# THE BLUETIDES SIMULATION

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# B L U E T I D E S

## T A L K   O U T L I N E

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 ~$577^3$ $Mpc^3$
  - Roughly 200 times larger than EAGLE and Illustris. 10,000 times that of a single NIRSpec pointing at z=8-9.
- $2 \times 7040^3$ ~ 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

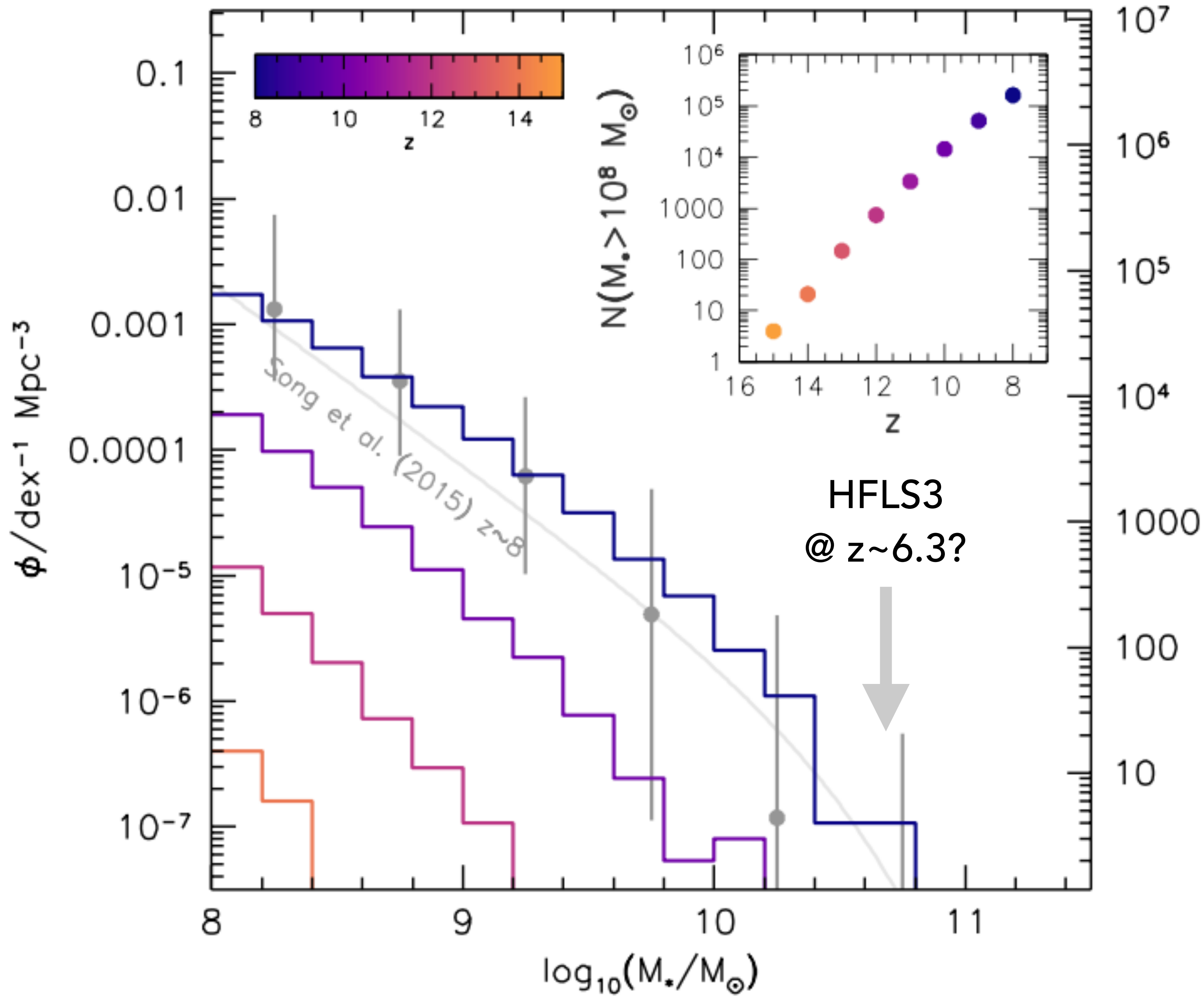
**BlueTides** reproduces observational constraints on the GSMF at z~8.

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.

Wilkins et al., 2016d, submitted.




Wilkins et al., 2016d, submitted.

# BLUETIDES

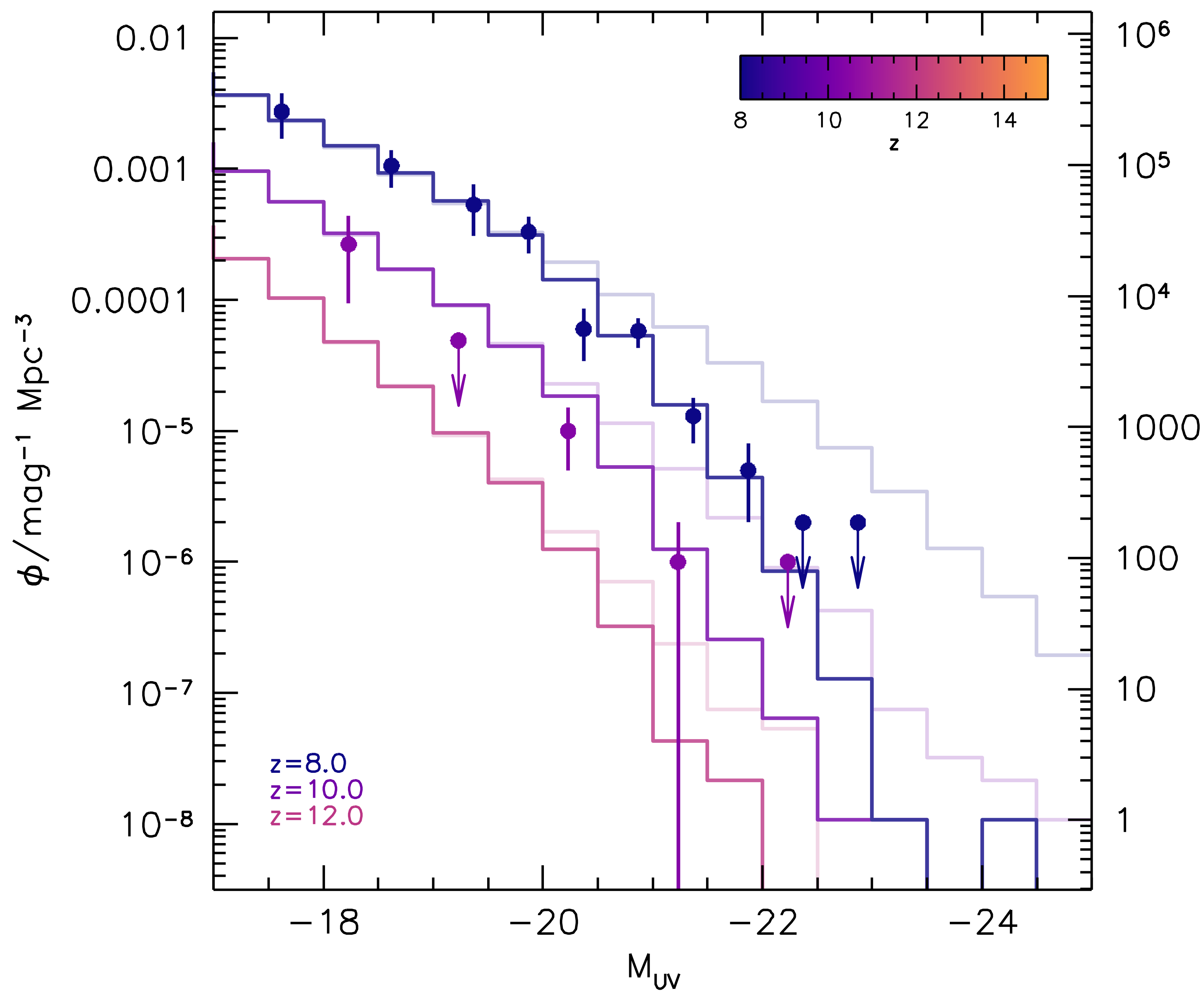
## GALAXY STELLAR MASS FUNCTION

BlueTides reproduces observational constraints on the UVLF at z~8 and 10.

(More on dust in a second)

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

number of galaxies in each mass bin in BLUETIDES.



