### THE BLUETIDES SIMULATION





#### B L U E T I D E S M O T I V A T I O N A N D R E Q U I R E M E N T S

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, VISTA, ALMA, JCMT, JWST, WFIRST, ELTs, and 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  $z\sim6-8$ .

#### B L U E T I D E S S I M U L A T I O N

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 ~577³ Mpc³
- Roughly 200 times larger than EAGLE and Illustris. 10,000 times that of a single NIRSpec pointing at z=8-9.
- $2 \times 7040^3 \sim 0.7$  trillion particles
- Mass/Spatial resolution is slightly worse than EAGLE and Illustris

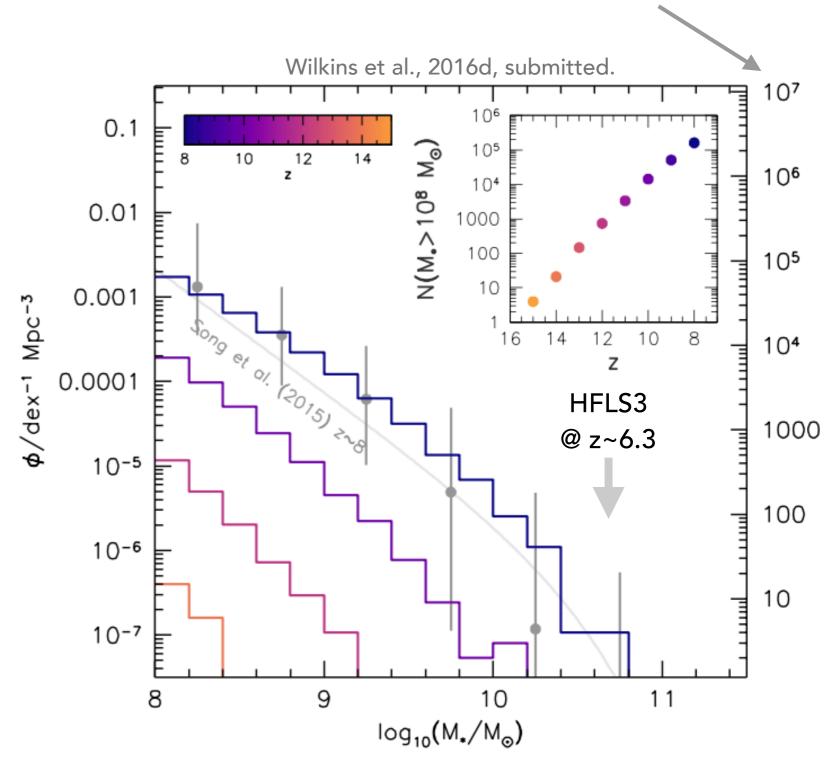
### BLUETIDES GALAXY STELLAR MASS FUNCTION

number of galaxies in each mass bin in BLUETIDES.

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.



Wilkins et al., 2016d, submitted.

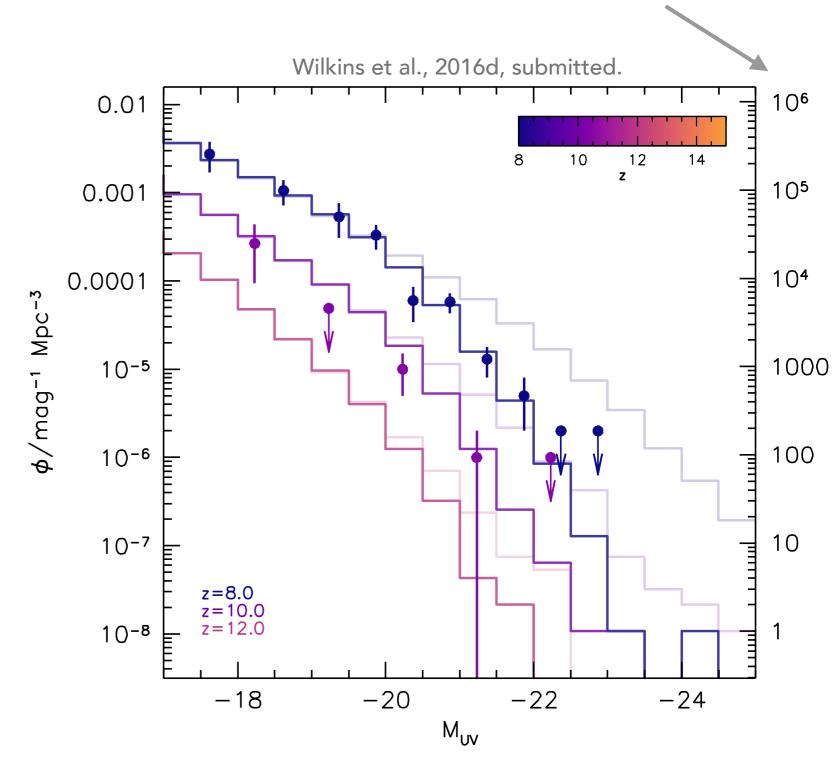
### BLUETIDES GALAXY STELLAR MASS FUNCTION

number of galaxies in each mass bin in BLUETIDES.

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.

