INSIGHTS FOR THE EPOCH OF REIONISATION FROM LOW-REDSHIFT **EXTREME EMISSION LINE SOURCES**

UNIVERSITY OF SUSSEX

STEPHEN M. WILKINS

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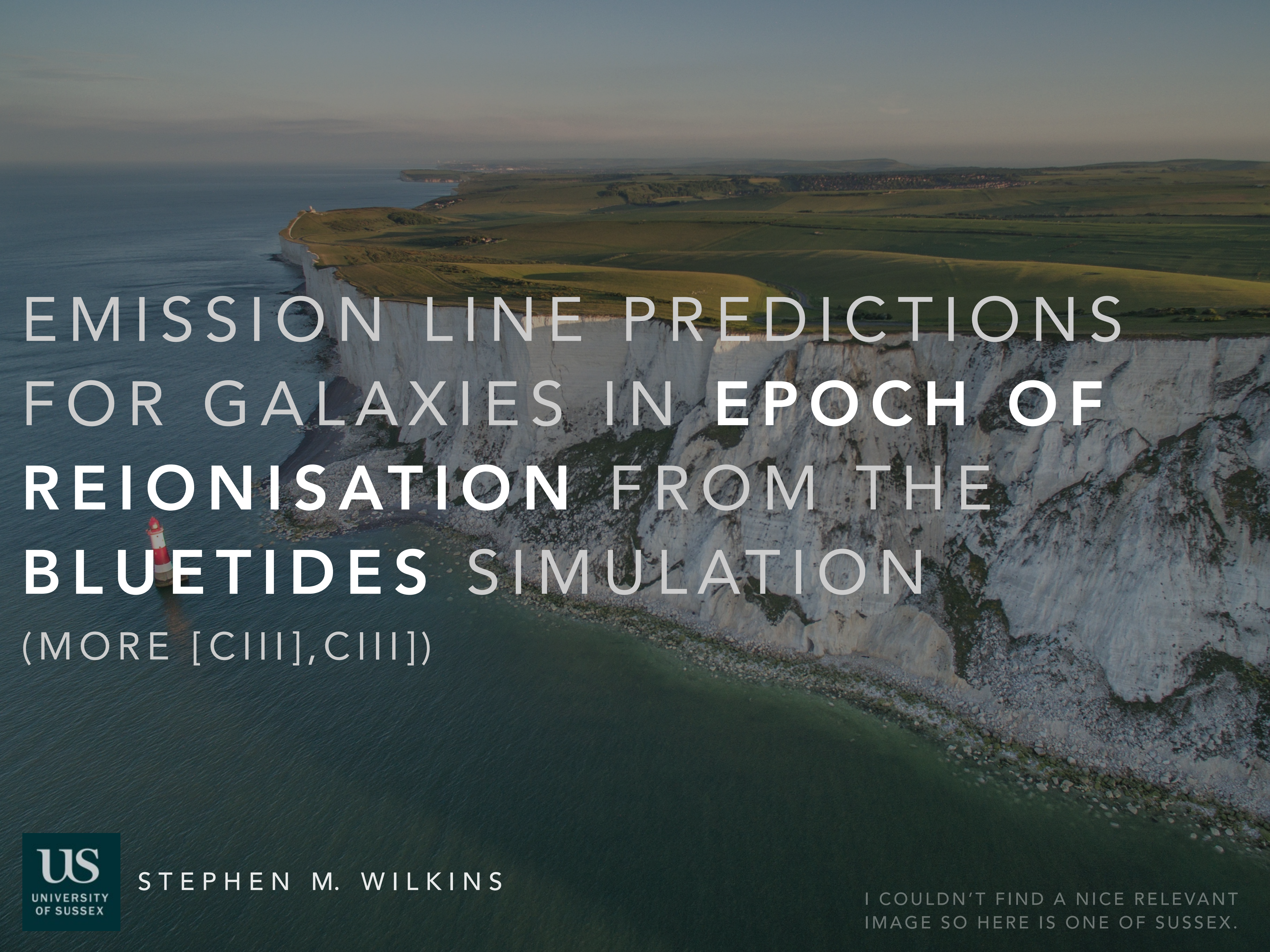

EMISSION LINE PREDICTIONS FOR GALAXIES IN **EPOCH OF REIONISATION** FROM THE **BLUETIDES** SIMULATION

(MORE [CIII],CIII])

UNIVERSITY OF SUSSEX

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THIS TALK

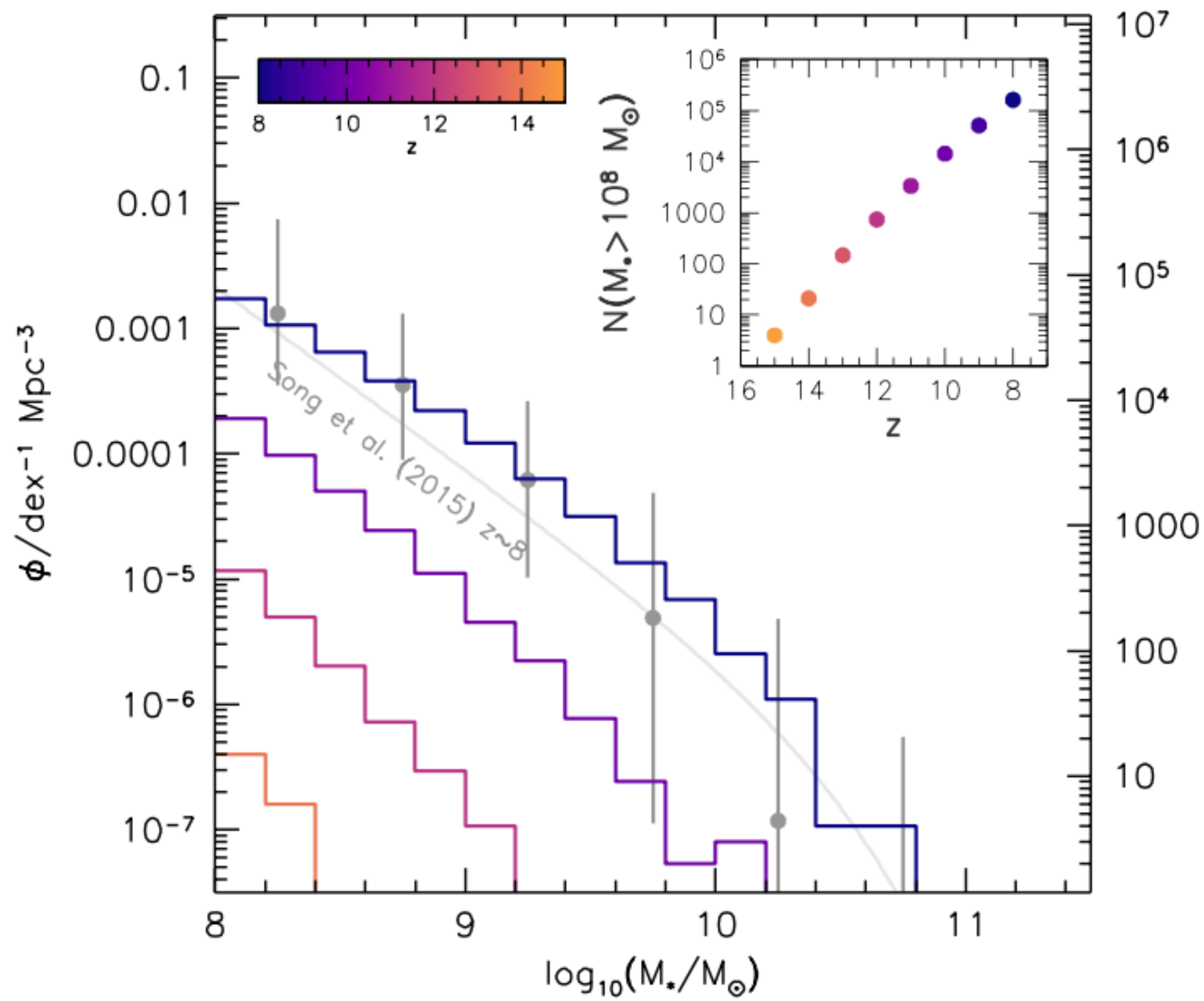
- INTRODUCTION TO **BLUETIDES**
- PREDICTIONS:
  - DUST-OBSCURED STAR FORMATION.
  - NEBULAR **[CIII],CIII] EMISSION**
- WHAT CAN WE LEARN FROM THE REST-FRAME UV?

BLUETIDES: THE SIMULATION

- IT SIMULATES DOWN TO Z=8 (PHASE I, COMPLETED) AND Z=6 (PHASE II, ONGOING)
- SIMULATES A VOLUME **~577³ MPC³**
- 2 × 7040³ ~ **0.7 TRILLION PARTICLES**
- MASS/SPATIAL RESOLUTION IS SLIGHTLY WORSE THAN EAGLE AND ILLUSTRIS

NUMBER OF GALAXIES IN EACH MASS BIN IN **BLUETIDES**

WILKINS ET AL., 2017A



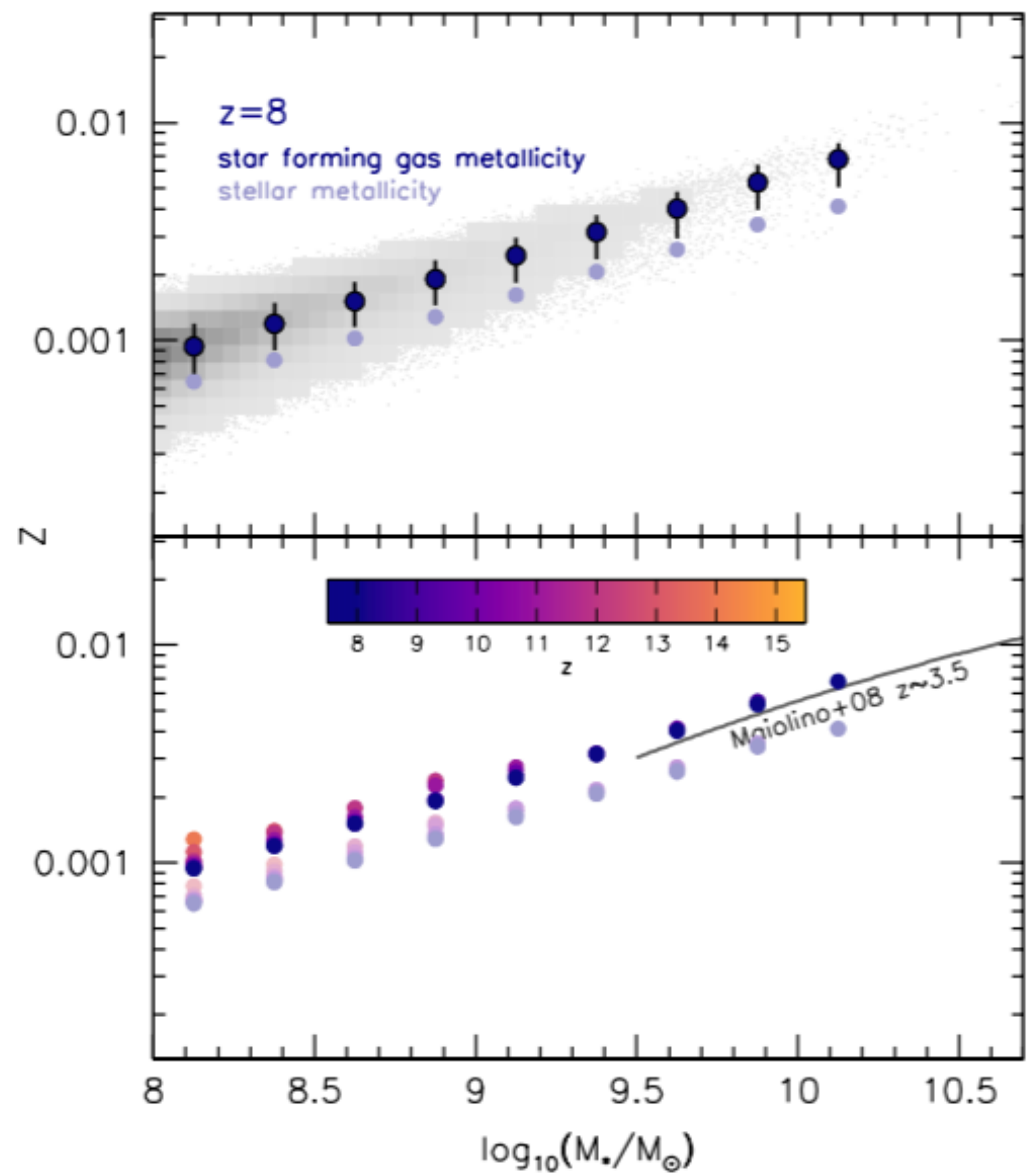
Feng et al. 2015, 2016; Wilkins et al. 2016bc, 2017ab; Waters et al. 2016ab; di Matteo et al. 2017

BLUETIDES: MASS-METALLICITY RELATION

THERE IS A **STRONG MASS-METALLICITY** RELATION IN PLACE.

