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Baryon acoustic oscillations in HI intensity mapping-galaxy clustering cross-correlation

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Summary. — Constraining cosmological parameters in the post-reionisation era (below redshift $\sim$ 4–5) via the radio emission of neutral hydrogen, a technique known as Intensity Mapping (IM), is one of the main goals of the forthcoming Square Kilometer Array (SKA). Baryon Acoustic Oscillations (BAO) are a relatively large-scale phenomenon, for the most part captured by linear theory, unlikely to be imitated by other physical processes and depending on fundamental cosmological quantities (the sound horizon is a function of the Hubble parameter). All these features justify their role as a benchmark for future instruments which will look for their signal in the sky. Despite the low transverse resolution, their footprint may be recovered in the radial power spectrum, as already shown in the literature. Here we compare those results with the cross-correlation of IM and galaxy surveys, a possible future synergy between SKA and the ESA flagship mission *Euclid*.

1. – Introduction

In the incoming decade, the Square Kilometer Array (SKA) radio-telescope and the ESA satellite *Euclid*, observing in visibile and infrared light, will pick up the legacy of the Cosmic Microwave Background-dedicated missions of the '90s and '00s, that collected the most precise measurements of cosmological fundamental quantities so far.

Whilst the latter were observing a 400000 years old universe, at the very end of its primordial phases, both SKA and *Euclid* will study the late Universe, *i.e.*, the cosmic epochs at z comprised between 6 and 0. During this temporal extension, the Universe assumed its present shape: it saw the birth of the first stars and galaxies, that would organise in the Large-Scale Structure (LSS), and a massive depletion of neutral hydrogen (HI) during the reionisation epoch, whose contribution to the baryon density parameter reduced, from being the dominant component, to an abundance Ω_{HI} of about 10^{-4}.

SKA will look for the HI that made it to the post-reionisation epoch by measuring its characteristic 21 cm transition: a standard method in astrophysics, the weakness of the signal limited until recently the use of this observable in cosmology. SKA will be able to observe such spectral line via HI Intensity Mapping (IM), a technique devised to collect large amounts of signal faster than galaxy surveys. Both *Euclid* and SKA are

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(*) Master Degree in Physics; E-mail: `andrea.rubiola97@gmail.com` expected to collect a large amount of data, $\sim O$ (Internet traffic/year): the forecasting effort before their activation is therefore of the utter importance.

2. – Theoretical foundations

Main tools for the study of LSS are the two-point correlation function (2PCF) —measuring the excess of probability of finding a pair of tracers, such as galaxies, at a given distance r with respect to random distribution— and its Fourier transform, the power spectrum (PS), telling us, for every given mode k (inverse of the scale, being $k \propto 1/r$), how important the contribution of matter (its "power") is. Now, in addition to the principal peak around 5 Mpc/h (as customary in cosmology, we set $H_0 = 100h$ km s^{-1} Mpc^{-1} and rescale every quantity accordingly; thus, distances are expressed in Mpc/h), the 2PCF shows a smaller secondary bump around 100–105 Mpc/h, whose PS counterpart is a characteristic "wiggled" signal.

Those "wiggles" are the footprint of Baryon Acoustic Oscillations (BAO), a consequence of the past coupling of baryonic matter and radiation. Until $z \sim 1000$, radiation pressure prevented baryons from collapsing under their gravity, determining sound waves in the matter with an acoustic horizon r_s of about 100–105 Mpc/h. After decoupling, baryons progressively realigned with the dark matter distribution, retaining the "memory" of the r_s scale, observable today as a distinct preferential distance among galaxies —a standard ruler. Due to SKA low transverse resolution in HI IM, a Gaussian beam with typical smoothing scale R of 20–50 Mpc/h at $z = 1$–2, BAO detection in the sky-averaged PS, the *monopole*, may be challenging or unfeasible; on the other hand, they should be efficiently detected in the *radial* PS [1], defined as

$$P\left(k_\parallel, z\right) = \frac{1}{2\pi}\int_{k_\parallel}^{\infty} dk_\perp \; k_\perp P_\mathrm{3D}\left(k_\parallel, k_\perp, z\right) \tag{1}$$

