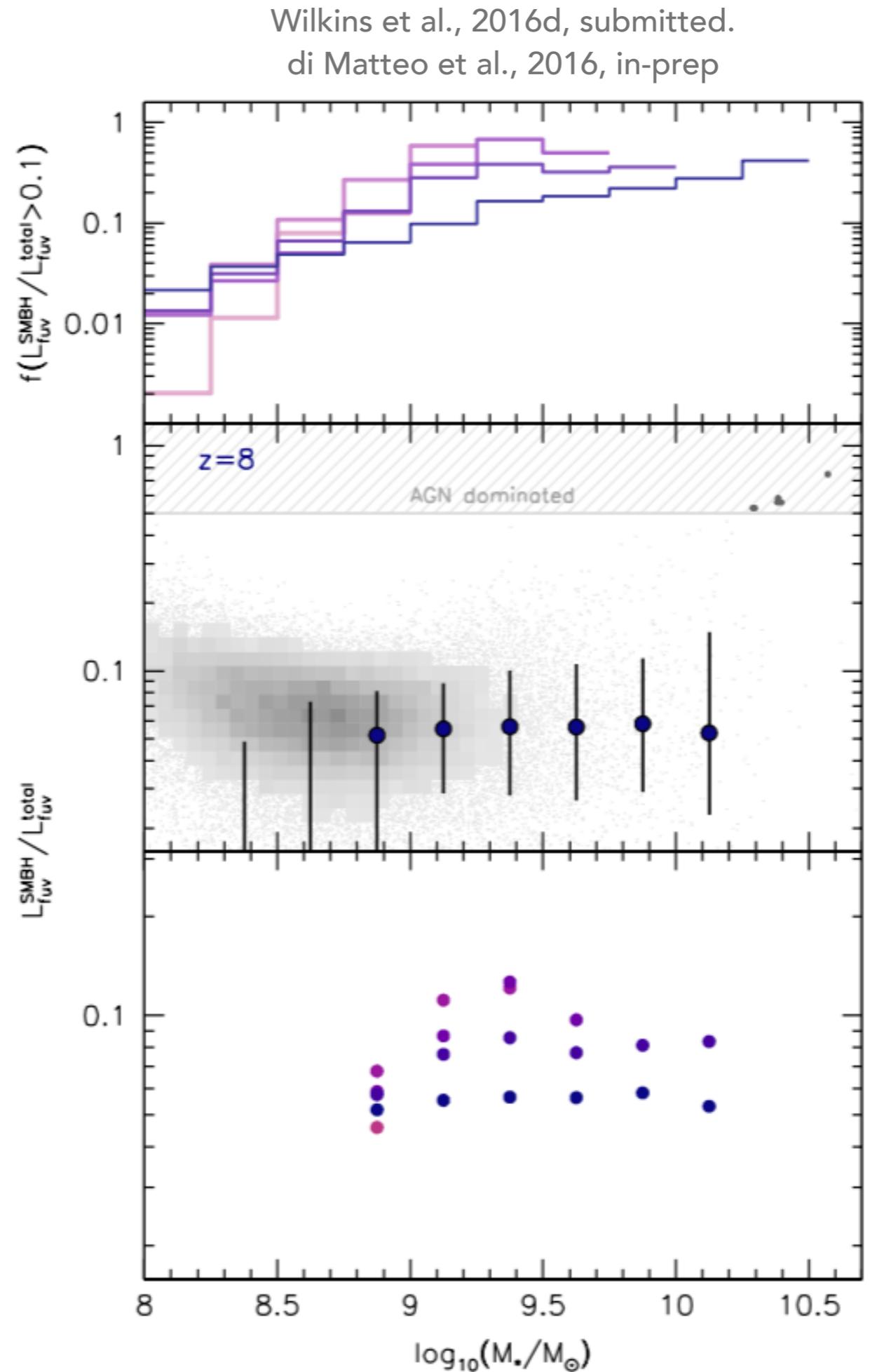
Includes the growth of SMBHs

SMBHs at $z \sim 8$ contribute $\sim 5\%$ of the average far-UV luminosity.

In the very most massive galaxies the SMBH dominates the far-UV luminosity.

For more information see Di Matteo et al., in-prep; Feng et al. 2015; Wilkins et al. 2016d, submitted

fraction of the UV luminosity arising from the SMBH



SED MODELLING

Star formation and
metal enrichment
history

construct pure stellar SED

Pure Stellar Spectral
Energy Distribution



SED MODELLING

Star formation and
metal enrichment
history



construct pure stellar SED
Choice of SPS model and IMF

Pure Stellar Spectral
Energy Distribution

SED MODELLING

Star formation and
metal enrichment
history

construct pure stellar SED

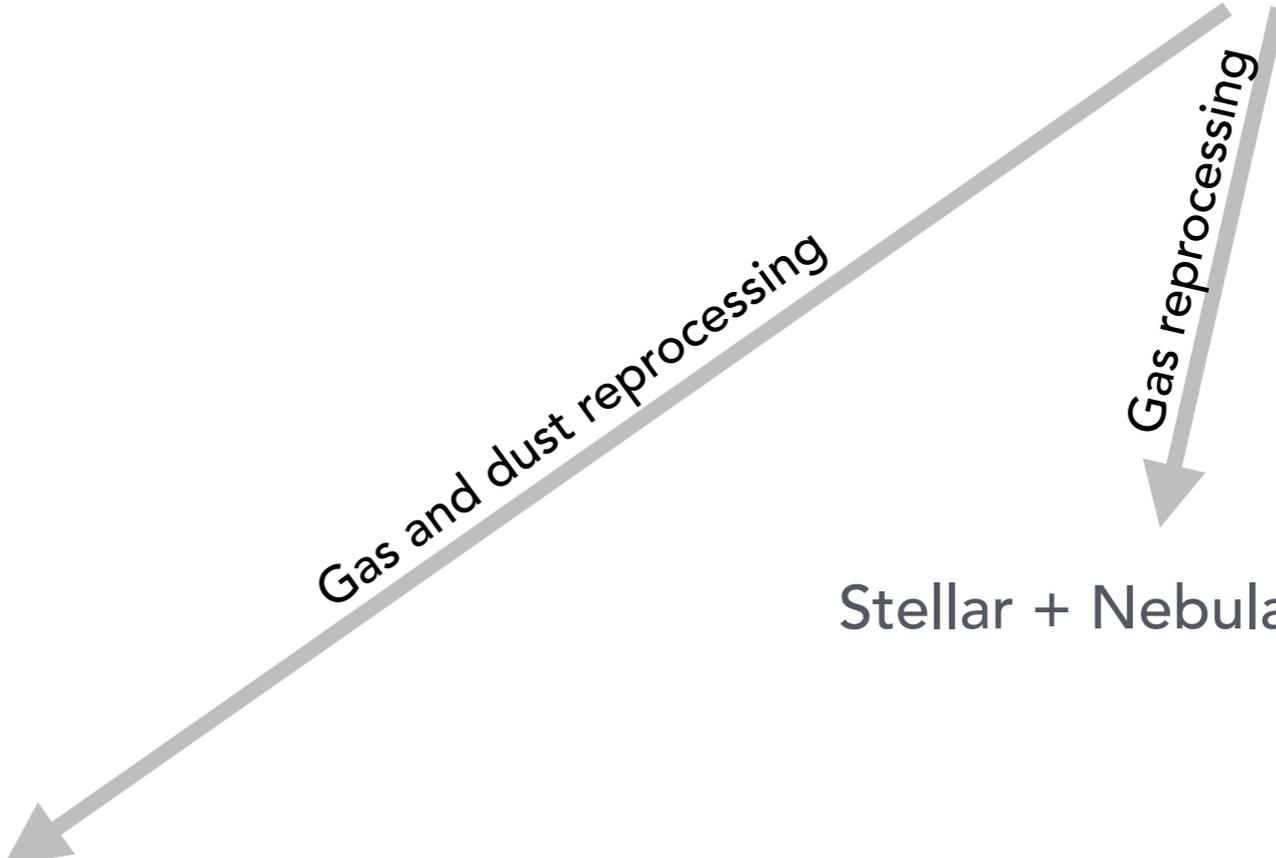
Pure Stellar Spectral
Energy Distribution

Gas and dust reprocessing

Gas reprocessing

Stellar + Nebular SED

Observed (stellar +
nebular + dust) SED



SED MODELLING

Star formation and
metal enrichment
history

construct pure stellar SED
Choice of SPS model and IMF

Pure Stellar Spectral
Energy Distribution

Gas and dust reprocessing
Choice of models (escape fraction,
attenuation curve, etc.)