APPROACHING **~50% SOLAR AT 10^{10} $M_\odot$**. OVERLAPS OBSERVATIONAL CONSTRAINTS AT Z~3.5.

WILKINS ET AL., 2017A

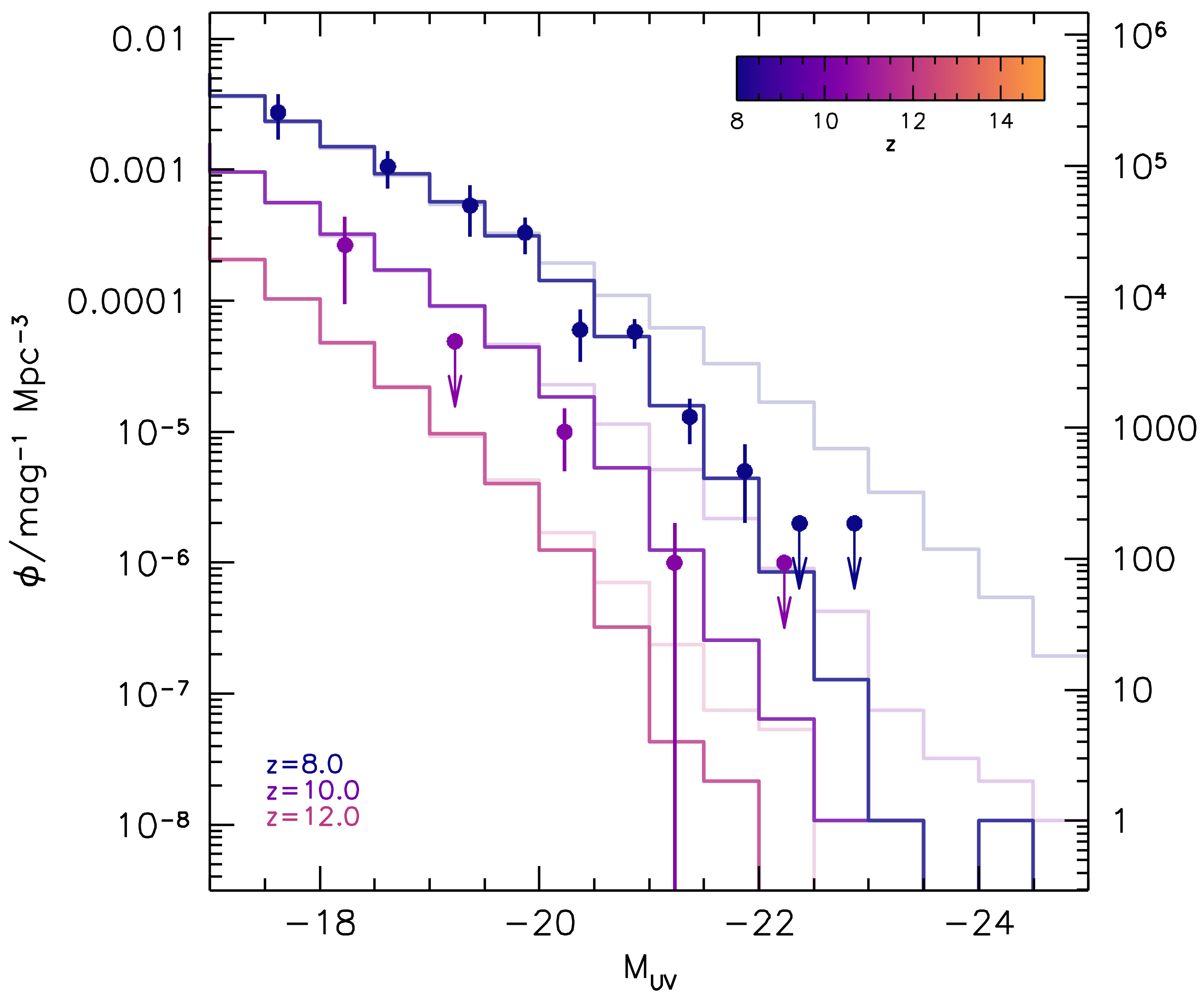


BLUETIDES: **DUST MODEL**

TO MODEL THE DUST ATTENUATION WE CALCULATE **THE LINE OF SIGHT SURFACE DENSITY OF METALS TO EACH STAR PARTICLE** AND ASSUME THAT IS PROPORTIONAL TO THE DUST OPTICAL DEPTH.

WE THEN **TUNE** THE PROPORTIONALITY CONSTANT TO RECOVER THE OBSERVED UV LUMINOSITY FUNCTION.

WILKINS ET AL., 2017A



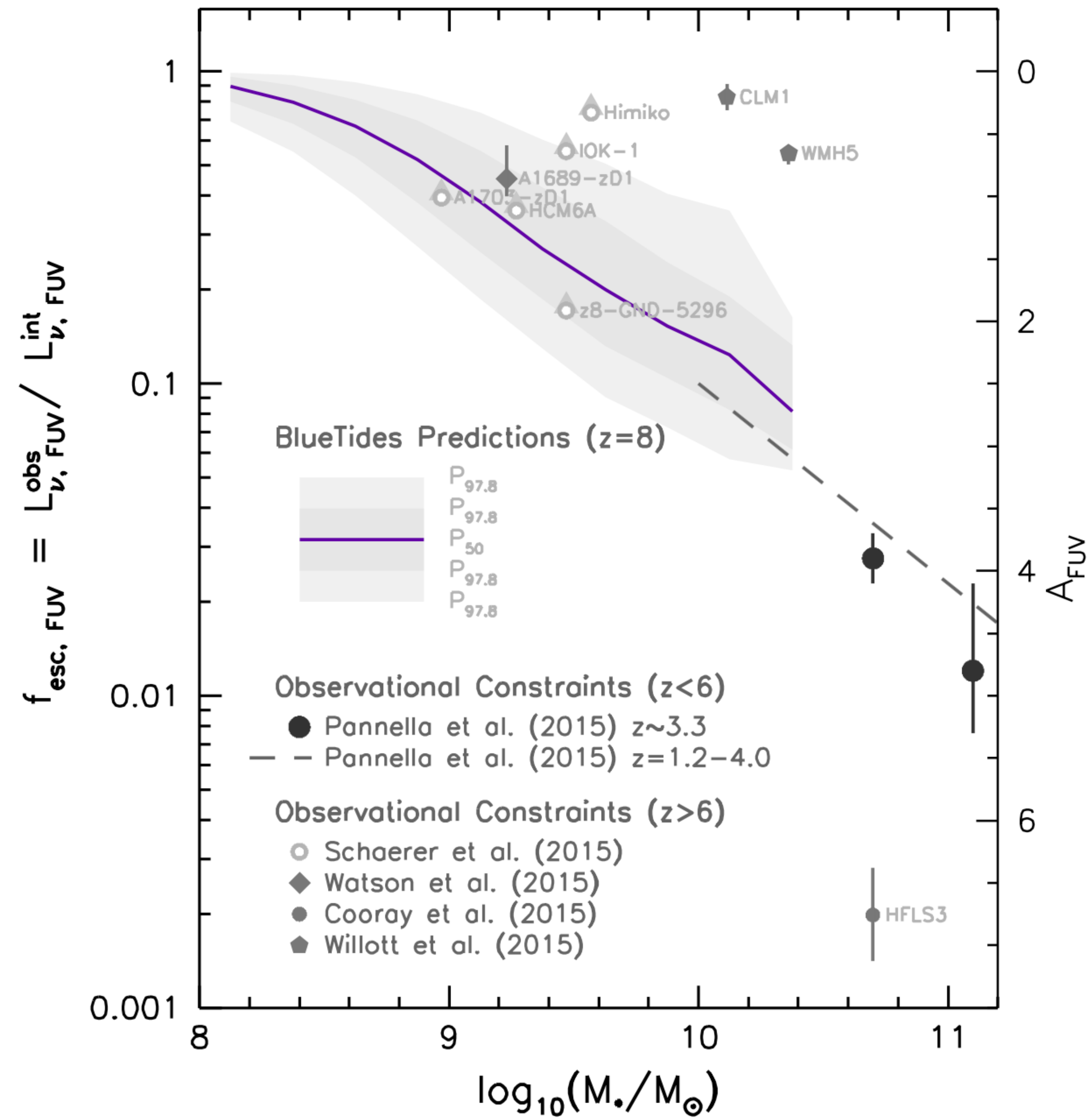
THIS IS SIMILAR TO ROMEEL DAVE'S CLOSER CODE.

BLUETIDES: DUST ATTENUATION

ESCAPE FRACTION OF FAR-UV PHOTONS (NOT LYC)

THERE IS A STRONG **CORRELATION BETWEEN STELLAR-MASS (M*>10⁸ M⊙) AND DUST ATTENUATION ATTENUATION**.

GALAXIES AT M*~10¹⁰ M⊙ ARE PREDICTED TO HAVE UV ATTENUATION OF A~2.5.

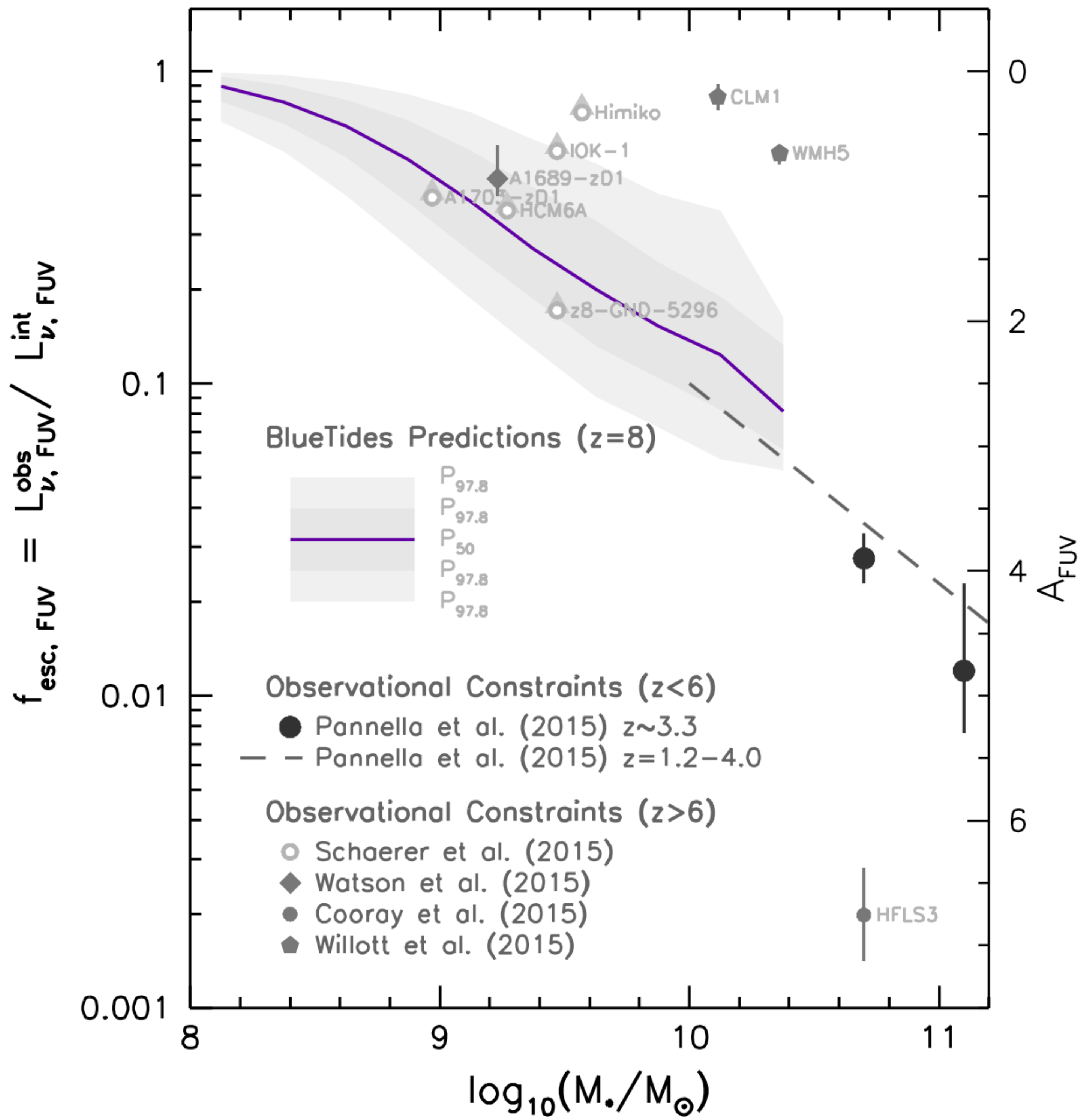


BLUETIDES: DUST ATTENUATION

ESCAPE FRACTION OF FAR-UV PHOTONS (NOT LYC)

THERE APPEARS TO BE **SOME TENSION** HERE. THIS COULD BE:

- THE SIMULATION IS WRONG.
- OBSERVATIONAL ESTIMATES ARE BASED ON INCORRECT ASSUMPTIONS.