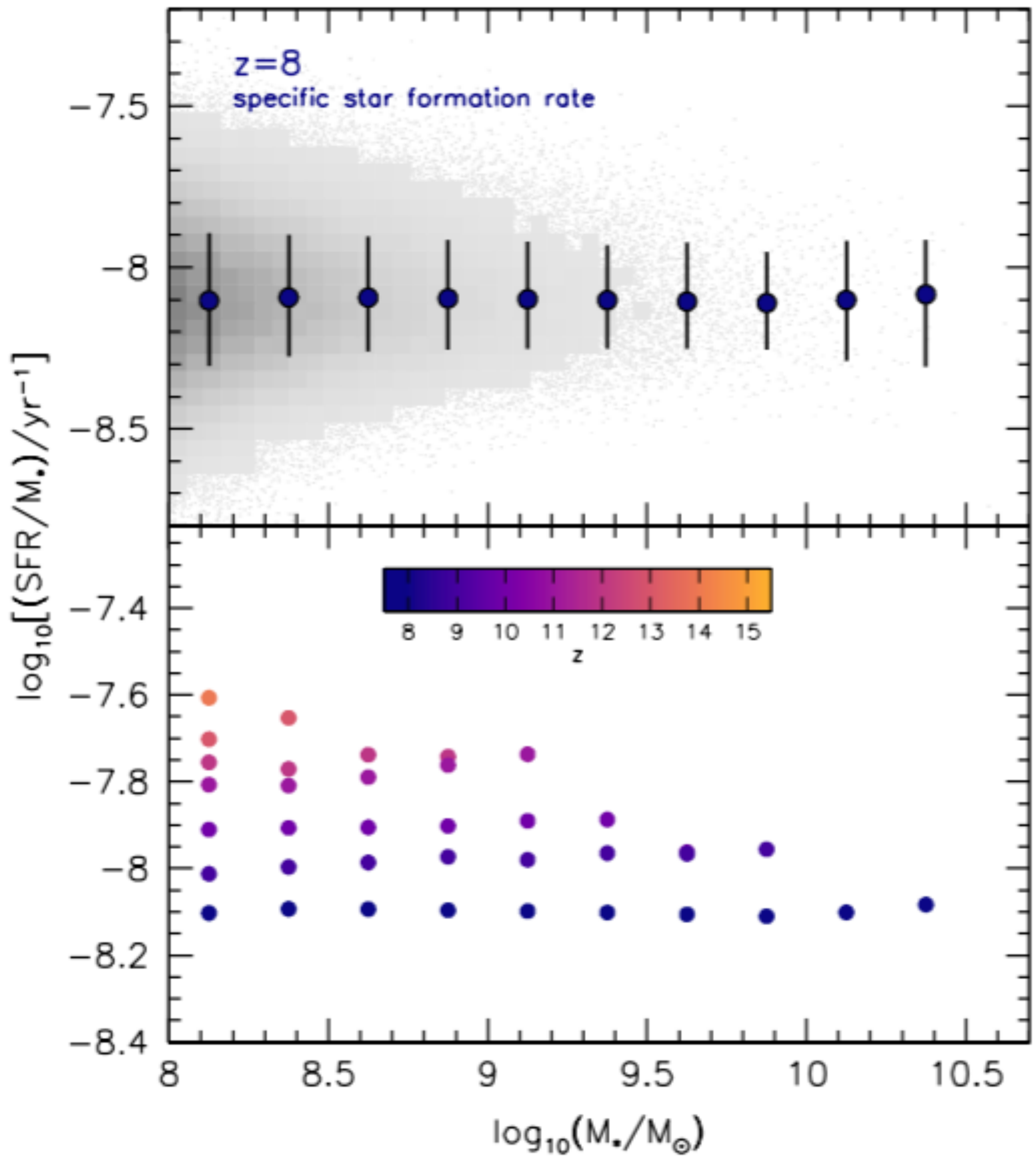

Wilkins et al., 2016d, submitted.

# 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.**

Wilkins et al., 2016d, submitted.

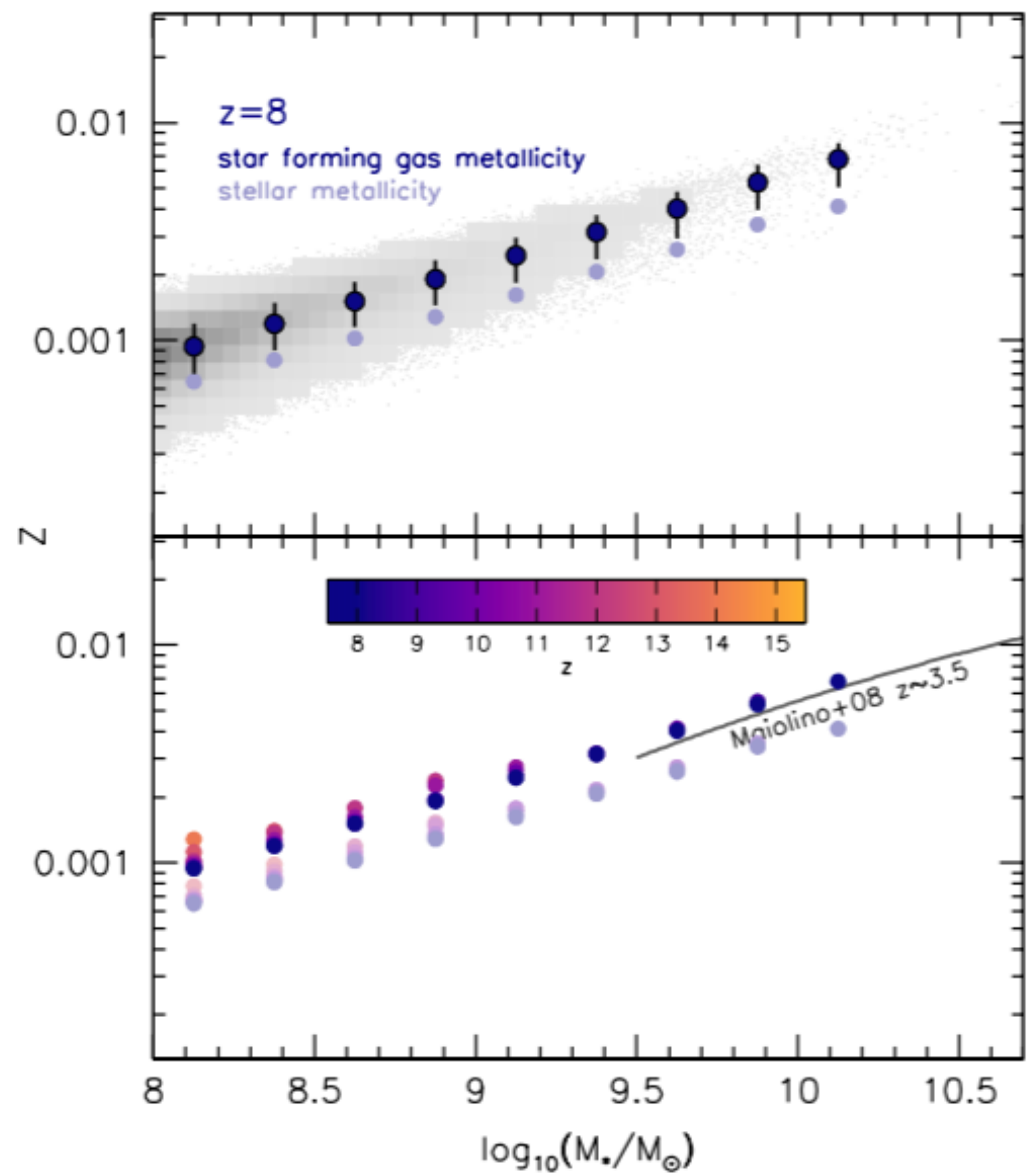


# BLUETIDES
## PHYSICAL PROPERTIES

There is a strong mass-metallicity relations in place.

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

Wilkins et al., 2016d, submitted.



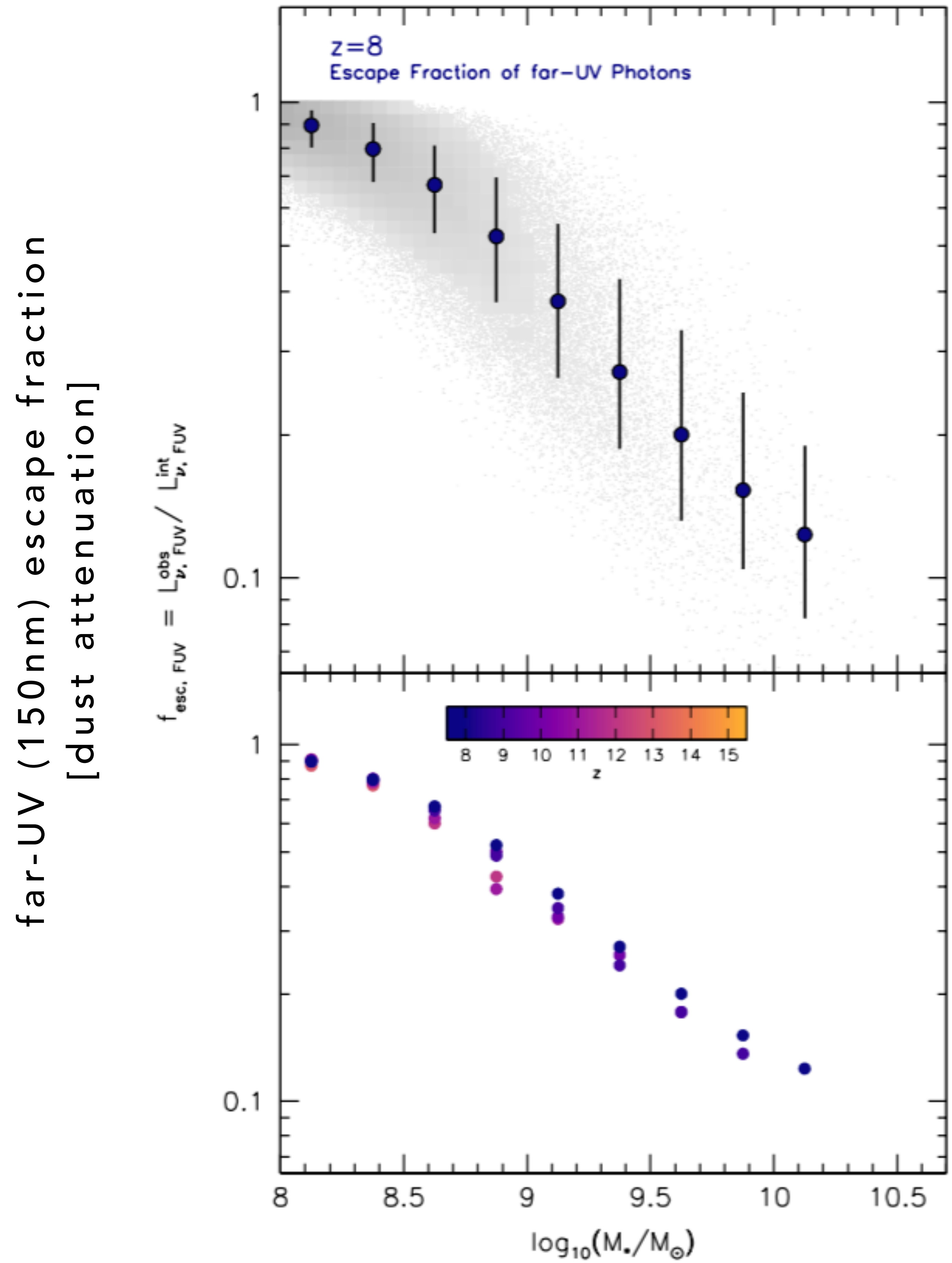
# BLUETIDES
## PHYSICAL PROPERTIES

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⊙) and the attenuation.** Galaxies at M*~$10^{10}$ M⊙ have a UV attenuation of A~2.5.