Equation (1) averages the PS on the low-resolution transverse modes: the larger $k_\perp$, the more important the signal loss. However, BAO are a middle-to-large-scale spectral feature, *i.e.*, at low $k_\perp$, whose relative weight is enhanced by integration. In other words, SKA will detect BAO provided we accept a trade-off with a radio brightness temperature sensitivity of some hundredths of mK.

We want then to test BAO detection cross-correlating a simulated SKA HI IM observation with a typical *Euclid* galaxy survey, only affected by a small radial resolution limit σ_r in the order of 5 Mpc/h at $z = 1$–2, again modelled with a Gaussian beam. Noise sources being uncorrelated, the signal will be automatically cleaned: thanks to their technical complementarity, interaction between *Euclid* and SKA is expected to be a standard practice for the cosmology of tomorrow. In our model, the PS is convolved with instrumental effects as well as tracer-specific bias factors (see [2]); redshift-space distortions, a kinematic effect on the cosmological fluid, are also taken into account. To enhance the realism of our results and differently from [1], a non-linear PS, calculated with the standard `halofit` method by the software `hmf` [3], is used. Finally, errors are assigned as standard Gaussian uncertainties, assuming a k-diagonal correlation matrix [4].

3. – Data generation and analysis

Once obtained the theoretical PS, we assign it as the mean value of a Gaussian random number generator, whose variance is the square of Gaussian uncertainties; this way, we scatter deterministic data similarly to real observational data. 100 PS realisations are thus fitted against the template:

$$P_{\mathrm{fit}}(k_{\parallel}, z) = [P_{\mathrm{w}}(k_{\parallel}/\alpha, z) - P_{\mathrm{nw}}(k_{\parallel}/\alpha, z)] + P_{\mathrm{nw}}(k_{\parallel}, z). \tag{2}$$

Here BAO appear as a "wiggled" P_{w} added in the proper region to a no-wiggles PS, P_{nw}; we use the standard transfer functions published in [5]. We fit the model via the MCMC sampler `emcee` [6], having defined the following parameter set: $\{\alpha, bias_{\mathrm{g}}, bias_{\mathrm{HI}}, R, \sigma_{\mathrm{r}}\}$. The focus is on α, equal to 1 if data and the reference cosmology adopted in the model (in our case, standard ΛCDM) correspond. Being at the denominator of $k_{\parallel}$, *i.e.*, the modes along the radial expansion direction, α indirectly measures the Hubble parameter at the given redshift, in the spirit of the so-called Alcock-Pasczynski test. We repeat the fit for a pure P_{nw} and evaluate the significance of BAO detection calculating for every fit $\sqrt{\chi^2_{\mathrm{fit,nw}} - \chi^2_{\mathrm{fit,w}}}$, which distributes as the number of σ. We compare the results with an analogous HI autocorrelation fit at $z = 0.9$, $z = 1.35$ and $z = 2.0$, within SKA and *Euclid* observational windows. Results are summarised in fig. 1, from which we infer:

- BAO detection methods can be compared, yielding a good significance at $z = 0.9$ and $z = 1.35$ ($\gg 3\sigma$), but cross-correlation fails in the farthest redshift bin. Such dynamics can be reconstructed also by looking at the SNR behaviour (fig. 2).
- At $z = 0.9$ and $z = 1.35$, α peaks narrowly around 1.00, within 5% of the prior; at $z = 2.0$, while for autocorrelation the best-fit values remain within about 10% of the prior, cross-correlation shows many distant outliers. Remarkably, α only