Gas reprocessing
choice of model (could
be as simple as escape
fraction)

Stellar + Nebular SED

Observed (stellar +
nebular + dust) SED

SED MODELLING NEBULAR EMISSION

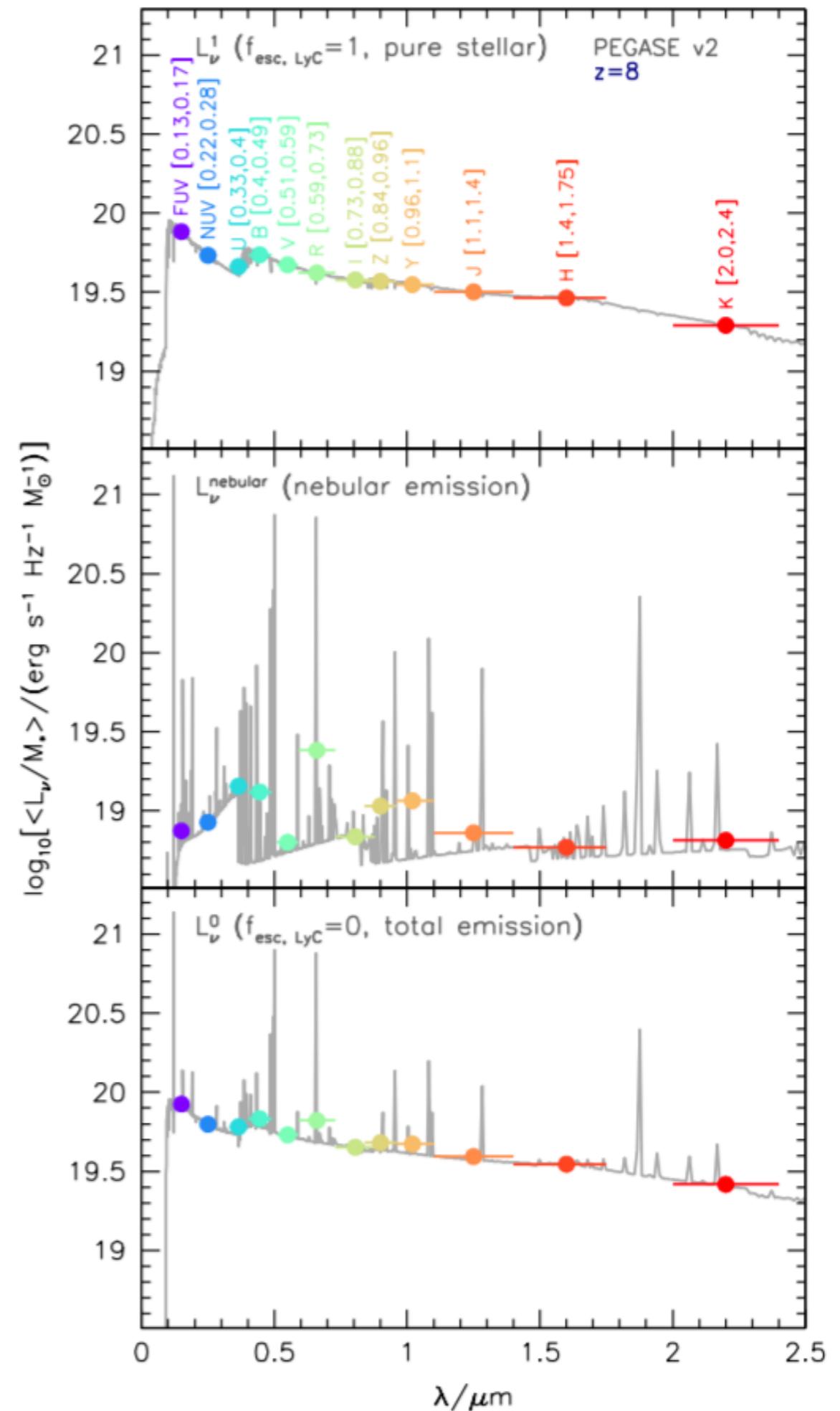
The simplest scenario is to utilise a photoionisation code (like CLOUDY) and assume a simple spherically symmetric density and gas-phase metallicity equal to calculate the nebular emission from each star particle.

Wilkins et al., 2016c, accepted (1605.05044).

Pure Stellar

Nebular

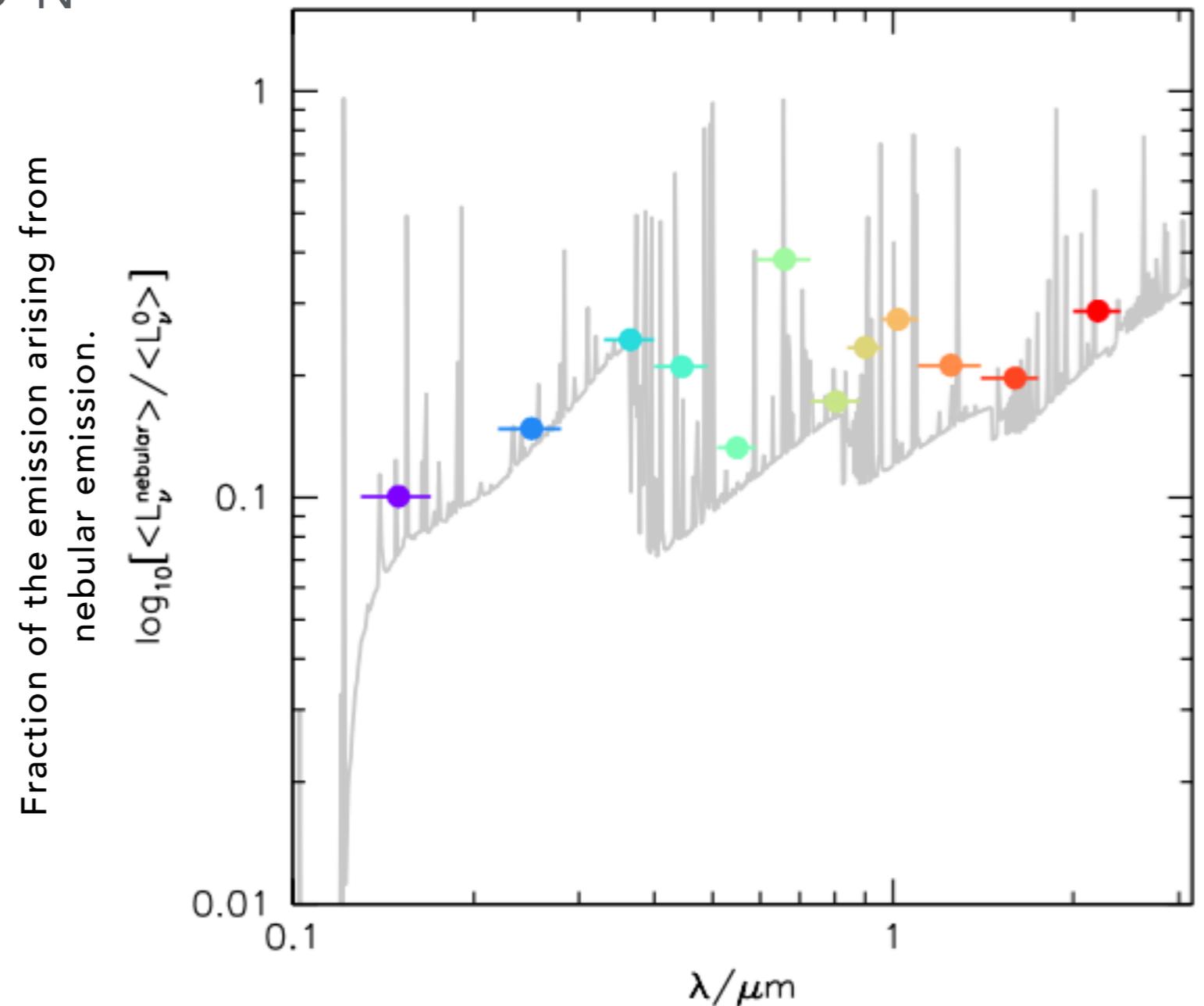
Reprocessed



SED MODELLING NEBULAR EMISSION

Assuming the PEGASE.2 SPS model for the galaxy population at $z=8$ nebular emission **accounts for between 10-40%** of the total emission in the various broad-bands.