Wilkins et al., 2016d, submitted.
Wilkins et al. in-prep



# BLUETIDES

## PHYSICAL PROPERTIES

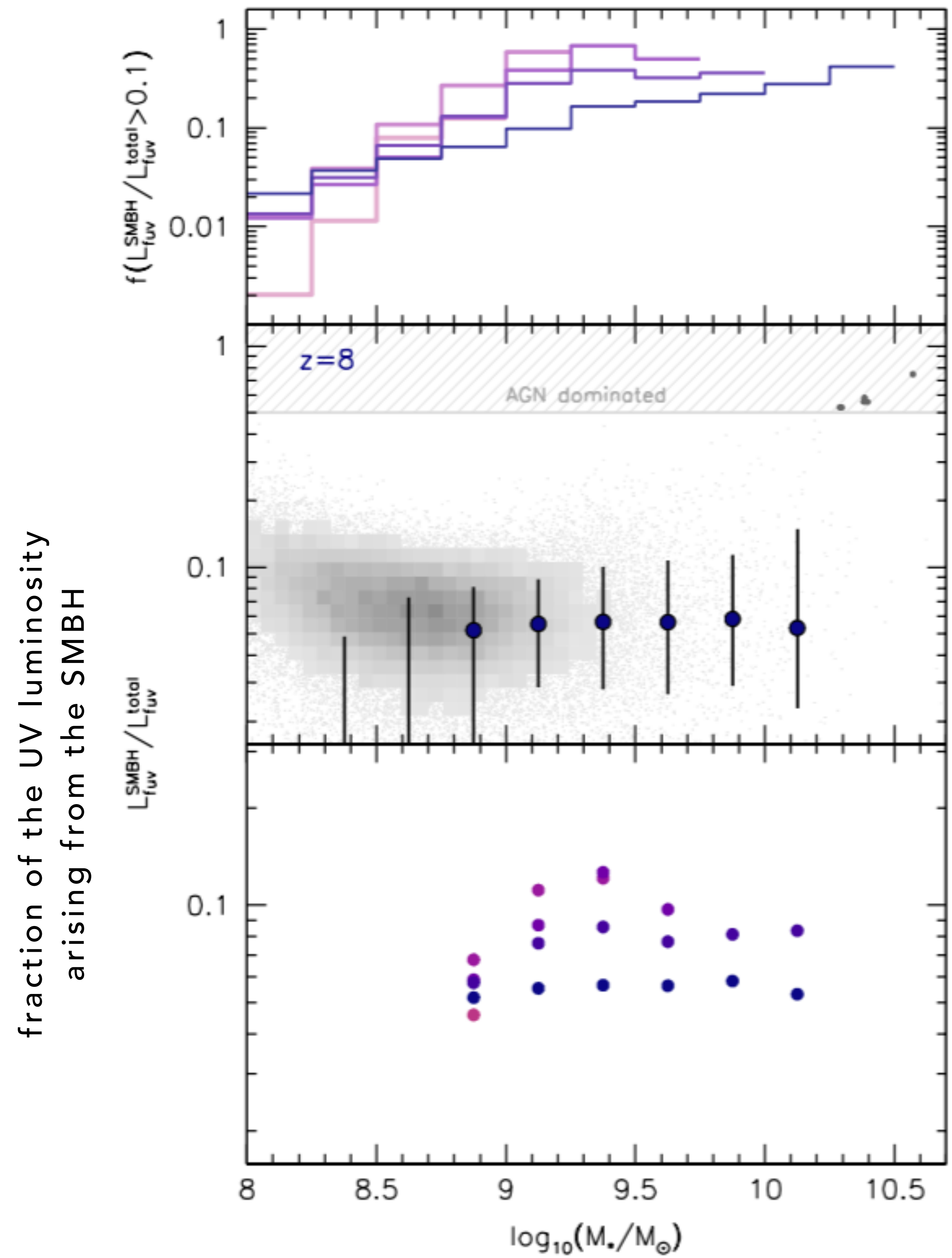
Includes the growth of SMBHs

SMBHs at z~8 contribute ~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*

Wilkins et al., 2016d, submitted.
di Matteo et al., 2016, in-prep



# SED MODELLING

Star formation and metal enrichment history

construct pure stellar SED →

Pure Stellar Spectral Energy Distribution

# SED MODELLING

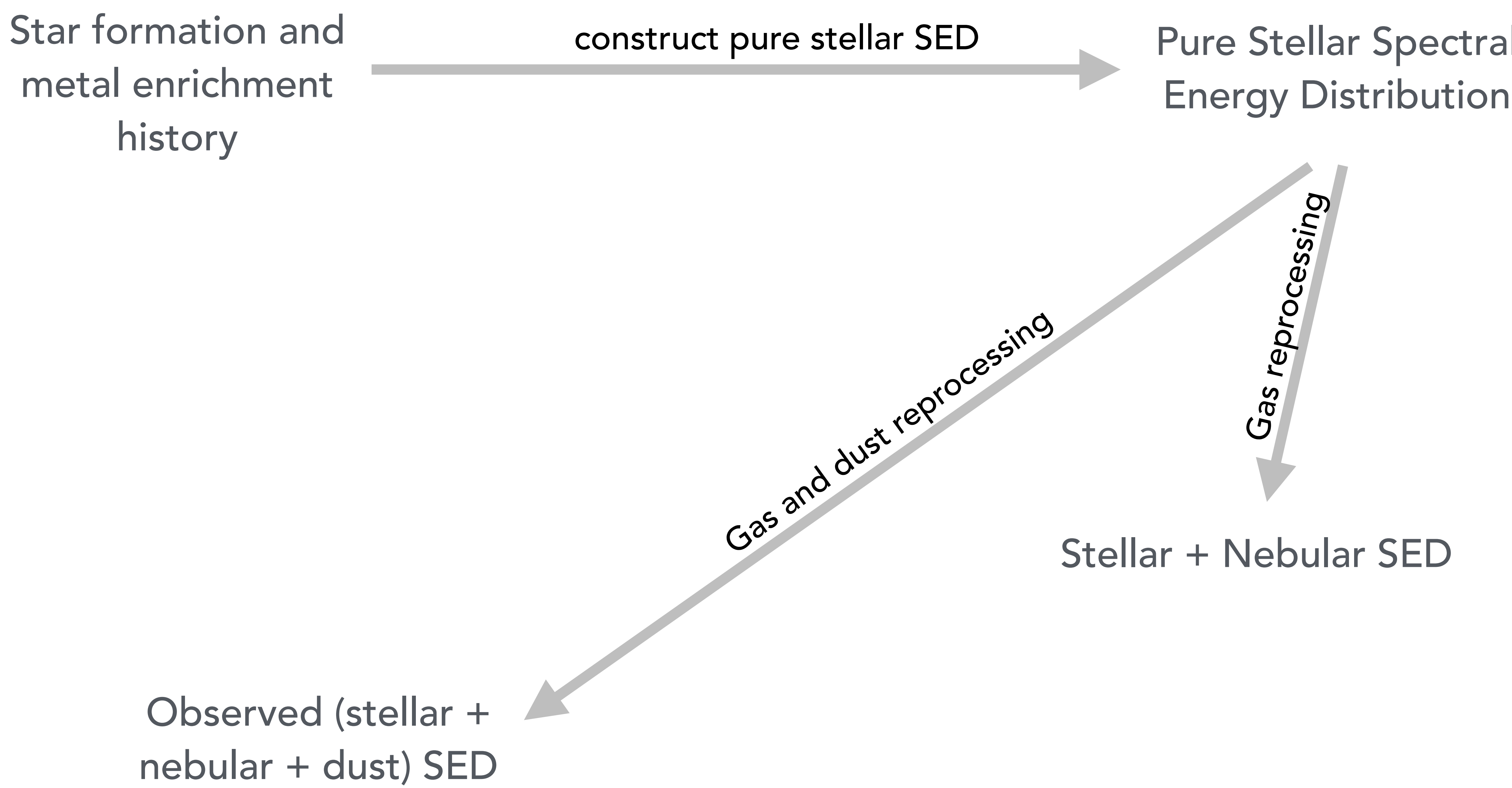
Star formation and metal enrichment history

