The Synthetic Emission Line COSMOS catalog: Hα and [OII] galaxy luminosity functions and counts at $0.3 < z < 2.5$

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Abstract

- COSMOS-2015 photometric catalog → SED and emission-line flux
- Stellar continuum of SED → Model (validated) → EL flux
- The model also gives ‘dust attenuation – redshift’ relationship

- Catalog → Hα and [OII] luminosity functions (to z ～ 2.5）
- LF → Predictions for Hα and [OII] galaxy number counts (Next-generation sky survey)

- Result of this paper: ‘EL-COSMOS’ in ASPIC database

Introduction

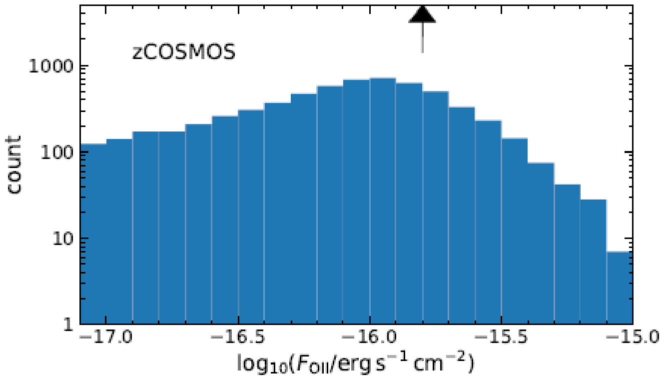
- Emission lines (ELs) → map out the large-scale structure
  - PFS ([OII] emitters $0.6 < z < 2.4$)
  - DESI ([OII] emitters $0.6 < z < 1.7$)
  - Euclid (Hα emitters $0.9 < z < 1.8$, [OII] emitters $z > 1.5$)
- EL fluxes traces photo-ionized gas in the ISM → Galaxy properties → $\begin{cases} \text{formation physics} \\ \text{cosmology} \end{cases}$
- Predicting the ELG number density can optimize future surveys and interpret their data.
- Aim of this paper:
  - Emission-line fluxes as a function of redshift and other galaxy properties
  - Providing a new reference catalog of modeled galaxy SEDs
- COSMOS → Empirical modelling of EL fluxes → calibrated and validated (spectroscopy)

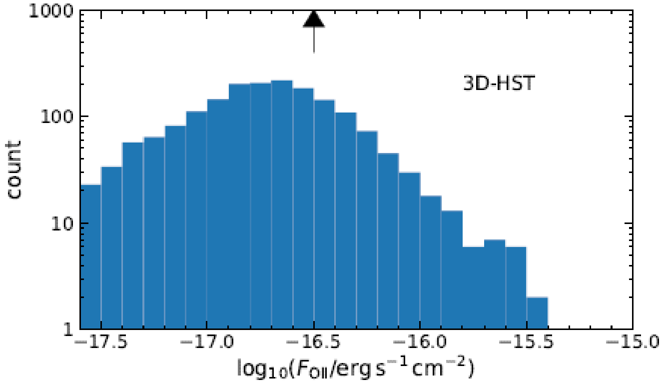
  → Derive emission line luminosity functions (LFs)
- Similar research:
  - COSMOS Field: Valentino et al. (2017): limited at $z \sim 1.6$
  - Semi-analytic Simulation: Merson et al. (2018), Izquierdo-Villalba et al. (2019)
- Advantages: 1. A wide redshift range ($0 < z < 2.5$) 2. Special dust attenuation calibration