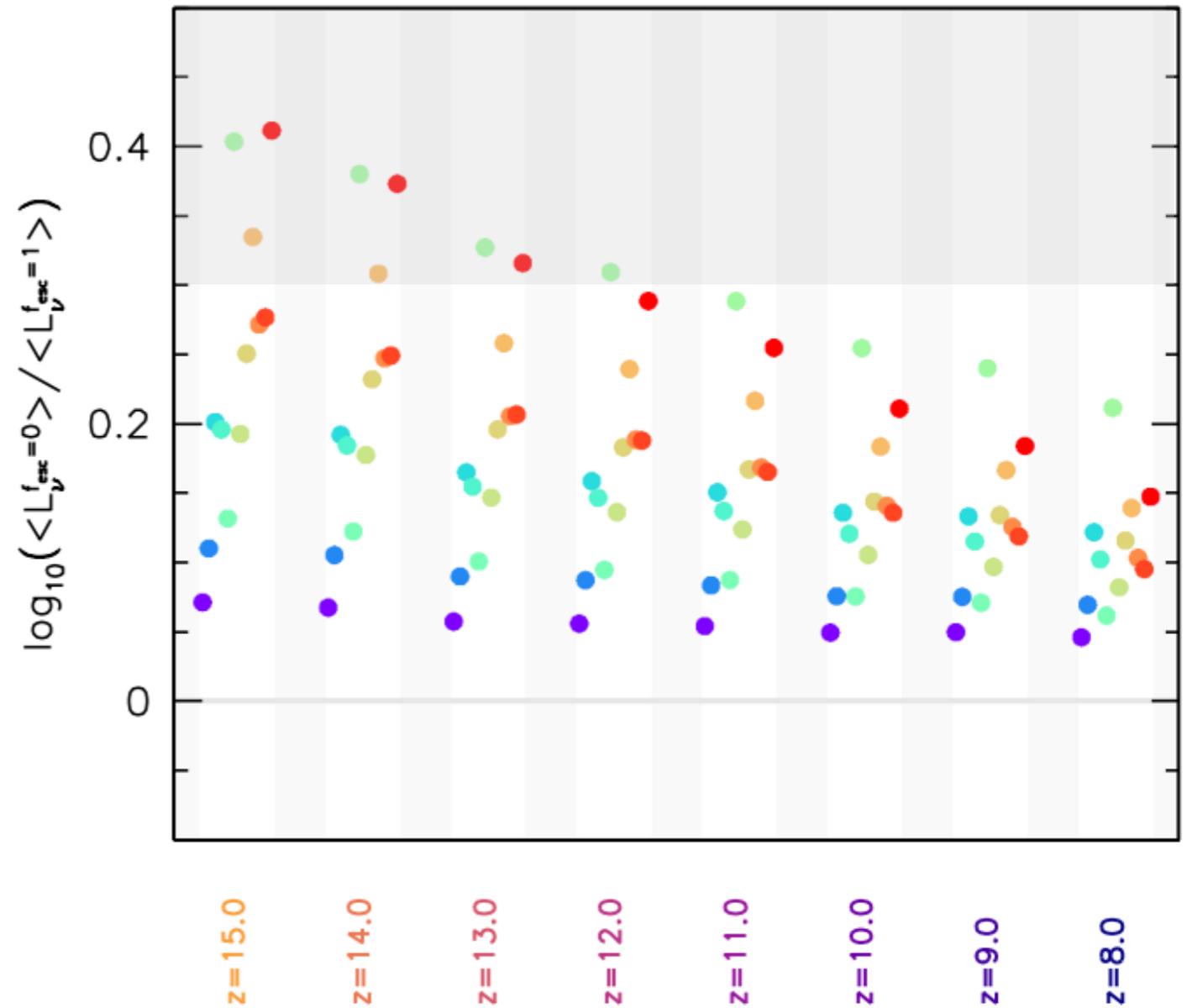
Wilkins et al., 2016c, accepted (1605.05044).



The fractional contribution of nebular (continuum and line) emission to the SED (medium resolution spectroscopy and selected broad-bands shown).

SED MODELLING NEBULAR EMISSION

The contribution of nebular emission **increases** to higher-redshift.



The fractional contribution of nebular (continuum and line) emission to broad-band SEDs from $z=15-8$.

Wilkins et al., 2016c, accepted (1605.05044).

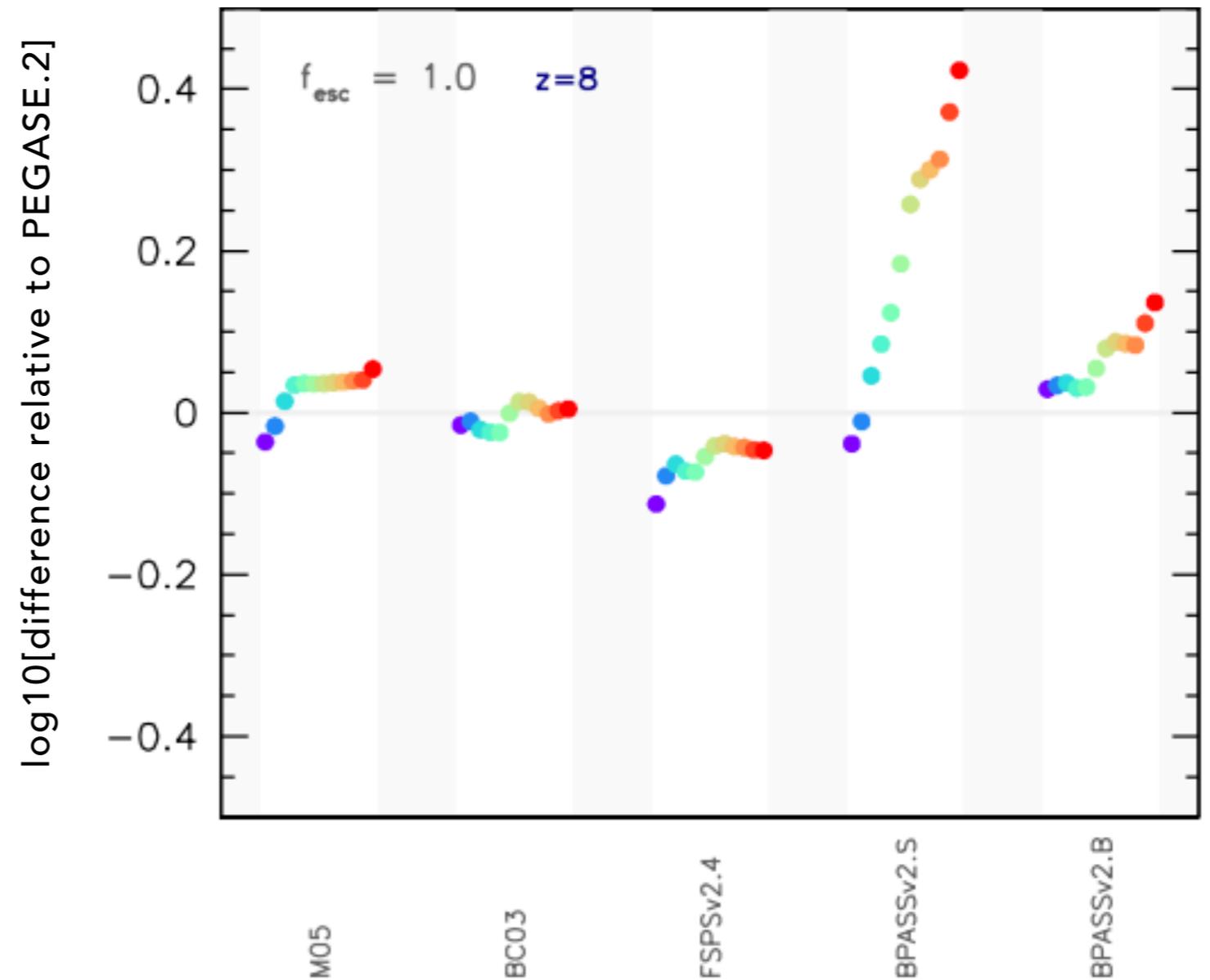
SED MODELLING

SPS MODEL

The choice of SPS model can also have a **significant impact** upon predicted SEDs.

The difference between the SEDs predicted using various SPS models (x-axis) and the PEGASE.2 model.