construct pure stellar SED

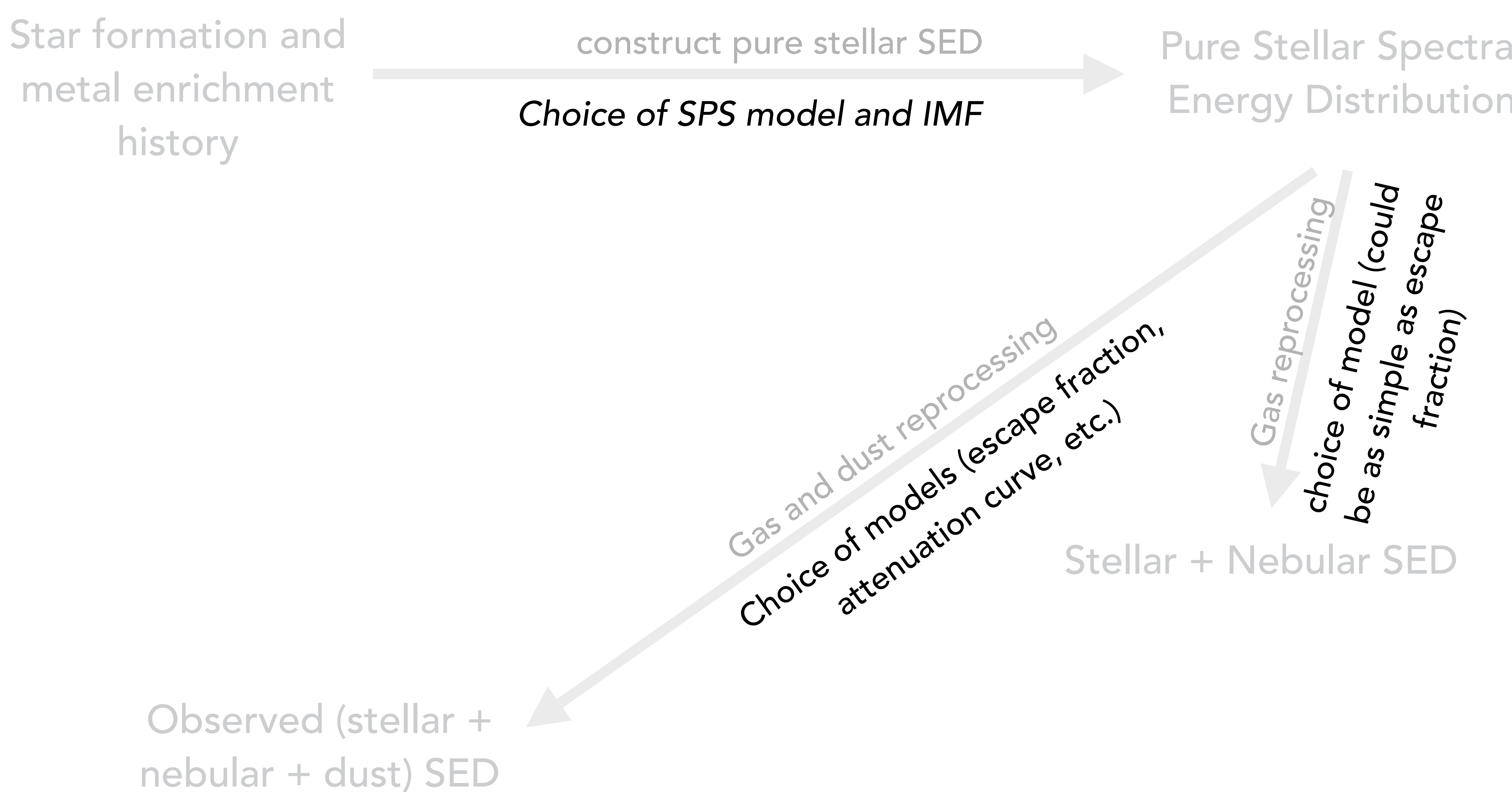
*Choice of SPS model and IMF*

Pure Stellar Spectral Energy Distribution

# SED MODELLING



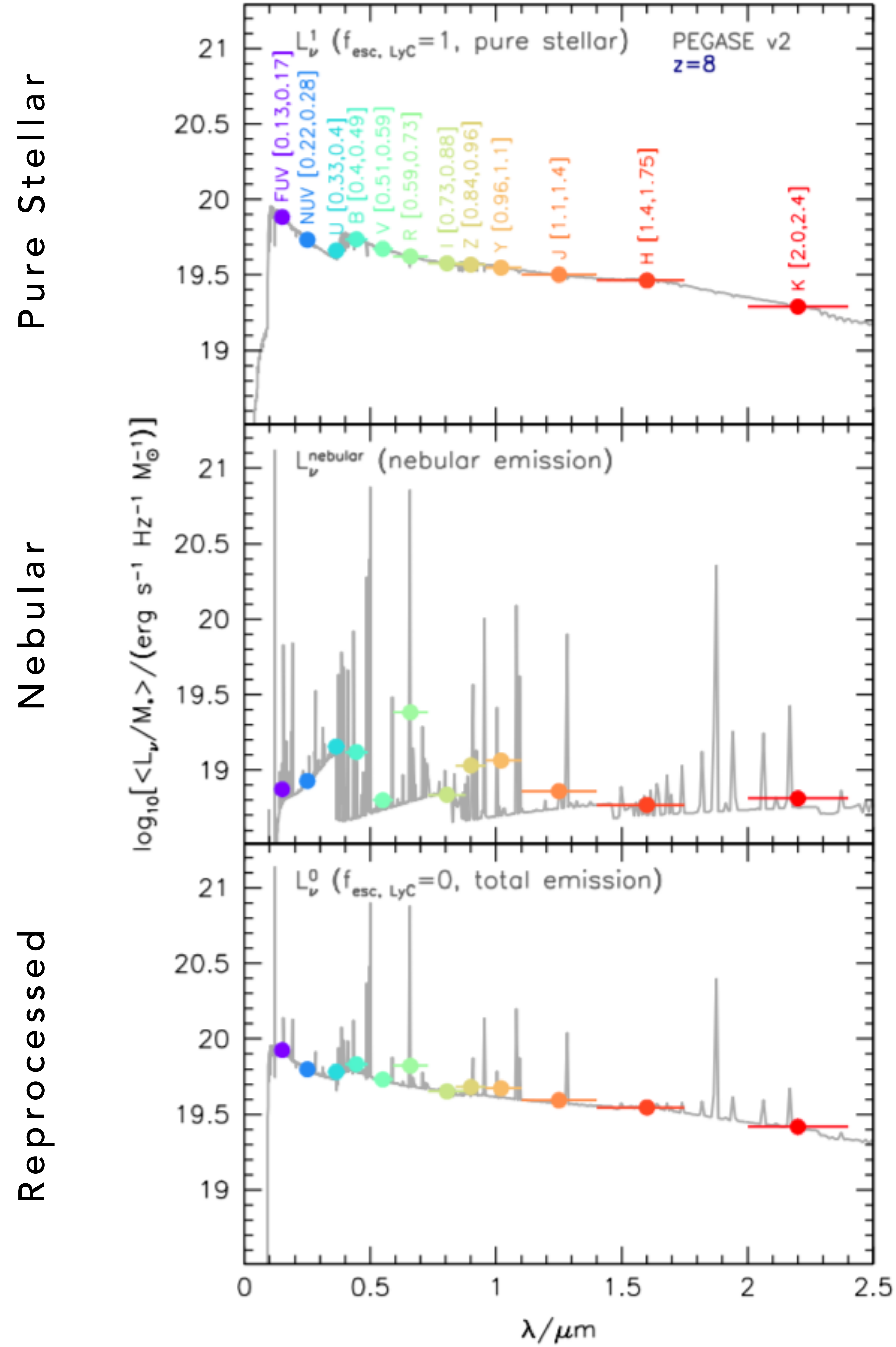
# SED MODELLING



# 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.

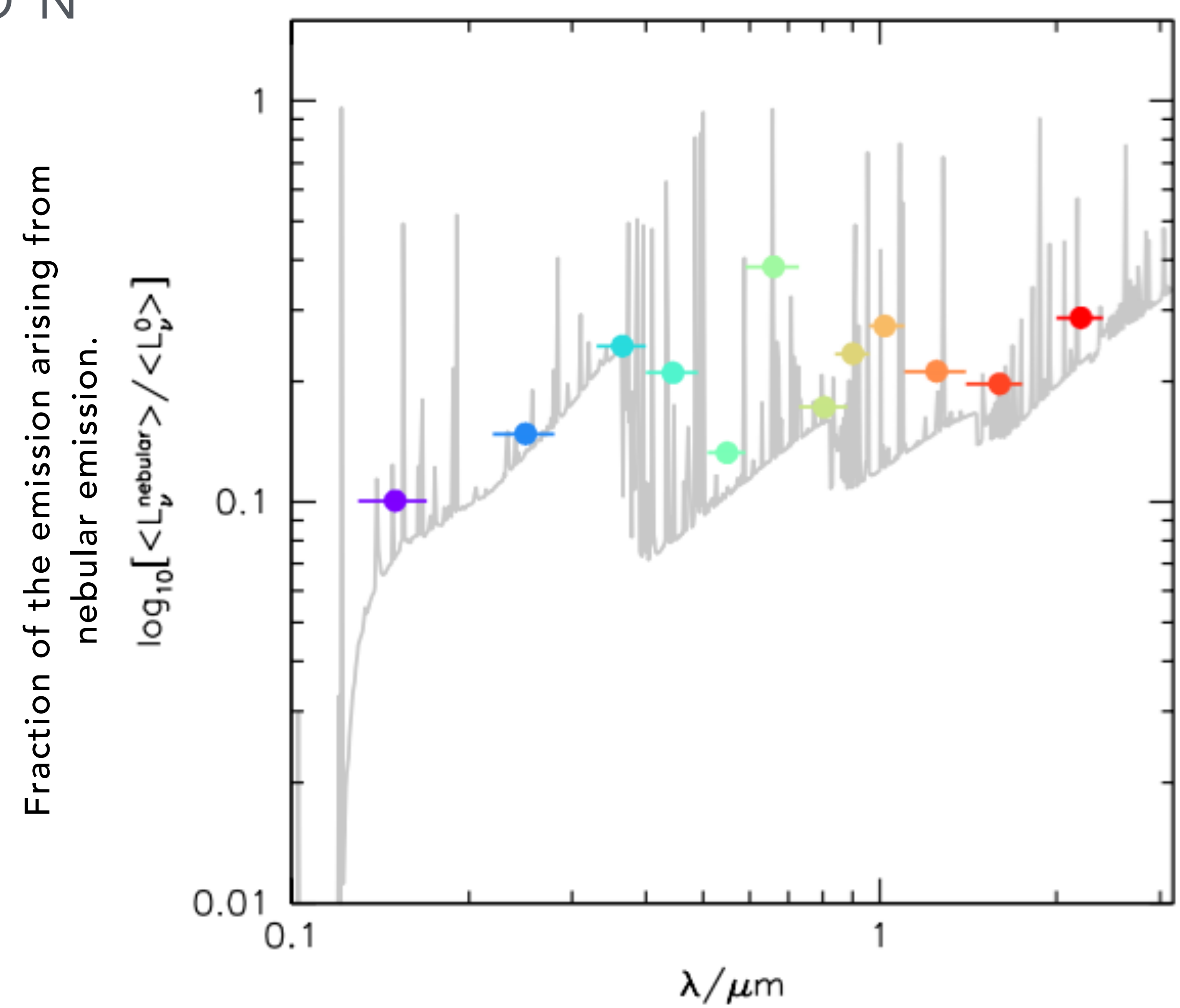
Wilkins et al., 2016c, accepted (1605.05044).



