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BAO from HI intensity mapping: studying the importance of cross-correlations in the monopole and the quadrupole

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Our paper (arXiv:2111.11347)

Baryon acoustic oscillations from HI intensity mapping: the importance of cross-correlations in the monopole and quadrupole

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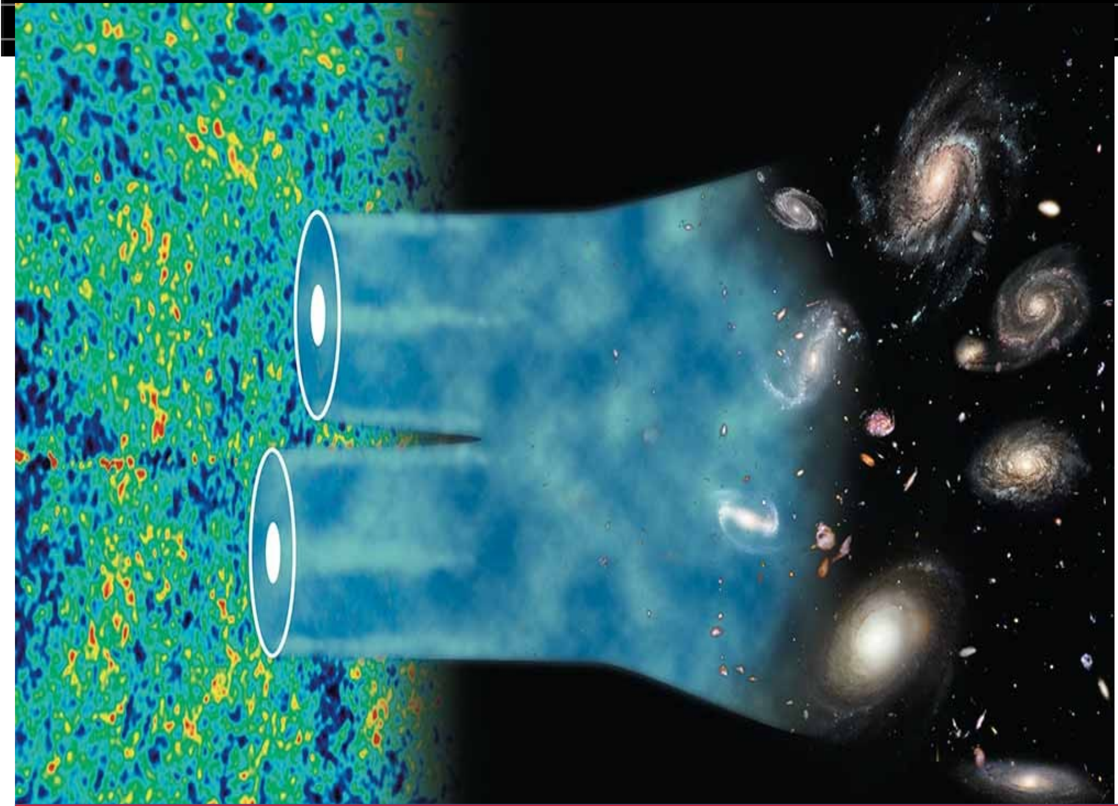
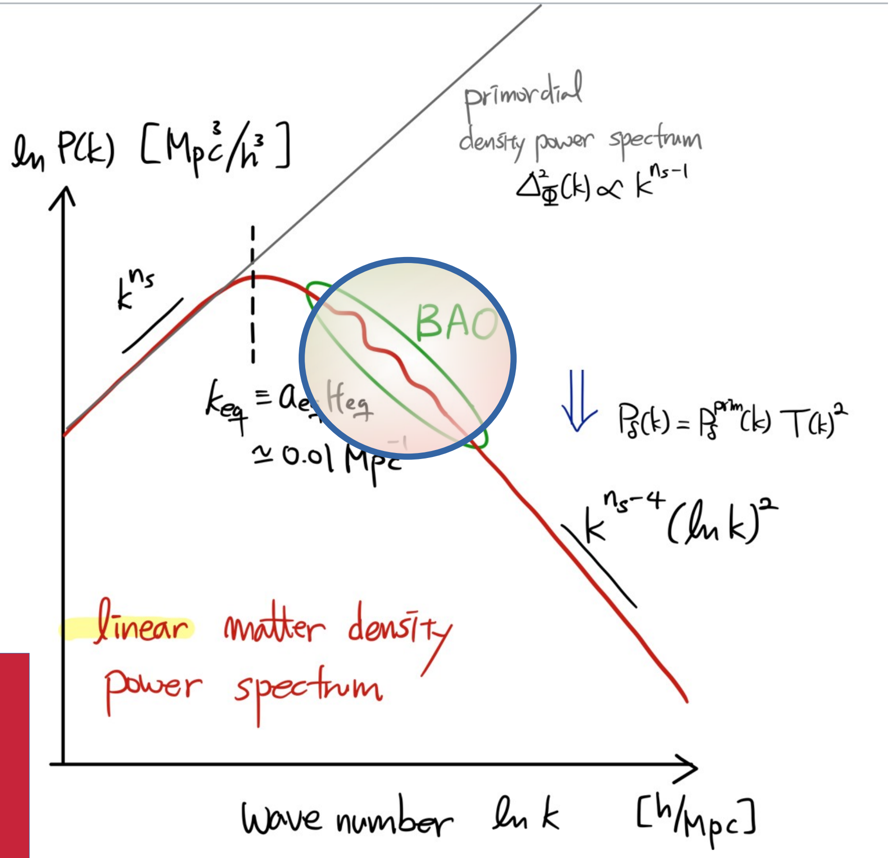
- ✔ Work embedded in SKAO forecasting effort; LSS in Late Universe as new key target for cosmologists.
- ✔ Submitted to MNRAS, currently under peer-reviewing process.
- ✔ Direct link to (*Cunnington et al. 2020; Soares et al. 2020*; *Avila et al., 2021; Kennedy, Bull, 2021*), "Fourier transform" of the latter works.
- ✔ We aknowledge counseling and support to a number of HITS attendants. Paper was written in spite of major threats to scientific collaboration, e.g. COVID-19 waves, England – Italy Euro 2020 final...