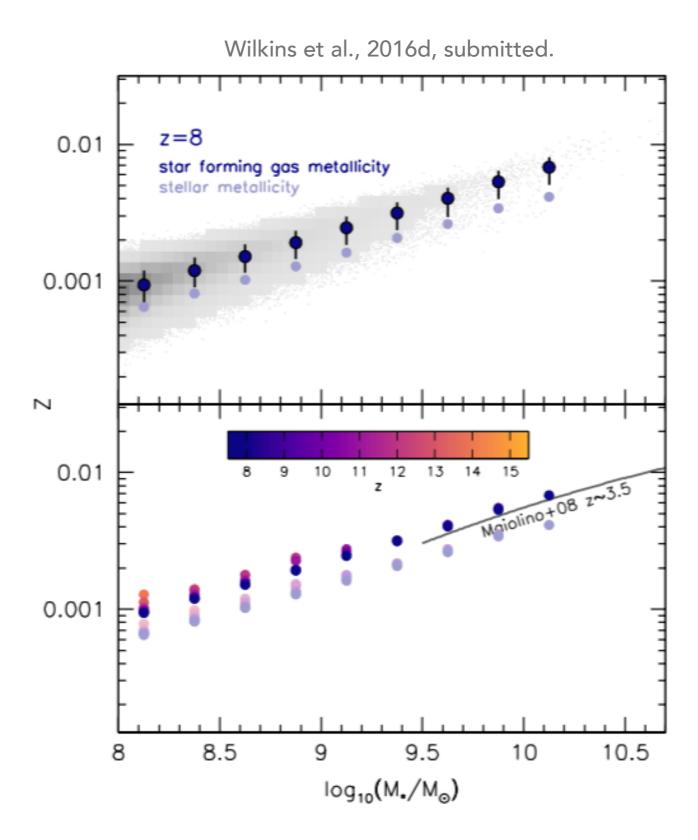


Wilkins et al., 2016d, submitted.

### BLUETIDES PHYSICAL PROPERTIES

There is a strong massmetallicity relations in place.

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

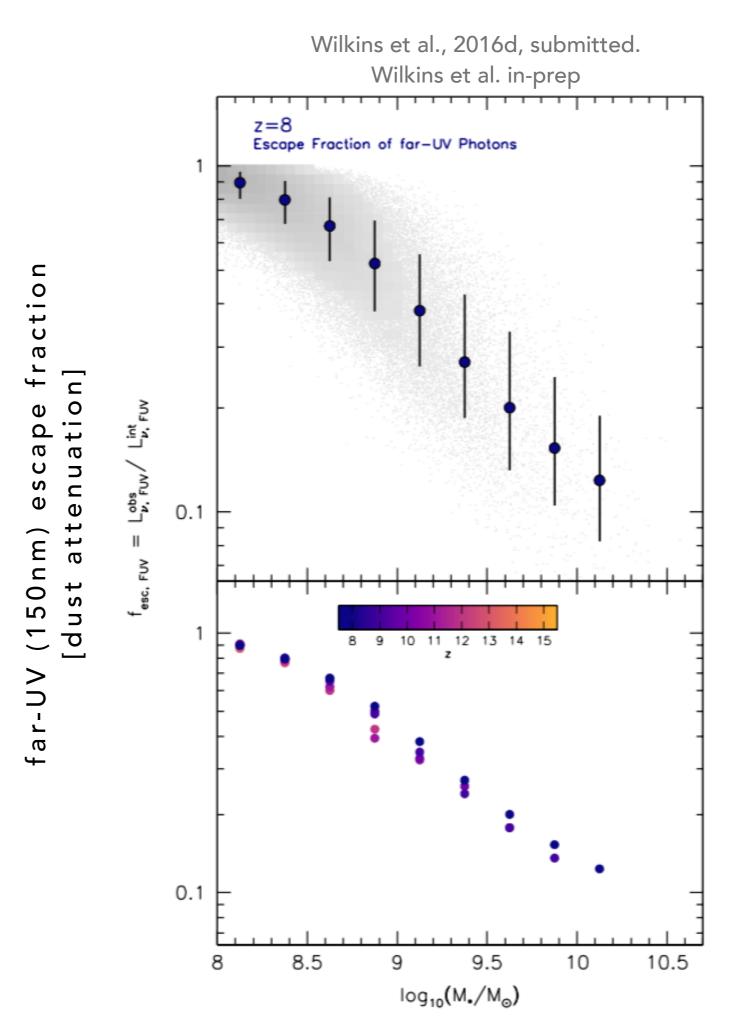


### BLUETIDES PHYSICAL PROPERTIES

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<sup>8</sup> M $\odot$ ) and the attenuation. Galaxies at M\*~10<sup>10</sup> M $\odot$  have a UV attenuation of A~2.5.



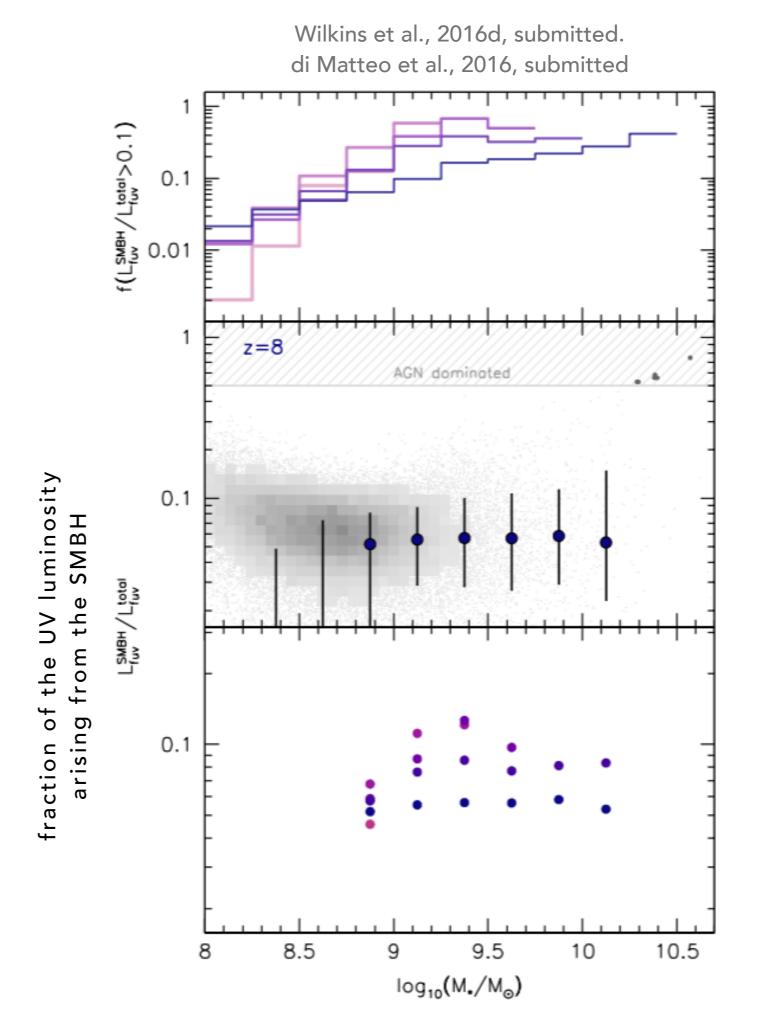
### BLUETIDES PHYSICAL PROPERTIES

Includes the growth of SMBHs

SMBHs at  $z\sim8$  contribute  $\sim5\%$  of the average far-UV luminosity.