Wilkins et al., 2016c, accepted
(1605.05044).



SED MODELLING

SPS MODEL AND IONISING PHOTON PRODUCTION EFFICIENCY.

The **ionising production efficiency** links the observed UV luminosity to the number of ionising photons produced by a galaxy. This is a critical component in assessing whether galaxies are capable of re-ionising the Universe.

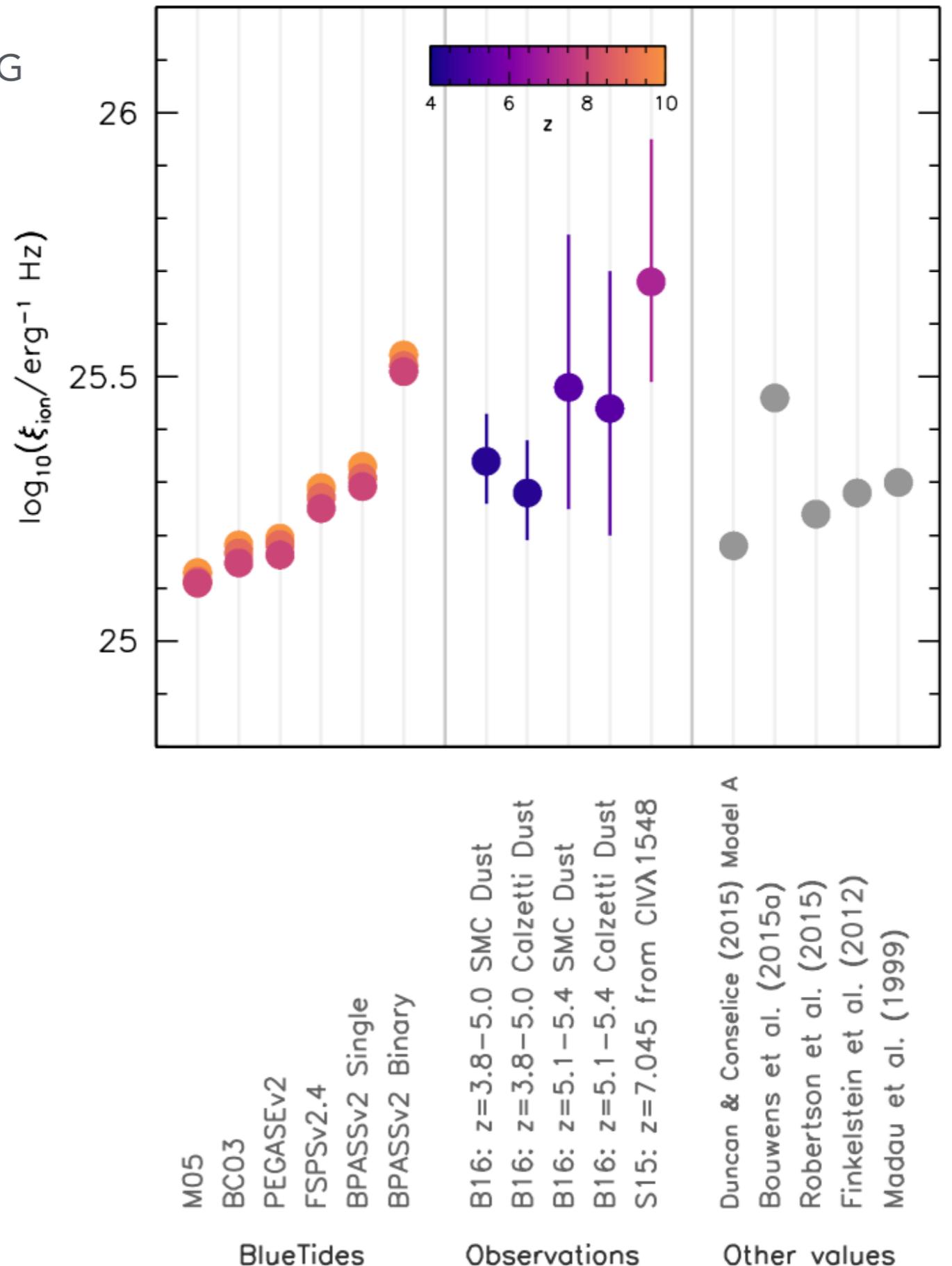
$$\dot{n}_{\text{ion}} = f_{\text{esc,LyC}} \xi_{\text{ion}} \frac{\rho_{\text{uv}}}{f_{\text{esc,uv}}}$$

We can predict this from simulations, however, because both the ionising photon production rate and the UV luminosity are affected by the choice **SPS model** it will be too.

SED MODELLING

SPS MODEL AND IONISING PHOTON PRODUCTION EFFICIENCY.

- The production efficiency varies by a factor of ~ 2.5 between different SPS models.
- The production efficiency evolves with redshift, although slowly.
- Current observational constraints appear to favour higher values than predicted by BlueTides+ most SPS models. Seemingly a model predicting a larger number of ionising photons (like the BPASS model, see Stanway et al. 2016) is preferred.



SED MODELLING

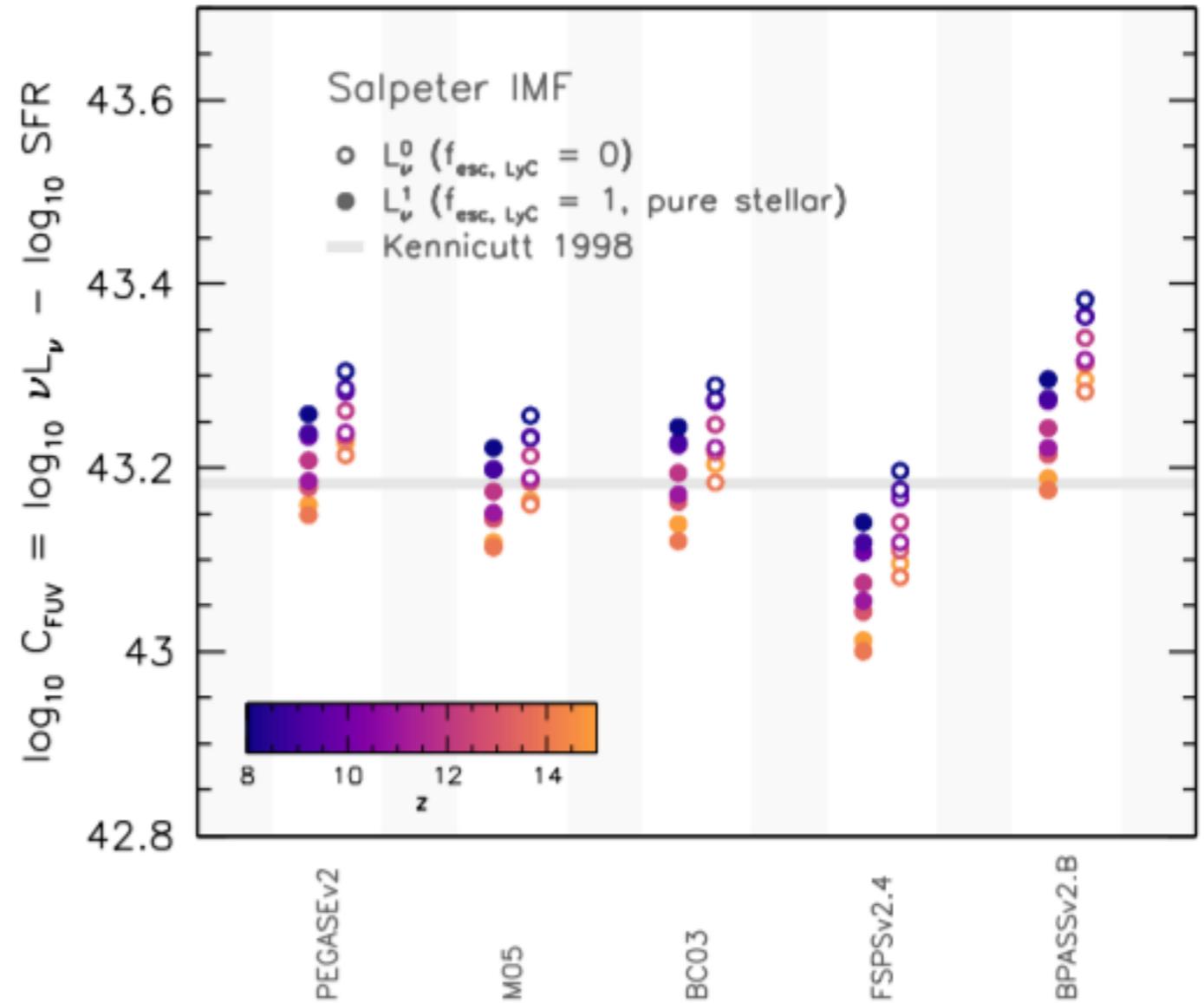
STAR FORMATION INDICATORS

We can also predict the value of the UV - SFR calibration.