Why BAO?





Baryon matter-radiation coupling, ended at z=1000.

Robust, peculiar signal surviving to baryon–DM realignment

Standard ruler (~ standard candles).

Fit in the power spectrum $\Longleftrightarrow$ constrain ΛCDM model

(*Eisenstein et al., 2005; Coles et al., 2005*)

... the importance of *cross* - correlations

- ✔ So far, discussed from the SKAO *(Bacon et al., 2017)* and hence of HI IM point of view.
- ✔ Soon, complementary technology available (Euclid, optical and infrared spectroscopy, weak lensing, *Blanchard et al., 2019*) or will be in a longer time horizon.
- ✔ In space: Nancy Grace Roman (infrared wide field, BAO measurement, weak lensing, *Spergel et al., 2015*), SPHEREx (infrared spectro-photometer, f_{NL}, HI measurements, *Doré et al., 2015)*.
- ✔ On Earth: DESI (spectroscopy, *DESI collaboration, 2016)*, Vera C. Rubin Observatory (optical probing of LSS, *LSST Collaboration*, 2018)
- ✔ Exploit signal complementarities (*Wolz et al., 2021*): resolution along different axes, min/max redshift, acquisition time, breaking of degeneracies.

...In the monopole and the quadrupole (*Rubiola, Cunnington, Camera, 2021*)

- ✔ Focus on the monopole (P_0) and the quadrupole (P_2) in the 0.9-2.0 redshift interval: wide literature and expertise available (*Cunnington et al., 2020; Soares et al., 2020*)
- ✔ Usual "modular" construction of the full power spectrum. Presence of a compensation factor: $B_{\rm fg,vol}$. Volume selection cut-off and excess power removal by PCA at the largest scales, with depletion of cosmological signal

$$P^{\ell}_{\rm HI,g}(k,z) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu\ \mathcal{L}_\ell(\mu)\mathrm{e}^{-k^2/2[R^2(1-\mu^2)+\sigma_r^2\mu^2]} b_{\rm HI}(z)\overline{T}_{\rm b}(z)b_{\rm g}(z)P_{\rm m}(k,z)\left[1+\frac{f(z)}{b_{\rm HI}(z)}\mu^2\right]\left[1+\frac{f(z)}{b_{\rm g}(z)}\mu^2\right]B_{\rm fg,vol}(k,\mu)$$

$$P^{\ell}_{\rm HI,HI}(k,z) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu\ \mathcal{L}_\ell(\mu)\mathrm{e}^{-k^2[R^2(1-\mu^2)]} b^2_{\rm HI}(z)\overline{T}^2_{\rm b}(z)P_{\rm m}(k,z)\left[1+\frac{f(z)}{b_{\rm HI}(z)}\mu^2\right]^2 B_{\rm fg,vol}(k,\mu)$$

Our recipe

WHAT WE NEED

- ✔ Euclid – SKAO overlapping z (0.9, 1.35, 2.0); galaxy density as (*Blanchard et al., 2019*).
- ✔ In the HI map, inject some thermal noise, 10,000 h of single-dish observations, (*Bacon et al. ,2019*)
- ✔ Underlying cosmology and PK: use some of Nbodykit (*Hand et al., 2017)* and HMF (*Murray et al., 2013)* features. Introduce BAO via (*Eisenstein, Hu, 1998*), mimick non-linearity via `halofit` (*Takahashi et al., 2012*) prescription.

WHAT WE DO

- ✔ Log-normal realisations *(Coles et al., 1991; Beutler et al., 2011).* (2400^2x600 Mpc/h, grid 400^3) fixed-volume mocks. Sky fraction decreasing from 12% to 5%.
- ✔ 100 log-normal sims for each z (*Villaescusa – Navarro et al.*, 2016).
- ✔ PyGSM (*A. de Oliveira-Costa et al., 2008; Zheng et al., 2016*) for radio foregrounds contaminating cosmological HI signal.
- ✔ Foreground "blind" removal via PCA (*Spinelli et al., 2021*; *Cunnington et al., 2019*), 4 main components detected.
- ✔ Auto- and cross-correlate HI and galaxy maps, extract monopole and quadrupole *(Blake, 2019).*
- ✔ Extract empirical errors from the sample variances and covariances, to be compared with analytic formulae.

Fitting template (*Villaescusa-Navarro et al., 2016*)