BLUETIDES: **EMISSION LINE PREDICTIONS**

WE CAN MODEL THE NEBULAR EMISSION FROM EACH GALAXY IN THE SIMULATION BY **ASSIGNING AN INTRINSIC STELLAR SED** TO EACH STAR PARTICLE (BASED ON ITS AGE AND METALLICITY) AND **PASSING THAT SED THROUGH A PHOTOIONISATION CODE**.

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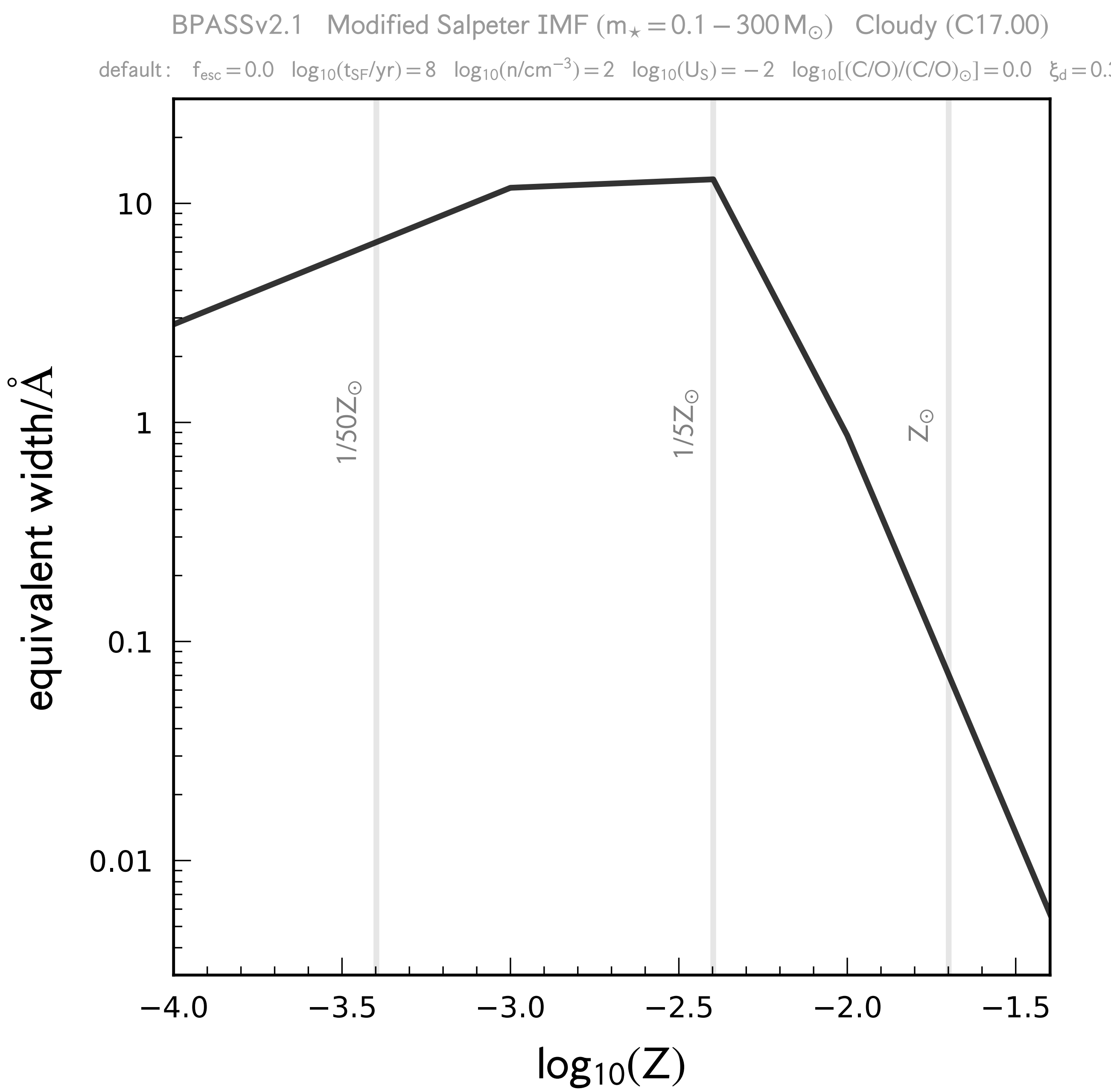
I'LL CONCENTRATE ON THE [CIII],CIII] LINE AT 1908.

- TYPICALLY SECOND BRIGHTEST LINE IN THE UV .
- CURRENTLY OBSERVABLE (AND OBSERVED, E.G. STARK ET AL. 2015,2017) AT HIGH-REDSHIFT (Z~6) AND ACCESSIBLE TO VERY-HIGH (Z>10) REDSHIFT WITH JWST.
- SENSITIVE TO THE METALLICITY.

UV DIAGNOSTICS: [CIII],CIII] EQUIVALENT WIDTH

DEPENDENCE ON METALLICITY

BASED ON BPASSV2.1 THE [CIII],CIII] EQUIVALENT WIDTH DECLINES AT > ~1/5 Z_{SOL} AND PLATEAUS BELOW.

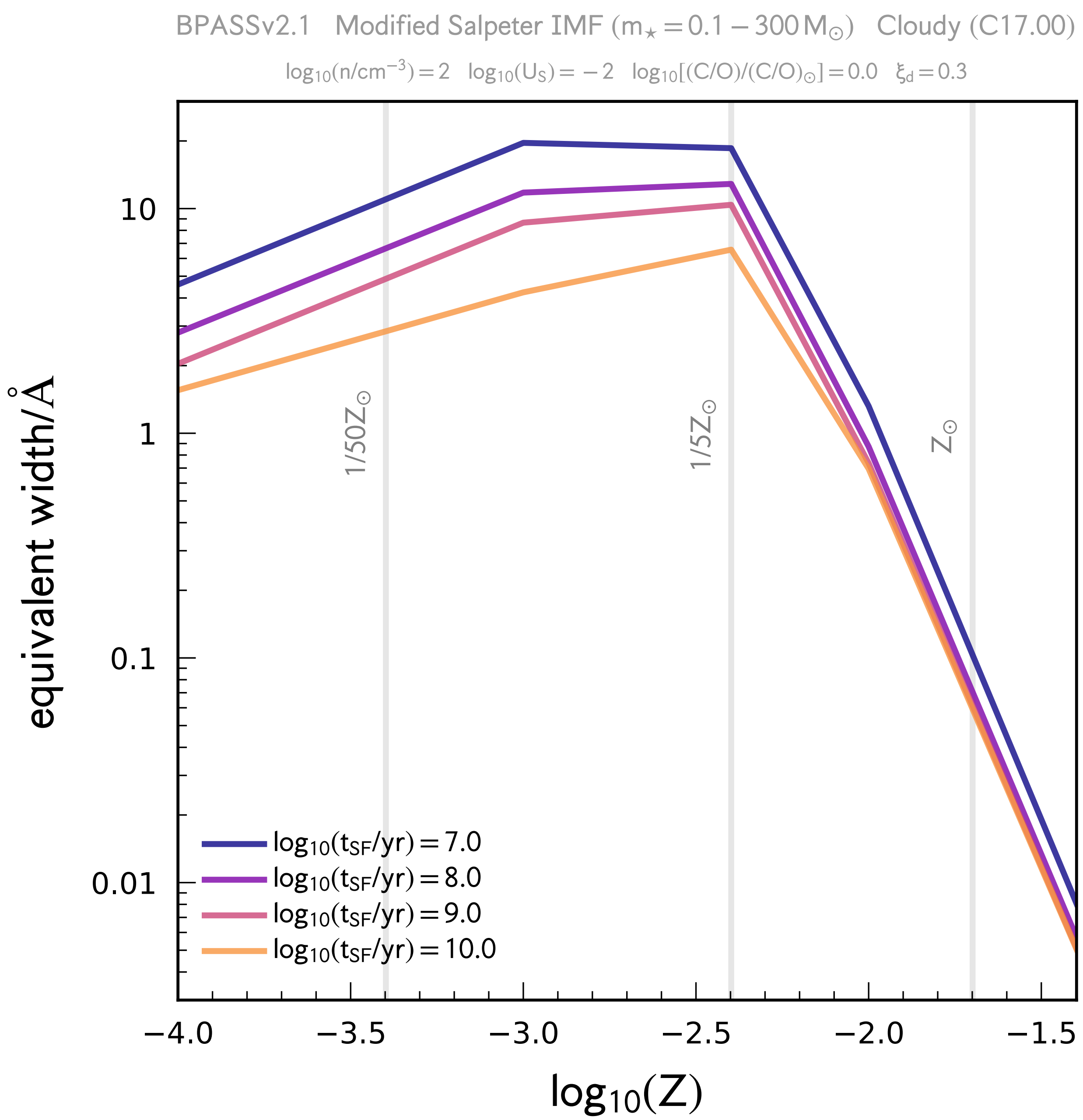


UV DIAGNOSTICS: [CIII],CIII] EQUIVALENT WIDTH

DEPENDENCE ON SFH

SENSITIVE TO THE THE STAR FORMATION HISTORY.