The choice of SPS model, escape fraction, and IMF also affect the calibration between the SFR and the intrinsic UV luminosity.

$$\log_{10}(\text{SFR}/M_{\odot} \text{ yr}^{-1}) = \log_{10}(\nu L_{\nu, \text{fuv}}/\text{ergs}^{-1}) - \log_{10} C_{\text{fuv}}$$

Wilkins et al., 2016c, accepted (1605.05044).



SED MODELLING

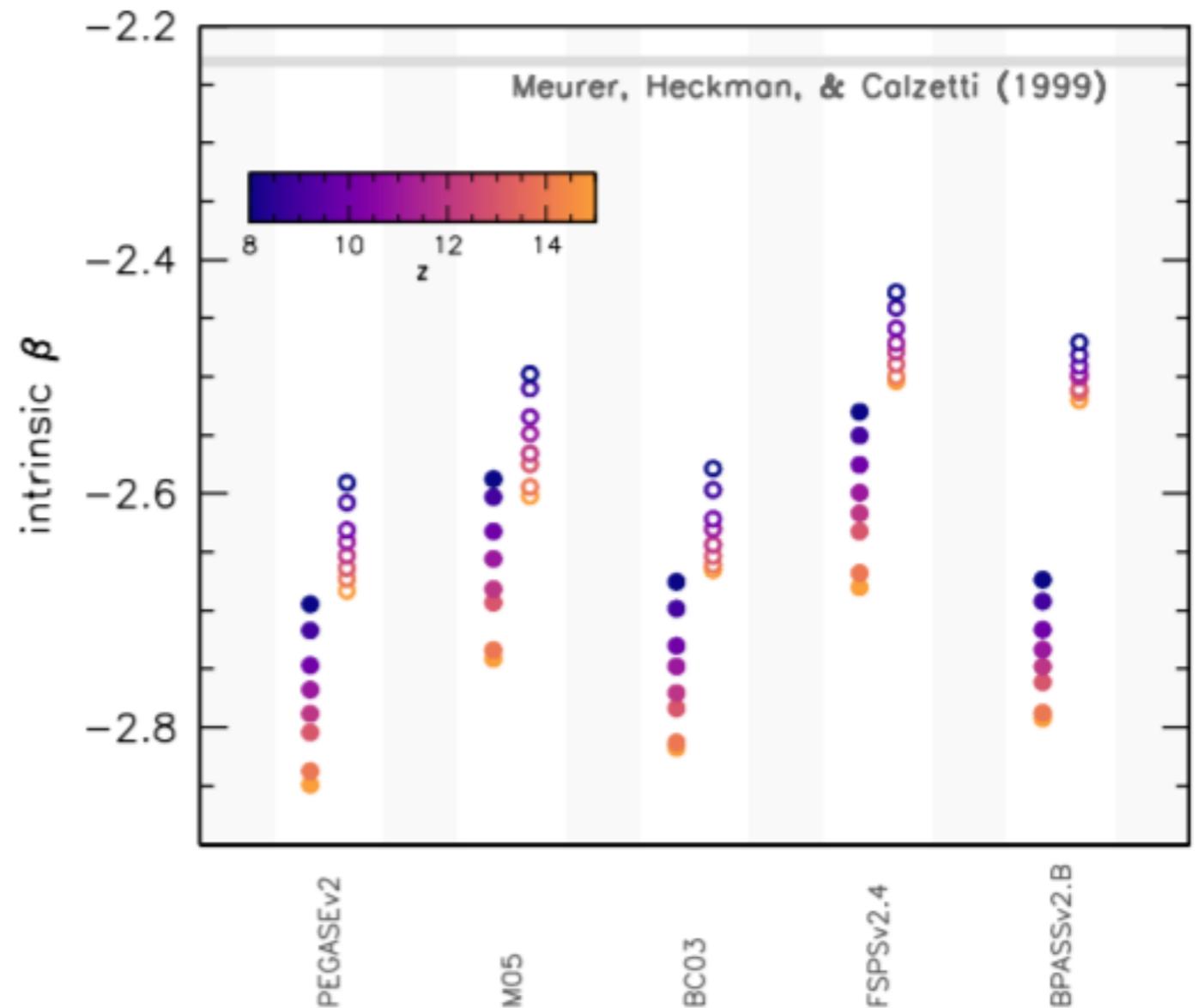
UV CONTINUUM SLOPE

Also, the intrinsic UV continuum slope.

This is important as the UV continuum slope is one of few diagnostics available for constraining dust attenuation at high-redshift.

$$A_\lambda = \frac{d\beta}{dA_\lambda} (\beta_{\text{obs}} - \beta_{\text{int}})$$

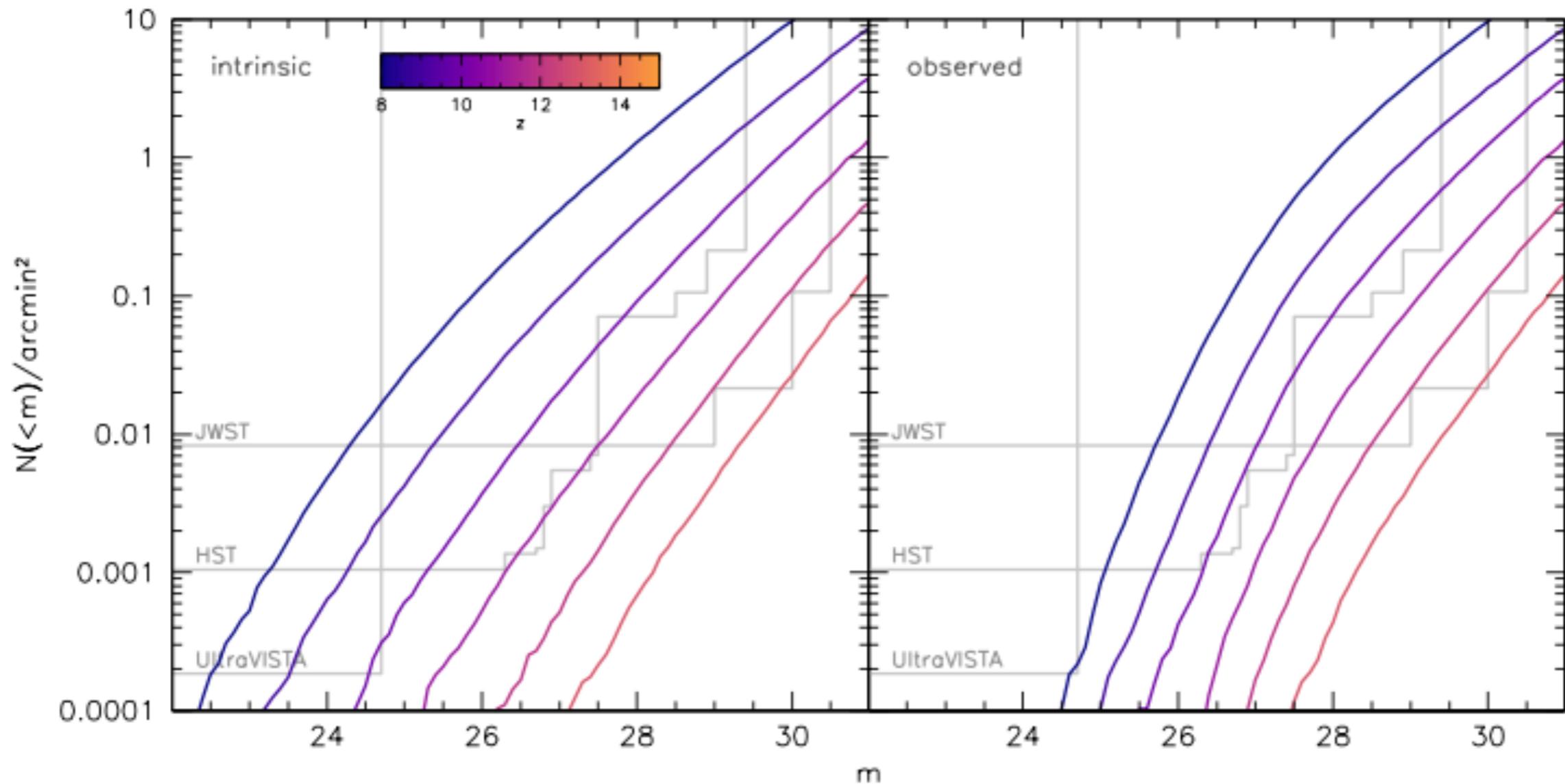
Wilkins et al., 2016c, accepted (1605.05044).