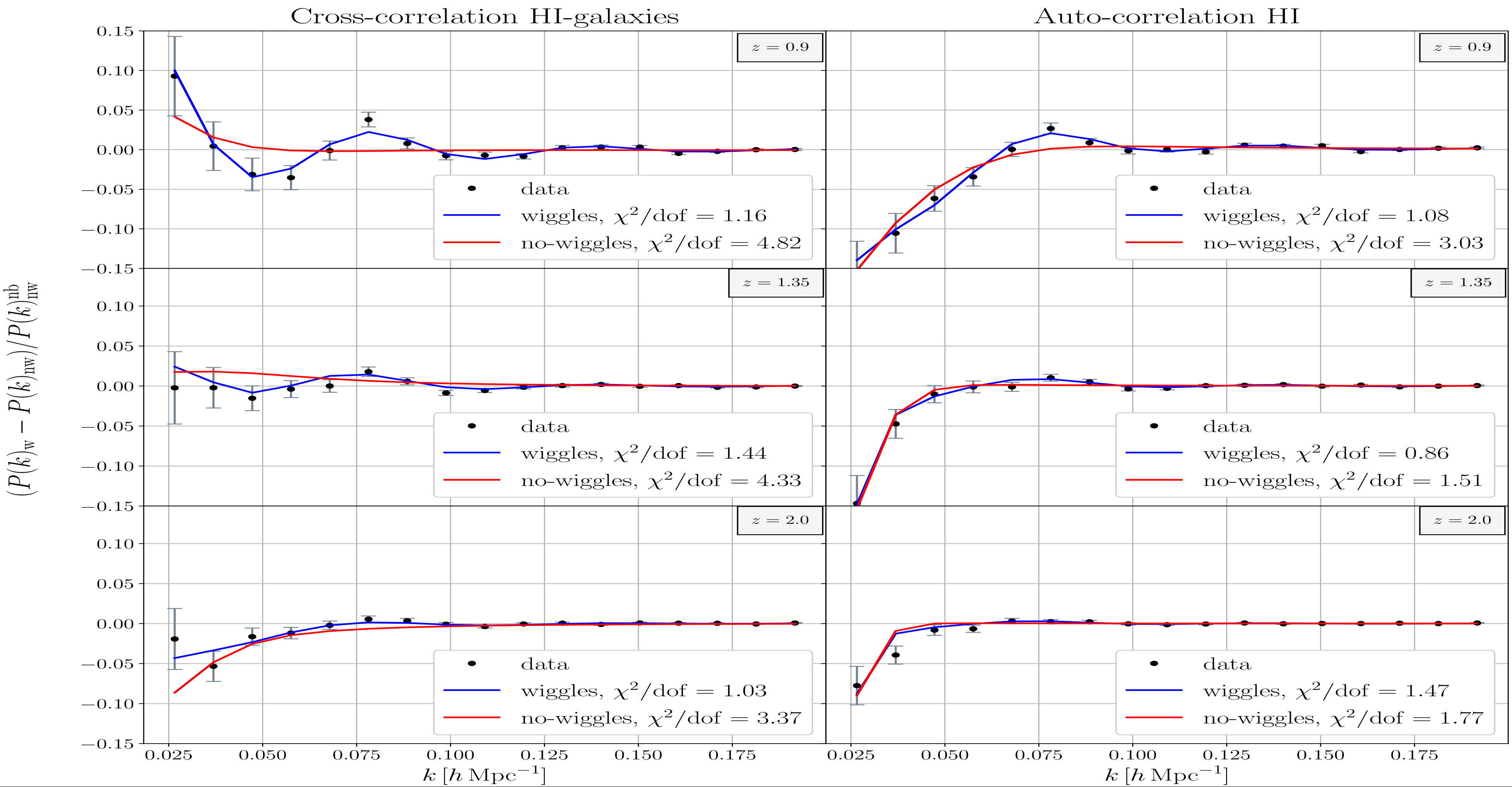
$$P_{\rm fit}(k,\mu,z) = P_{\rm nw}(k,\mu,z) + \frac{1}{\alpha_\perp^2\alpha_\parallel}\left\{P_{\rm w}\left[k\left(\alpha_\parallel,\alpha_\perp\right),\mu,z\right] - P_{\rm nw}\left[k\left(\alpha_\parallel,\alpha_\perp\right),\mu,z\right]\right\},$$

$$P_{\rm null}(k,\mu,z) = P_{\rm nw}(k,\mu,z)$$

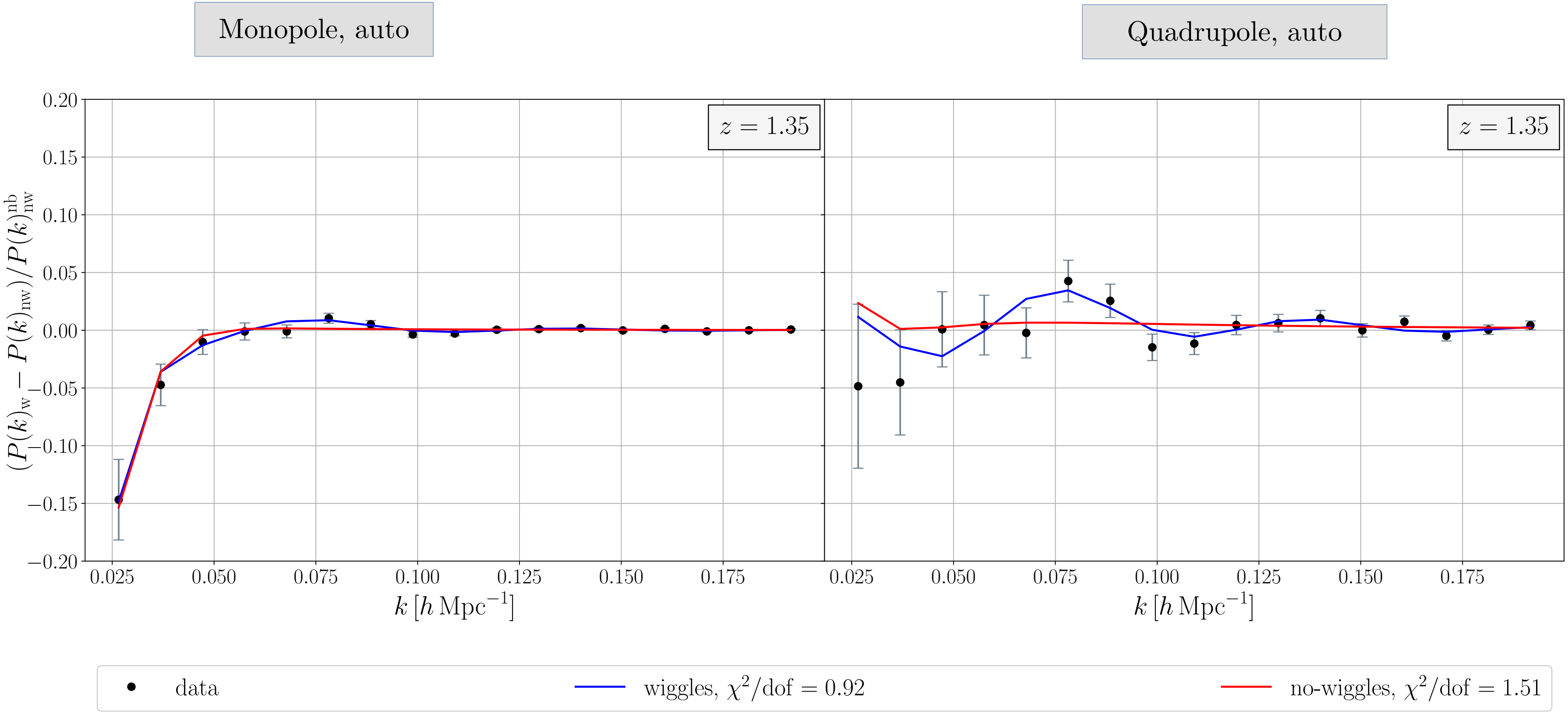
$$\Theta = \{\alpha_\parallel,\alpha_\perp,b_{\rm g},b_{\rm HI}\overline{T}_{\rm b},R,\sigma_{\rm r},n_\parallel,n_\perp\}$$