DURATION OF CONSTANT STAR FORMATION



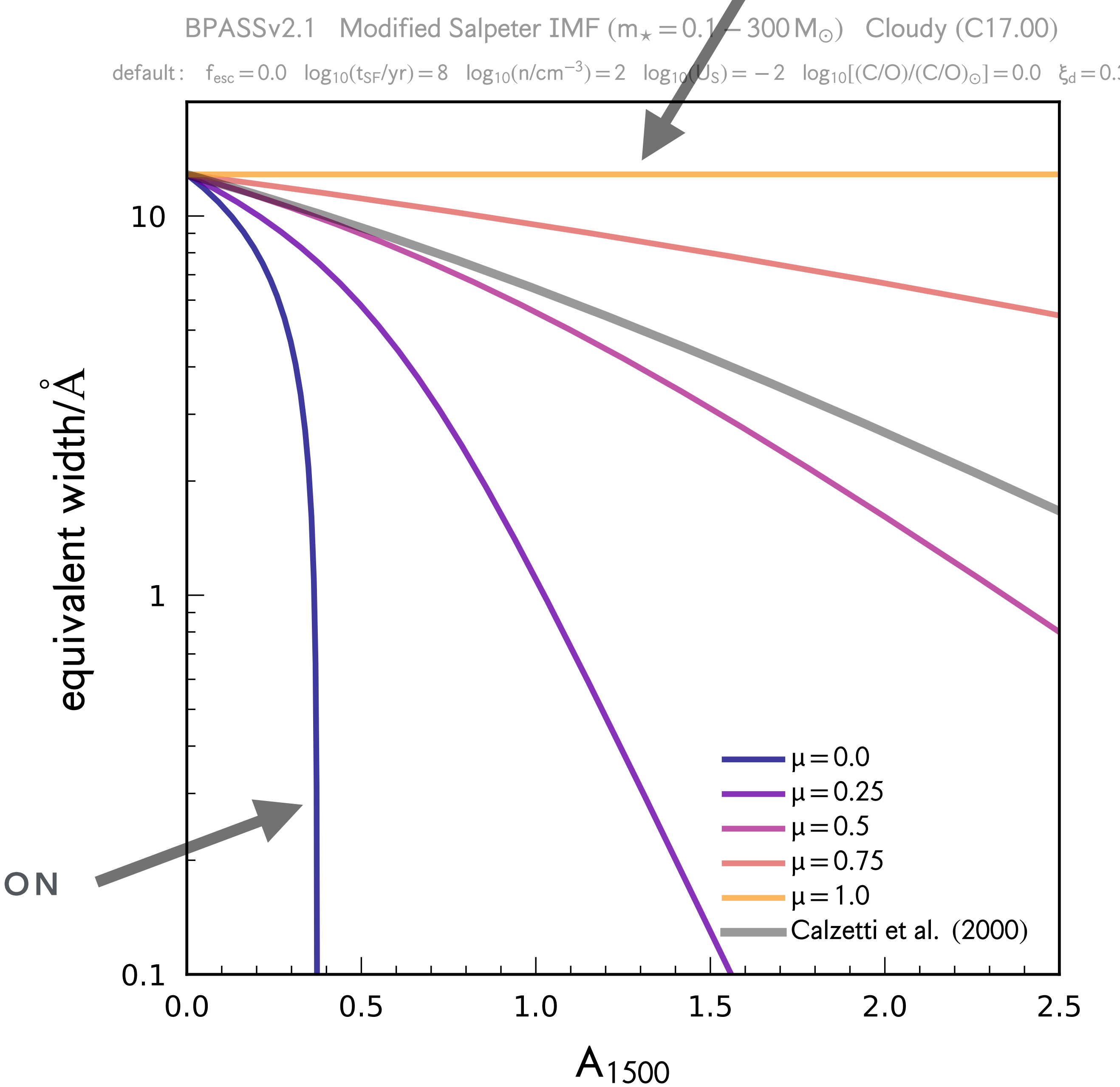
UV DIAGNOSTICS: [CIII],CIII] EQUIVALENT WIDTH

DEPENDENCE ON DUST

IF DUST AFFECTS NEBULAR EMISSION **MORE STRONGLY** THAN CONTINUUM EMISSION THE EQUIVALENT WIDTH WILL ALSO **BE SENSITIVE TO THE AMOUNT OF ATTENUATION**.

HERE WE ARE SHOWING PREDICTIONS USING THE CHARLOT & FALL (2000) MODEL FOR VARIOUS VALUES OF MU.

DUST AFFECTS ALL EMISSION UNIFORMLY



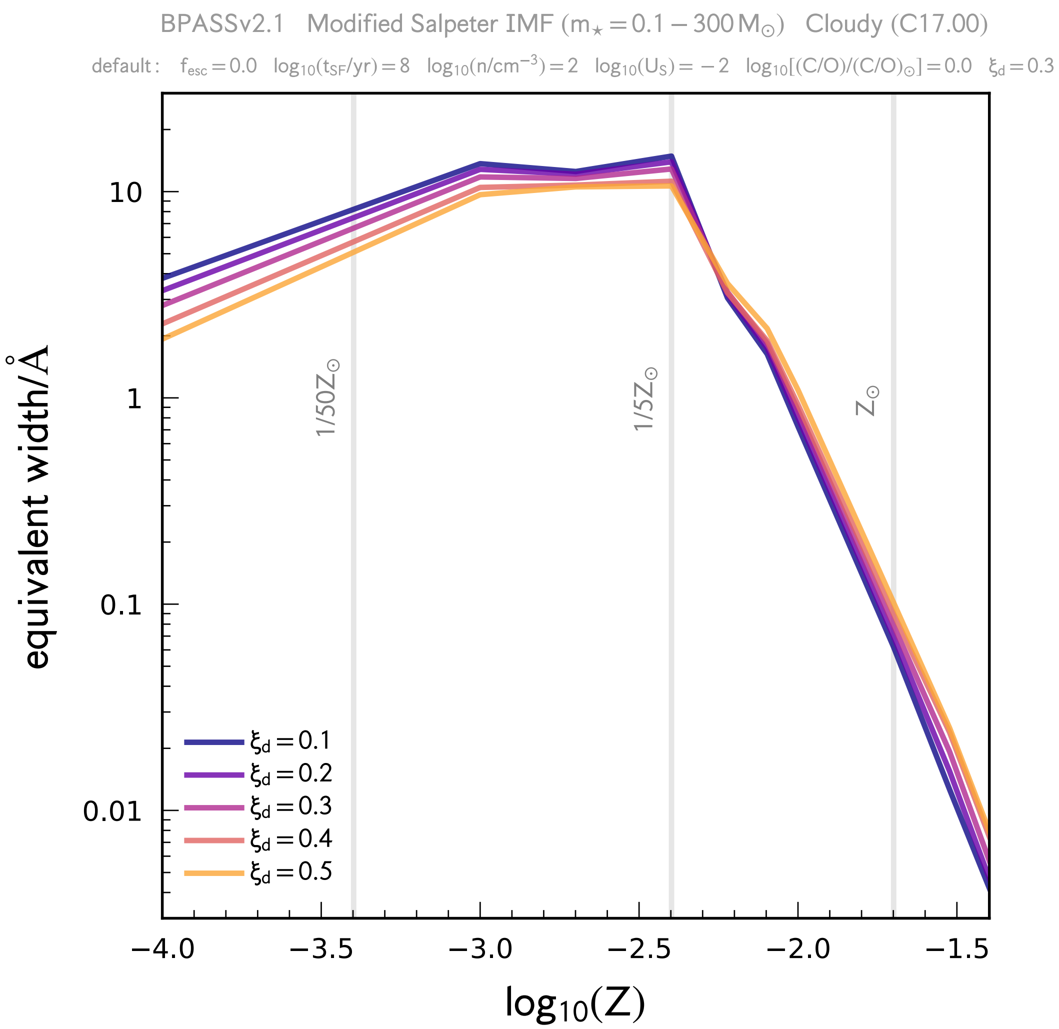
DUST ONLY AFFECTS EMISSION FROM YOUNG STARS

UV DIAGNOSTICS: [CIII],CIII] EQUIVALENT WIDTH

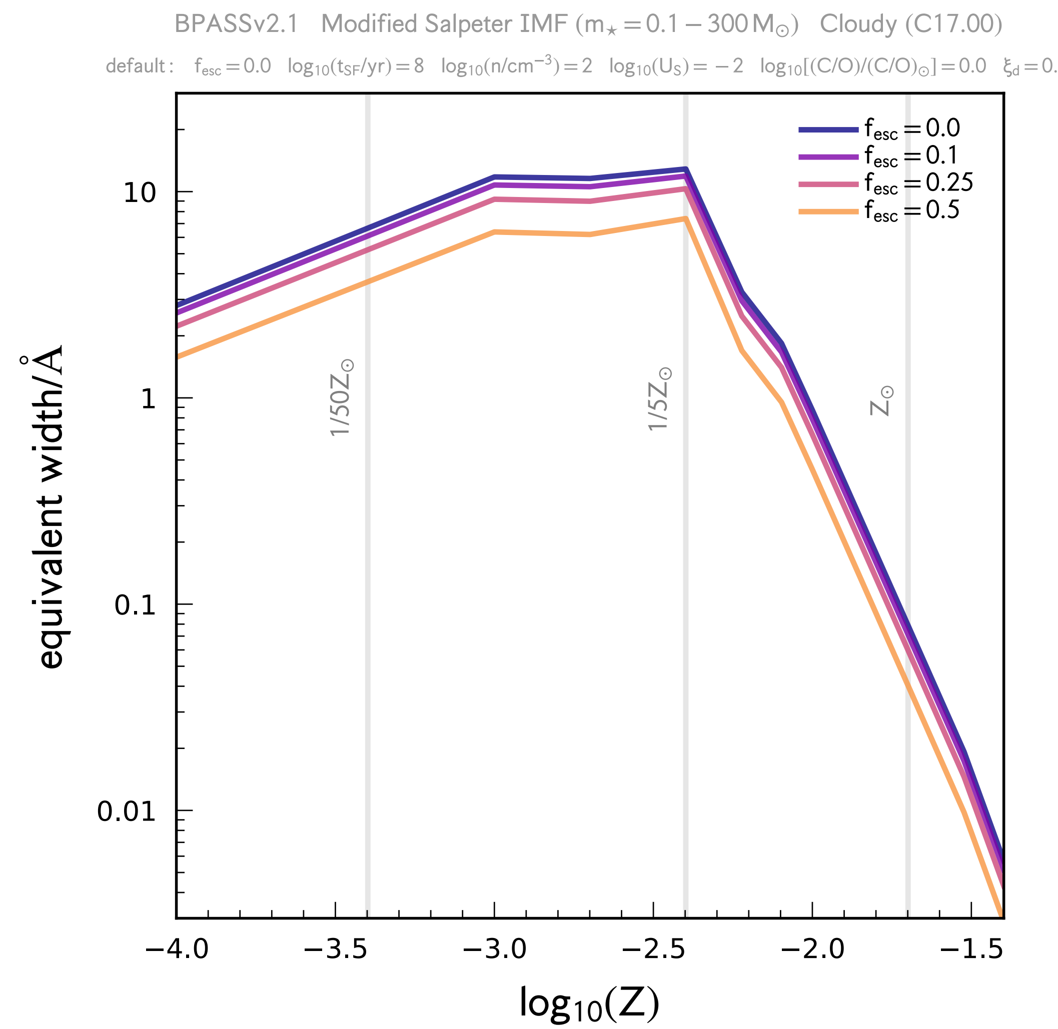
DEPENDENCE ON OTHER PHOTOIONISATION PARAMETERS

THE **[CIII],CIII]** LUMINOSITY IS ALSO SENSITIVE TO TO RANGE OF OTHER PARAMETERS WHICH ARE NOT PREDICTED BY THE SIMULATION.

