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Fast and accurate modeling of the Lyman-alpha forest for current and forthcoming surveys

Francesco Sinigaglia[1,2,3,4]

Francisco-Shu Kitaura, Kentaro Nagamine, Yuri Oku & Andrés Balaguera-Antolínez

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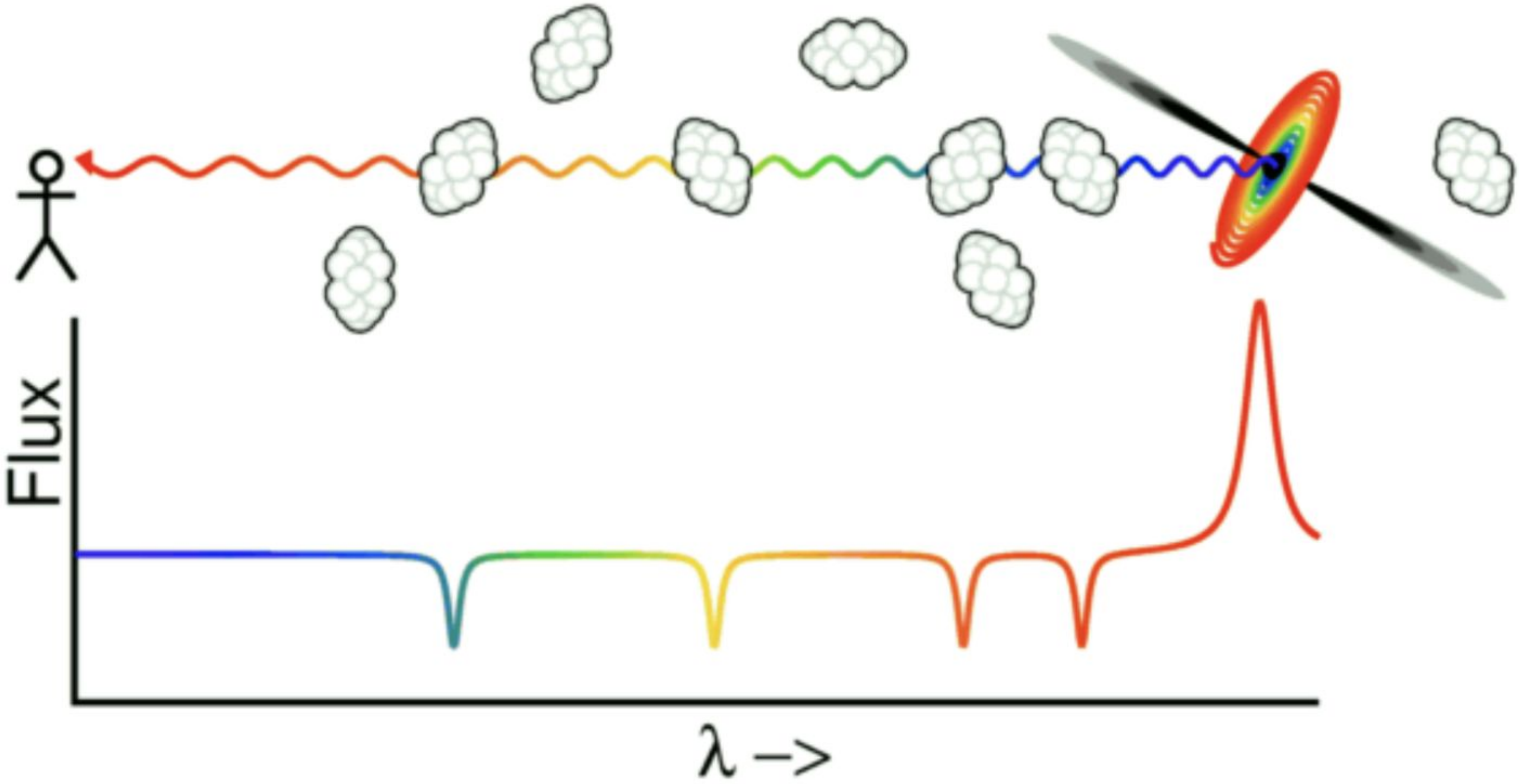
[1]Department of Physics and Astronomy, Università degli Studi di Padova, Vicolo dell' Osservatorio, 3, 35122 Padova, Italy
[2]INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122, Padova, Italy
[3]Instituto de Astrofísica de Canarias, Calle Via Láctea s/n, E-38205, La Laguna, Tenerife, Spain
[4]Departamento de Astrofísica, Universidad de La Laguna, E-38206, La Laguna, Tenerife, Spain