- ✔ $\sqrt{\Delta\chi}$ with *nw* to assess detection significance
- ✔ Alcock-Paczynski formalism (*Alcock & Pasczynski, 1979*) to evaluate agreement with the reference cosmology (ΛCDM) underlying our sims
- ✔ "Nuisance parameters": bias, beam factors, FG compensations
- ✔ Assign Gaussian analytic uncertainties (*Blake,2019*)

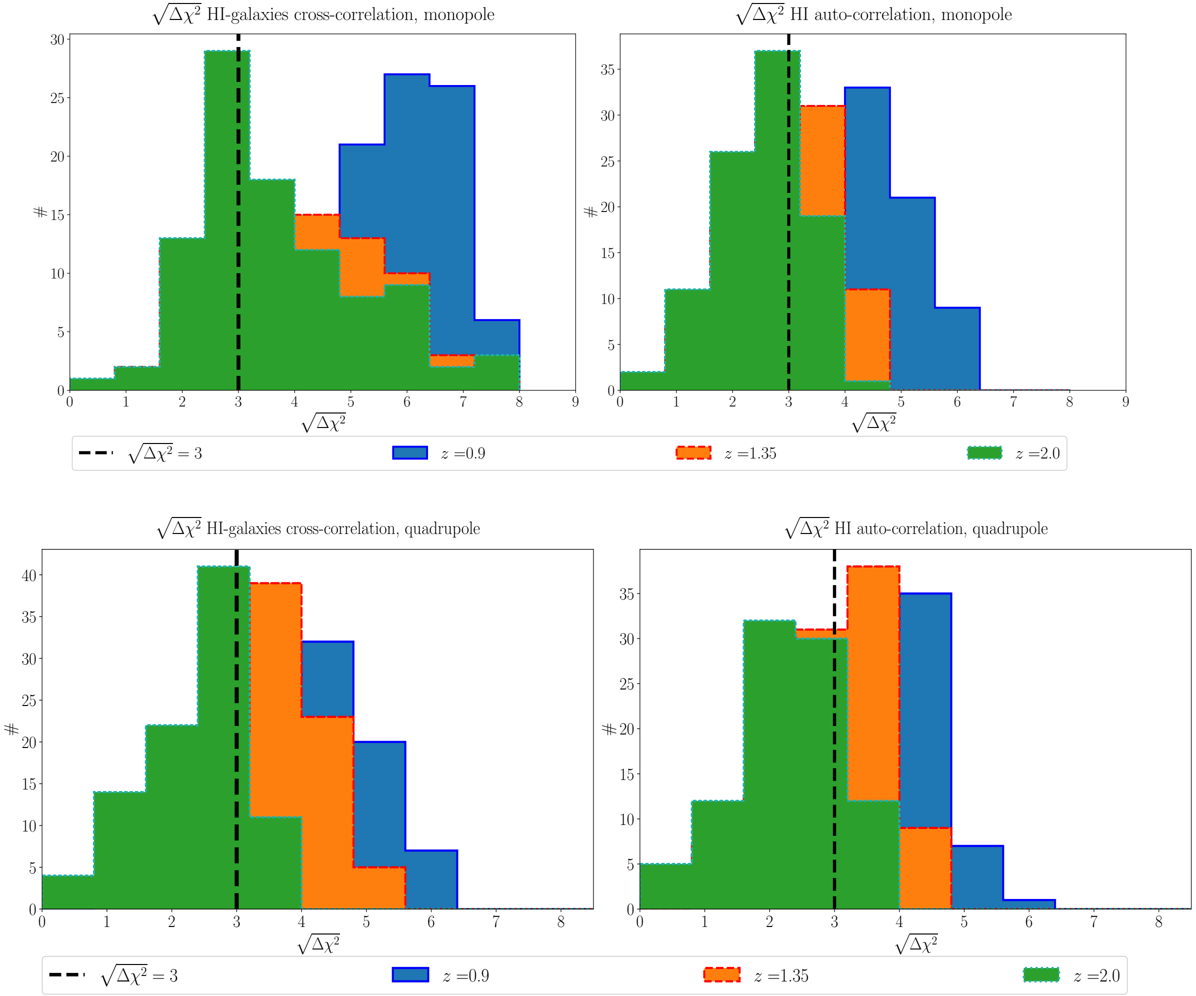
Results: BAO detection in auto- and cross-correlation, monopole qualitative comparison