DUST DEPLETION



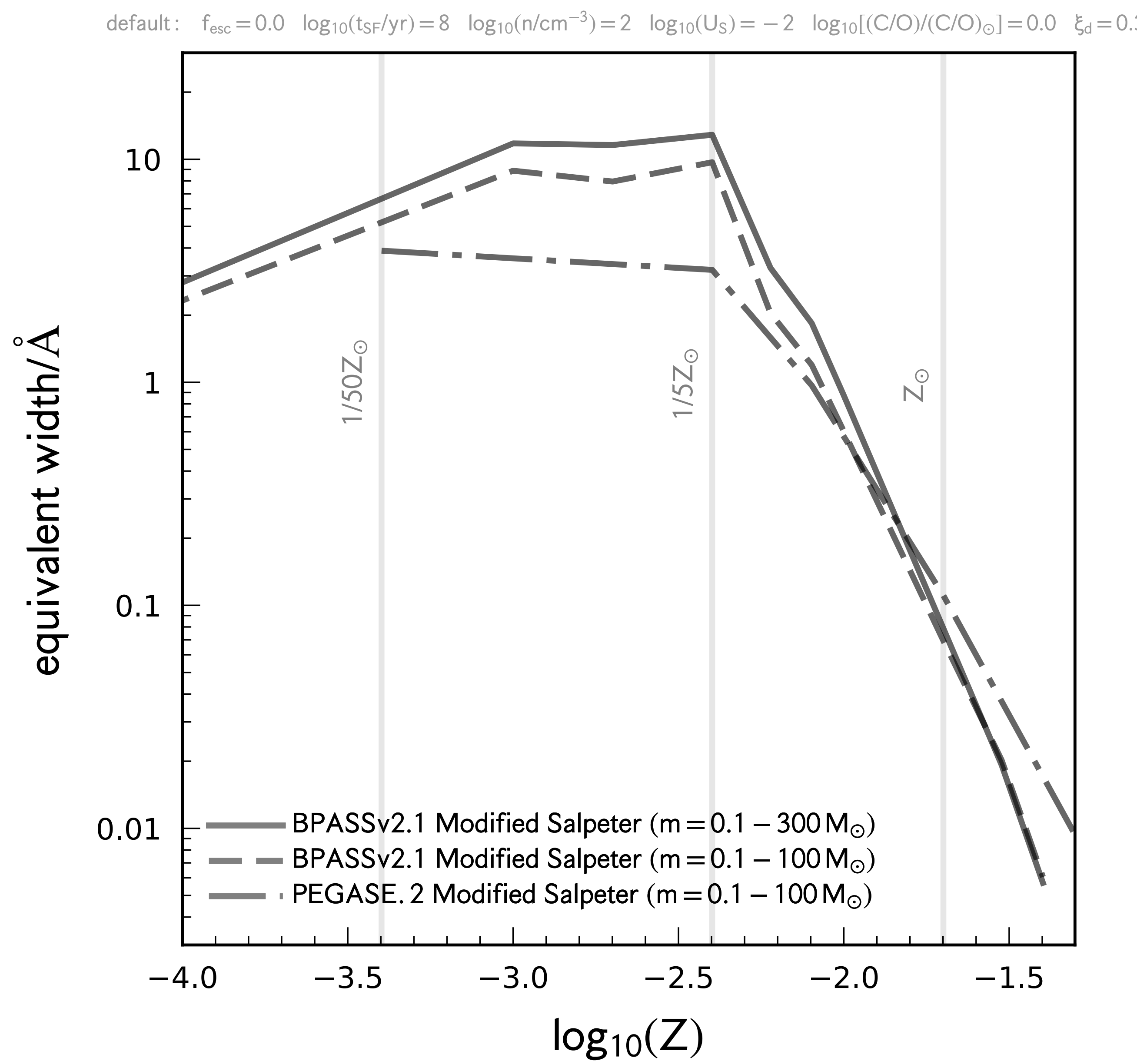
LYC ESCAPE FRACTION



UV DIAGNOSTICS: [CIII],CIII] EQUIVALENT WIDTH

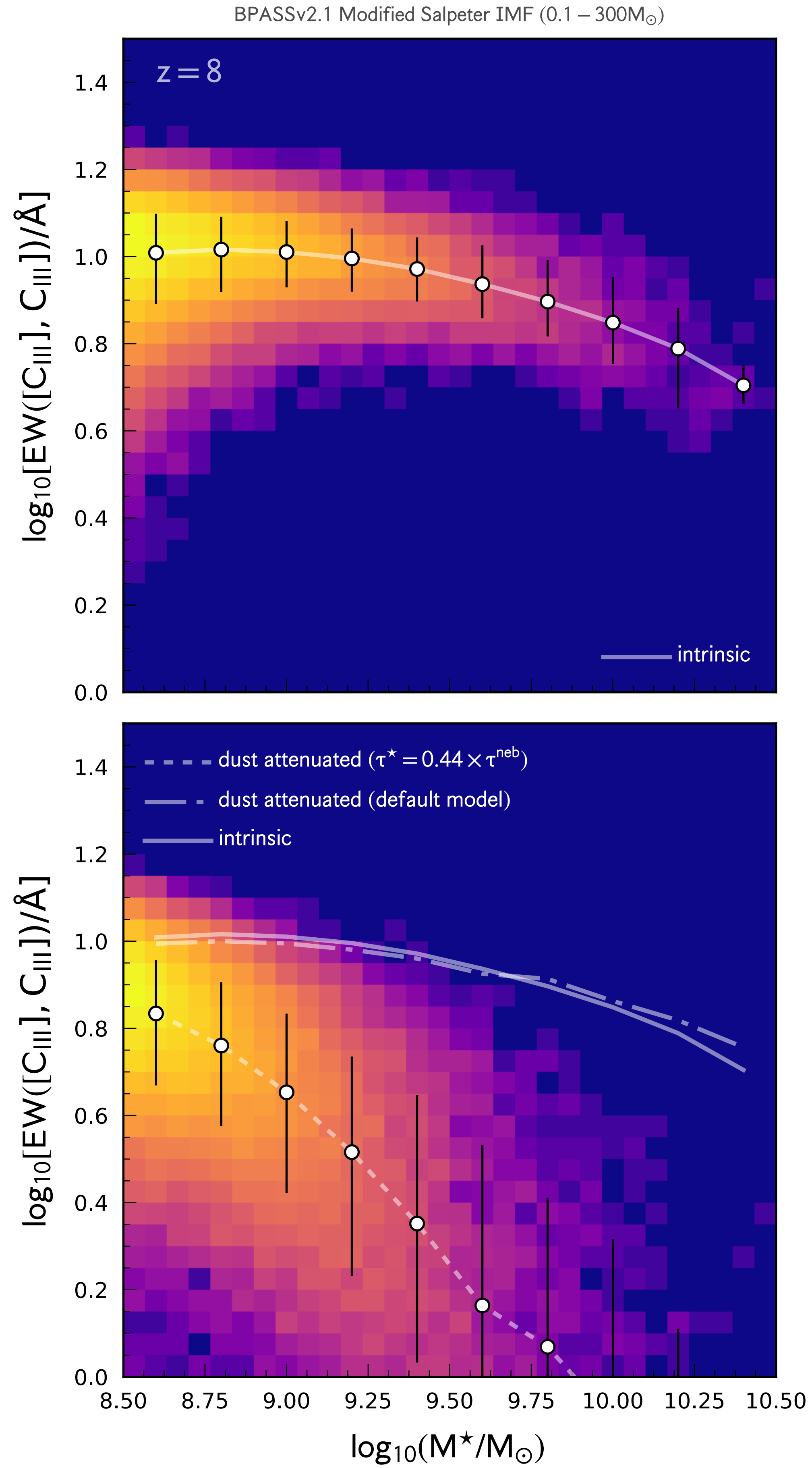
DEPENDENCE ON IONISING SOURCE (AND/OR SPS MODEL)

SENSITIVE TO THE CHOICE OF SPS MODEL AND IMF.



BLUETIDES: [CIII],CIII] EW DISTRIBUTION

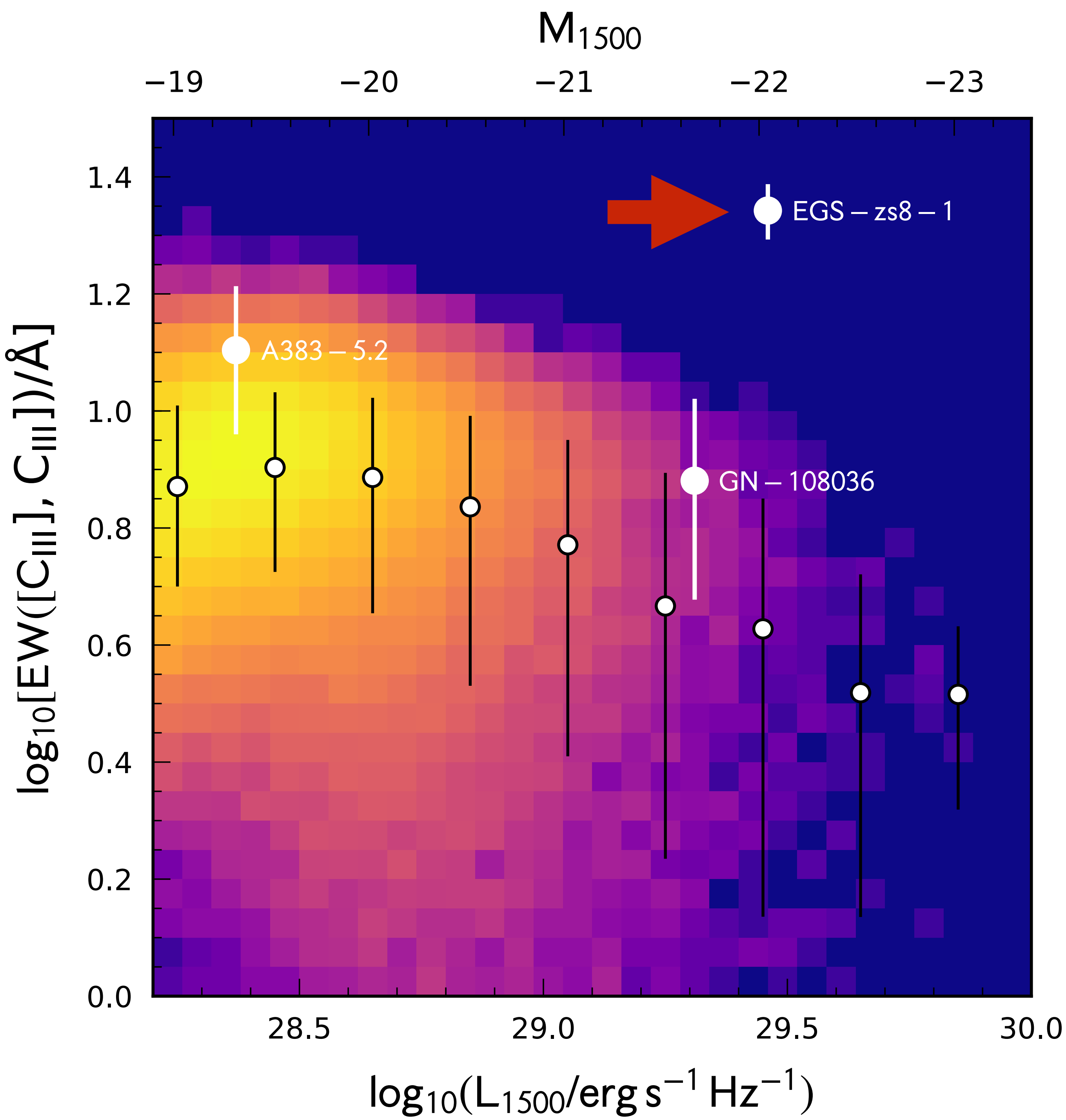
PREDICTED **INTRINSIC AND OBSERVED [CIII],CIII] EW DISTRIBUTION AS A FUNCTION OF STELLAR MASS.**



BLUETIDES: [C III], C III] EW DISTRIBUTION

IF INSTEAD WE COMPARE THE EW AGAINST OBSERVED UV LUMINOSITY **WE CAN MAKE A DIRECT COMPARISON WITH OBSERVATIONS AT Z>6.**

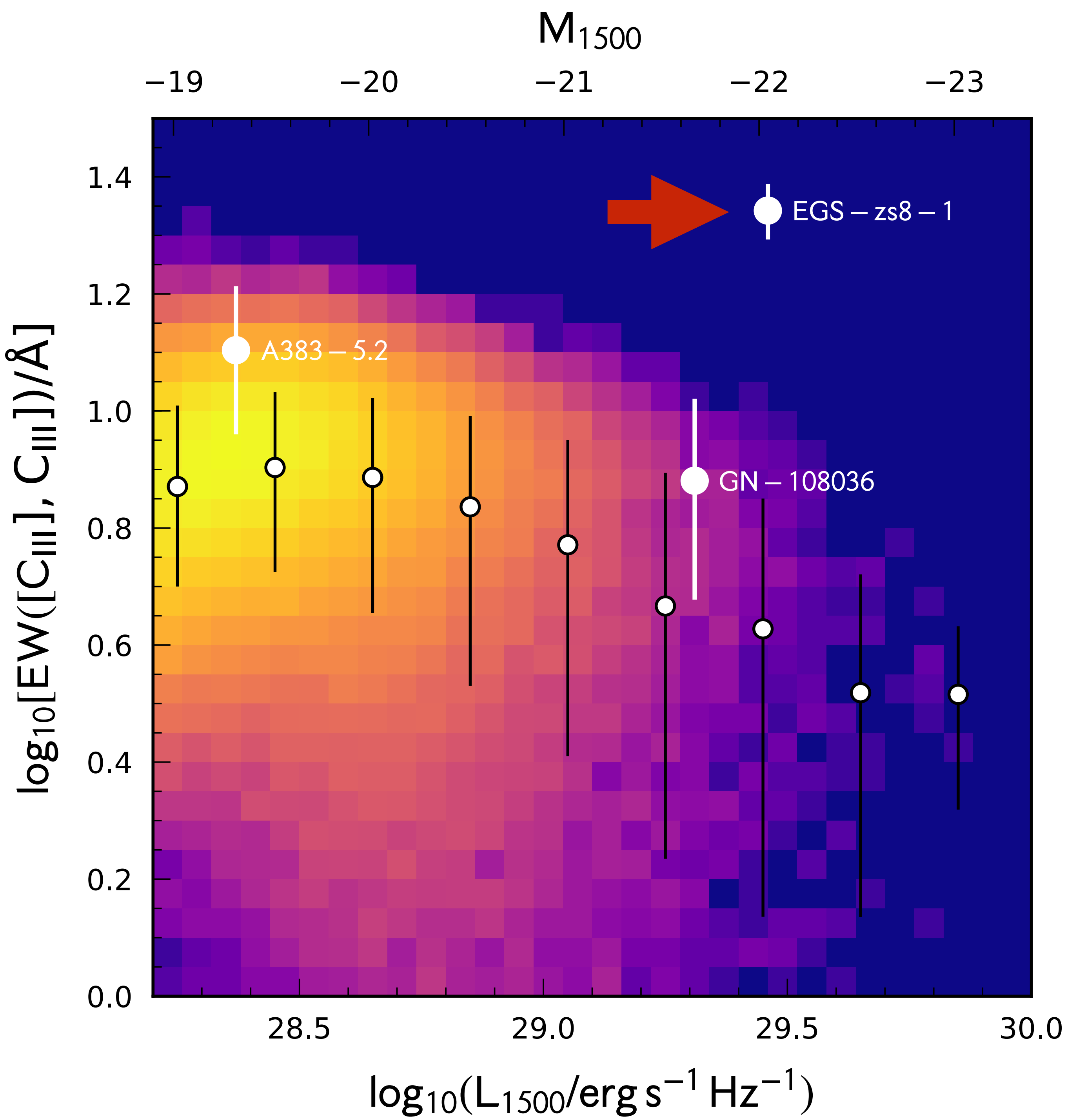
WHILE TWO OBJECTS ARE CONSISTENT WITH THE BLUETIDES PREDICTIONS, THE **FINAL ONE LIES FAR OUTSIDE THE PREDICTED DISTRIBUTION**.