Outline and motivation

- Need for accurate Lyman-alpha forest modelling at the field level at coarse resolutions for fast large-volume mock lightcones generation
- Several efforts to do it: analytical, calibrated methods, machine learning
- Goal: expand and improve upon a widely-used analytical approximation (FGPA)
- We introduce further terms accounting for non-local bias
- We fit the free parameters of our model using a cosmological hydrodynamic simulation
- We assess the performance by testing the predicted summary statistics

The Lyman-alpha forest



The Lyman-alpha forest efficiently traces the matter distribution at z>1.8

T-web classification and non-local bias

$$\mathcal{T}_{ij}(\mathbf{r}) = \partial_i \partial_j \phi(\mathbf{r})$$

– a knot, if $\lambda_1, \lambda_2\, \lambda_3 \geq 0$;
– a filament, if $\lambda_1, \lambda_2 \geq 0, \lambda_3 < 0$;
– a sheet, if $\lambda_1 \geq 0, \lambda_2, \lambda_3 < 0$;
– a void, if $\lambda_1, \lambda_2, \lambda_3 < 0$.

Hahn et al. (2007)

	Real space (%)	Redshift space (%)
Knots	2.1	2.7
Filaments	21.4	21.9
Sheets	49.2	48.8
Voids	27.3	26.6

– $I_1 = \lambda_1 + \lambda_2 + \lambda_3$;
– $I_2 = \lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3$;
– $I_3 = \lambda_1\lambda_2\lambda_3$.

Kitaura et al. (2022)

– knots: $I_3 > 0\ \&\ I_2 > 0\ \&\ I_1 > \lambda_1$;
– filaments: $I_3 < 0\ \&\ I_2 < 0\ \|\ I_3 < 0\ \&\ I_2 > 0\ \&\ \lambda_3 < I_1 < \lambda_3 - \lambda_2\lambda_3/\lambda_1$;
– sheets: $I_3 > 0\ \&\ I_2 < 0\ \|\ I_3 < 0\ \&\ I_2 > 0\ \&\ \lambda_1 - \lambda_2\lambda_3/\lambda_1 < I_1 < \lambda_1$;
– voids: $I_3 < 0\ \ \&\ \ I_2 > 0\ \ \&\ \ I_1 < \lambda_1$.

FGPA in real and redshift space

$$T_{\rm gas} = T_0(\rho_{\rm gas}/\bar{\rho}_{\rm gas})^{\gamma}$$

→ Tight relation between temperature and matter density

After some algebra, one can write the Fluctuating Gunn–Peterson approximation (FGPA) → $$\tau = A(1+\delta_{\rm dm})^{\alpha}$$

Mapping from real to redshift space

$$\boldsymbol{s}_i = \boldsymbol{r}_i + \frac{(\boldsymbol{v}_i \cdot \hat{\boldsymbol{r}}_i)\,\hat{\boldsymbol{r}}_i}{aH}$$

→

$$\boldsymbol{s}_j = \boldsymbol{r}_j + b_v \frac{(\boldsymbol{v}_{{\rm dm},j} \cdot \hat{\boldsymbol{r}}_j)\,\hat{\boldsymbol{r}}_j}{aH}$$

Beyond the FGPA: non-local FGPA

1) Addition of a boosting and a damping terms →

$$\tau = A(1+\delta)^{\alpha} \exp\left(-\frac{\delta}{\delta_1^*}\right) \exp\left(\frac{\delta}{\delta_2^*}\right)$$

$$\tau = A_i(1+\delta)^{\alpha_i} \exp\left(-\frac{\delta}{\delta_{1,i}^*}\right) \exp\left(\frac{\delta}{\delta_{2,i}^*}\right)$$