# 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.

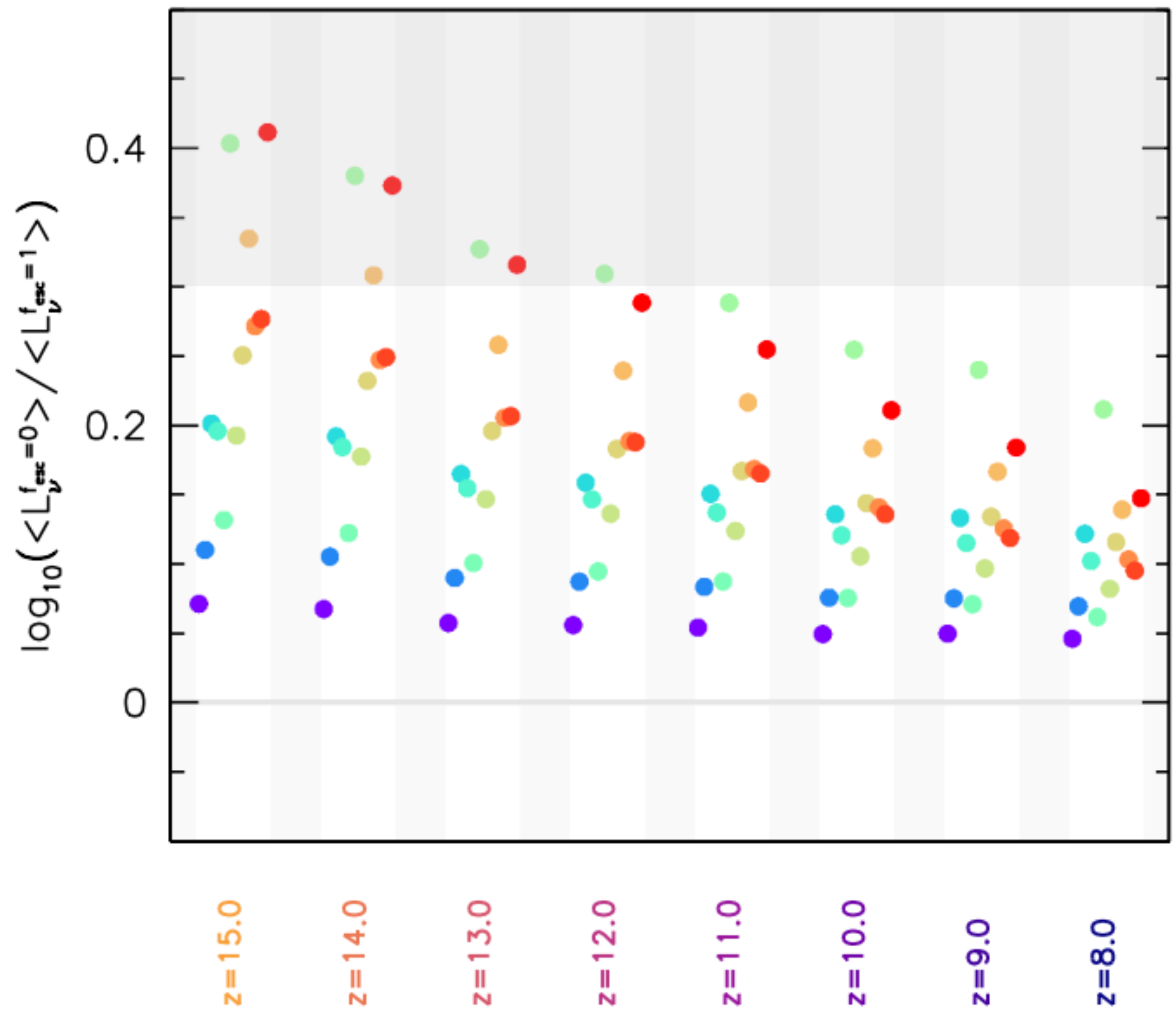
Wilkins et al., 2016c, accepted (1605.05044).




*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.

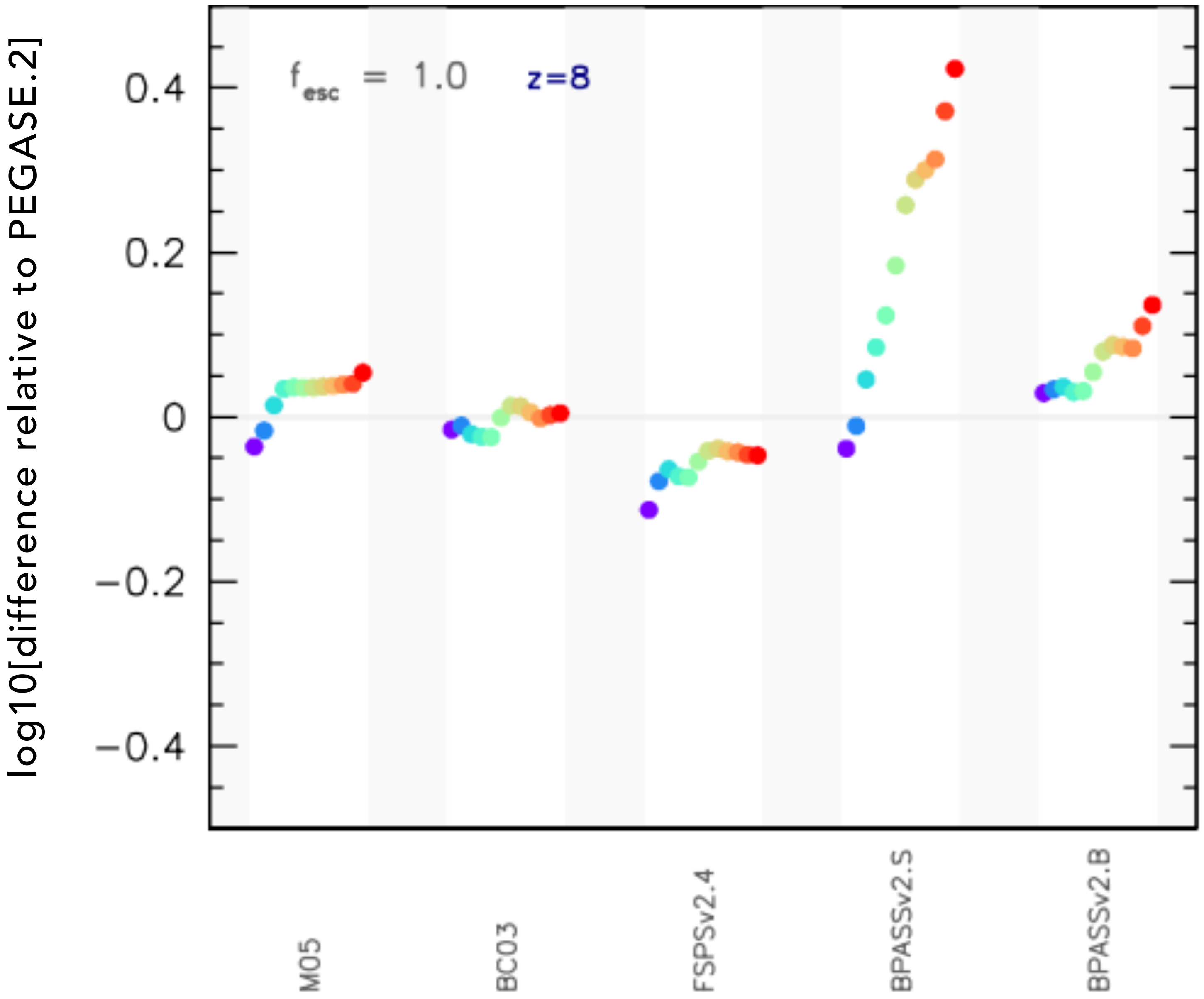



*The fractional contribution of nebular (continuum and line) emission to broad-band SEDs from z=15-8.*

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.

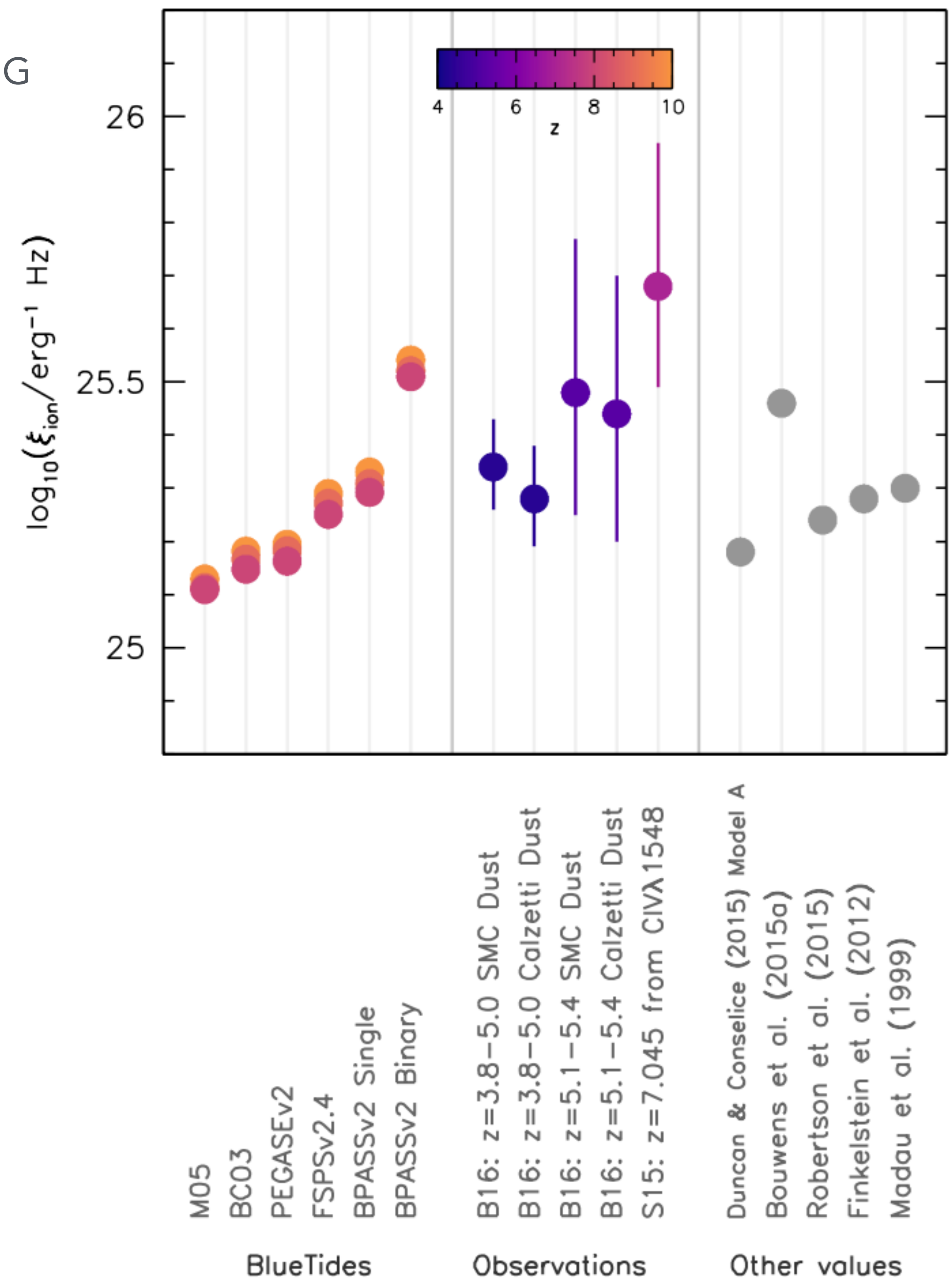
$$\dot{n}_{\rm ion} = f_{\rm esc,LyC}\,\xi_{\rm ion}\,\frac{\rho_{\rm uv}}{f_{\rm esc,uv}}$$

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.