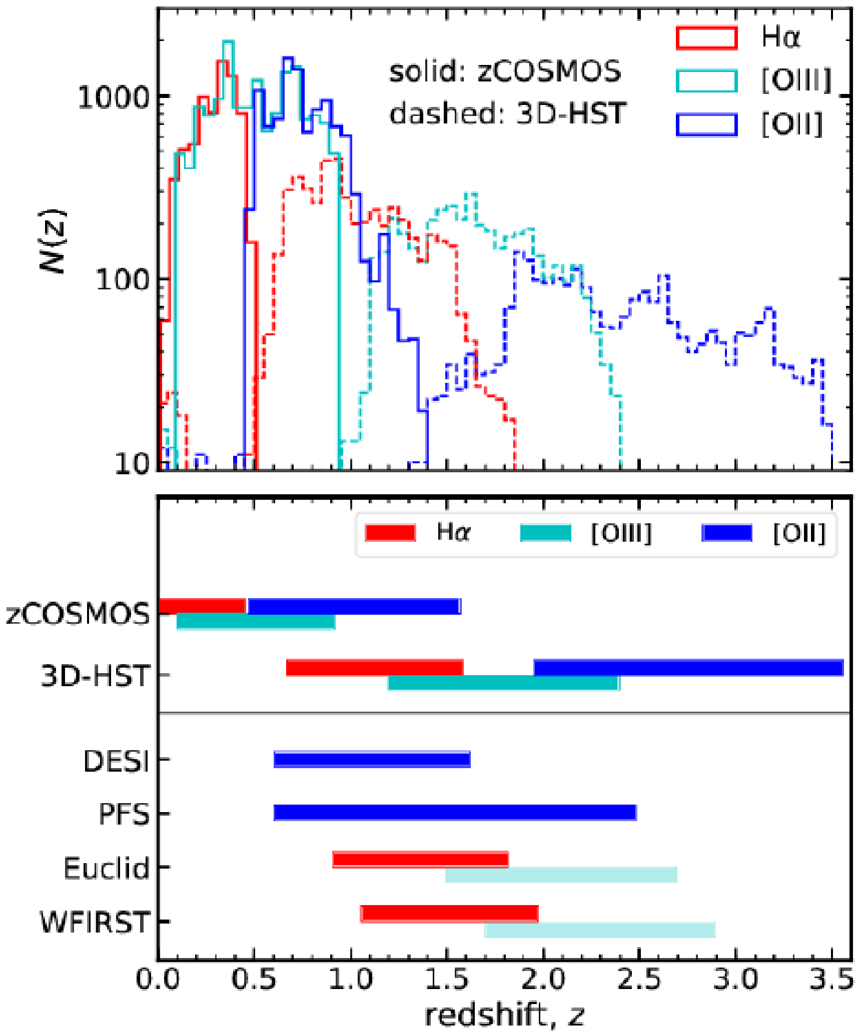
Observational data

- 1. COSMOS2015 multi-band photometry
  - Laigle et al. (2016), 31 photometric bands ($2000\text{Å} - 10^5\text{Å}$)
  - A homogeneous population of galaxies ($K_s < 24.7$)
  - 518404 objects over 1.38 deg^2 (AGNs may include)

- 2. Spectroscopic measurement of emission line fluxes
  - zCOSMOS-Bright (Lilly et al. 2007) 5500 < λ[Å]< 9600
  - 3D-HST (Momcheva et al. 2016) 11000 < λ[Å]< 17000
  - EL measurements: pipeline PLATEFIT
  - Aperture correction: Mainly Subaru and others ACS
  - Flux completeness: zCOSMOS -15.8 3D-HST -16.5







Modeling of the emission line flux

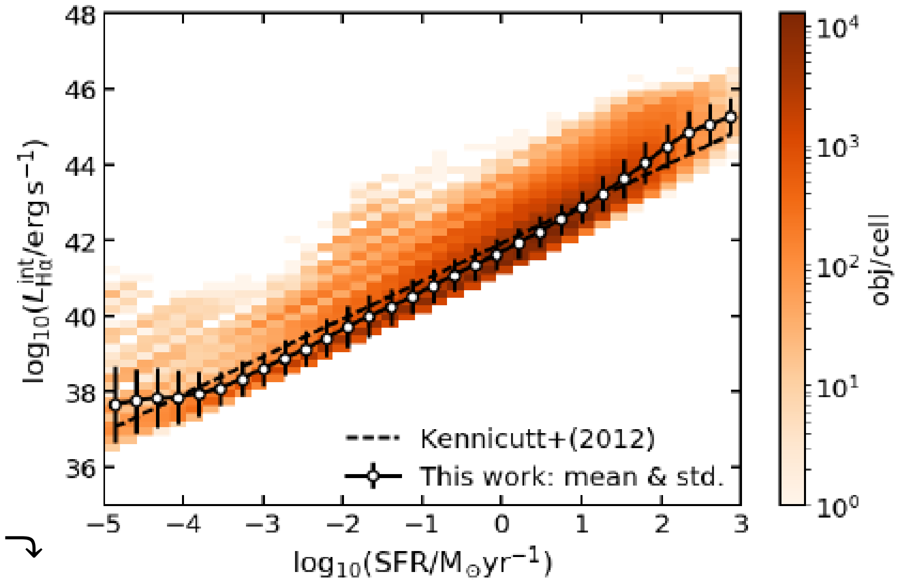
- 1. Overview
  - Overall 99072 templates:
    - stellar population synthesis (SPS) model
    - Two kinds of star formation histories:
      exponentially declining SFH, delayed SFH
    - Dust reddening: $10^{-0.4k(\lambda)E(B-V)}$, $k(\lambda) = \lambda^{0.9}$ or the starburst curve (Calzetti et al. (2000))
    - Two metallicities: $Z_{\odot}$ and $0.5\ Z_{\odot}$
  - The contribution of the star-forming nebular regions:
    - The Hβ luminosity: From Lyman continuum photons Q_{LyC},
      $$L_{\mathrm{H}\beta}^{\mathrm{int}} = 4.78 \times 10^{-13}\ f_{\gamma}\ Q_{\mathrm{LyC}}.$$
    - Other lines: Anders & Fritze-v. Alvensleben (2003)
      Osterbrock & Ferland (2006)
      $O[II]/H_{\beta} = 3$, $\mathrm{H}_{\alpha}/H_{\beta} = 2.9$
      $O[III]/H_{\beta} = 4.1$ * a free scaling parameter (0.25,0.5,1,2,4)
    - The amount of dust attenuation for the ELs from nebular regions
      $$E_{\mathrm{neb}}(B-V) = \frac{E_{\mathrm{star}}(B-V)}{f}.$$ f(z) here

Table 1. Non-hydrogen emission lines and their line strengths, normalized to H_{β} line strength, as a function of metallicity ($Z1 = 0.0004$, $Z2 = 0.004$, $Z3 = 0.008$, $Z4 = 0.02 = Z_{\odot}$, $Z5 = 0.05$).

Line	λ [Å]	$\frac{F_L}{F_{H_\beta}}$ Z1	$\frac{F_L}{F_{H_\beta}}$ Z2	$\frac{F_L}{F_{H_\beta}}$ Z3–Z5
[CII]	1335.00	0.000	0.000	0.110
[OIII]	1663.00	0.000	0.058	0.010
[CIII]	1909.00	0.000	0.000	0.180
[NII]	2141.00	0.000	0.000	0.010
[CII]	2326.00	0.000	0.000	0.290
[MgII]	2798.00	0.000	0.310	0.070
[OII]	3727.00	0.489	1.791	3.010
[NeIII]	3869.00	0.295	0.416	0.300
H_{ζ} + [HeI]	3889.00	0.203	0.192	0.107
H_{ϵ} + [NeIII]	3970.00	0.270	0.283	0.159
[HeI]	4026.00	0.015	0.015	0.015
[SII]	4068.60	0.005	0.017	0.029
[SII]	4076.35	0.002	0.007	0.011
[OIII]	4363.00	0.109	0.066	0.010
[HeI]	4471.00	0.036	0.036	0.050
[ArIV] + [HeI]	4711.00	0.010	0.014	0.000
[OIII]	4958.91	1.097	1.617	1.399
[OIII]	5006.84	3.159	4.752	4.081