Results: BAO detection in P_0 and P_2, qualitative comparison



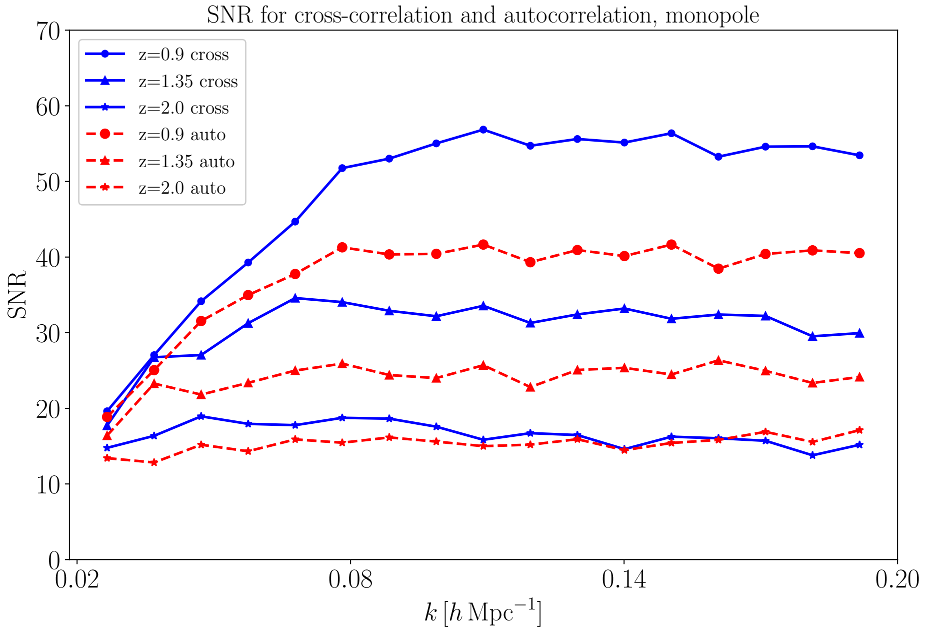
Detection distribution per method and ℓ-pole

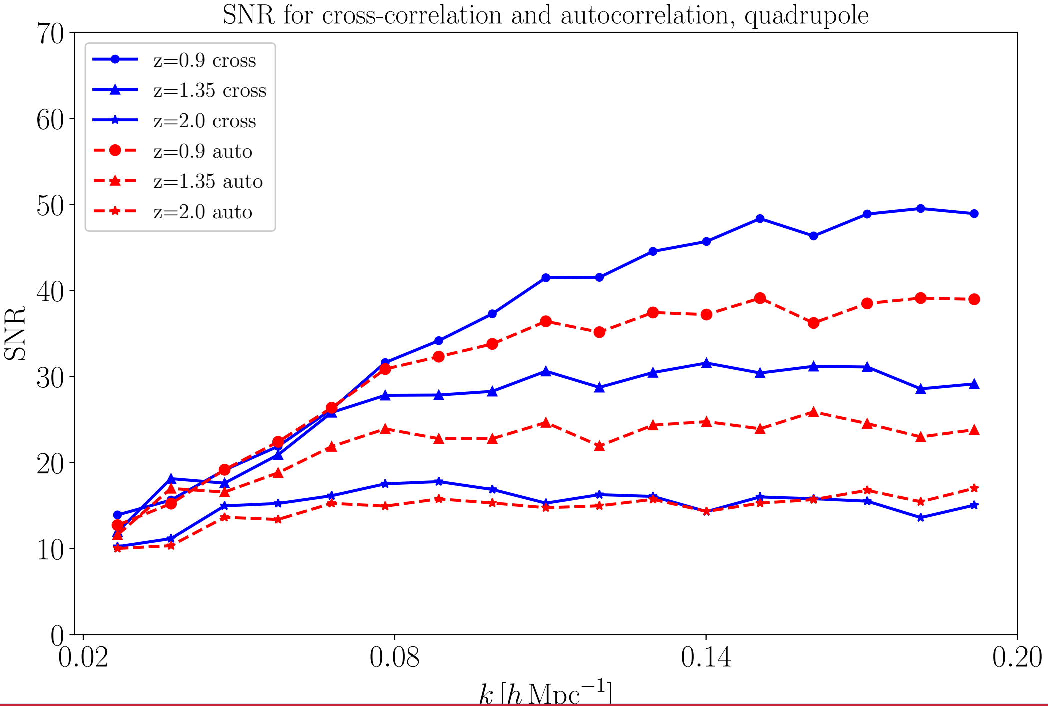


Method	Redshift	% of realisations – monopole		
		$\geq 3\sigma$ ($\leq \chi^2_{0.95}$)	$< 3\sigma$	failed
auto	0.90	78 (76)	19	3
cross	0.90	99 (92)	1	0
auto	1.35	50 (43)	46	4
cross	1.35	59 (31)	38	3
auto	2.00	25 (14)	71	4
cross	2.00	50 (43)	46	4