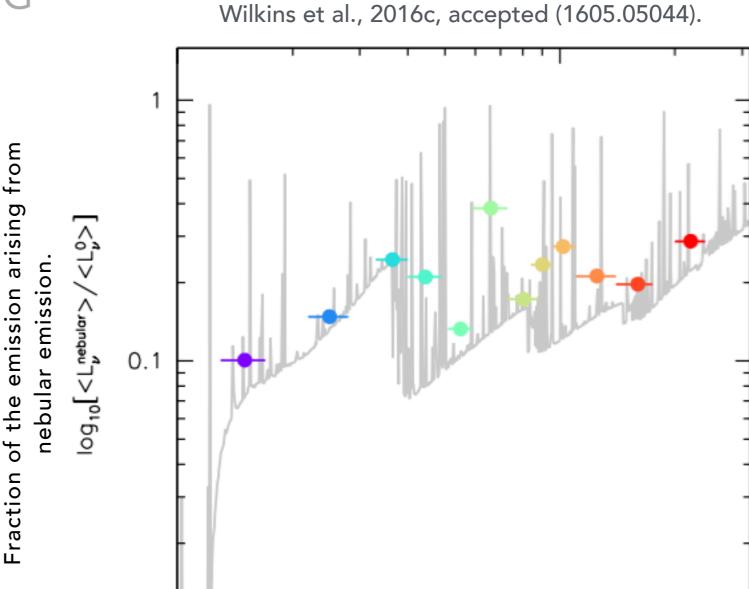
In the very most massive galaxies the SMBH dominates the far-UV luminosity.

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



#### 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 if the escape fraction is zero.



0.01

0.1

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

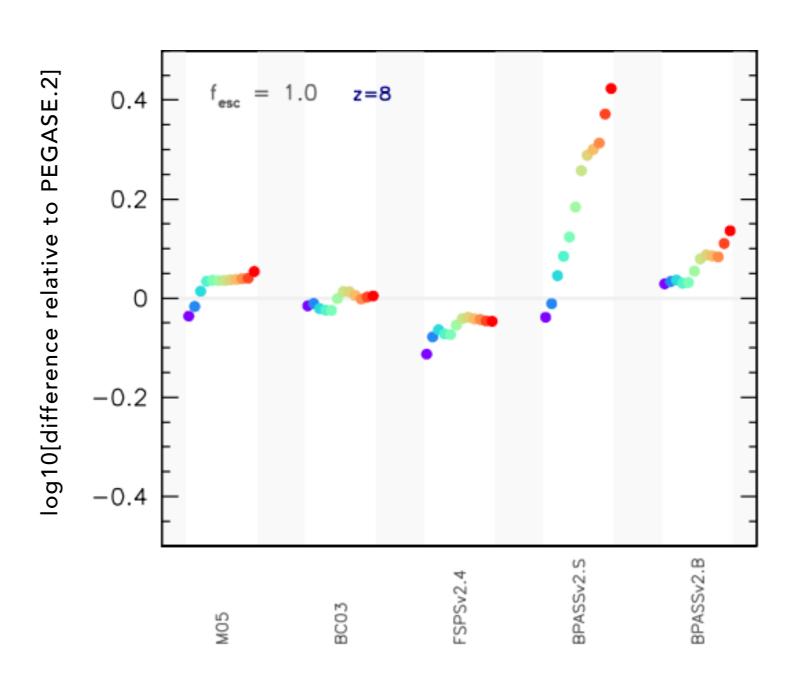
 $\lambda/\mu$ m

#### 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.

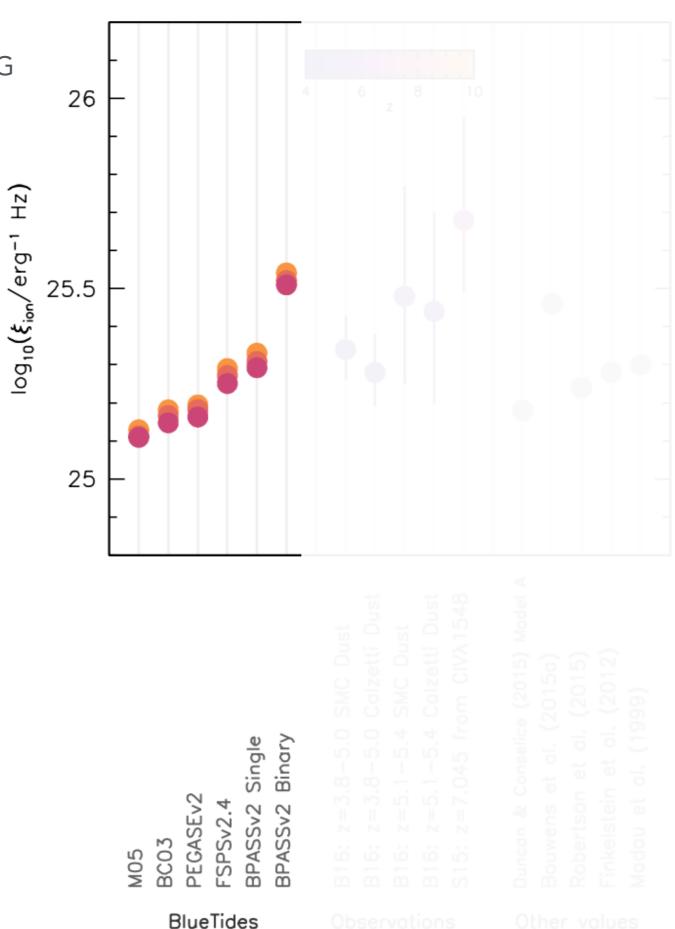
The ionising production efficiency links the observed UV luminosity to the number of ionising photons produced by a galaxy. This is a critical component in assessing whether star forming galaxies are capable of re-ionising the Universe.

$$\dot{n}_{
m ion} = f_{
m esc,LyC} \, \xi_{
m ion} \, rac{
ho_{
m uv}}{f_{
m esc,uv}}$$

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.