PREDICTIONS FOR JWST SURFACE DENSITIES

Wilkins et al., 2016e, submitted.

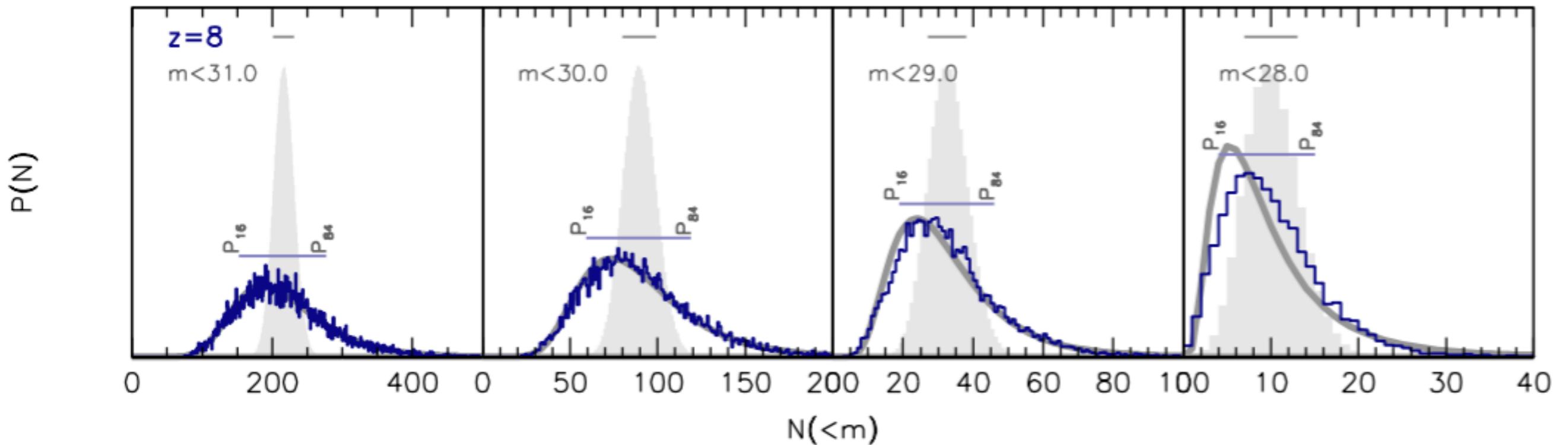
We can predict the surface density of sources across a wide redshift and luminosity range.



PREDICTIONS FOR JWST COSMIC VARIANCE

Wilkins et al., 2016e, submitted.

BlueTides simulates sufficient volume to calculate the effect of field-to-field variance (cosmic variance) for reasonably sized surveys with JWST.



The distribution of number counts in a single JWST/NIRCam pointing at $z=7.5-8.5$. The grey histograms show the result if galaxies were spread randomly.

P R E D I C T I O N S
 F O R J W S T
 S U R F A C E D E N S I T I E S

Wilkins et al., 2016e, submitted.

Expected surface densities for a **single** JWST/NIRcam pointing.

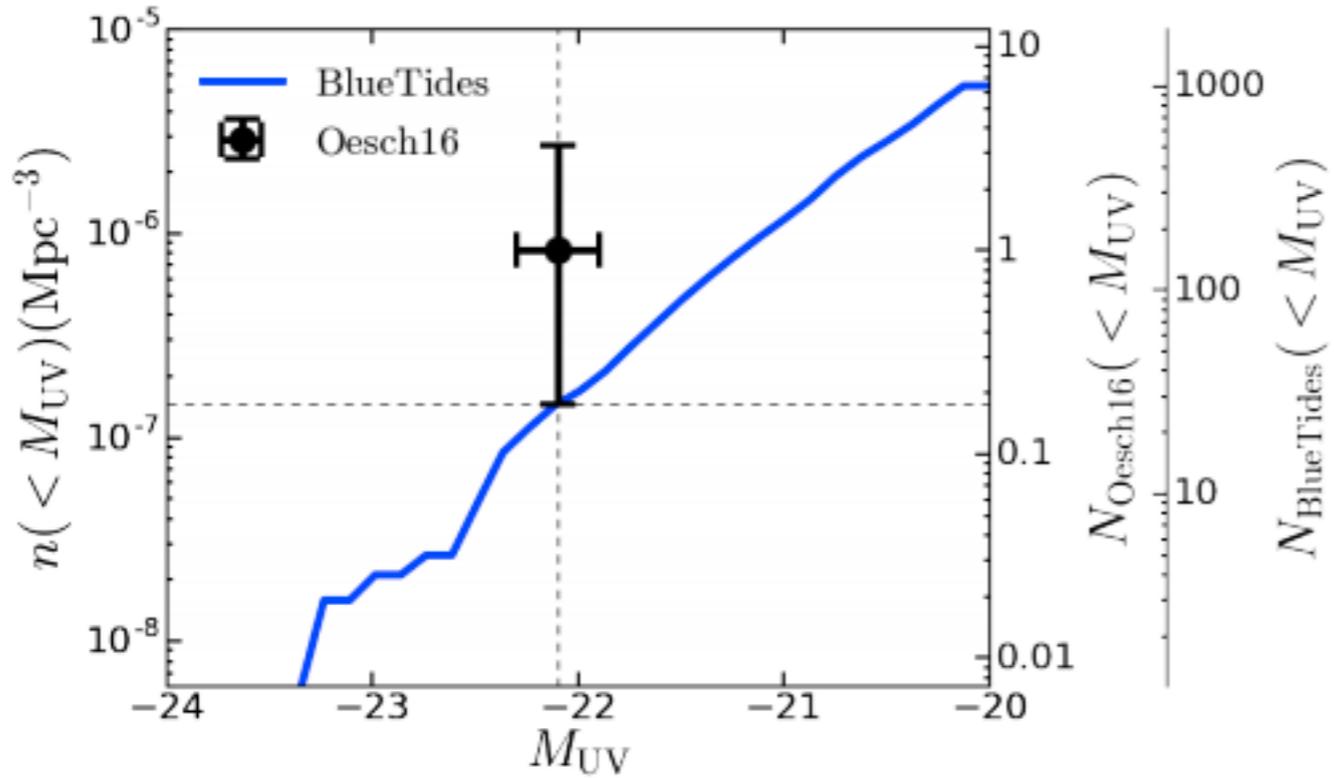
Dust attenuated far-UV photometry												
z	$m < 28$			$m < 29$			$m < 30$			$m < 31$		
	P_{16}	P_{50}	P_{84}	P_{16}	P_{50}	P_{84}	P_{16}	P_{50}	P_{84}	P_{16}	P_{50}	P_{84}
8	4	9	15	19	30	46	59	85	119	152	208	277
9	0	2	4	4	8	15	16	26	40	50	74	107
10	0	0	1	1	2	5	5	10	17	19	31	48
11	0	0	0	0	0	2	1	3	6	6	11	19
12	0	0	0	0	0	0	0	1	2	1	4	7