BLUETIDES: [C III],C III] EW DISTRIBUTION

THERE ARE SEVERAL SOLUTIONS:

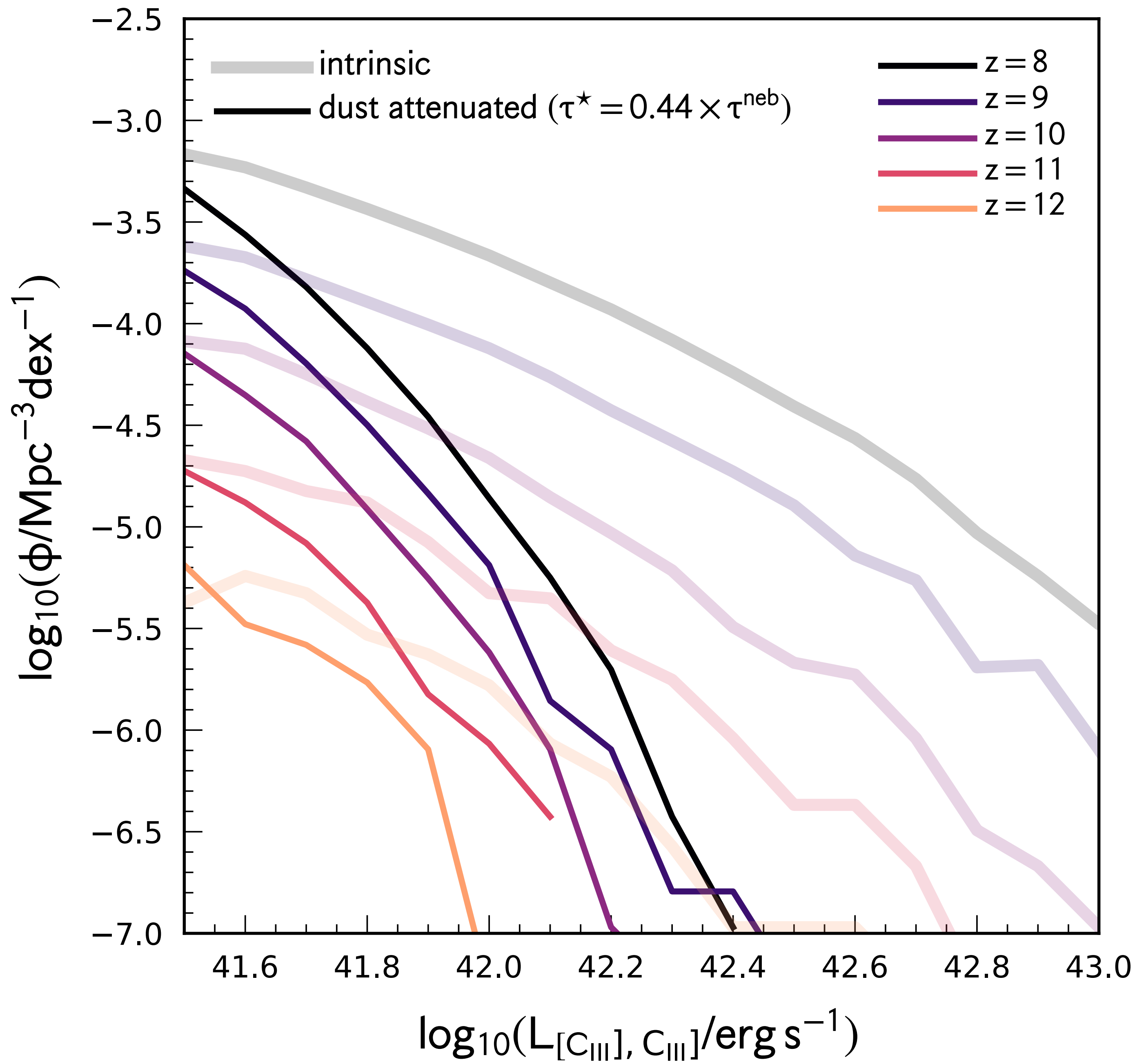
- THE SIMULATION IS WRONG.
- THE DUST MODEL IS WRONG.
- THE ASSUMED PPOTOINIONSATION PARAMETERS ARE WRONG.
- SPS MODELS ARE INCOMPLETE.
- THE WRONG IMF IS ASSUMED.
- IT'S AN AGN.



BLUETIDES: [C III], C III LUMINOSITY FUNCTION

THE [C III],C III LUMINOSITY FUNCTION EVOLVES STRONGLY WITH REDSHIFT AND **THE BRIGHT-END IS STRONGLY IS VERY SENSITIVE TO DUST**.

INTRINSIC AND OBSERVED [C III],C III LUMINOSITY FUNCTIONS

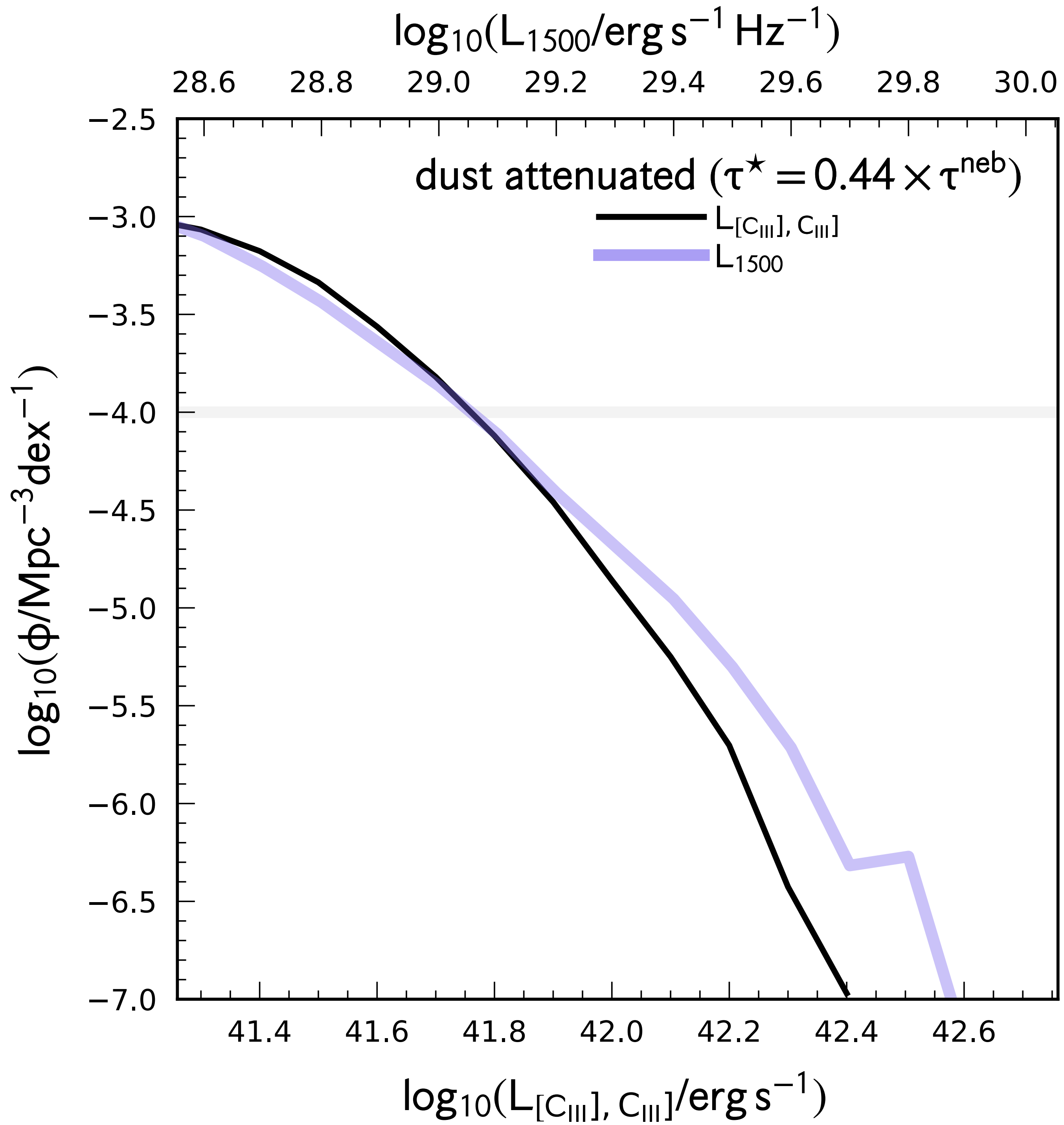


BLUETIDES: [CIII],CIII] LUMINOSITY FUNCTION

THE OBSERVED [CIII],CIII] LUMINOSITY FUNCTION **DECLINES MORE RAPIDLY** THAN THE FUV LUMINOSITY FUNCTION.

NOTE: THE X-SCALES ARE CHOSEN TO COVER THE SAME DYNAMIC RANGE IN LUMINOSITY AND TO NORMALISE THE CURVES AT PHI=-4.