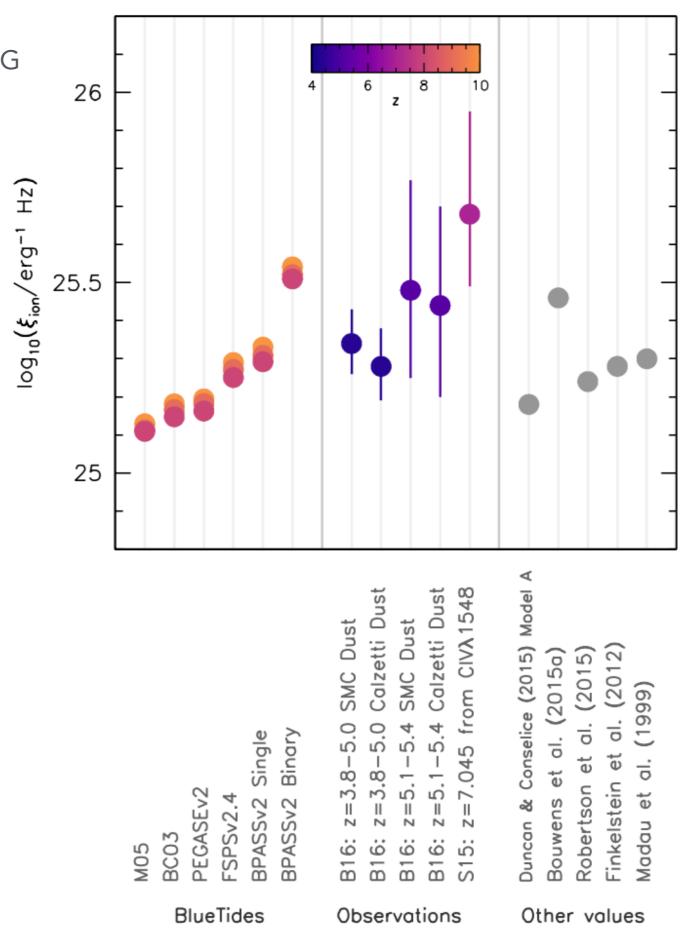
## S E D MODELLING SPS MODEL AND IONISING PHOTON PRODUCTION EFFICIENCY.

- The production efficiency varies by a factor of ~2.5 between different SPS models.
- The production efficiency evolves with redshift, although slowly.



# SED MODELLING SPS MODEL AND IONISING PHOTON PRODUCTION EFFICIENCY.

- The ionising photon production efficiency can be observationally constrained from emission line measurements.
- 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.



#### S E D M O D E L L I N G

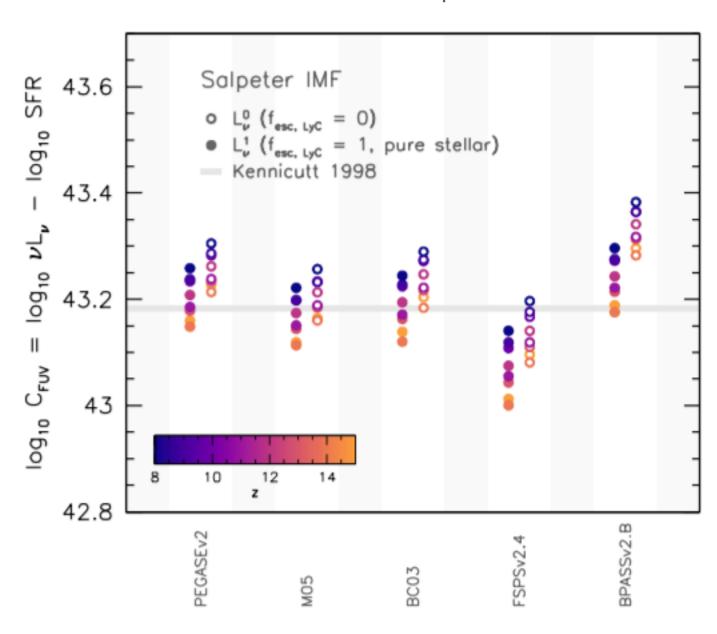
#### STAR FORMATION INDICATORS

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.

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

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



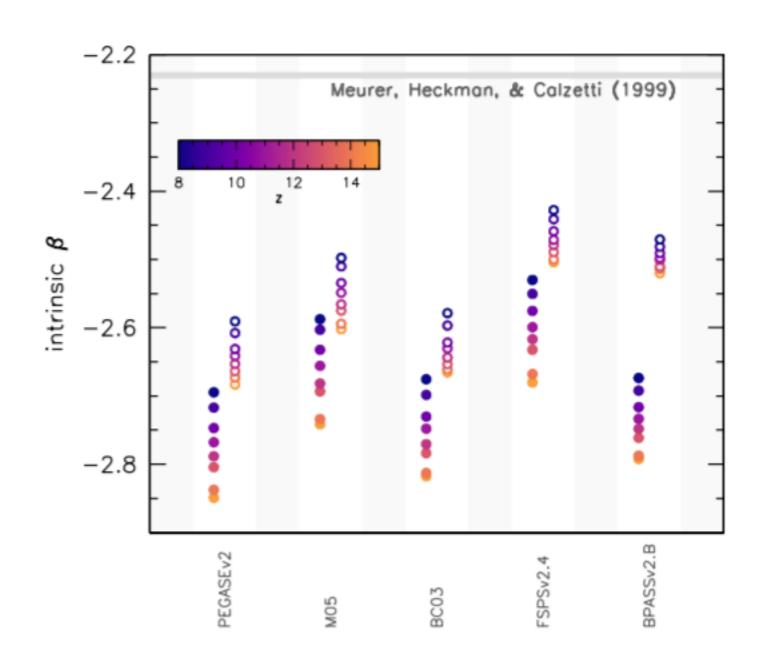
#### SED MODELLING UV CONTINUUM SLOPE

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.