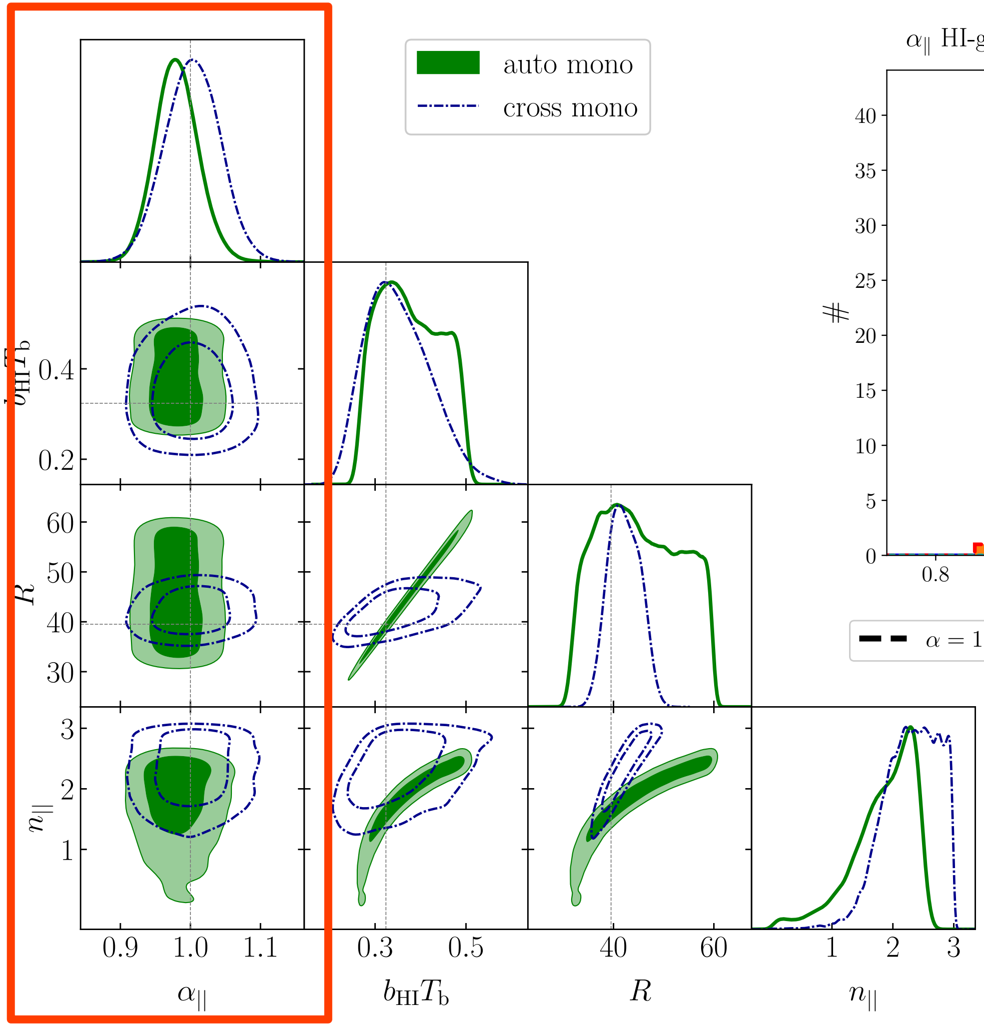
Method	Redshift	% of realisations – quadrupole		
		$\geq 3\sigma$ ($\leq \chi^2_{0.95}$)	$< 3\sigma$	failed
auto	0.90	77 (74)	21	2
cross	0.90	89 (80)	10	1
auto	1.35	54 (49)	44	2
cross	1.35	72 (57)	27	1
auto	2.00	17 (14)	74	9
cross	2.00	17 (11)	75	8

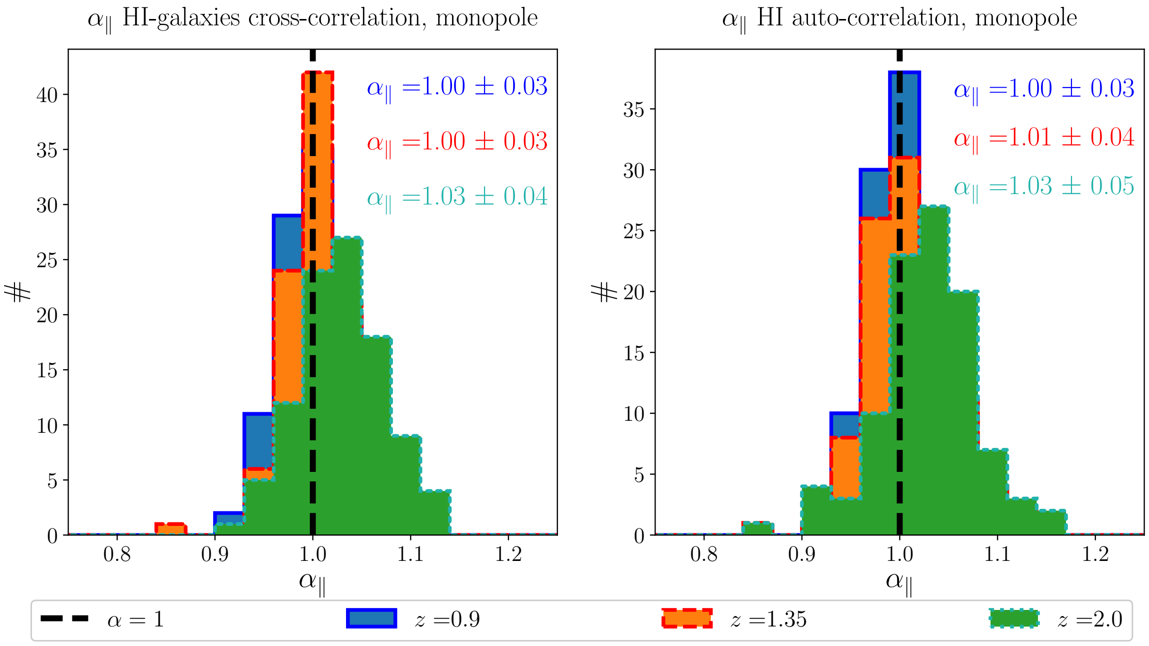
Results: SNR and differences in detection