- 2. Calibration
  - Intrinsic EL luminosity
    - Hα ↔ SFR Kennicutt 1998: within 1σ error →

$$\log_{10}(L^{\rm int}_{\rm H\alpha}/{\rm erg\,s^{-1}}) = 41.92 + \log_{10}({\rm SFR}/M_\odot\,{\rm yr^{-1}}).$$

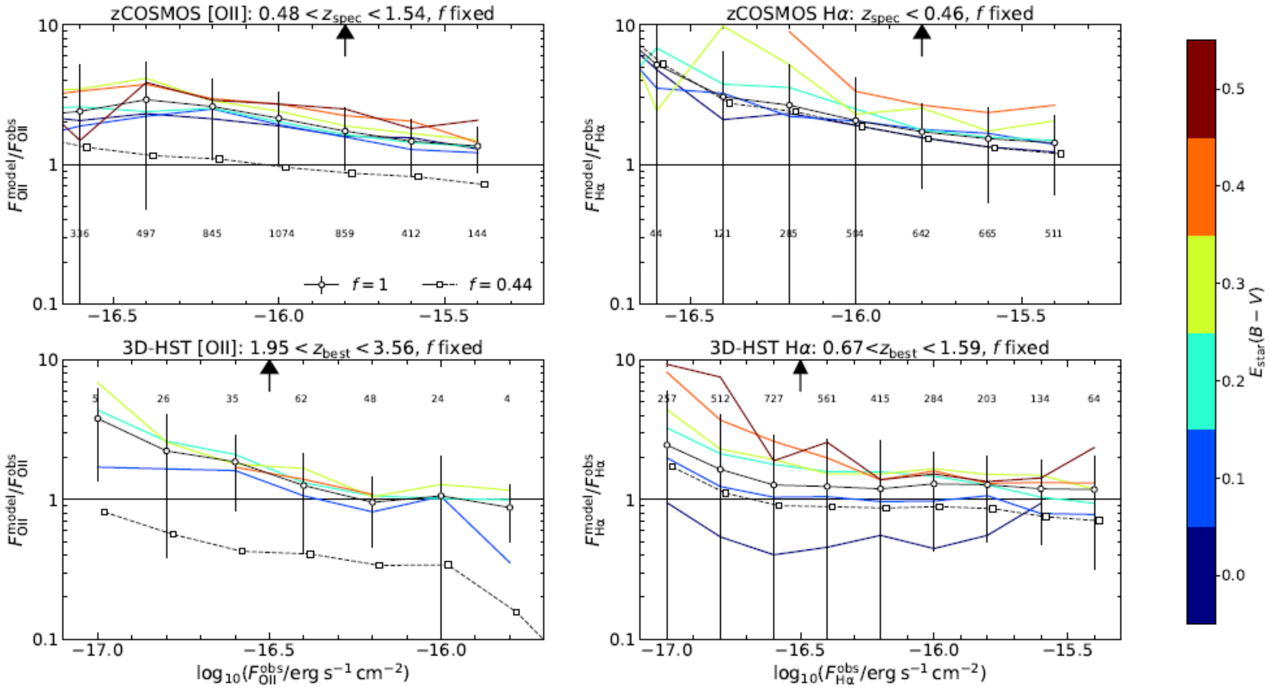


  - Dust attenuation

$$E_{\rm neb}(B-V) = \frac{E_{\rm star}(B-V)}{f}.$$

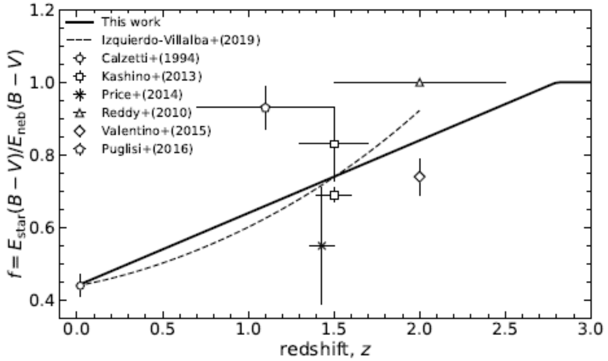
f = 1 and f = 0.44

    - The f = 1 model tends to overestimate the EL fluxes
    - More overpredicts EL fluxes at lower z
    - Overestimate the EL fluxes at a shorter λ
    - f = 0.44: too aggressive and underpredict
    - dust attenuation in star-forming nebulae is not so important at z ~ 0

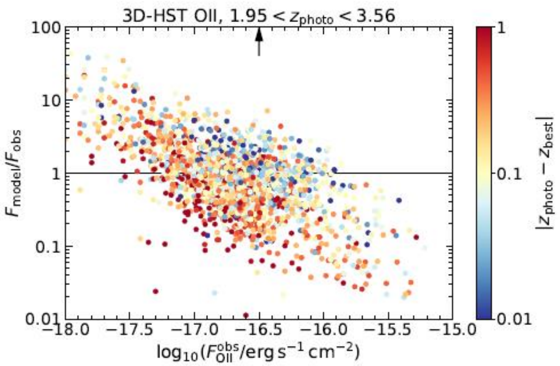


  - Redshift-dependent:

$$f(z) = \begin{cases} 0.44 + 0.2z & (z \le 2.8) \\ 1 & (z > 2.8) \end{cases}$$

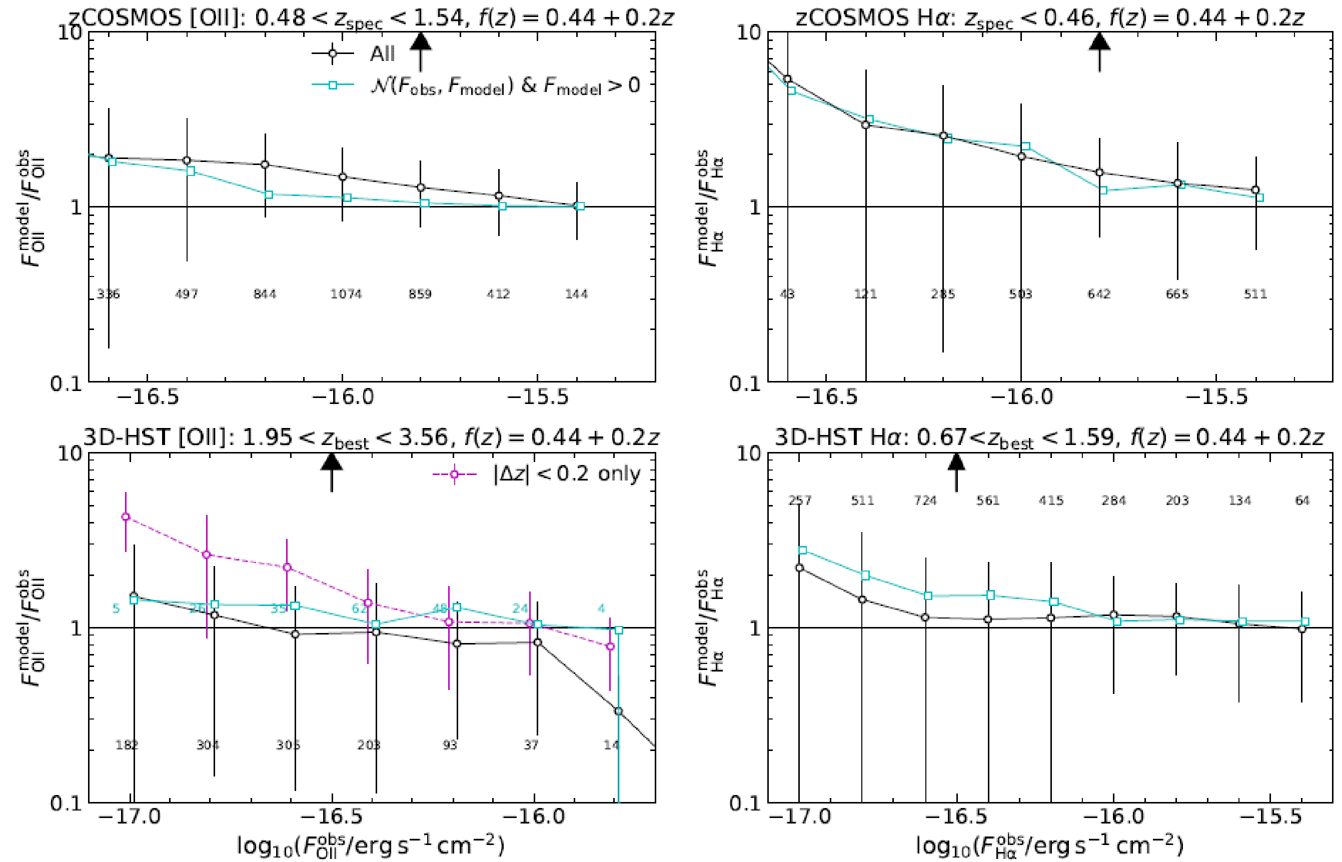


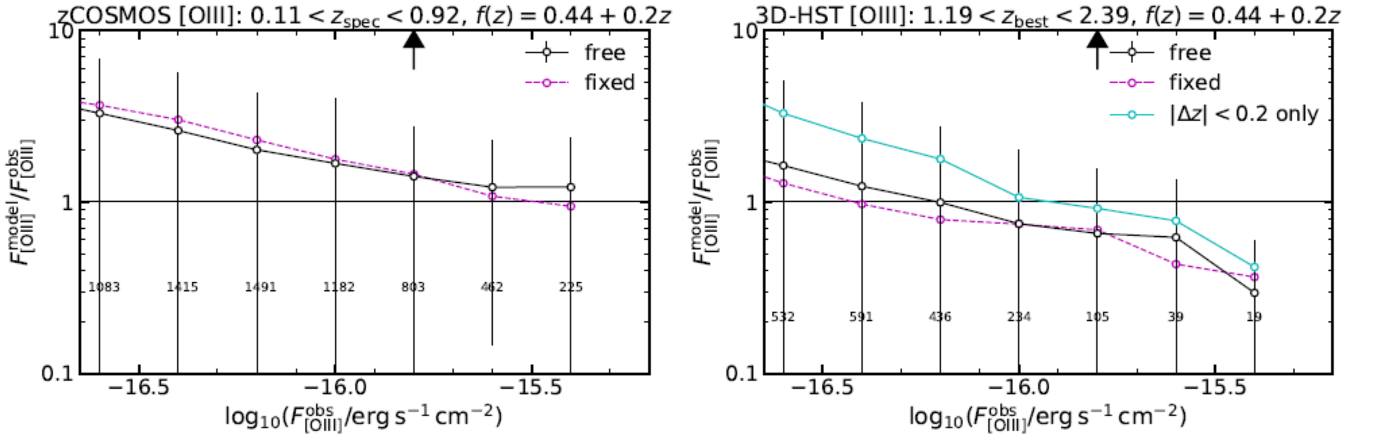
- 3. Results
  - 3.1 Hα and [OII]
    - The model works well on average, but tends to more overestimate the EL fluxes in smaller flux ranges. Caused by large uncertainty in SED fitting.
    - Bottom-left: uncertainty of photo-z determination (z > 2), underestimated results for $|z_{best} - z_{photo}| > 0.1$



  - 3.2 [OIII]
    - The result looks very similar to the [OII] case.
    - Magenta color line: free scaling parameter

- In general, our model works well within a factor of two beyond the completeness limit.