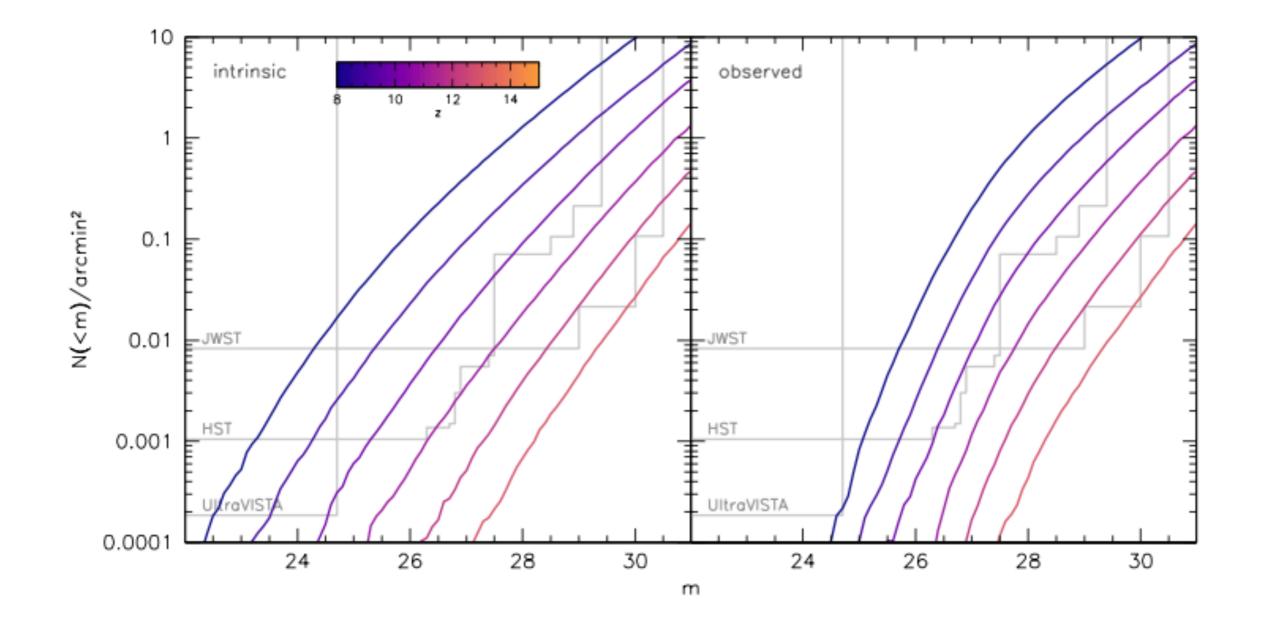
$$A_{\lambda} = \frac{\mathrm{d}\beta}{\mathrm{d}A_{\lambda}} (\beta_{\mathrm{obs}} - \beta_{\mathrm{int}})$$

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



## PREDICTIONS FOR JWST SURFACE DENSITIES

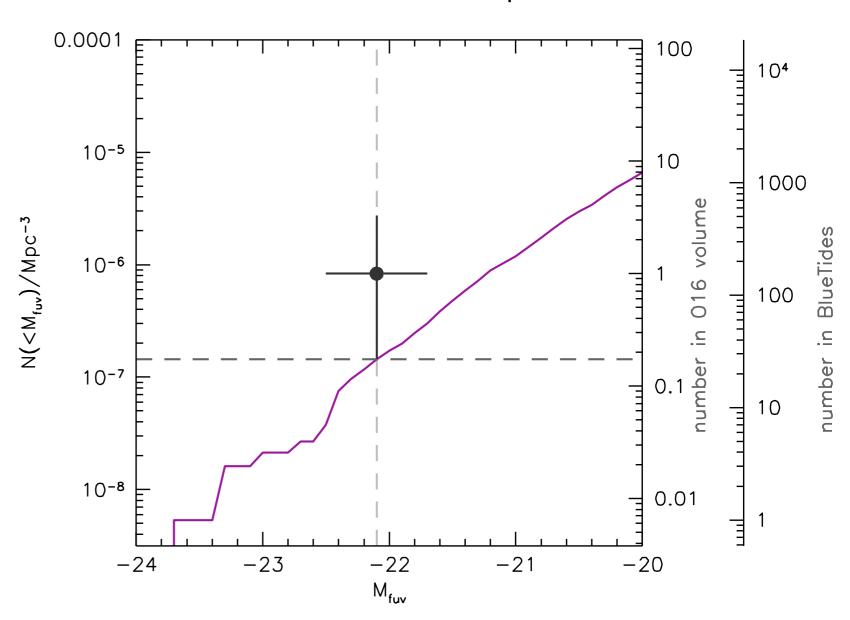
We can predict the surface density of sources across a wide redshift and luminosity range.



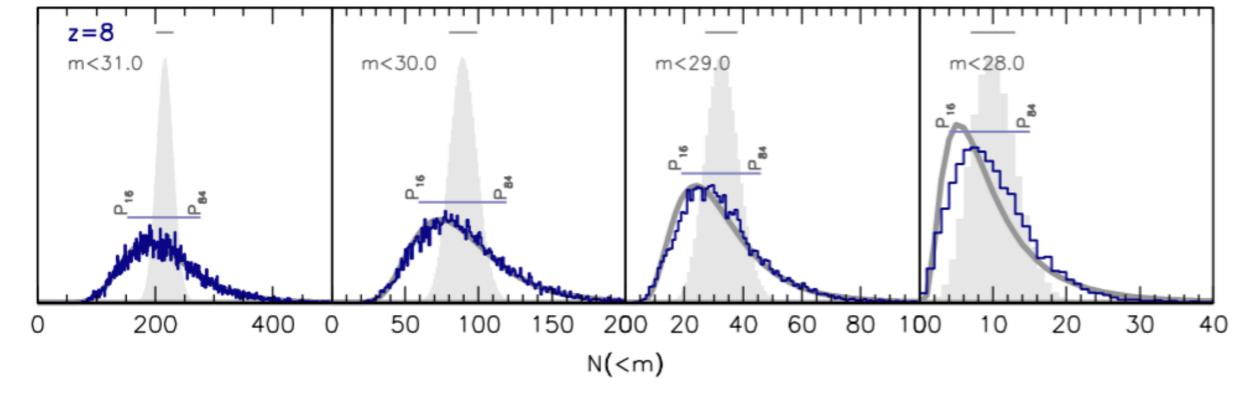
#### B L U E T I D E S M O N S T E R S

The predicted surface density of sources is consistent with the discovery of a bright galaxy at z~11 by Oesch et al. (2016).