Wilkins et al., 2016b, published (1512.03214).

# SED MODELLING

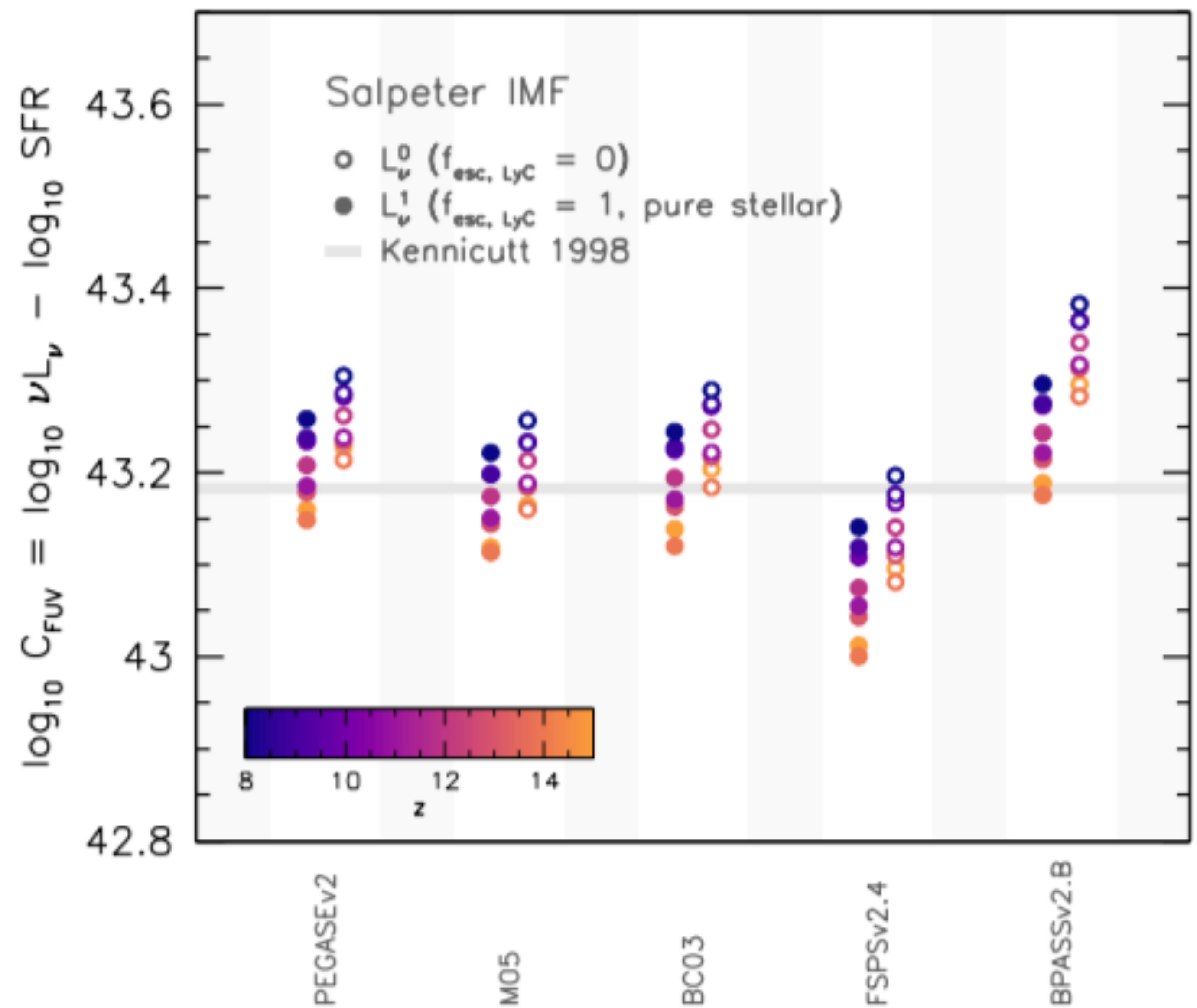
## STAR FORMATION INDICATORS

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

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.

$$\log_{10}(\mathrm{SFR}/\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}) = \log_{10}(\nu L_{\nu,\,\mathrm{fuv}}/\mathrm{erg\,s}^{-1}) - \log_{10} C_{\mathrm{fuv}}$$



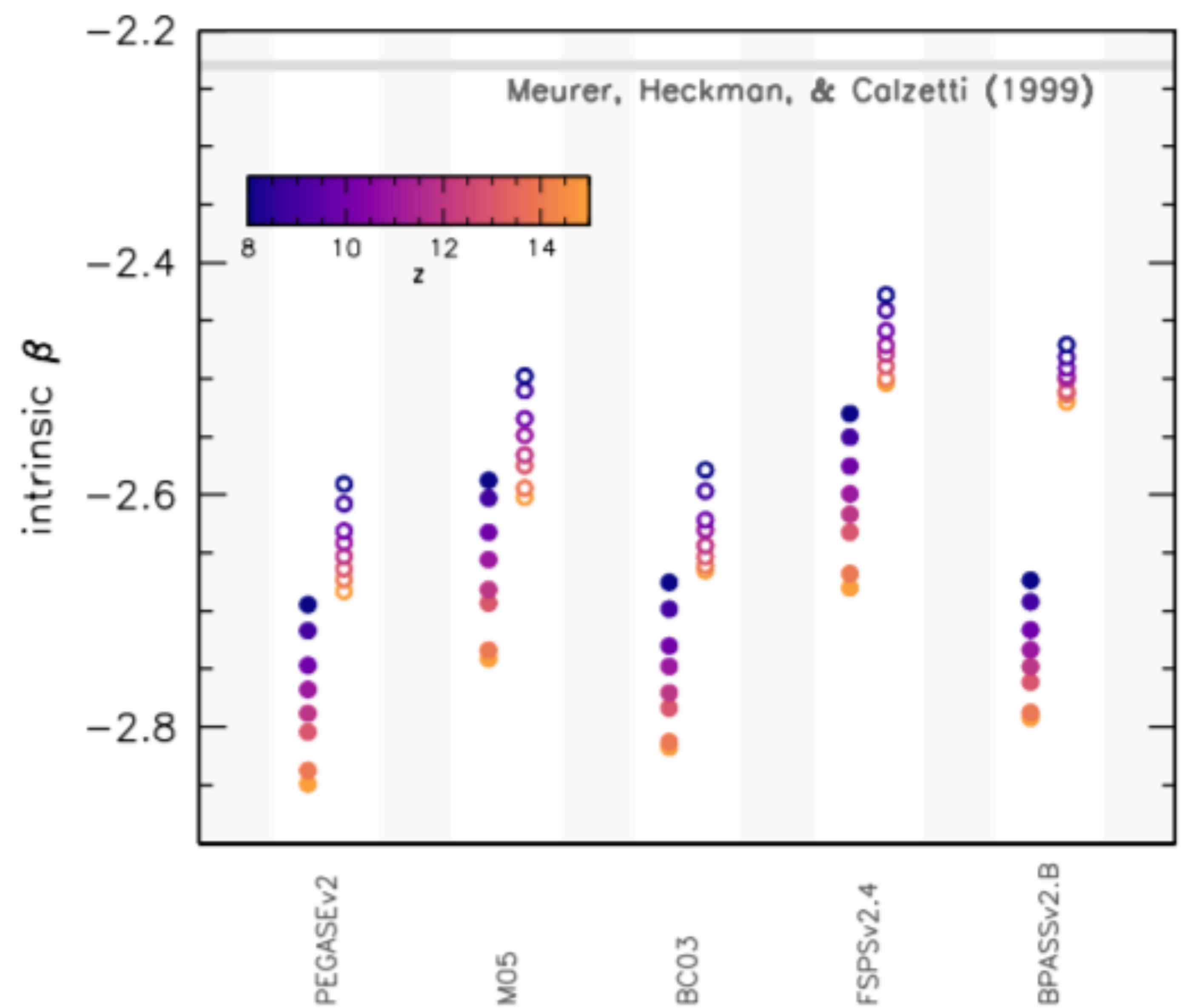
# SED MODELLING
## UV CONTINUUM SLOPE

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

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.

