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BAO from HI intensity mapping: The role of multipoles and cross-correlations(*)

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Summary. — A standard ruler akin in application to standard candles, Baryon Acoustic Oscillations (BAO) are a main feature of the matter power spectrum, depending on fundamental quantities cosmologists are striving to measure. The SKA Observatory (SKAO) will look for their signal in the post-reionisation universe via neutral hydrogen Intensity Mapping, a task made challenging by astrophysical foregrounds and resolution limitations. To tackle these issues, we investigate the results emerging from the multipole expansion approach as a mitigation of such limitations and we showcase the gains made from cross-correlating the HI intensity mapping with spectroscopic galaxy observations. This is to be intended as an anticipation of future synergies between the SKAO Project and LSS Stage 4- or DESI-like instruments. Adding then the information from the quadrupole term allows for a detection of the BAO feature up to 4.5–6 σ at the lowest redshifts, providing robust constraints on the radial Alcock-Paczyński parameter (a proxy for the Hubble parameter). On the other hand, the corresponding perpendicular parameter remains unconstrained and prior dominated due to beam effects.

1. – Introduction

Precision cosmology is expected to thrive in the current and forthcoming decade. A number of instruments and spacecrafts, *e.g.*, DESI, the Vera Rubin Observatory, Euclid or the Nancy Grace Roman Telescope, will enable cosmologists to combine the properties of traditional galaxy surveys with alternative large scale structure (LSS) tracers. Much expectation relies on the 21 cm HI Intensity Mapping (IM) measurements the SKAO radiotelescope will perform; further cross-correlations with a number of other observables, from galaxies to gravitational waves, will probe most part of the cosmic evolution after the CMB formation at $z \approx 1100$.

Such synergies will provide a number of benefits. Resorting to the habitual 2-point power spectra and correlation functions as well as to higher order statistics, two main goals are being sought:

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- Control and elimination of instrumental systematics or astrophysical foregrounds, to be disentangled from the cosmological signal.
- Constraining parameters independently or in combination with Planck past observations as well as future CMB Stage 4 campaigns, thus breaking or mitigating degeneracies and increasing the level of precision and accuracy of our measurements. Such task is fundamental to refine our understanding of the tensions in the standard cosmological ΛCDM model.

2. – Methodology

Baryon acoustic oscillations are the signature imprinted in the LSS of the acoustic horizon at the baryon-radiation decoupling redshift ($z \approx 1100$). The correlation length ($\approx 150\,\mathrm{Mpc}$) thus induced on the LSS and its tracers acts as a statistical standard ruler, allowing the partly direct, partly indirect measurement of fundamental cosmological quantities. Our test of BAO detection in HI IM, a relevant result the SKAO is expected to achieve, has therefore two main objectives:

- Assessing the number of significant BAO detections in the HI IM auto-correlation and cross-correlation with a LSS Stage 4-like galaxy survey power spectra, taking advantage of their complementarities. Namely, the former has excellent radial resolution and a very poor transverse one, whereas the opposite is true for the latter.
- Indirect estimation of the constraining power of IM on the Hubble parameter $H(z)$. The radial and transverse size of the sound horizon can indeed be scaled in the power spectrum (PS) via the usual Alcock - Paczyński (AP) test parameters $\alpha_\parallel$, $\alpha_\perp$. Under the isotropy condition and if the underlying cosmology correctly fits the data – or, the fit properly recovers the cosmology underlying the simulations – $\alpha_\parallel$ and $\alpha_\perp$ are equal to 1.

Simulation and analysis: the multipole formalism at $0.9 < z < 2.0$. – We analyse the output of a suite of log-normal simulations, 100 for each of the three selected redshift bins ($z = [0.9, 1.35, 2.0]$). The limited radial (for the spectroscope) and transverse resolutions (for the radiotelescope) of the instruments are modelled as Gaussian beams; radio foregrounds are injected in the HI maps and subsequently cleaned via Principal Component Analysis, a promising blind method based on the statistical properties of the signal variance [1]. The fitting template follows [2], inclusive of the terms in [3], *i.e.*, redshift space distortions (RSD) and foreground/volume compensation windows, reading

$$P(k,\mu,z) = P_{nw}(k,\mu,z) + \frac{1}{\alpha_\perp^2 \alpha_\parallel}\left\{P_w\left[k(\alpha_\parallel,\alpha_\perp),\mu,z\right] - P_{nw}\left[k(\alpha_\parallel,\alpha_\perp),\mu,z\right]\right\}. \tag{1}$$

Equation (1) is then multiplied by the Legendre polynomial associated to each multipole and integrated on the cosine μ. The scheme combines a flat PS P_{nw} with a "wiggled" contribution P_w; a null fit against the pure P_{nw} is also performed.