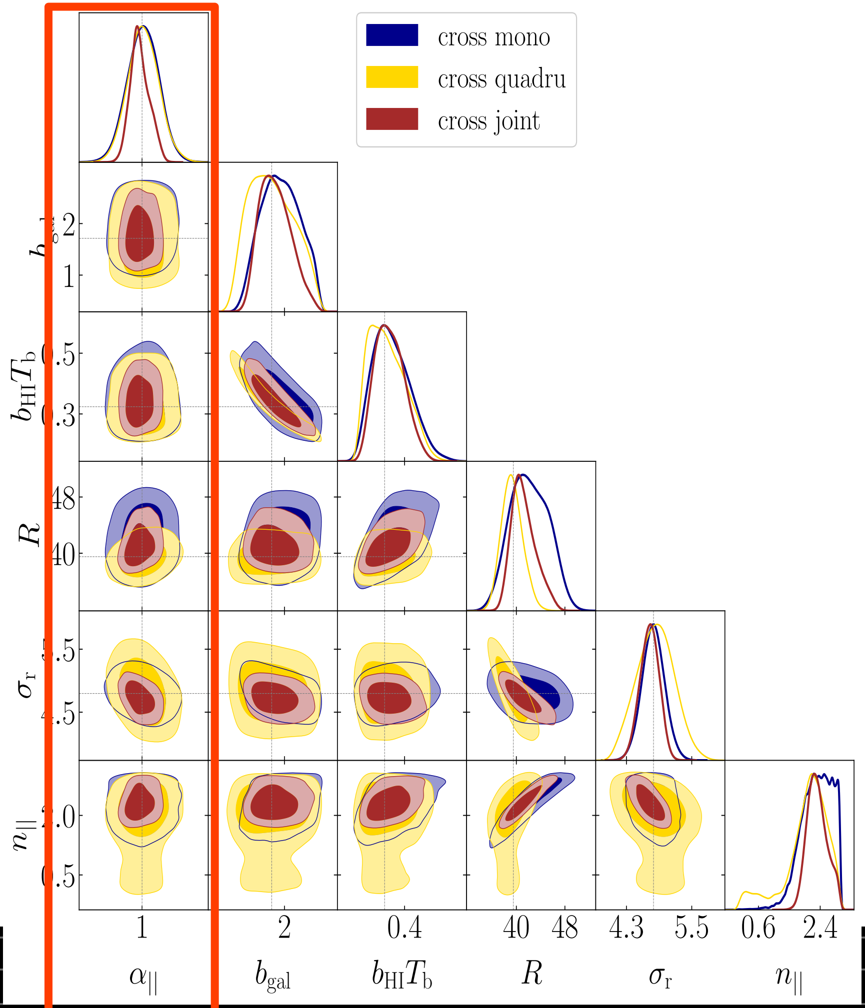
The *signal* is better recognisable in the quadrupole, but the *SNR* tends to favour the monopole, especially at largest scales, Consequences for the detection and the likelyhoods. Definition of hierarchy between cross- and auto – correlation, and *z*. Competition between the beam damping and the thermal/shot noise levels.



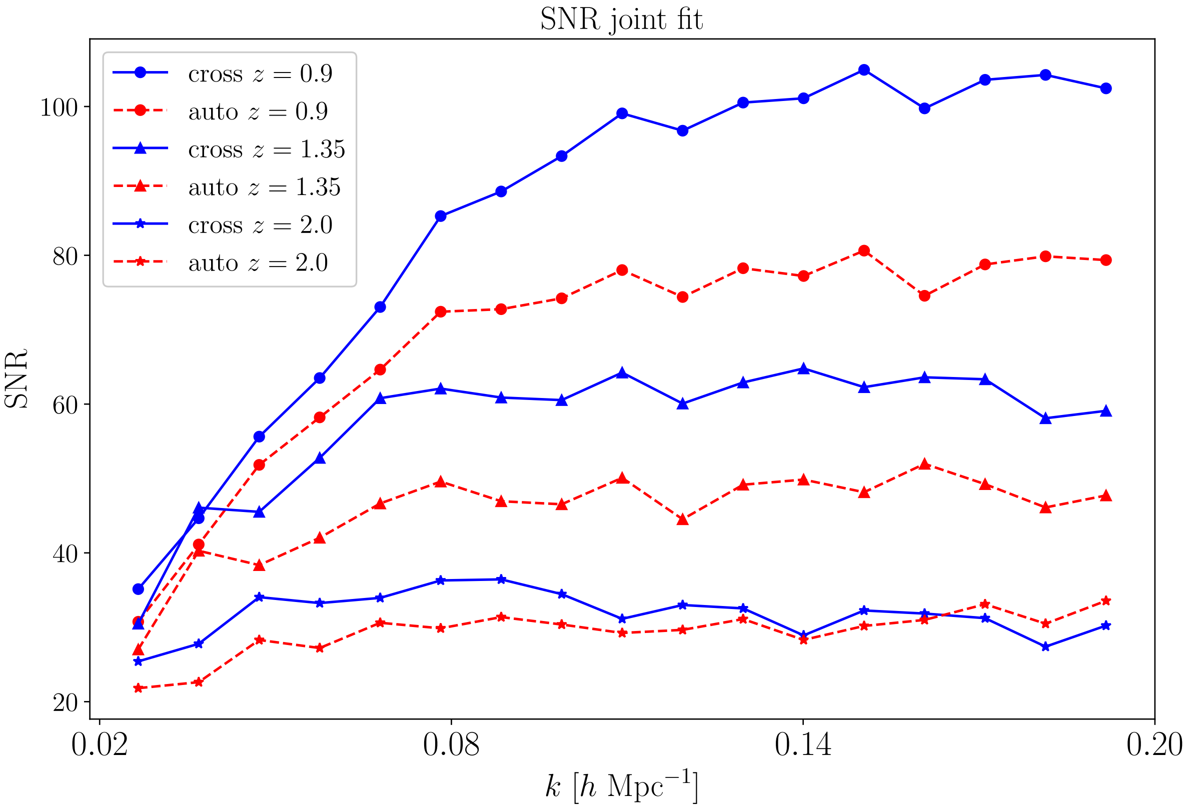


- ✓ **Cosmology (Alcock-Paczynski) is robust against nuisance parameters**
- ✓ **Good reconstruction along the line of sight (=*H(z)*)**
- ✓ **Loss of information along the transverse direction**