Hα AND [OII] LUMINOSITY FUNCTIONS

- 1. Estimation of the luminosity function
  - Deconvolution- or convolution-based estimators: $\Phi(L) = \int dL' N(L') \frac{P(L|L')}{V_{\max}(L)}, \rightarrow \Phi(L) = \sum_{L'} \frac{P(L|L')}{V_{\max}(L)} \Theta(L),$
  - ***LePhare*** code → $P(z'|z) \rightarrow P(z|z') = P(z'|z)P(z) \rightarrow P(L|L')$

- 2. Modelling luminosity error
  - $\Phi^{\rm obs}(L) = \Phi^{\rm true}(L) * P(\Delta L|L), \quad \Delta L = L_{est} - L$ — L is the true luminosity, L_{est} is the estimated luminosity
  - Lack of some spectroscopic samples → Gaussian mixture to get ΔL

$$M(\theta) = \sum_{i=1}^{K} w_i G(\mu_i, \Sigma_i),$$

  - luminosity error is also redshift-dependent
  - The best-fitting model is obtained by using a mixture of three bivariate Gaussians (with K = 3). It is the baseline model for the conditional luminosity error in the analysis of the luminosity function.

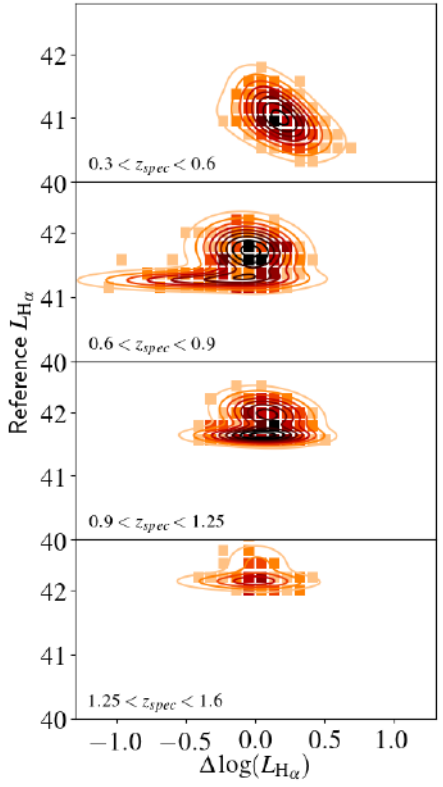


Figure 10. Joint probability distribution of H_α luminosity error and true luminosity in the spectroscopic samples zCOSMOS-Bright and 3D-HST. The various panels correspond to different spectroscopic redshift intervals. The colour scheme from yellow to black encodes the level of probability with arbitrary normalisation. The squares show the two-dimensional histogram of the data and the contours correspond to the best-fitting Gaussian mixture model. The colours scale similarly for both cases.

- 3. Measurements of the Hα and [OII] galaxy luminosity functions
  - 0.3 < z < 0.6 (40), 0.6 < z < 0.9 (41.1), 0.9 < z < 1.25(41.5) , 1.25 < z < 1.6 (42), 1.6 < z < 2 (42.3)
  - Model the observed luminosity functions (Black curves):
    - Schechter function → redshift variations (1 + z) → double power law model

$$\bar{z} = \frac{\int \left(\sum_{z'} P(z|z')\right) z dz}{\int \sum_{z'} P(z|z') dz}$$

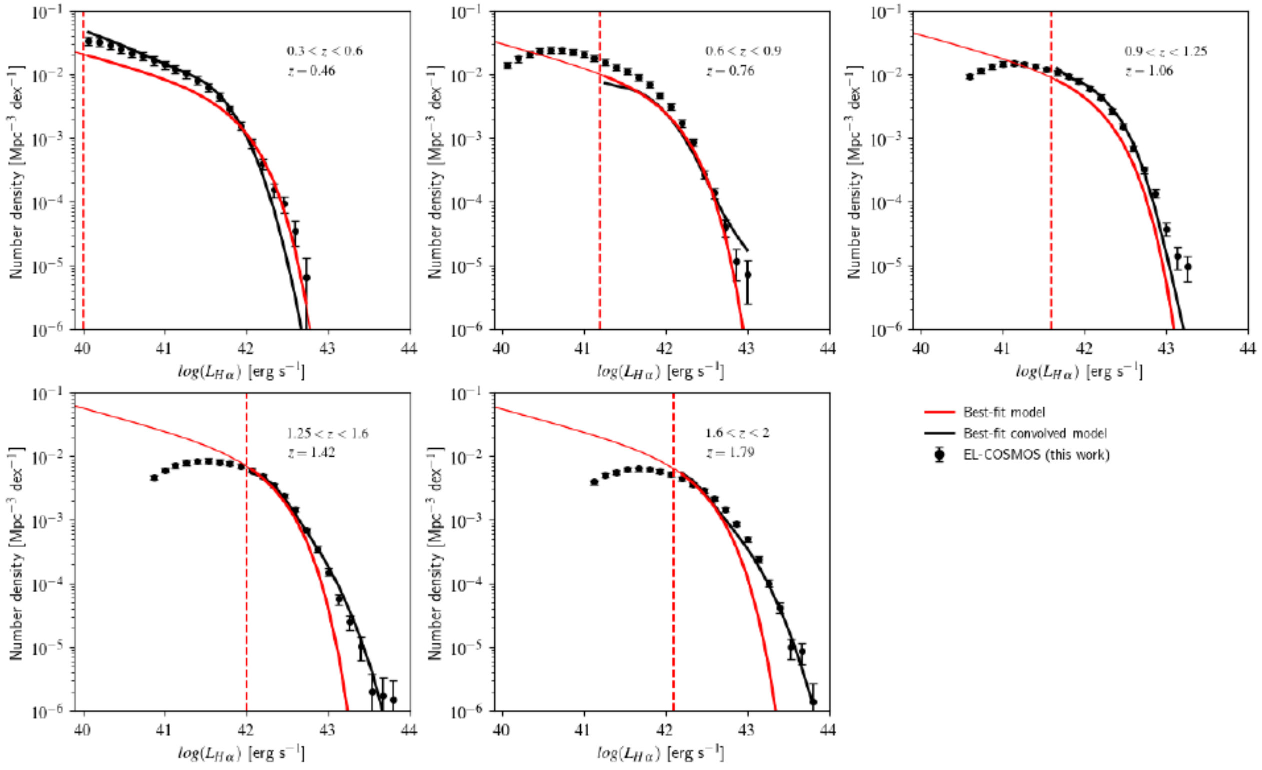
$$\Phi^{\rm obs}(L|z) = \Phi^{\rm true}(L|z) * P(\Delta L|L, z), \quad (10)$$