#### Waters et al. 2016a, accepted



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

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	<b>26</b>	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

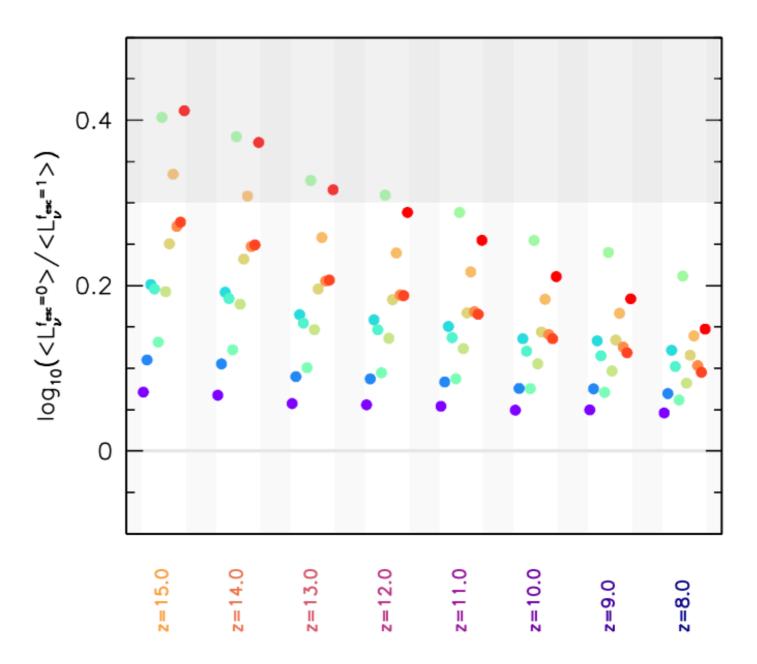
#### CONCLUSIONS

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  $z\sim8-10$  though relatively few at  $z\sim12$  and above.

#### S E D M O D E L L I N G N E B U L A R E M I S S I O N

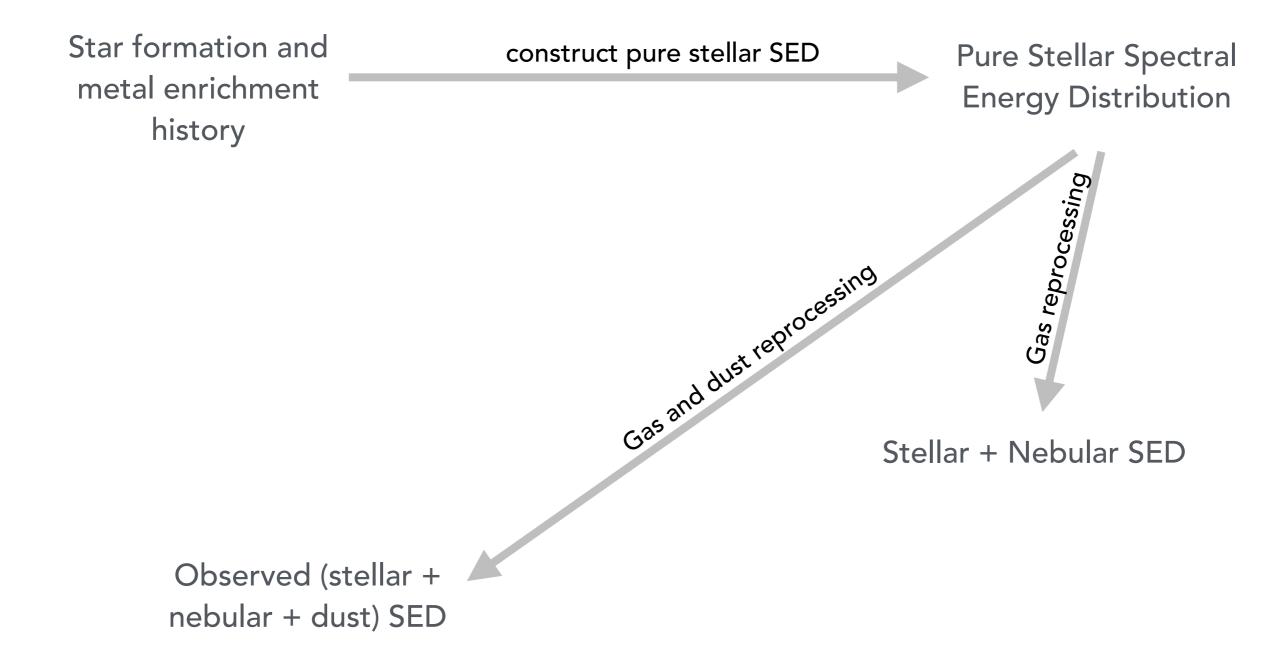
The contribution of nebular emission **increases** to higher-redshift.