→ 2) Make the model cosmic web dependent

3) Add stochasticity to model small-scale power

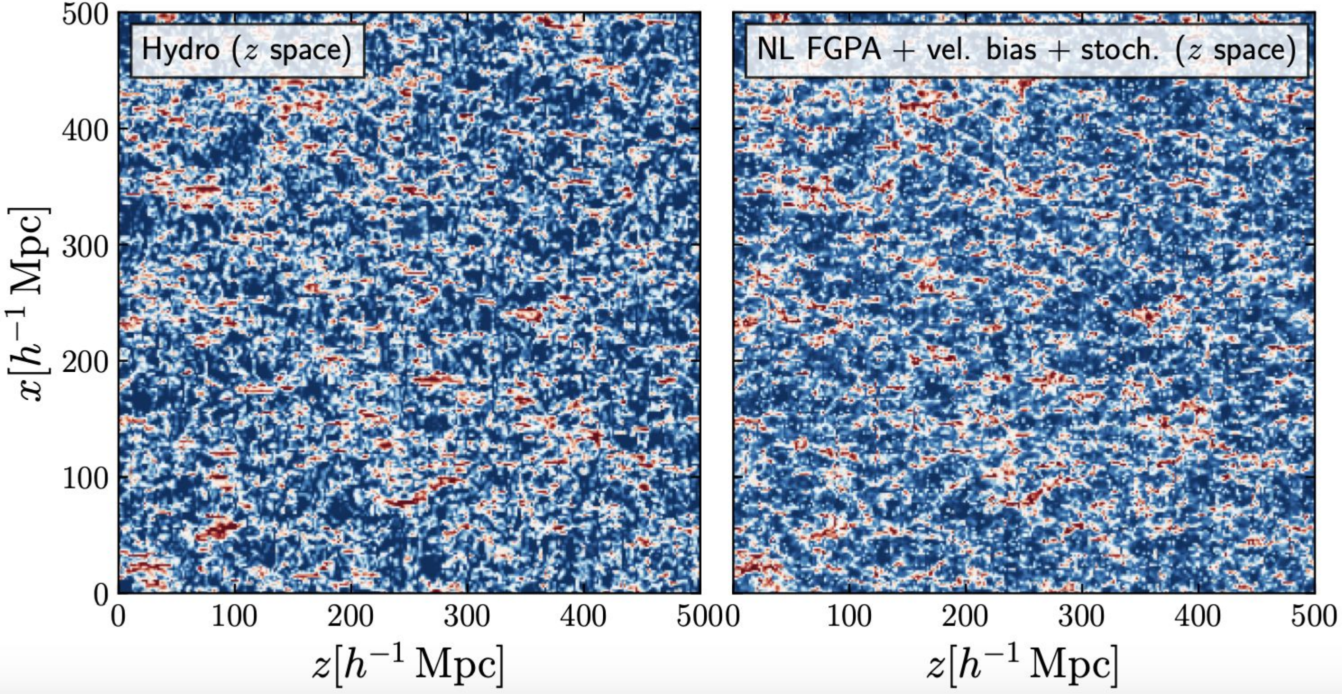
$$\tau = A_i(1+\delta)^{\alpha_i} \exp\left(-\frac{\delta}{\delta_{1,i}^*}\right) \exp\left(\frac{\delta}{\delta_{2,i}^*}\right) + \epsilon \longrightarrow P(N\,|\,n,p) = \frac{\Gamma(N+n)}{N!\,\Gamma(n)}\, p^n (1-p)^N$$

4) Fit model parameters via an efficient MCMC scheme →

$$P(\rho(F)\,|\,\theta) = \prod_F \frac{1}{\sqrt{2\pi\sigma_F}} \exp\left[-\frac{(\rho_{\rm ref}(F)-\rho_{\rm mock}(F))^2}{2\sigma_F^2}\right]$$