where

$$\Phi^{\rm true}(L|z)dL = \Phi_*(z)\left(\frac{L}{L_{*,0}(1+z)^\beta}\right)^\alpha e^{-\frac{L}{L_{*,0}(1+z)^\beta}} \frac{dL}{L_{*,0}(1+z)^\beta}, \quad (11)$$

and

$$\Phi_*(z) = \begin{cases} \Phi_{*,0}(1+z)^\gamma & \text{for } z < z_{\rm pivot} \\ \Phi_{*,0}(1+z_{\rm pivot})^{\gamma+\epsilon}(1+z)^{-\epsilon} & \text{for } z > z_{\rm pivot}. \end{cases} \quad (12)$$



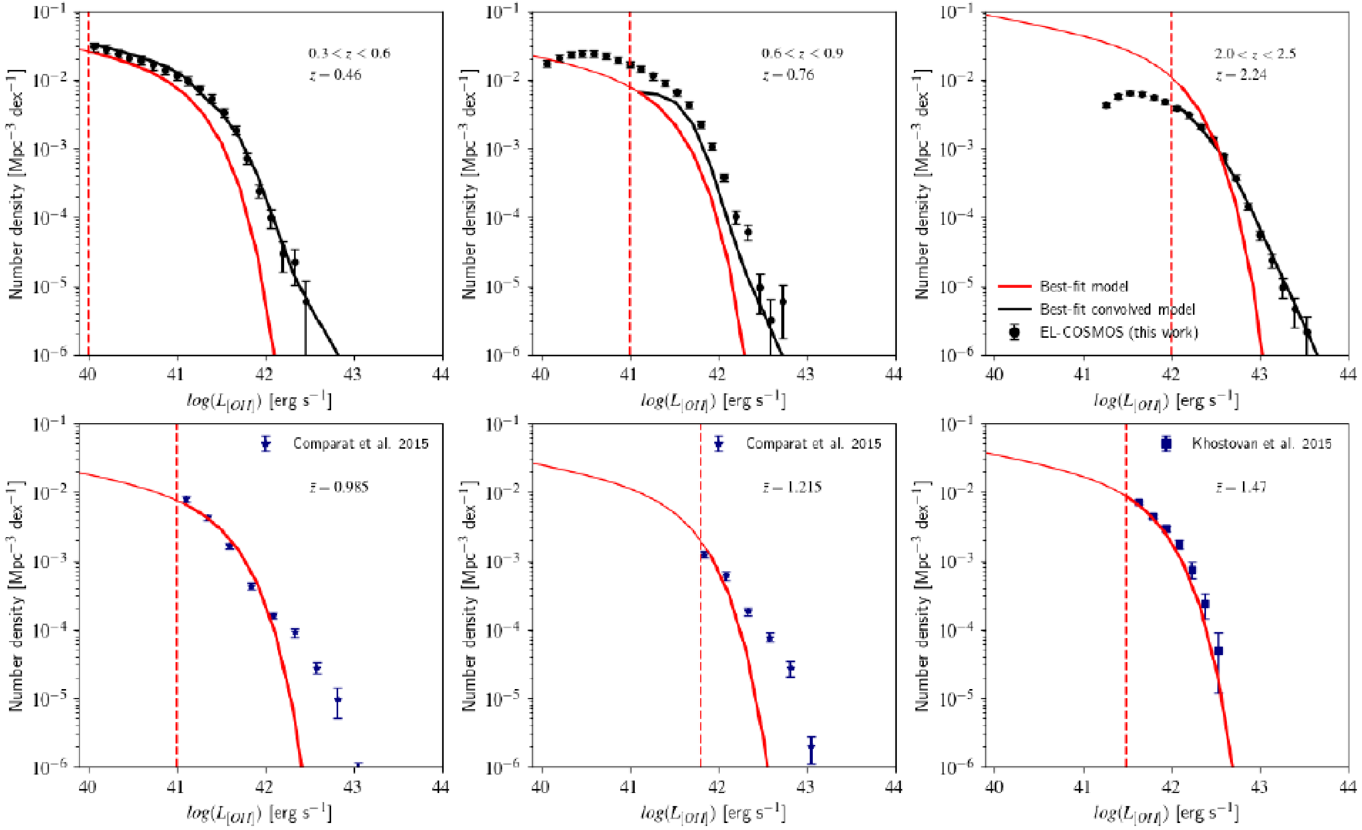
Hα

- In high-z interval, the observed luminosity function is significantly above the best-fitting model. There is potentially a high overdensity that locally boosts the number of Hα emitters.