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

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

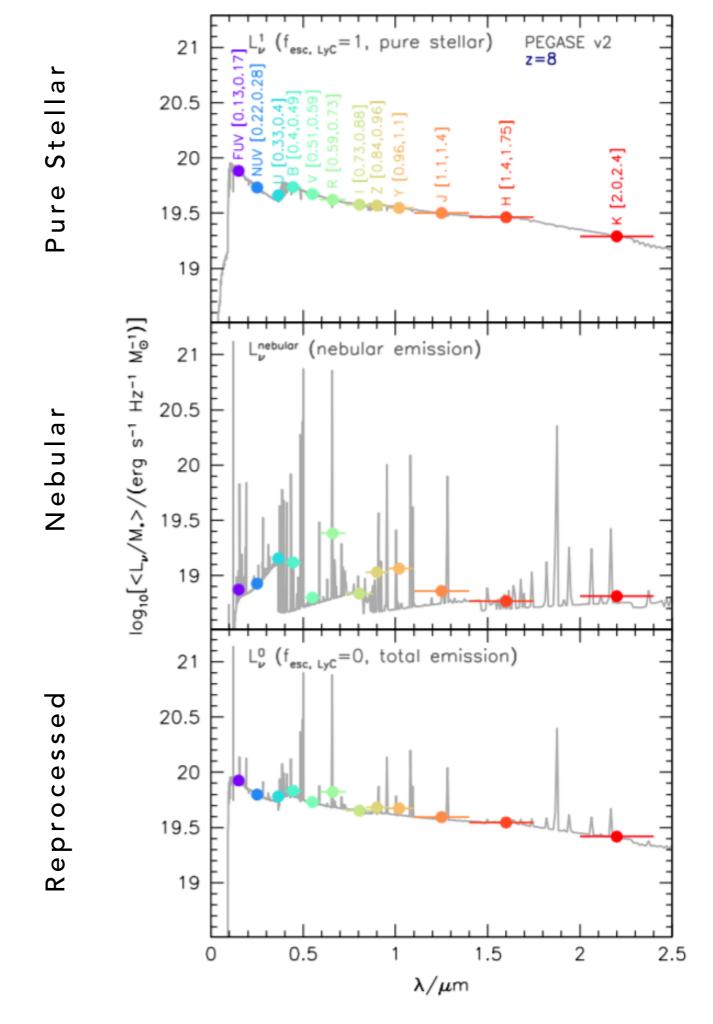
#### SED MODELLING



#### S E D M O D E L L I N G N E B U L A R E M I S S I O N

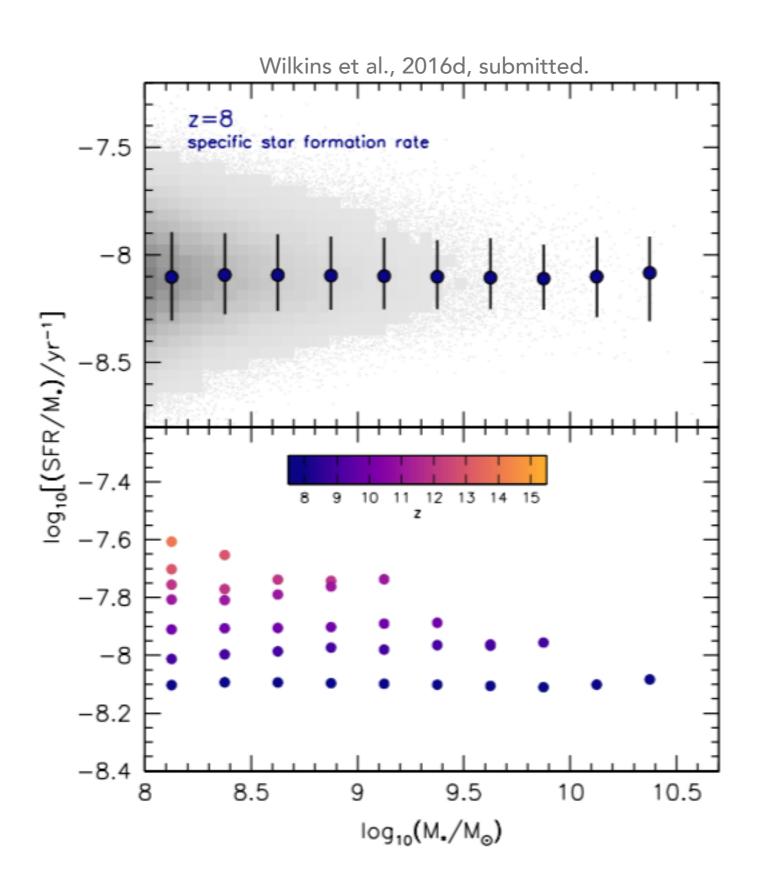
The simplest scenario is to utilise a photoionisation code (like CLOUDY) and assume a simple spherically symmetric density and gas-phase metallicity equal to calculate the nebular emission from each star particle.