[CIII],CIII] AND FUV LUMINOSITY FUNCTIONS



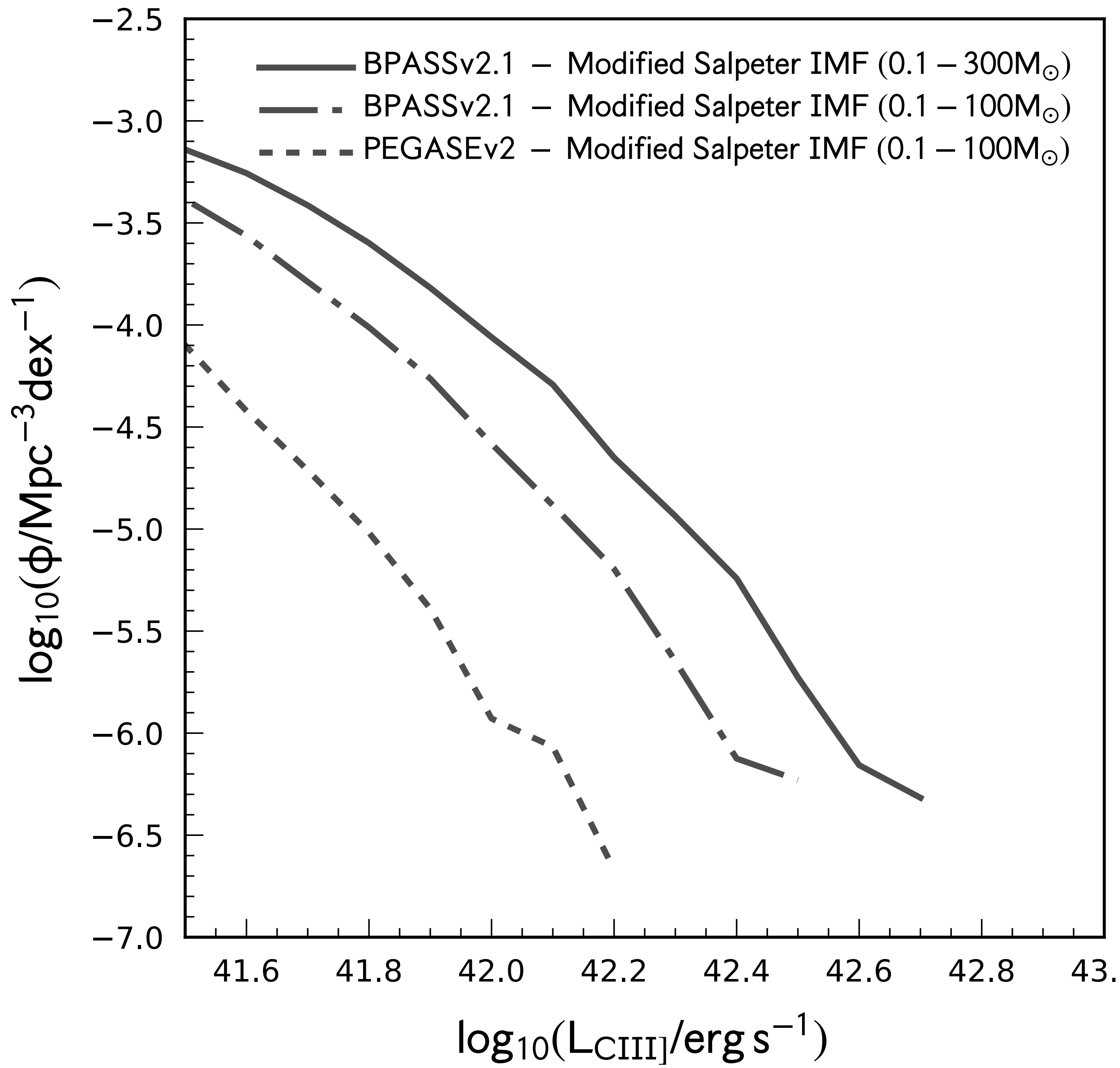
BLUETIDES: [CIII],CIII] LUMINOSITY FUNCTION

HOWEVER, THE LUMINOSITY FUNCTION IS **VERY SENSITIVE** TO THE ASSUMED IMF AND SPS MODEL.

THE MODIFIED SALPETER IS DEFINED AS:

$$\frac{\mathrm{d}N}{\mathrm{d}m} = \begin{cases} m^{-1.3} & \text{for } 0.1 \leq m < 0.5, \\ m^{-2.35} & \text{for } 0.5 \leq m < m_{\mathrm{up}}. \end{cases}$$

[CIII],CIII] LUMINOSITY FUNCTIONS FOR DIFFERENT SPS/IMF ASSUMPTIONS



BRIEF ASIDE: **WHAT CAN WE ACTUALLY LEARN FROM REST-FRAME UV OBSERVATIONS?**

USING THE **INTERROGATOR** SED FITTING CODE WE HAVE INVESTIGATED **HOW WELL VARIOUS PARAMETERS CAN BE CONSTRAINED FROM REST-FRAME UV OBSERVATIONS**.

Interrogator

WILKINS ET AL. IN PREP
FAIRHURST ET AL. IN PREP

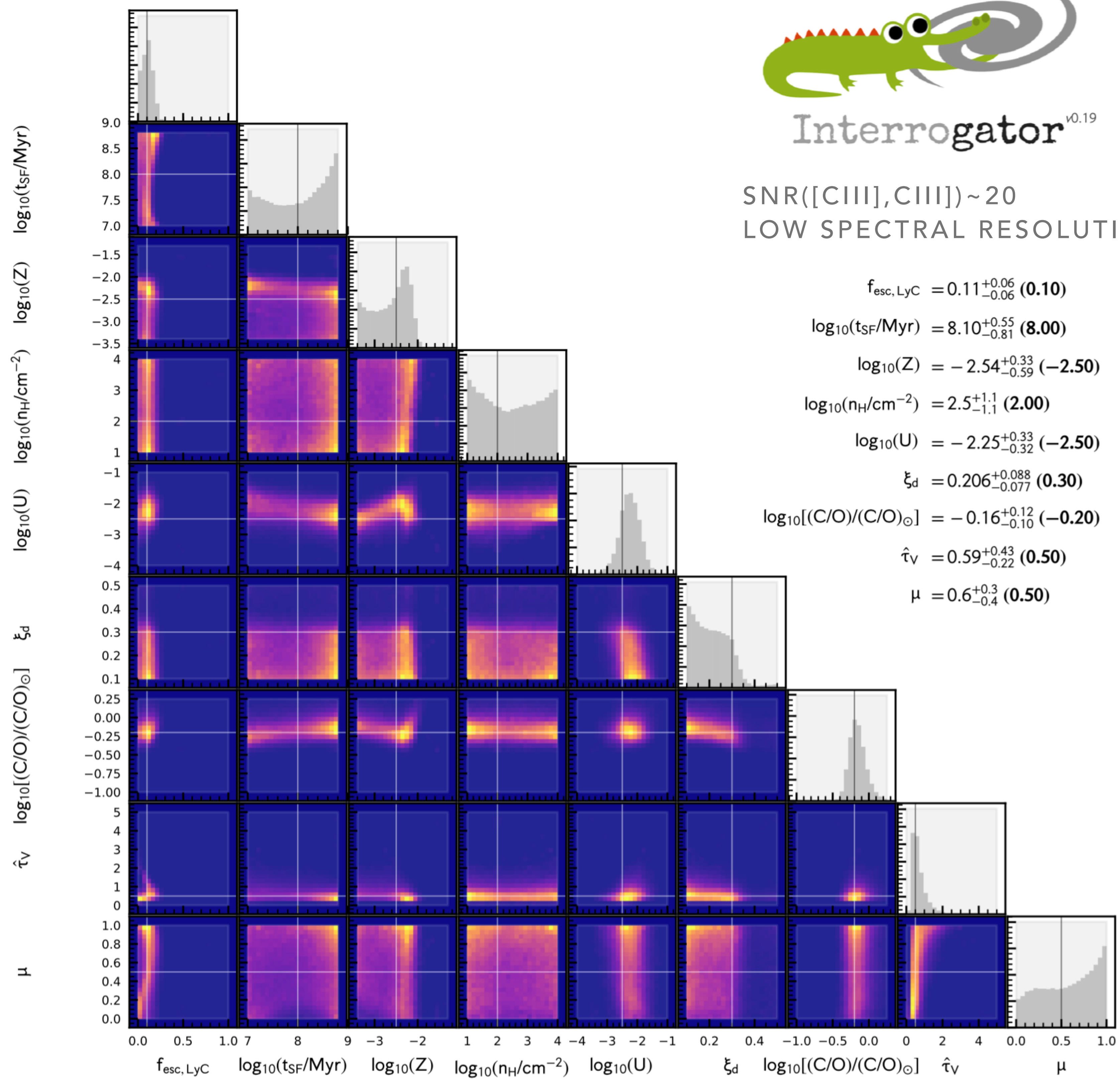
INTERROGATOR COMBINES AN SED MODEL (INCLUDING STARS, NEBULAR EMISSION, DUST, AND AGN) WITH **AN MCMC INFERENCE ENGINE** TO DETERMINE THE POSTERIOR ON EACH OF THE MODEL PARAMETERS.

INTERROGATOR IS VERY SIMILAR TO BEAGLE AND PROSPECTOR THOUGH HAS DIFFERENT OPTIONS FOR THE ASSUMED DUST/GAS REPROCESSING MODEL AND SPS MODEL.

TYPICAL CONSTRAINTS FROM **THE ENTIRE REST-FRAME UV SED**.

ASSUMES WE KNOW THE SLOPE OF THE DUST CURVE, LEAVING THIS AS A FREE PARAMETER, EVEN WITH A RELATIVELY CONSERVATIVE PRIOR SIGNIFICANTLY REDUCES THE GOODNESS OF THE FITS.

ALSO ASSUMES NO AGN CONTRIBUTION.



Interrogator v0.19

SNR([CIII],CIII])~20
LOW SPECTRAL RESOLUTION.

$f_{\rm esc,LyC} = 0.11^{+0.06}_{-0.06}$ **(0.10)**

$\log_{10}(t_{\rm SF}/{\rm Myr}) = 8.10^{+0.55}_{-0.81}$ **(8.00)**

$\log_{10}(Z) = -2.54^{+0.33}_{-0.59}$ **(−2.50)**

$\log_{10}(n_{\rm H}/{\rm cm}^{-2}) = 2.5^{+1.1}_{-1.1}$ **(2.00)**

$\log_{10}(U) = -2.25^{+0.33}_{-0.32}$ **(−2.50)**

$\xi_d = 0.206^{+0.088}_{-0.077}$ **(0.30)**

$\log_{10}[({\rm C/O})/({\rm C/O})_\odot] = -0.16^{+0.12}_{-0.10}$ **(−0.20)**

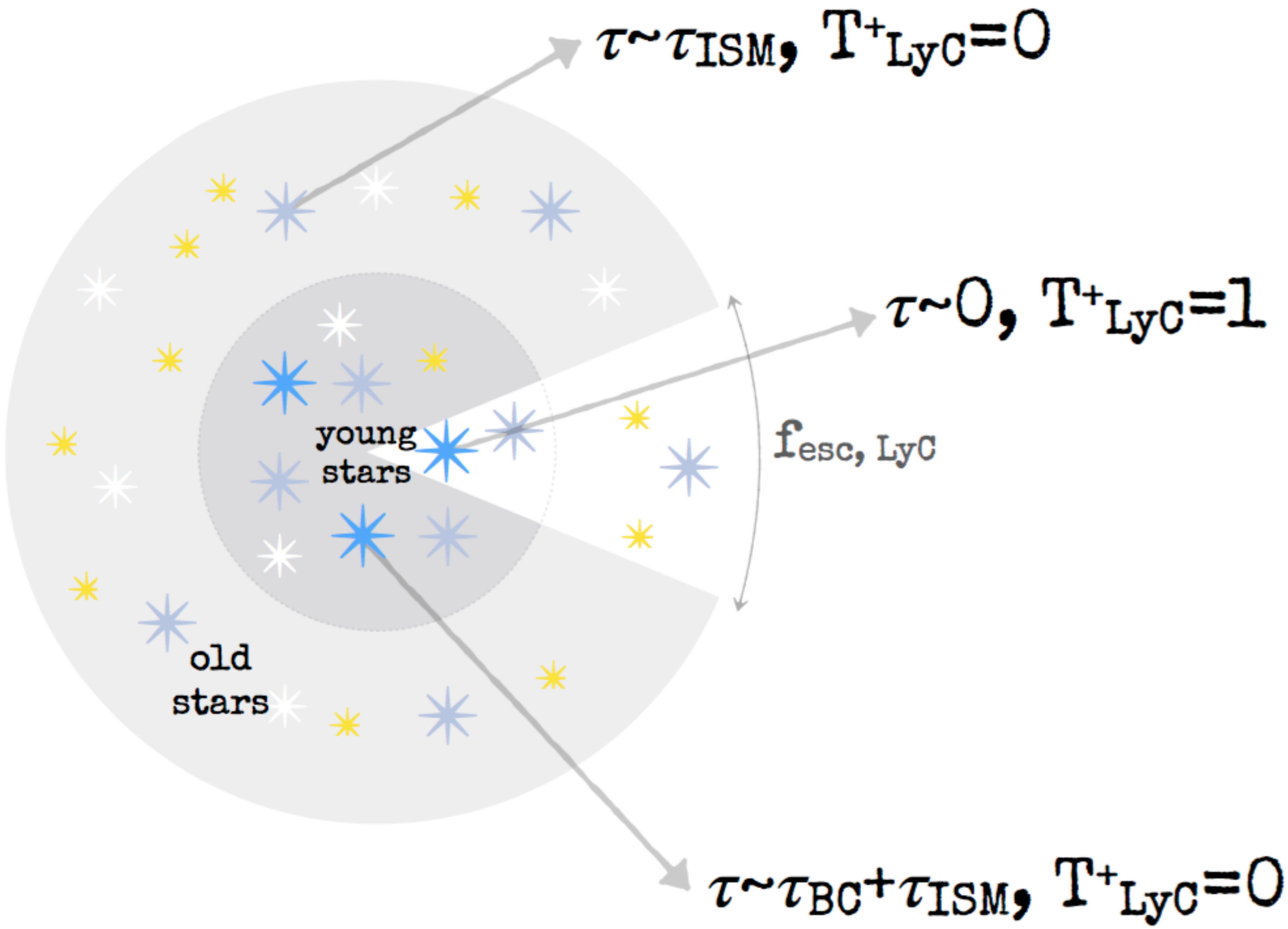
$\hat{\tau}_V = 0.59^{+0.43}_{-0.22}$ **(0.50)**

$\mu = 0.6^{+0.3}_{-0.4}$ **(0.50)**

CONCLUSIONS

- THE VERY LARGE BLUETIDES SIMULATION REPRODUCES THE OBSERVED UV LUMINOSITY FUNCTION THOUGH PREDICTS THAT MASSIVE GALAXIES ARE HEAVILY OBSCURED.
- PREDICTED [CIII],CIII] EQUIVALENT WIDTHS LARGELY IN AGREEMENT WITH OBSERVATIONS EXCEPT ONE OBJECT.
- INFERRING PARAMETERS FROM THE UV ALONE IS DIFFICULT.