Emission line	$\log_{10}\Phi_{*,0}$	γ	ϵ	$z_{\rm pivot}$	$\log_{10}L_{*,0}$	β	α (fixed)
Hα	2.92±0.03	1.30±0.12	1.86±1.40	1.53±0.12	41.59±0.03	1.91±0.08	-1.35
[OII]	1.89±0.04	-1.96±0.18	-2.48±0.21	1.00±0.02	40.73±0.02	2.61±0.08	-1.25

OIII

- External data (0.9 < z < 2.0)
- Fitting reasonably well with the model luminosity functions at all redshifts, including those coming from external datasets.
- Show an excess in the bright end.
  - AGN contamination
  - The contribution from starburst galaxies (Gonzalez-Perez et al. 2018)



- 4. Comparison to the literature

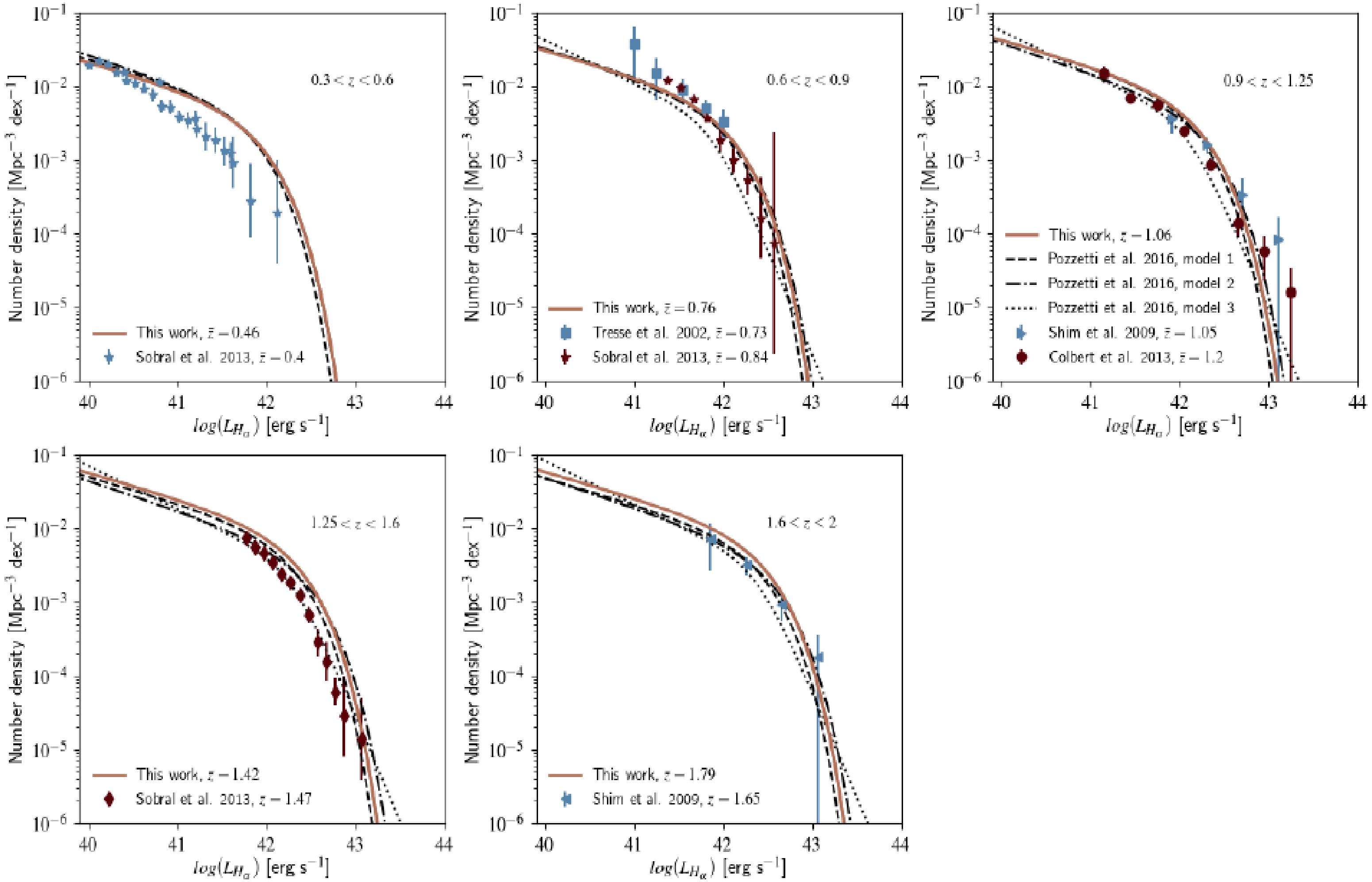
Hα

- There is an overall agreement with previous direct measurements
- Compare with Pozzetti et al. (2016)
  - A very good agreement between this paper and their model 1 and model 2 predictions. This model tends to fall in between those two models in the bright end.
- Compare to Valentino et al. (2017)
- Advantage here:
  - redshift-dependent dust attenuation
  - redshift and intrinsic luminosity dependences estimation error
  - consider photometric redshift error