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

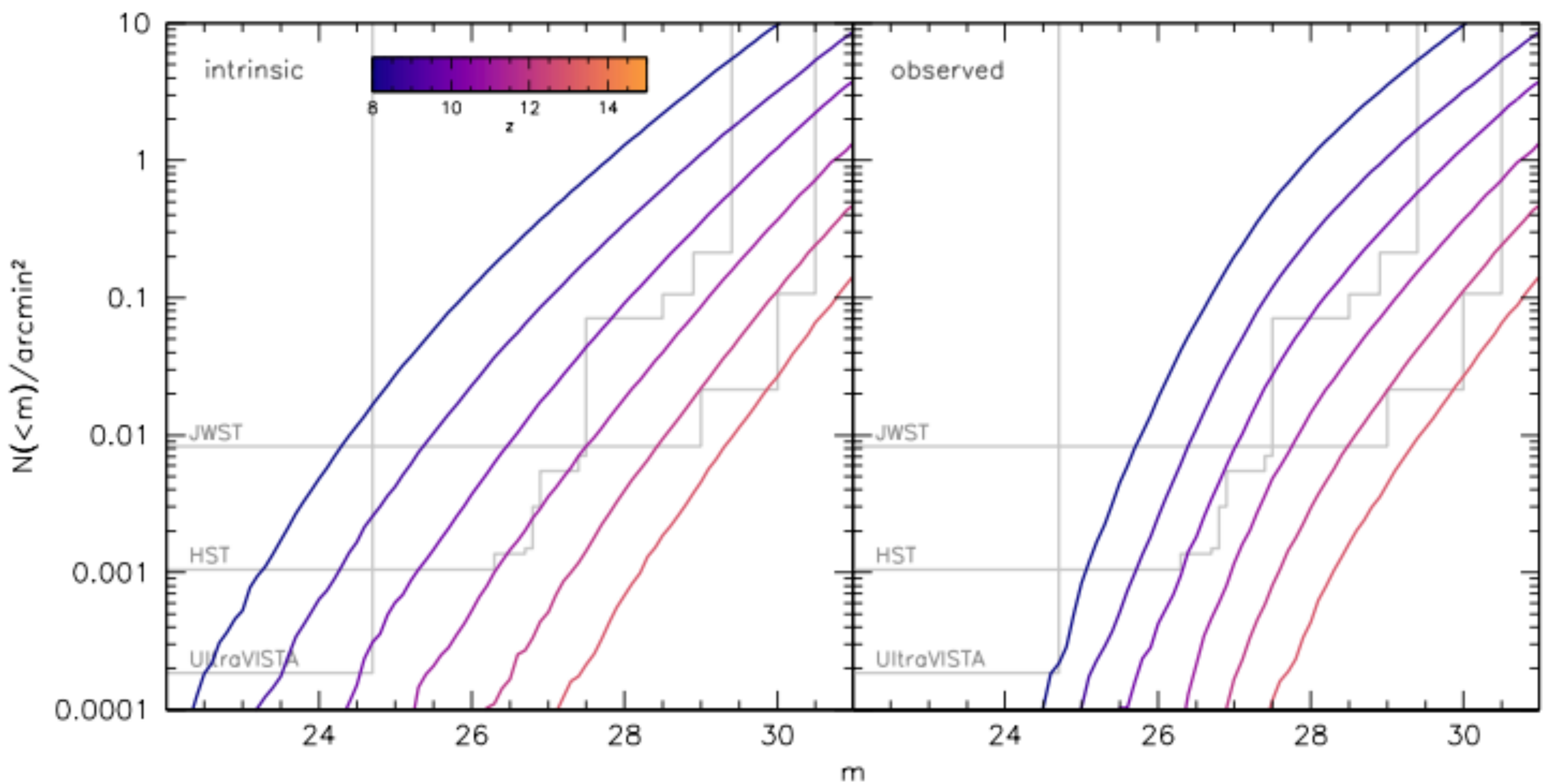


# PREDICTIONS FOR JWST

## SURFACE DENSITIES

Wilkins et al., 2016e, submitted.

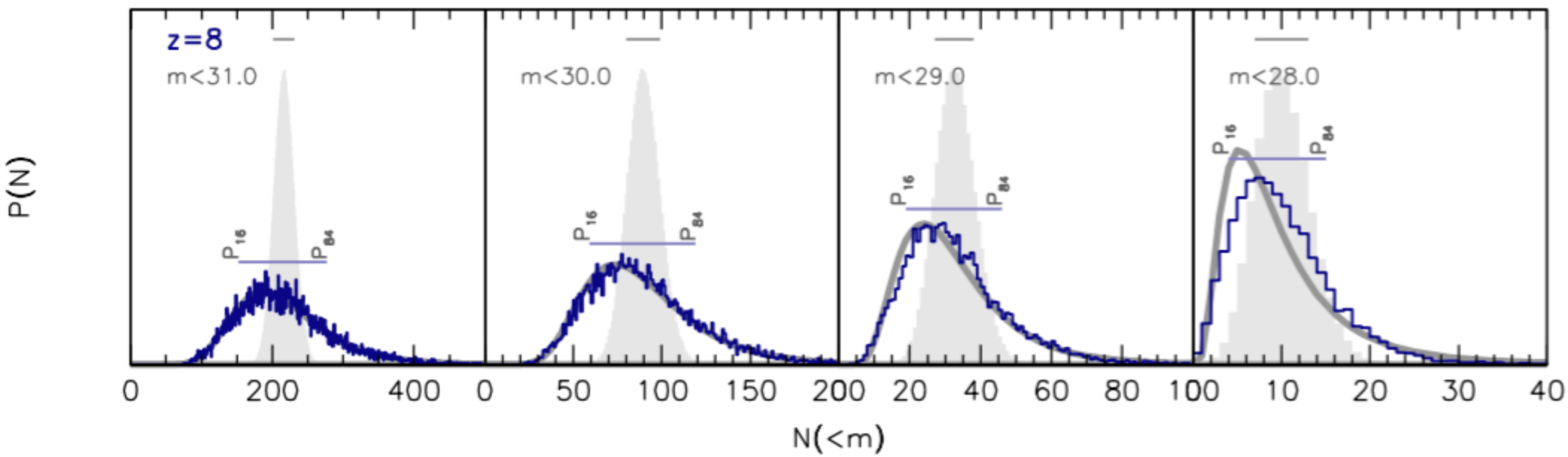
We can predict the surface density of sources across a wide redshift and luminosity range.



# 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.*

# PREDICTIONS FOR JWST

## SURFACE DENSITIES

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 |

# CONCLUSIONS

**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~8 and above.

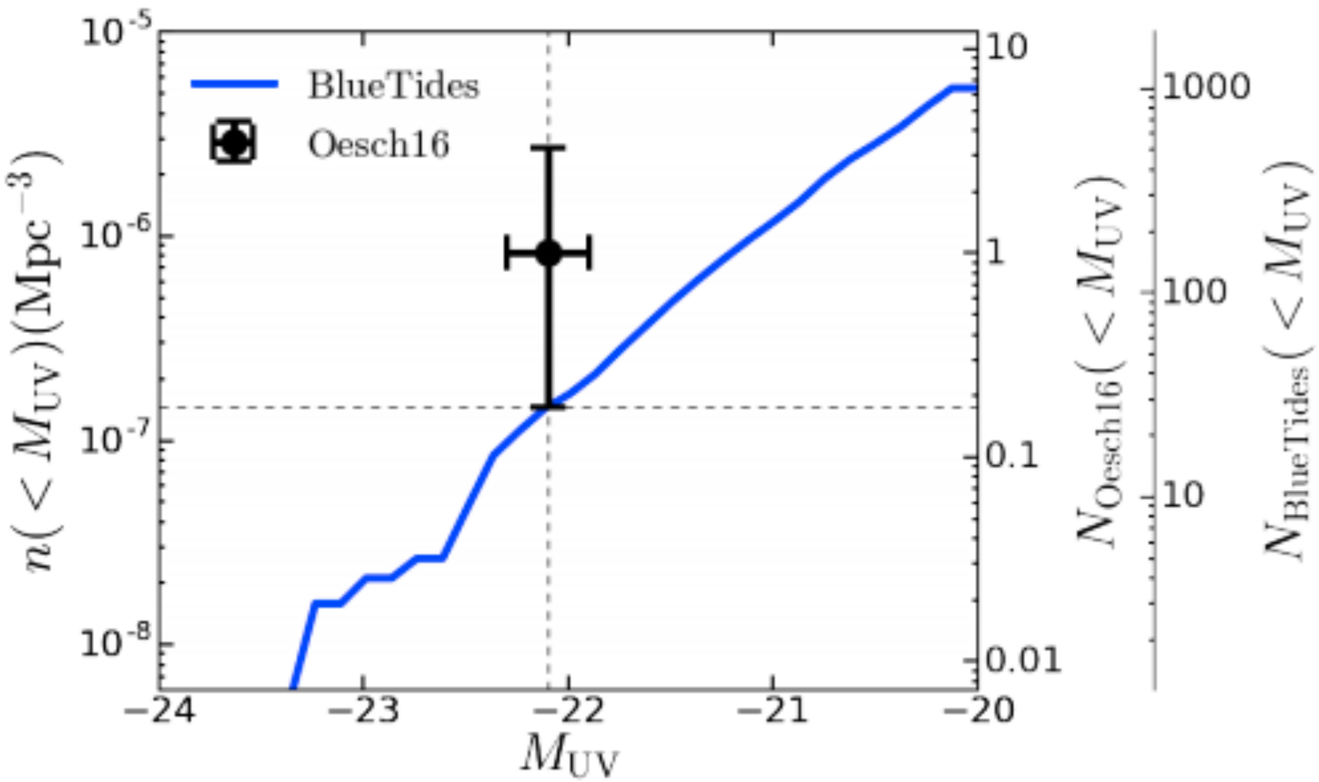
- We can predict the SEDs of galaxies, these are sensitive to our choice of assumptions (IMF, nebular emission, dust emission, SPS model etc.)

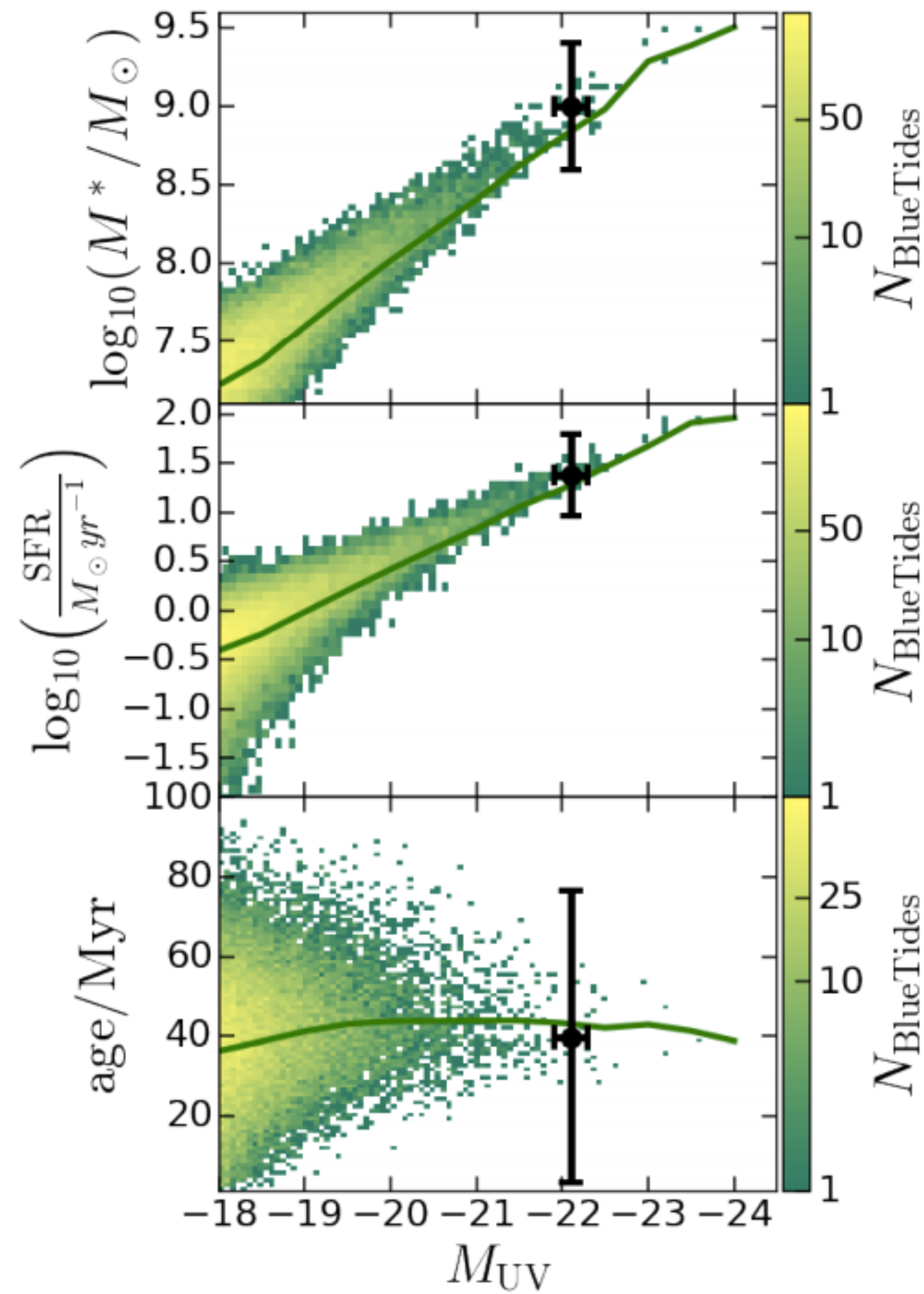
- We can predict the ionising photon production efficiency. This is very sensitive to the choice of SPS model.