PACMAN MODEL

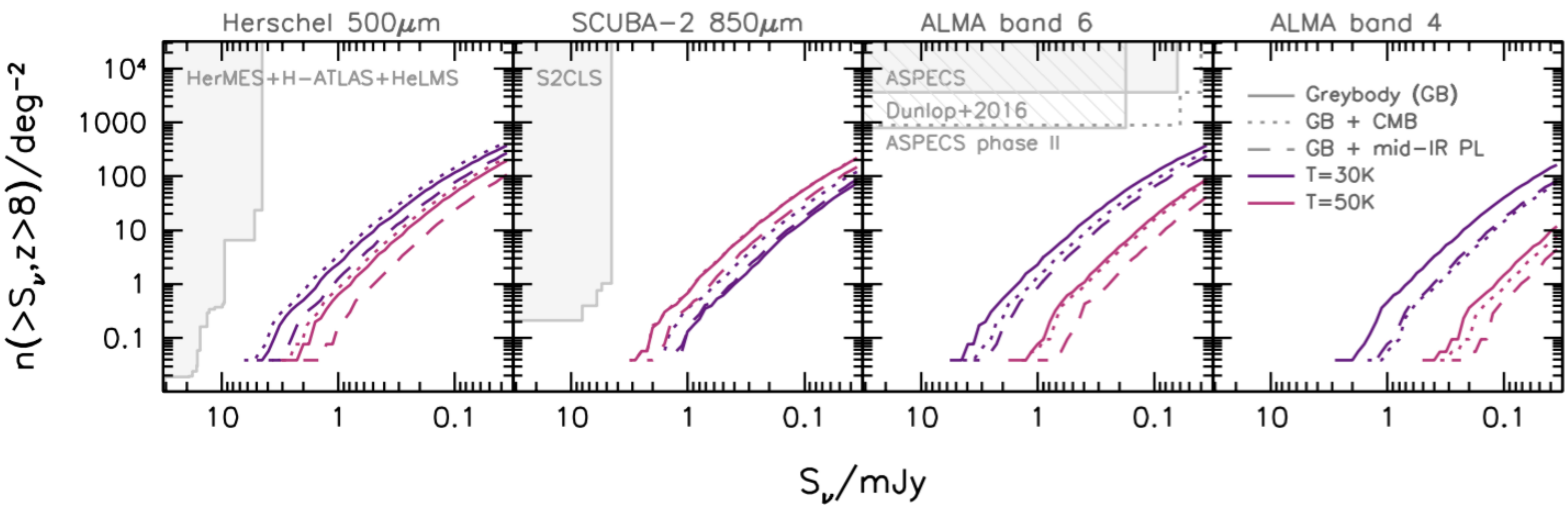


BLUETIDES: **DUST ATTENUATION**

SUB-MM PREDICTIONS

BELOW ARE **SUB-MM NUMBER COUNT PREDICTIONS** FOR GALAXIES AT Z>8 IN VARIOUS BANDS SHOWING REGIONS PROBED BY CURRENT SURVEYS.

- PREDICTIONS ARE VERY SENSITIVE TO THE ASSUMED INFRARED TEMPLATE.
- NO SURVEY SHOULD HAVE SEEN Z>8 GALAXIES BUT ALMA COULD IN THE NOT TOO DISTANT FUTURE.

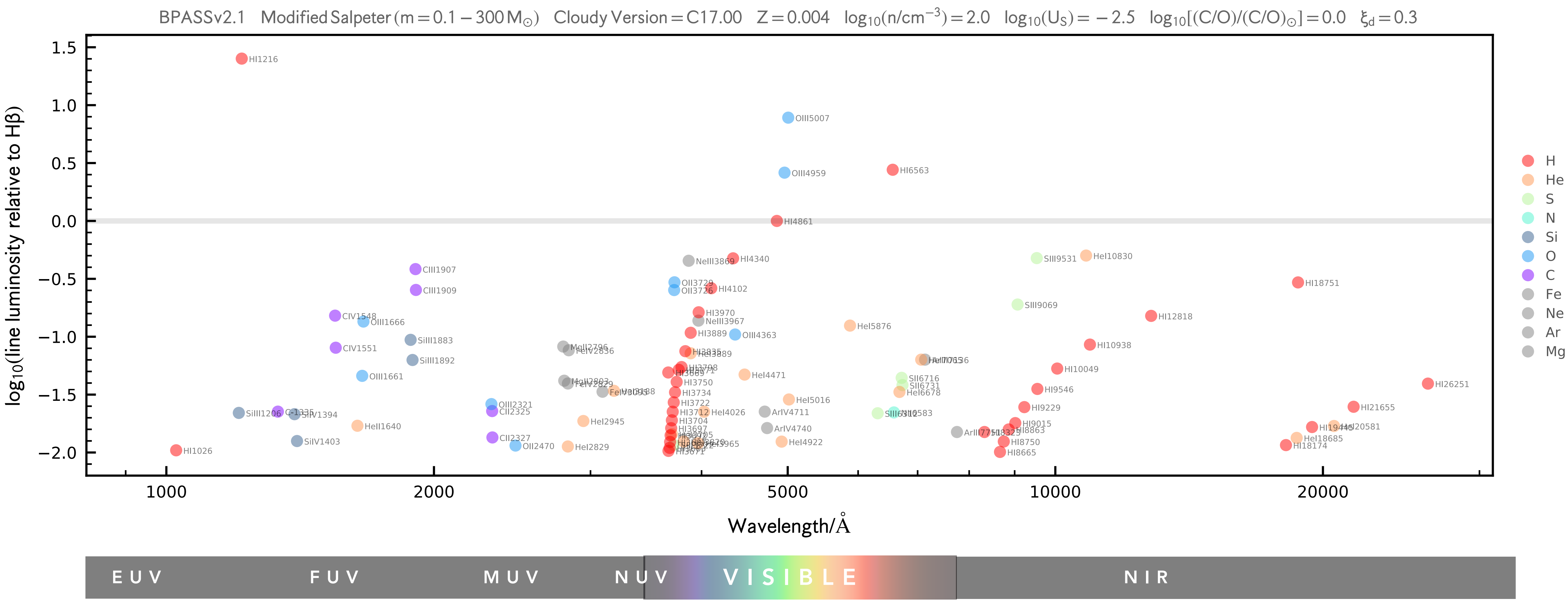


OTHER THINGS I'M WORKING ON

- JWST PUBLIC ENGAGEMENT (WHY I'M HERE TODAY)
- EVERY OTHER ASPECT OF THE SIMULATION
- (FLEXIBLE) SED FITTING.

UV DIAGNOSTICS: **UV EMISSION LINES**

INTRINSIC LINE LUMINOSITY (RELATIVE TO H-BETA) PREDICTIONS FROM **BPASS/CLOUDY**



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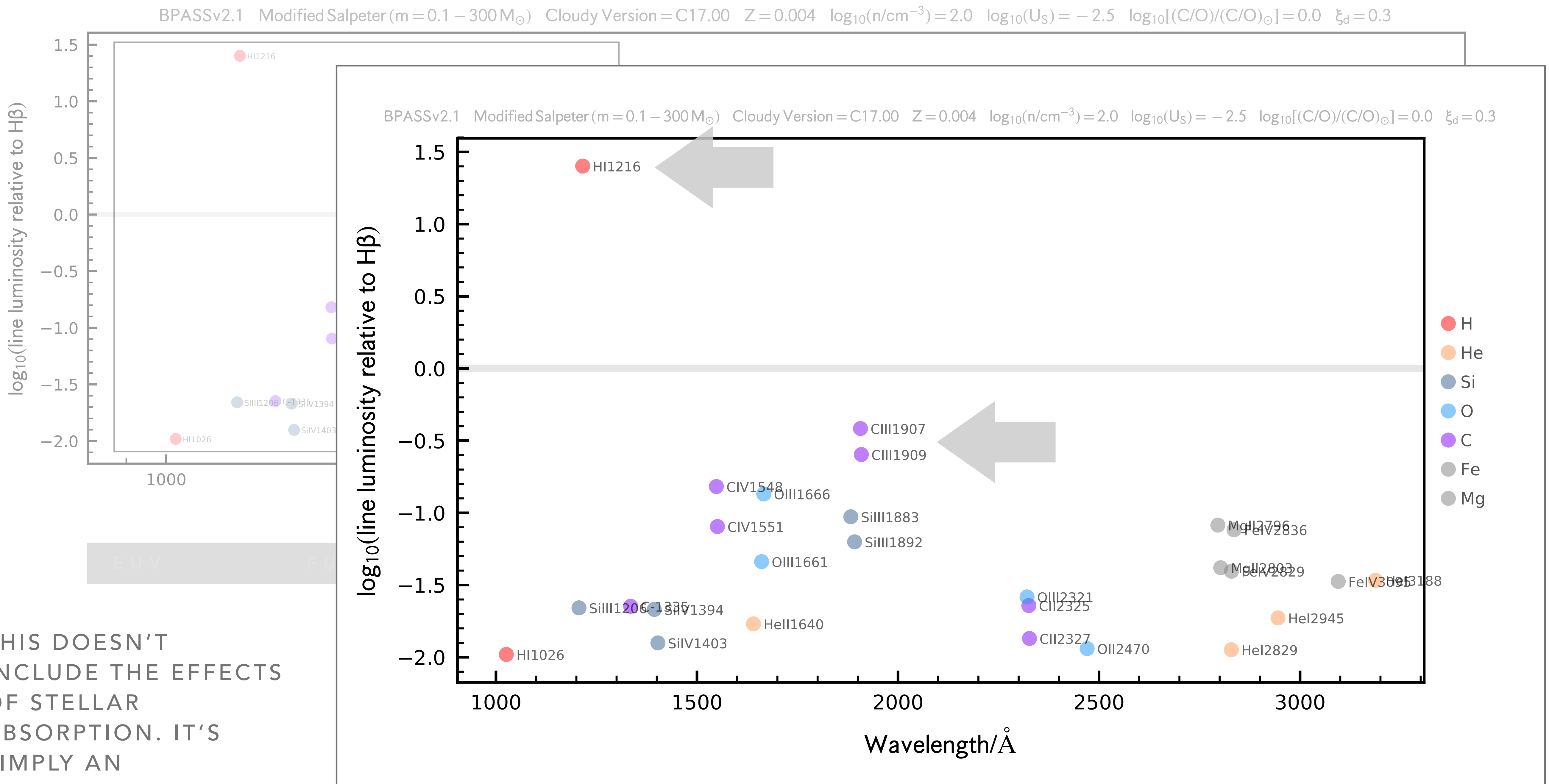

THIS DOESN'T INCLUDE THE EFFECTS OF STELLAR ABSORPTION. IT'S SIMPLY AN ILLUSTRATION.

UV DIAGNOSTICS: [CIII],CIII]

- COMBINATION OF TWO LINES ([CIII]@~1907 AND CIII]@~1909).
- OFTEN THE SECOND BRIGHTEST UV LINE (AFTER LYA).
- VERY SENSITIVE TO METALLICITY (AT LEAST ABOVE Z=0.004).
- BUT... SENSITIVE TO OTHER PROPERTIES OF THE IONISING SOURCE / ISM AS WELL.
- ALREADY OBSERVED AT HIGH-REDSHIFT (E.G. STARK ET AL. 2015,2017)

OBSERVATIONS OF [CIII],CIII] DOUBLET IN A ***Z~7.7*** LYMAN BREAK GALAXY (STARK ET AL. 2017).