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



#### B L U E T I D E S 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.



#### B L U E T I D E S 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.

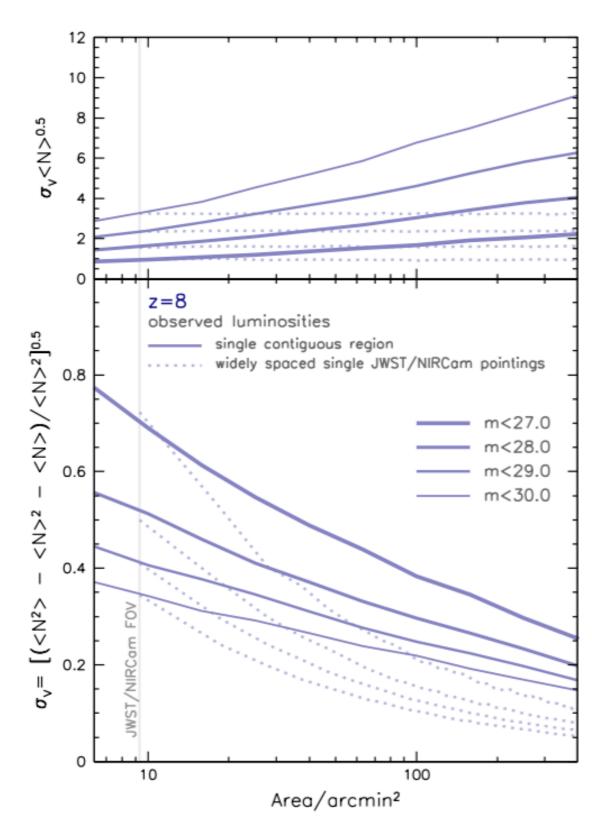
**Predictions for JWST** 

## 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.



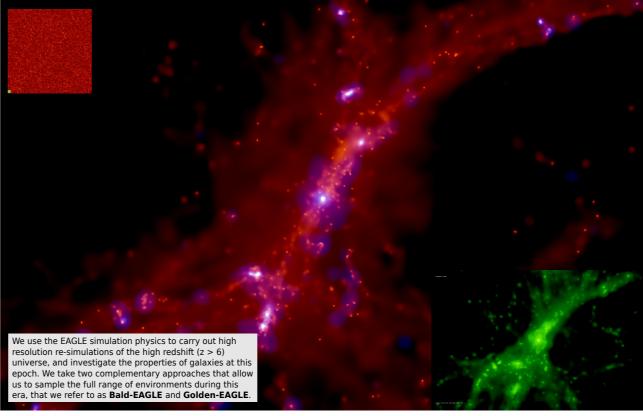
#### Re-simulations of the high redshift Universe

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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  $(\pm 2\sigma, \pm 1\sigma, \mu)$ at z ~ 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

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

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 ~ 6 with a mass of 5 x 105 Mo., 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.

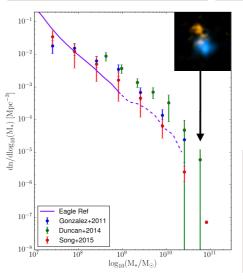
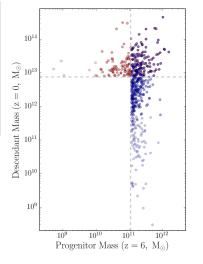


Figure 1 The Galaxy Stellar Mass Function in EAGLE plotted against observational results from Gonzalez 2011, Duncan 2014 & Song 2015. Where there are less than 100 galaxies in a given bin, the mass function is plotted as a dashed line. The black arrow indicates the approximate mass of HFLS3 ( $\sim 5 \times 10^{10} \, \mathrm{M}_{\odot}$ ) 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

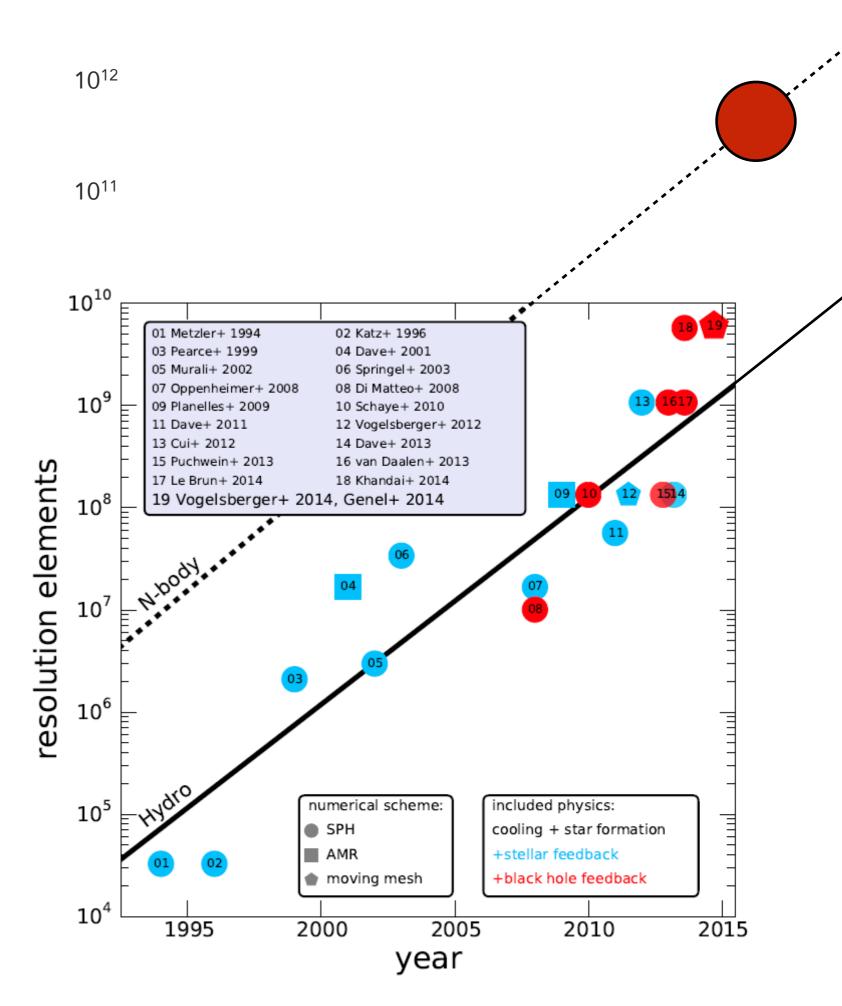
Figure 2 The most massive subhalos at both z = 0 and z = 6 from the EAGLE reference simulation (100cMpc) are matched with their most massive progenitors / descendants on the merger tree, respectively. For the top subhalos at z = 0, there is a spread over four orders of magnitude in their progenitor masses.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



References 1. Cooray, A. et al. Apj 790, 40 (2014). 2. Gonzalez, V. et al. Apj 735, L34 (2011). 3. Duncan, K. et al. MNRAS 444, 2960-2984 (2014). 4. Song, M. et al. [astro-ph] (2015). 5. Schaye, J. et al. MNRAS 446, 521-554 (2014). 6. Crain, R. A. et al. MNRAS 450, 1937-1961 (2015).

#### B L U E T I D E S S I M U L A T I O N

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



#### 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

#### S E D M O D E L L I N G

Star formation and metal enrichment history

construct pure stellar SED

Choice of SPS model and IMF

Pure Stellar Spectral Energy Distribution

Choice of models (could attenuation curve)

Choice attenuation curve

Stellar + Nebular SED

Observed (stellar + nebular + dust) SED