- JWST will likely discover many galaxies at z~8-10 though relatively few at z~12 and above.

# BLUETIDES

## MONSTERS

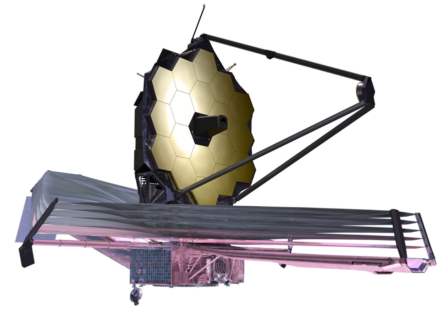


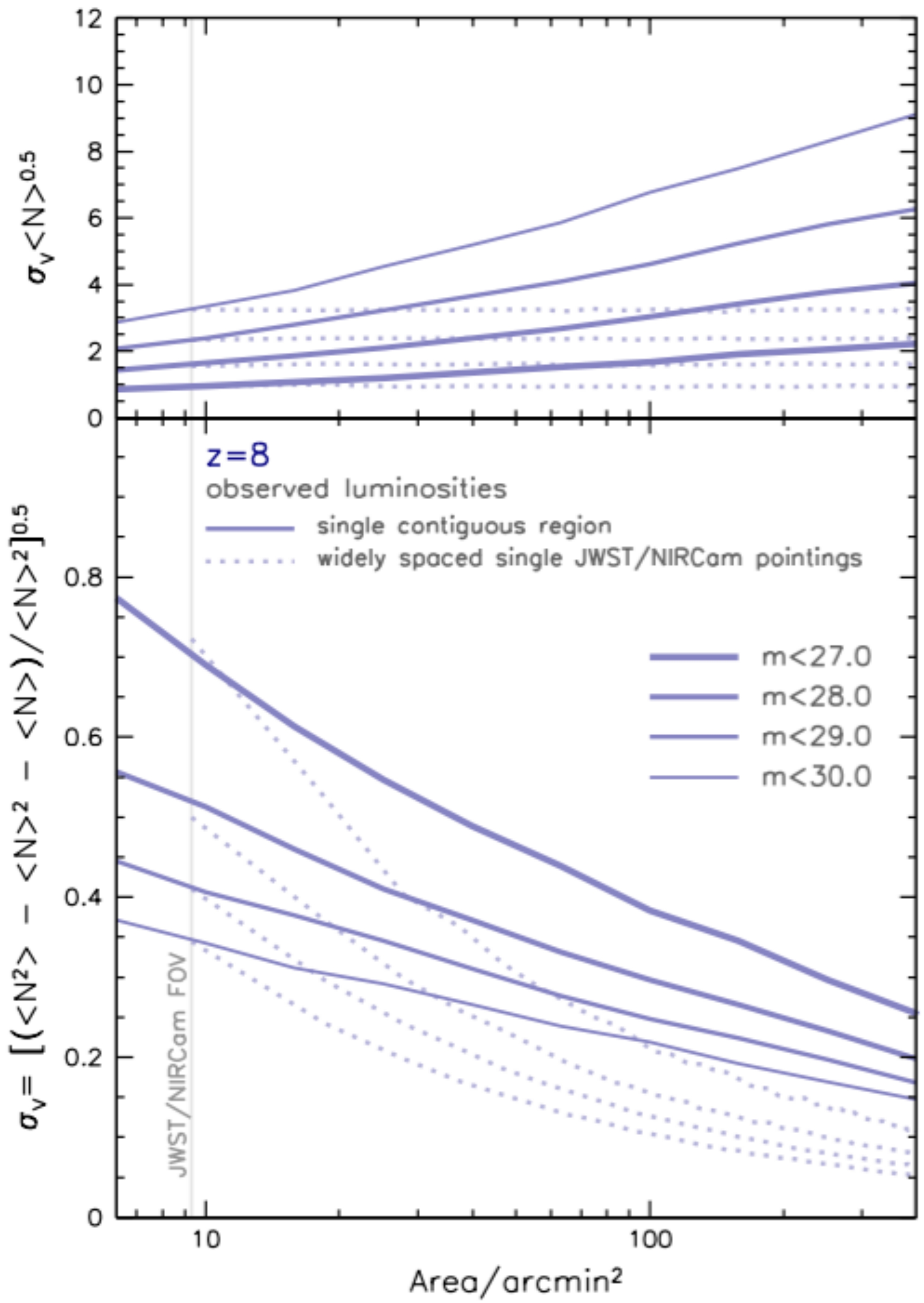

The predicted surface density of sources is (just about) consistent with the discovery of a bright galaxy at z~11 by Oesch et al. (2016). The measured physical properties are also consistent.

Waters et al. 2016a, accepted

# PREDICTIONS FOR JWST
## SURFACE DENSITIES



Wilkins et al., 2016e, submitted.

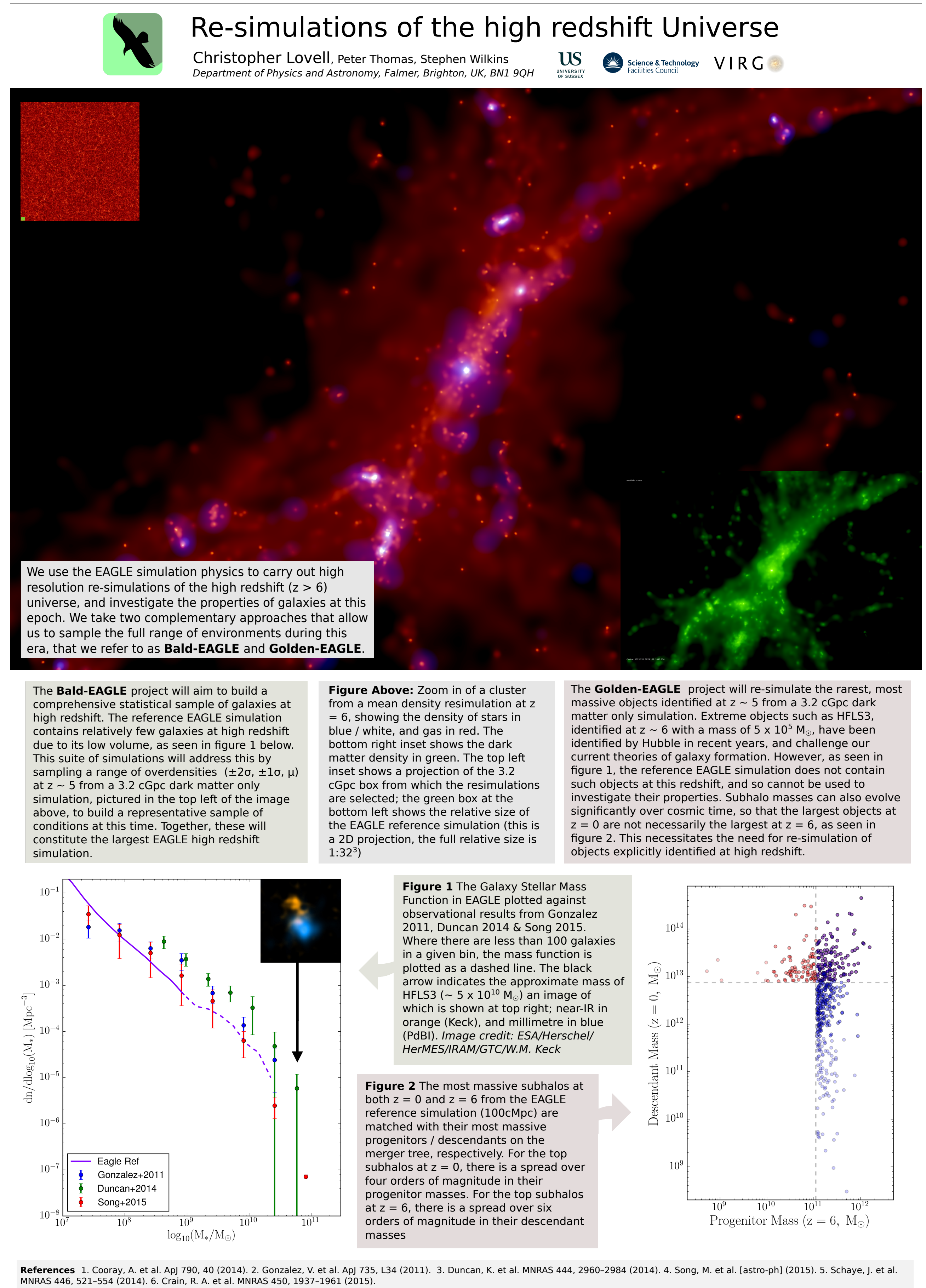



*Bottom: How cosmic variance is affected by the area covered (both for a contiguous region and widely spaced random pointings) and magnitude limit. Top: The ratio of cosmic variance to sample (Poisson) variance.*

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.*



# BLUETIDES
## SIMULATION

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