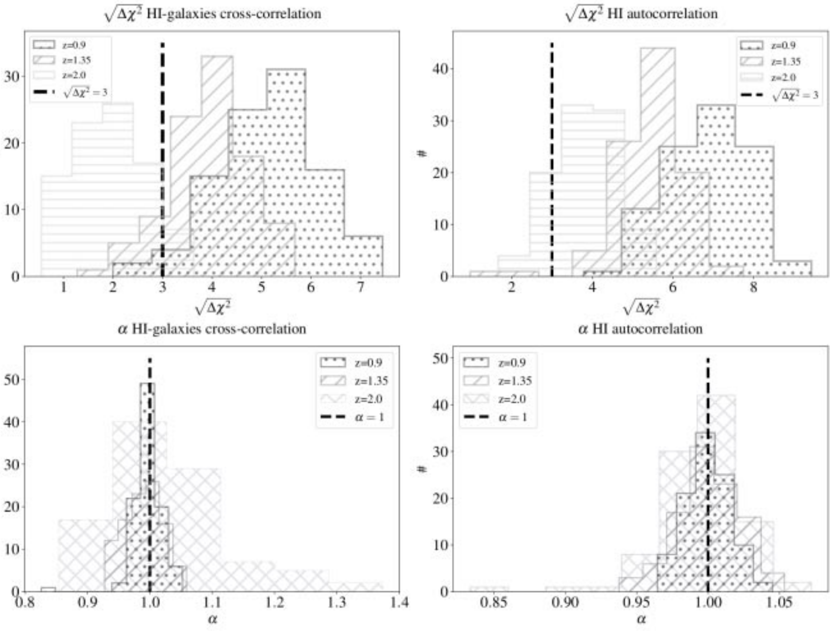

Fig. 1. – BAO detection significance (in σ) throughout 100 PS realisations in both methods and α posteriors. Simulation box size ($2000 \times 2000 \times 1000$ Mpc$^3/h^3$) and voxel size ($8 \times 8 \times 1.1$ Mpc$^3/h^3$) are defined to satisfy resolution requirements for all redshift bins at the same time.

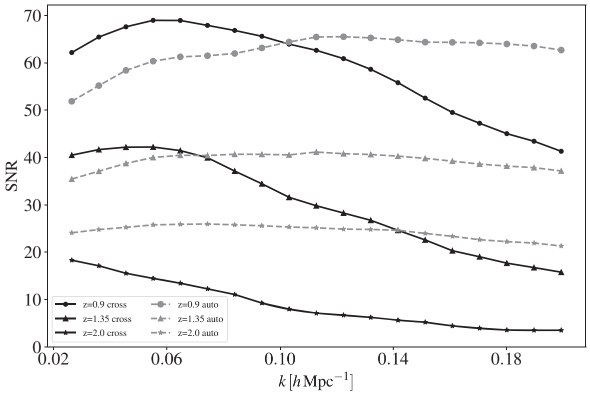

Fig. 2. – SNR for autocorrelation (dashed line) and cross-correlation (solid line) at the BAO scale, the former prevailing at large k and for $z = 2$. An important contribution to the different slopes and trends should be imputed to the shot-noise, influencing the sole cross-correlation uncertainties.

weakly correlates with instrumental parameters: robustness is important given its role as a cosmological indicator.

4. – Conclusions

Our results are somehow preliminary, using a method alternative to simulation software after the insurgence of some technical issues, whose solution proved difficult in the limited timespan of a graduation work, as confirmed once the author could eventually access a fully working simulation with a view to a final publication. However, future results are not expected to significantly diverge from what discussed above: the robustness of α is confirmed by the literature and the detection of the BAO in the radial PS is supported by a first inspection of the simulation output.

We believe the main value of this work to be the insight it provides into 21st century's cosmology, a discipline aiming at a growing precision of measurements: an achievement to be obtained thanks to the dialogue among different instruments and intertwining astrophysical-cosmological observables, each providing its own tracer-specific contribution to our effort to understand the universe.

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