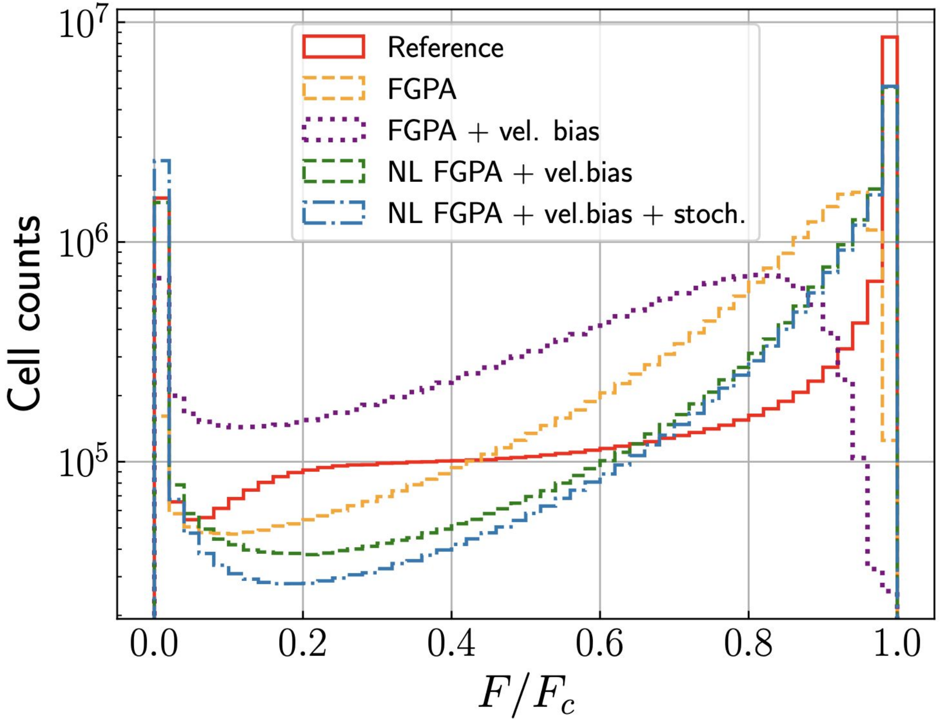
Results: Ly-alpha forest flux slices

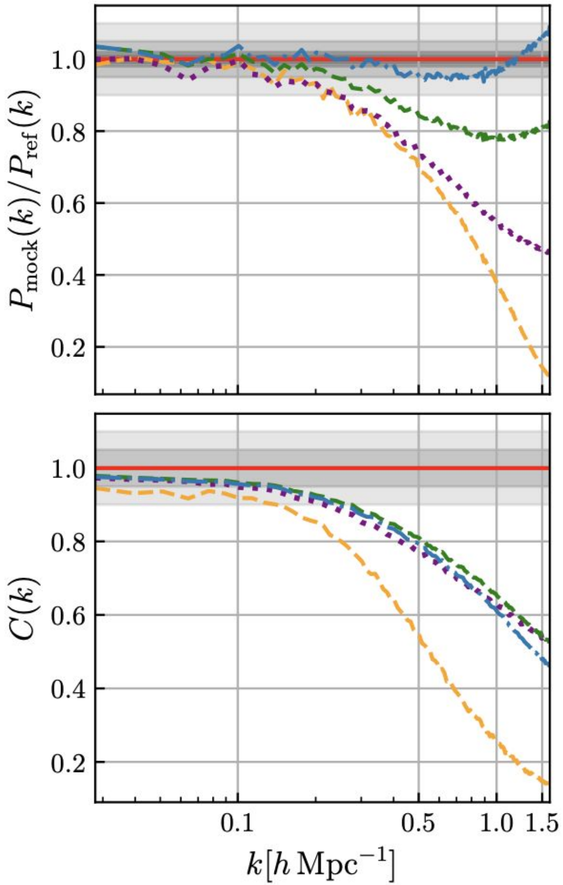
Reference simulation: 500 Mpc/h box size, 1024^3 particles, detailed galaxy formation physics, ~2 Mpc/h cell size mesh resolution