C O N C L U S I O N S

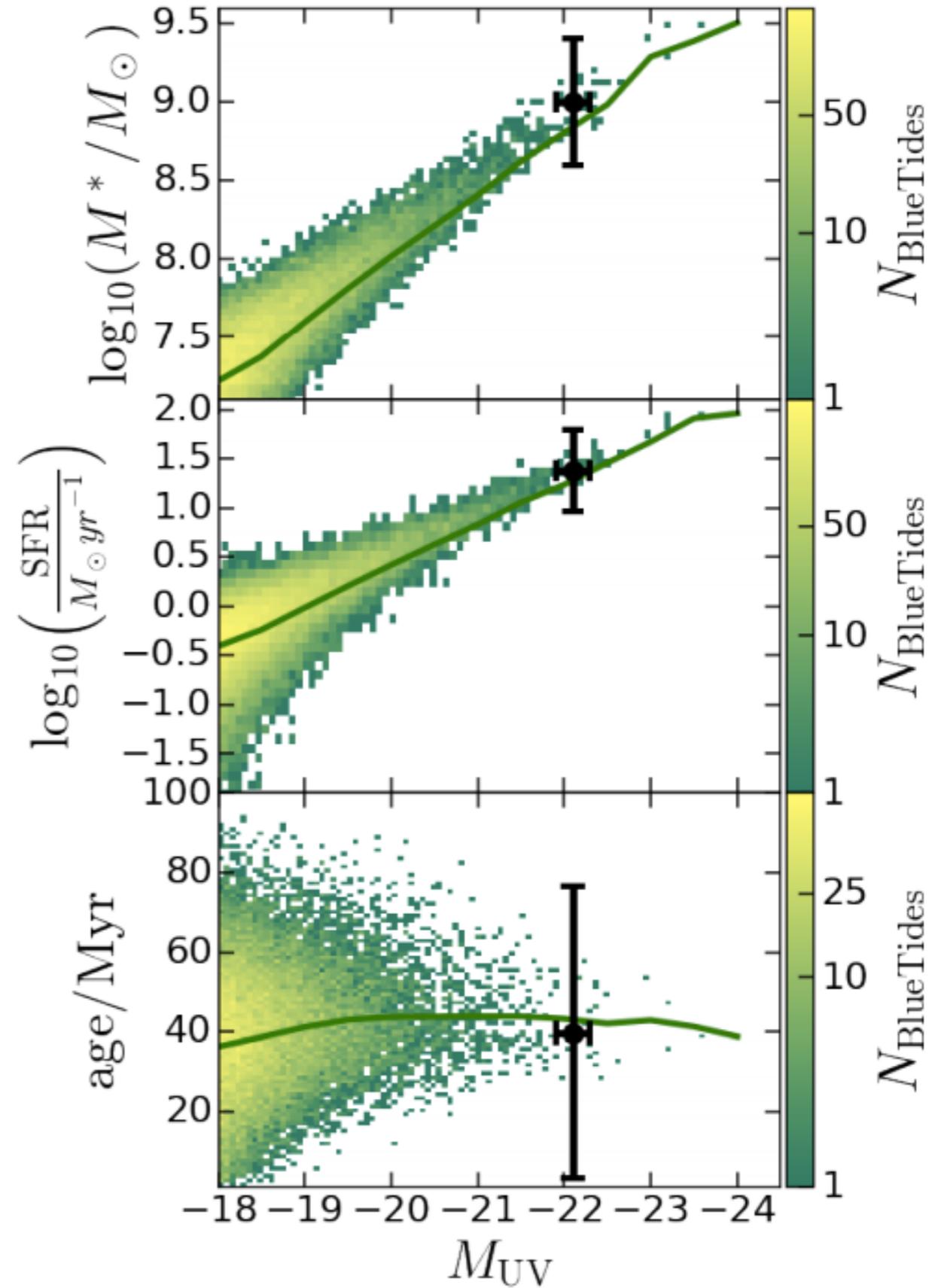
BlueTides is a very large cosmological hydrodynamical simulation that has a resolution and volume well matched to current and future observational constraints.

- BlueTides reproduces the Galaxy Stellar Mass Function and UV luminosity function at $z \sim 8$ and above.
- We can predict the SEDs of galaxies, these are sensitive to our choice of assumptions (IMF, nebular emission, dust emission, SPS model etc.)
- We can predict the ionising photon production efficiency. This is very sensitive to the choice of SPS model.
- JWST will likely discover many galaxies at $z \sim 8-10$ though relatively few at $z \sim 12$ and above.

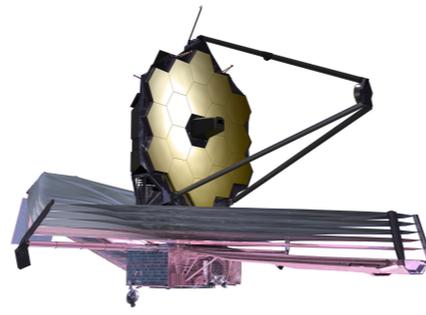
BLUETIDES MONSTERS



The predicted surface density of sources is (just about) consistent with the discovery of a bright galaxy at $z \sim 11$ by Oesch et al. (2016). The measured physical properties are also consistent.

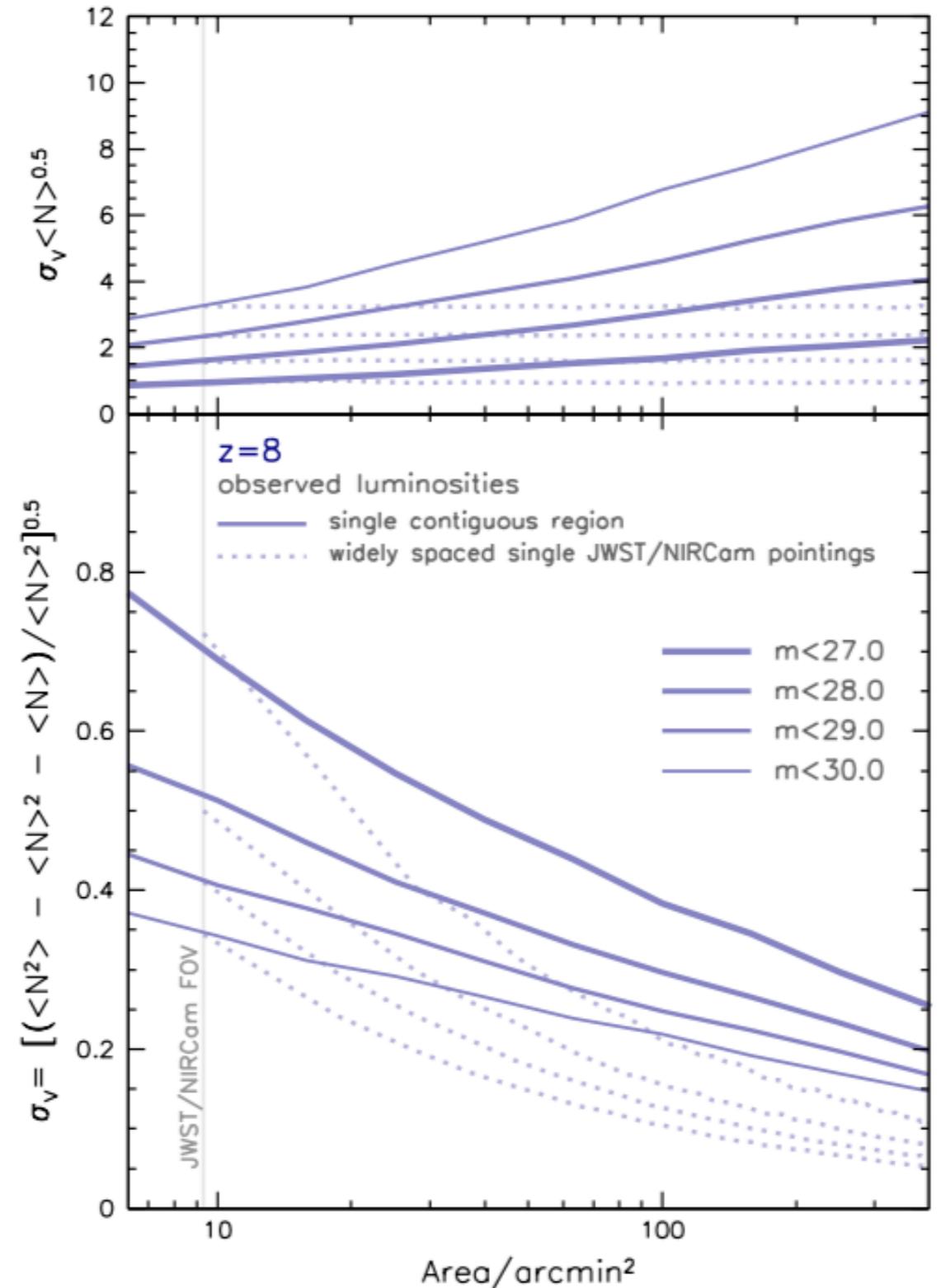


PREDICTIONS
FOR JWST
SURFACE DENSITIES



Wilkins et al., 2016e, submitted.

Bottom: How cosmic variance is affected by the area covered (both for a contiguous region and widely spaced random pointings) and magnitude limit. Top: The ratio of cosmic variance to sample (Poisson) variance.