3. – Discussion and results

BAO detection significance. – BAO detection is assessed by calculating the $\sqrt{\Delta\chi^2}$ between eq. (1) and the null fit outcome. Inspection of fig. 1(a) shows the significance

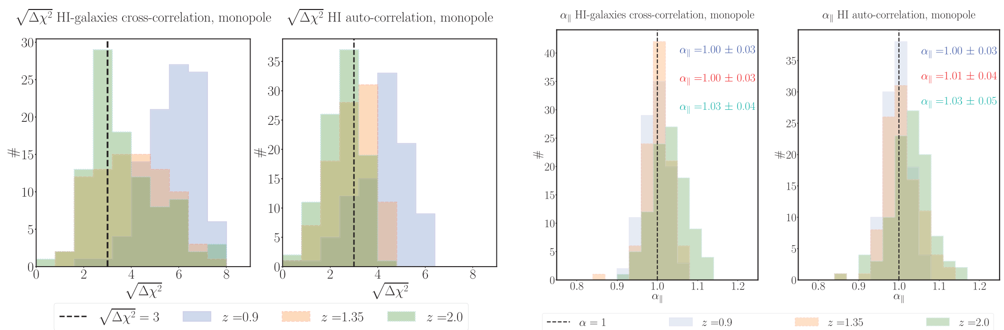

Fig. 1. – Left: detection significance in the monopole at the three chosen redshifts, in both cross-correlation (left) and auto-correlation (right). Right: $\alpha_\parallel$ posteriors distribution, same conditions of panel (a). Best fit parameters are typically clustered around the fiducial value of 1.0 within 10%.

decreasing with redshift. Starting from the 5-6 σ reached by both the monopole and the quadrupole at $z = 0.9$, the detection efficiency remarkably drops at $z = 2.0$.

Alcock-Paczyński test. – $\alpha_\parallel$ (fig. 1(b)) is typically well reconstructed at all z (within 10% of the fiducial value), the dispersion increasing together with the inception of a slight bias at $z = 2.0$. $\alpha_\perp$ is in turn prior-dominated and, due to poor transverse IM resolution, unconstrained.

The role of the SNR. – The SNR plot (fig. 2) allows a comparison between the error bar size and the signal, thus assessing to what extent the BAO feature can be resolved from the flat PS. The cross-correlation signal always dominates its auto counterpart, with a noteworthy plateau being reached right at the BAO scale for both multipoles. Both auto- and cross-correlation decrease with z, and, in general, a trade-off involving transverse beam damping and noise terms is determinant in establishing the detection efficiency.

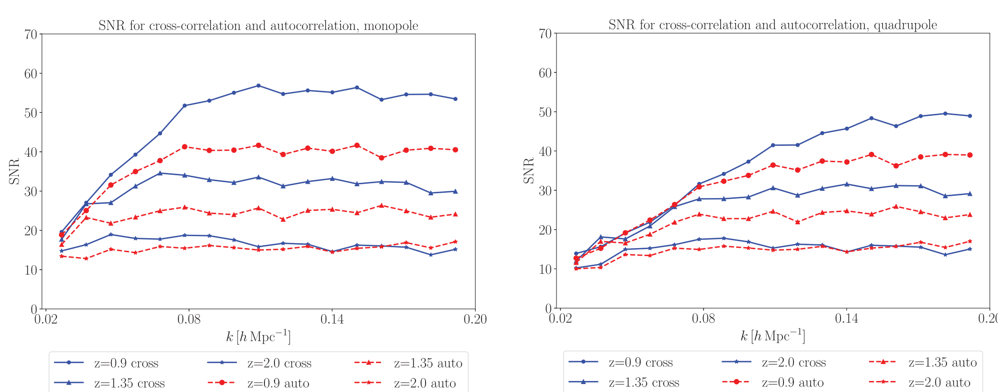

Fig. 2. – SNR for the monopole (left) and the quadrupole (right).

4. – Conclusions and perspectives

Our setup, although simplifying some of the real-world challenges scientists are progressively becoming aware of, displays encouraging results for future IM - galaxy clustering synergies.

- The quadrupole BAO detectability is relevant in that it implies the measurement of higher order effects, such as RSD.
- Galaxy-IM cross-correlation is a good strategy to improve BAO detectability; nevertheless, low-z HI autocorrelation proves competitive.
- Concerning the effect of systematics, we demonstrated the power of blind foreground cleaning techniques, provided one correctly compensates for cosmological signal removal at the largest scales. The good outcome of AP test in the radial direction contrasts with the poor $\alpha_{\perp}$ posteriors, a behaviour confirmed in similar literature [4, 5]. The above-mentioned systematics represent the main obstacles to single-dish observations [6].
- SNR can be leveraged as an insightful tool to interpret and optimise observations. To improve it, a monopole-quadrupole joint fit was also considered. By feeding the likelihood with both pieces of information at a time, we further enhanced the differential BAO detection assessment and shrunk some of the posteriors contours. Combined with larger – yet attainable by the SKAO – observational volumes and longer signal integration times, the approach can be considered in parallel or alternatively to more sophisticated estimators, like those described in [2, 3]. Alternative standard rulers, such as the turnover scale, can also be considered [7].

It is worth concluding by mentioning that [8] announced the detection of the cross-correlation PS signal between WiggleZ and MeerKat (an SKAO precursor) in June 2022, effectively shifting 21 cm single-dish observations from the realm of simulations to actual data. The next step to be taken, from the broadband fit of the PS shape and amplitude to the resolution of specific features, notably, the BAO "wiggles", is a challenging task. Yet, if successful, it will mark a milestone moment for the new age of cosmology.

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