Our model visually resembles much more accurately the reference simulation

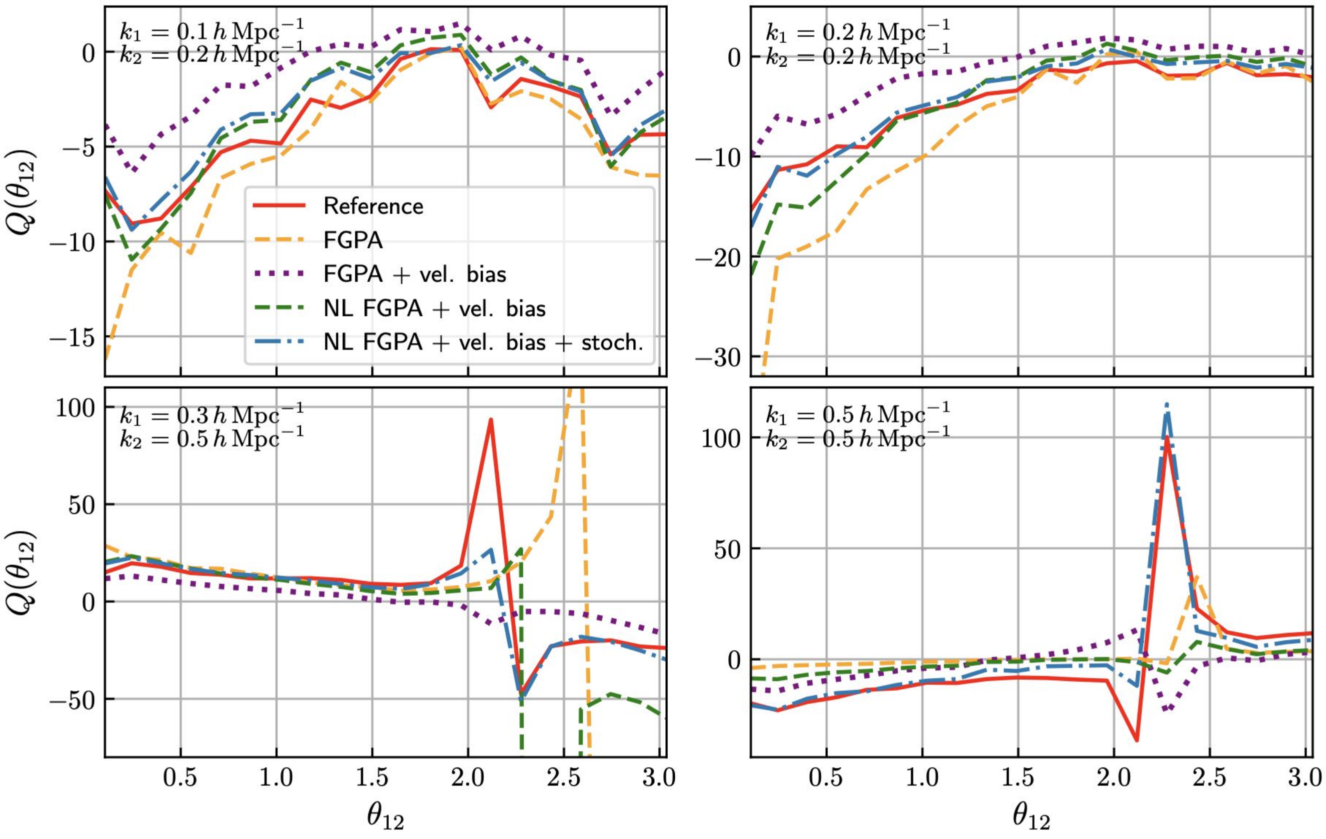
Results: PDF, power spectrum and cross-correlation





Our model outperforms the other tested models in the one- and two.point statistics

Results: reduced bispectrum



Our model improves the other tested models in reproducing the three-point statistics and captures peculiar features which other models fail to replicate

Summary & conclusions

- Devised a method to predict the Lyman-alpha forest expanding upon the FGPA
- We explicitly modelled non-local bias & a damping and a boosting term
- The summary statistics predicted by our model outperforms the standard FGPA
- Currently being used to study BAO prediction, coming soon!
- Our model can be used to generate fast mock Lyman-alpha forest lightcones, to perform reconstruction, and to quickly simulate the Lyman-alpha forest to study 3D correlations