Re-simulations of the high redshift Universe

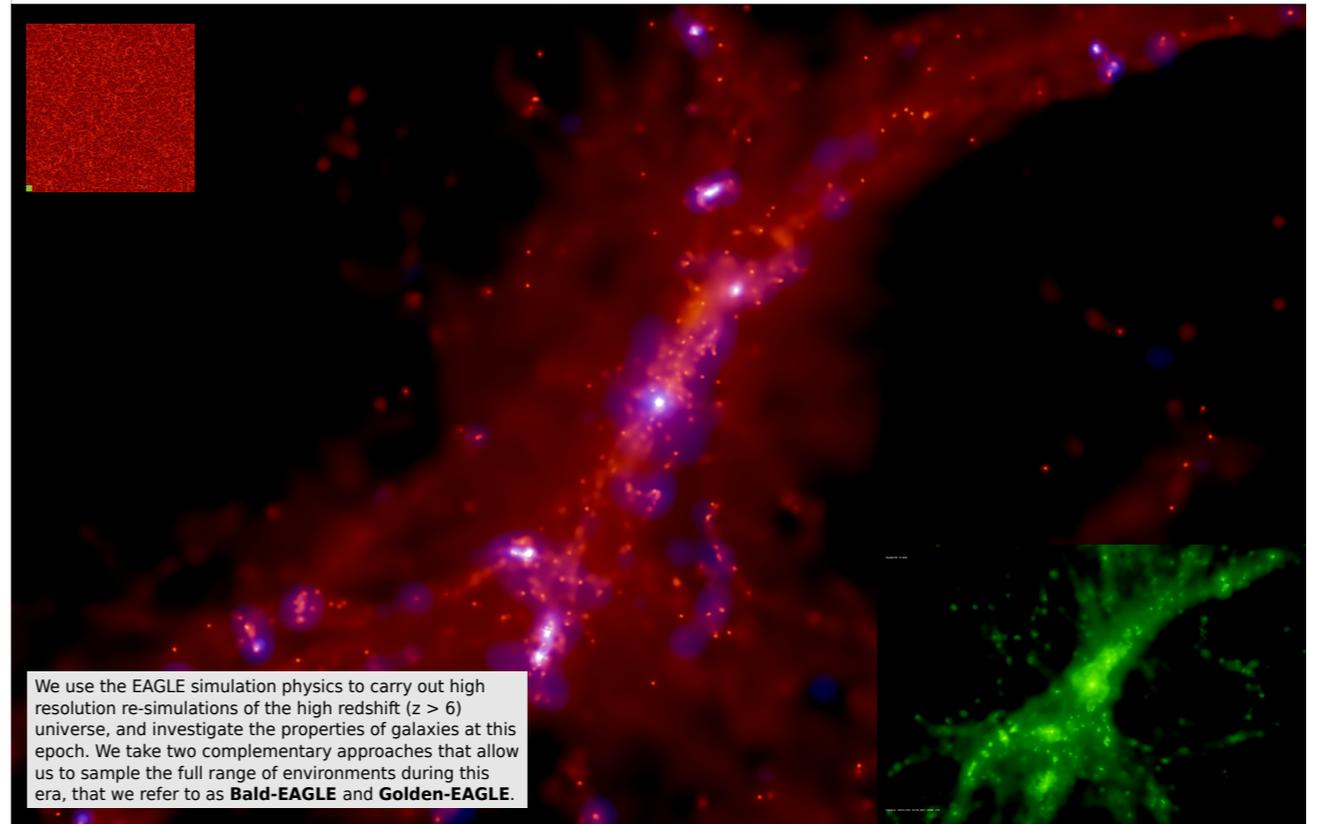
Christopher Lovell, Peter Thomas, Stephen Wilkins
Department of Physics and Astronomy, Falmer, Brighton, UK, BN1 9QH



To complement BlueTides at the highest masses and push to lower redshift we are re-simulating massive galaxies.

We will also look closely at the physics implementation (initially using the EAGLE physics) and how that affects the results.

See poster by Chris Lovell.



We use the EAGLE simulation physics to carry out high resolution re-simulations of the high redshift ($z > 6$) universe, and investigate the properties of galaxies at this epoch. We take two complementary approaches that allow us to sample the full range of environments during this era, that we refer to as **Bald-EAGLE** and **Golden-EAGLE**.

The **Bald-EAGLE** project will aim to build a comprehensive statistical sample of galaxies at high redshift. The reference EAGLE simulation contains relatively few galaxies at high redshift due to its low volume, as seen in figure 1 below. This suite of simulations will address this by sampling a range of overdensities ($\pm 2\sigma$, $\pm 1\sigma$, μ) at $z \sim 5$ from a 3.2 cGpc dark matter only simulation, pictured in the top left of the image above, to build a representative sample of conditions at this time. Together, these will constitute the largest EAGLE high redshift simulation.

Figure Above: Zoom in of a cluster from a mean density resimulation at $z = 6$, showing the density of stars in blue / white, and gas in red. The bottom right inset shows the dark matter density in green. The top left inset shows a projection of the 3.2 cGpc box from which the resimulations are selected; the green box at the bottom left shows the relative size of the EAGLE reference simulation (this is a 2D projection, the full relative size is $1:32^3$)

The **Golden-EAGLE** project will re-simulate the rarest, most massive objects identified at $z \sim 5$ from a 3.2 cGpc dark matter only simulation. Extreme objects such as HFLS3, identified at $z \sim 6$ with a mass of $5 \times 10^5 M_\odot$, have been identified by Hubble in recent years, and challenge our current theories of galaxy formation. However, as seen in figure 1, the reference EAGLE simulation does not contain such objects at this redshift, and so cannot be used to investigate their properties. Subhalo masses can also evolve significantly over cosmic time, so that the largest objects at $z = 0$ are not necessarily the largest at $z = 6$, as seen in figure 2. This necessitates the need for re-simulation of objects explicitly identified at high redshift.

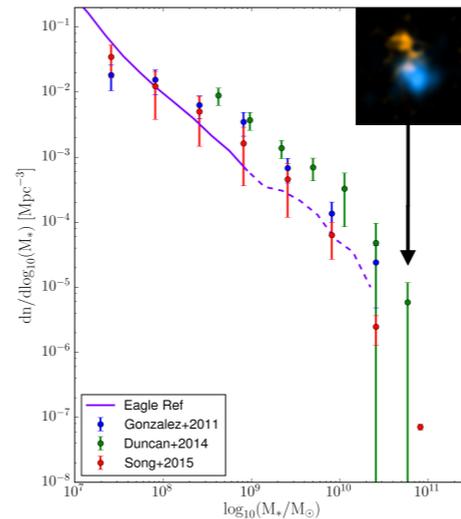


Figure 1 The Galaxy Stellar Mass Function in EAGLE plotted against observational results from Gonzalez 2011, Duncan 2014 & Song 2015. Where there are less than 100 galaxies in a given bin, the mass function is plotted as a dashed line. The black arrow indicates the approximate mass of HFLS3 ($\sim 5 \times 10^{10} M_\odot$) an image of which is shown at top right; near-IR in orange (Keck), and millimetre in blue (PdBI). Image credit: ESA/Herschel/HerMES/IRAM/GTC/W.M. Keck

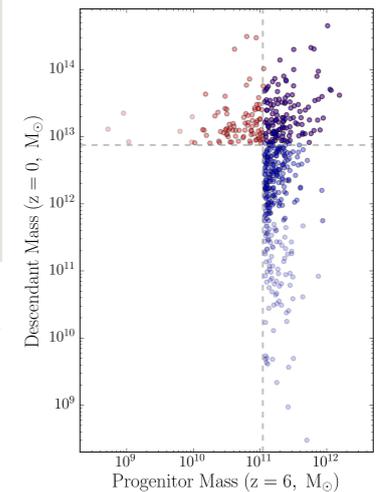


Figure 2 The most massive subhalos at both $z = 0$ and $z = 6$ from the EAGLE reference simulation (100cMpc) are matched with their most massive progenitors / descendants on the merger tree, respectively. For the top subhalos at $z = 0$, there is a spread over four orders of magnitude in their progenitor masses. For the top subhalos at $z = 6$, there is a spread over six orders of magnitude in their descendant masses

BLUETIDES SIMULATION

Of course this is **very misleading** as BlueTides only runs to $z=8$ ($z=6$ in the future).