Extensions: monopole-quadrupole joint-fit

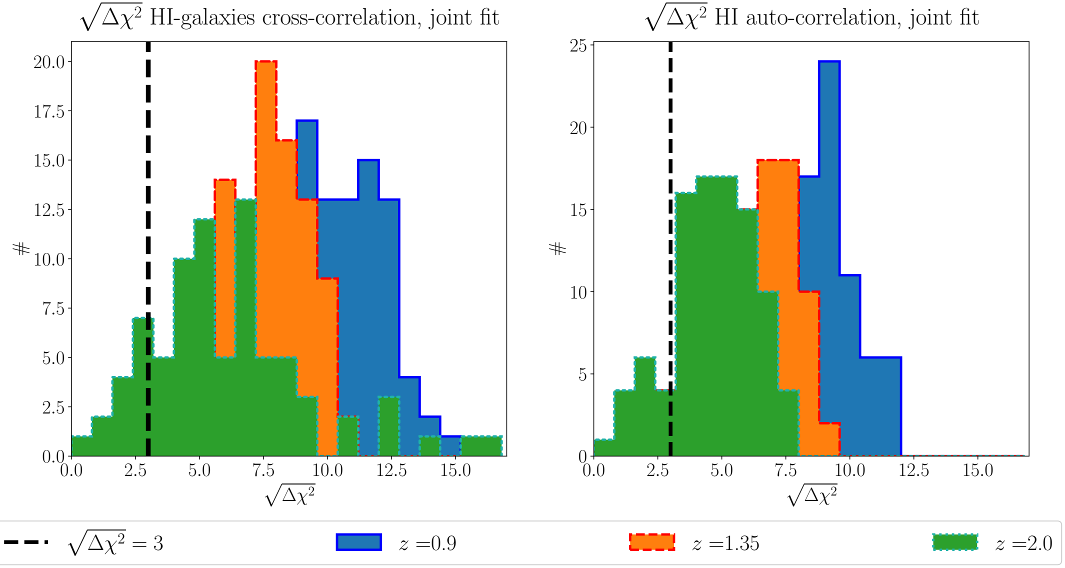


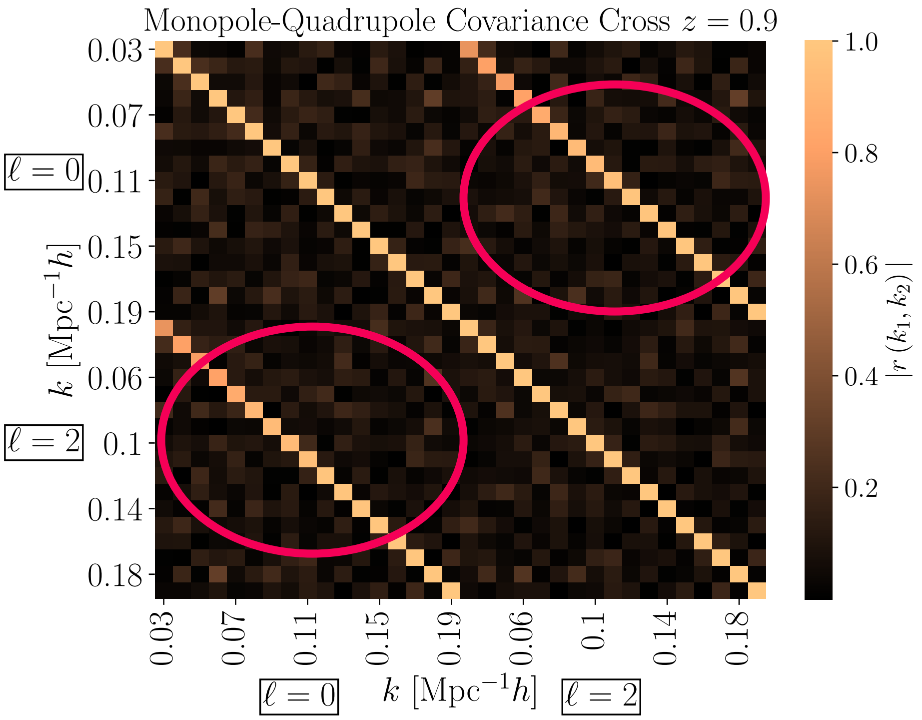
$$-2\ln\mathcal{L} = (\mathbf{P}_{\rm data} - \mathbf{P}_{\rm model})^{\mathsf{T}} C^{-1} (\mathbf{P}_{\rm data} - \mathbf{P}_{\rm model})$$



Joint fit detection results

Method	Redshift	% of realisations – joint		
		$\geq 3\sigma$ ($\leq \chi^2_{0.95}$)	$< 3\sigma$	failed
auto	1.35	91 (40)	8	1
cross	1.35	95 (38)	4	1





- ✔ **Stronger constraints: positive impact on the posteriors.**
- ✔ **Higher SNR leads to detections above 10 σ.**
- ✔ **Side effect of additional covariance terms: larger value for the χ^2**

In conclusion:

- ✔ Good-to-discrete BAO detection in P_0 e P_2 (alone) at low-intermediate z.
- ✔ Additional benefits from joint fit, detection significance ~10σ. Odd(?) covariance effect on χ^2.
- ✔ Very good validation of analytic uncertainties on data.
- ✔ Significance trend decreasing with redshift; auto-correlation alone not completely ruled out
- ✔ AP factors: cosmology-check is feasible on $\alpha_{||}$, not excessively correlated with the other parameters. Prior dependence on $\alpha_\perp$ and on $n_\perp$.
- ✔ SNR as a main interpretative instrument: margin for volume increase.
- ✔ Difficult but promising task: SKAOxEuclid synergy.
- ✔ Efficient FG-cleaning by means of PCA.
- ✔ Beam effect must be mitigated. Effects of more sophisticated beams?

Thank you for your gentle attention!