Model 1: $L_{\star,z} = L_{\star,0}(1+z)^{\delta}$

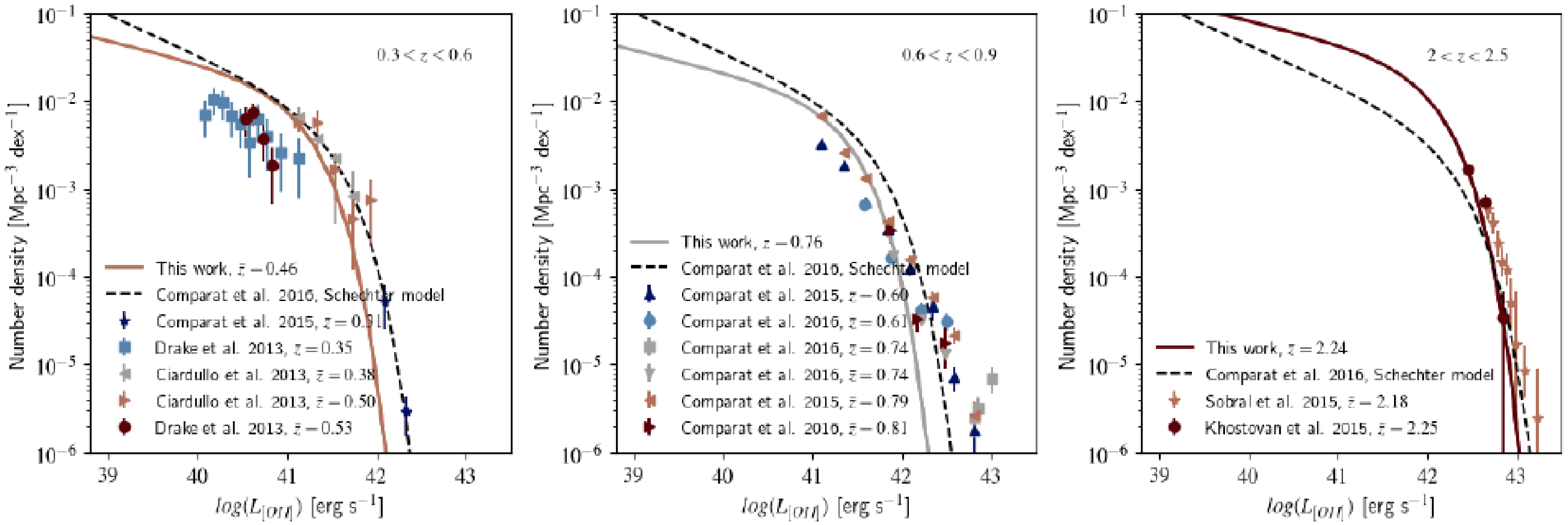
$$\phi_{\star,z} = \begin{cases} \phi_{\star,0}(1+z)^{\epsilon} & z < z_{\rm break} \\ \phi_{\star,0}(1+z_{\rm break})^{2\epsilon}(1+z)^{-\epsilon} & z > z_{\rm break}, \end{cases}$$

Model 2: $\log_{10} L_{\star,z} = -c(z - z_{\rm break})^2 + \log_{10} L_{\star,z_{\rm break}}.$



OIII

- Compare with Comparat et al. (2016)

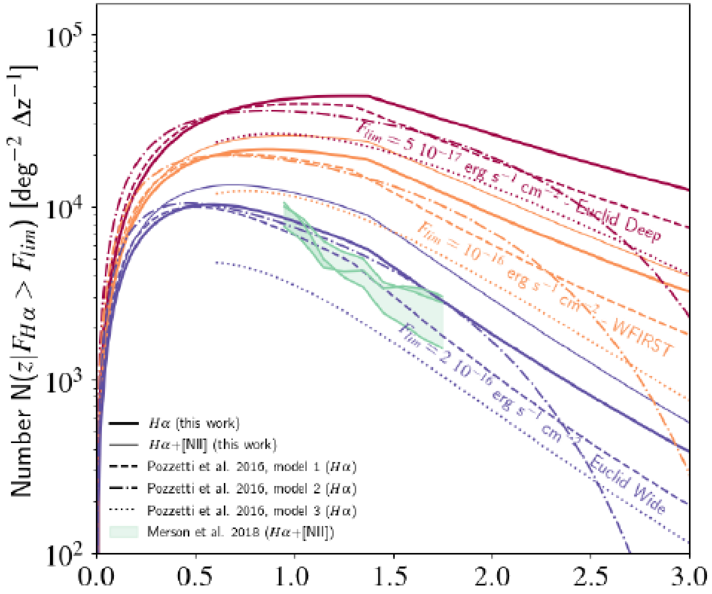


Prediction of Hα- and [OII]-emitter galaxy counts

- [Hα] Compare with Pozzetti et al. (2016)
  - The model here predicts more Hα-emitter galaxies than Pozzetti et al. (2016) and semi-analytical model (Merson et al. (2019)).
  - Flux limit bin:

Euclid
- $F_{H\alpha} = 2 \times 10^{-16} erg\ s^{-1} cm^{-2}$: 6484 ± 69 galaxies per deg^2
- $F_{H\alpha} = 5 \times 10^{-17} erg\ s^{-1} cm^{-2}$: 47955 ± 186 galaxies per deg^2

WFIRST
- $F_{H\alpha} = 10^{-16} erg\ s^{-1} cm^{-2}$: 28600 ± 144 galaxies per deg^2



- [OII] Forthcoming PFS detection and Comparat et al. (2016)

$$23.2 < g < 24.2 \ \ \& \ \ 0.05 < g - r < 0.35 \ \ \& \ \ \mathrm{SNR}_{[\mathrm{OII}]} > 6.$$

$$\overline{6\sigma(F_\lambda)} = 6.3 \times 10^{-17} \ \mathrm{erg\ s^{-1}\ cm^{-2}},$$

  - The model here predicts 8% less galaxies than Comparat et al. (2016)
  - Integrating the estimated PFS (SNR corrected) counts 0.6 < z < 2.4, an expecting number of 3886 ± 53 galaxies per deg^2