MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

On the recoverability of the BAO signal with the BINGO telescope

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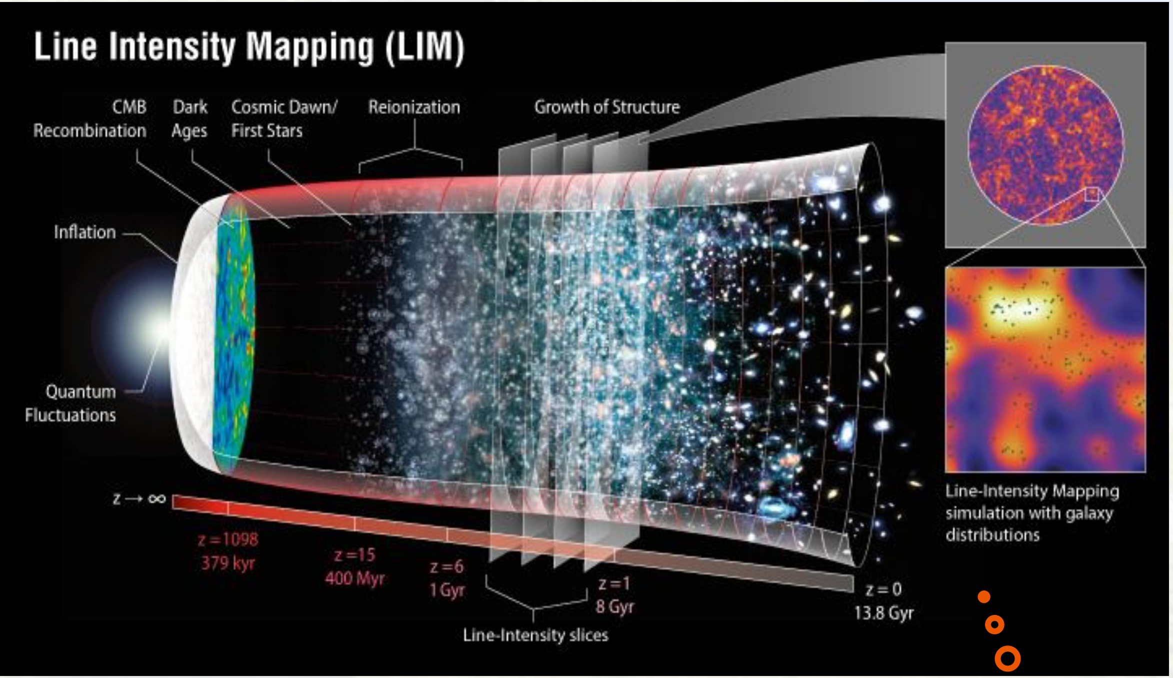
on behalf of the BINGO collaboration

Divisão de Astrofísica, INPE

COSMO'22

August 22, 2022

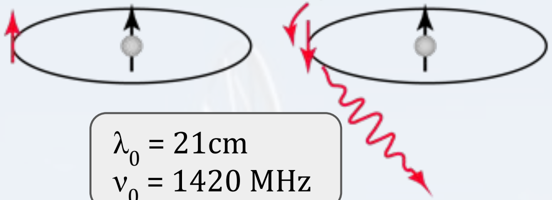
The 21 cm Intensity Mapping



[NASA / LAMBDA Archive Team]

CMB?!

Hydrogen 21 cm emission



λ_0 = 21cm
ν_0 = 1420 MHz

Cosmological redshift: $\lambda = \lambda_0(1+z)$

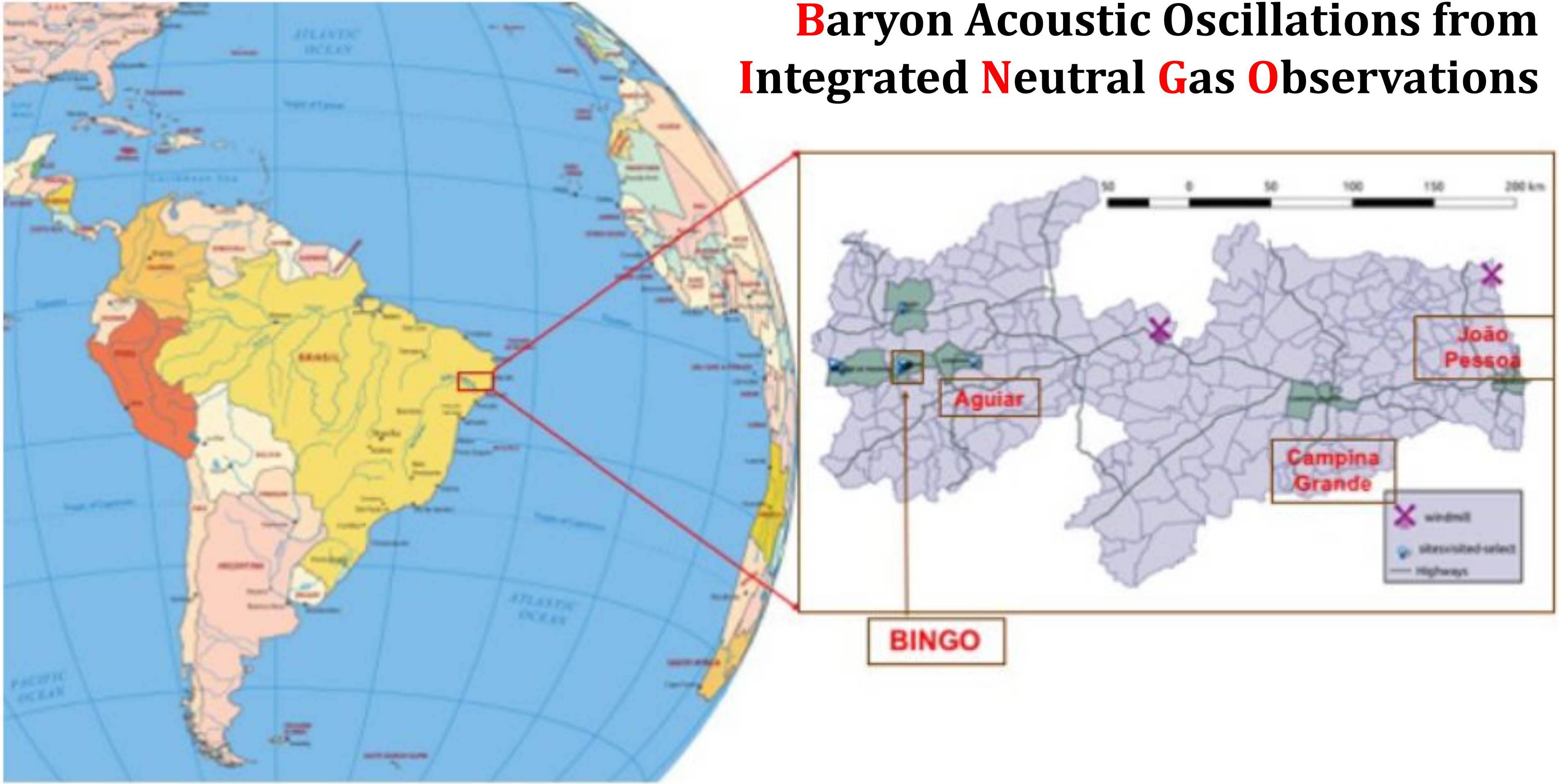
➔ Very high z coverage in tomographic analysis.

21 cm + optical surveys:

- Improve confidence in the results from optical/NIR.
- Completely different systematics.

The BINGO telescope

Baryon Acoustic Oscillations from Integrated Neutral Gas Observations

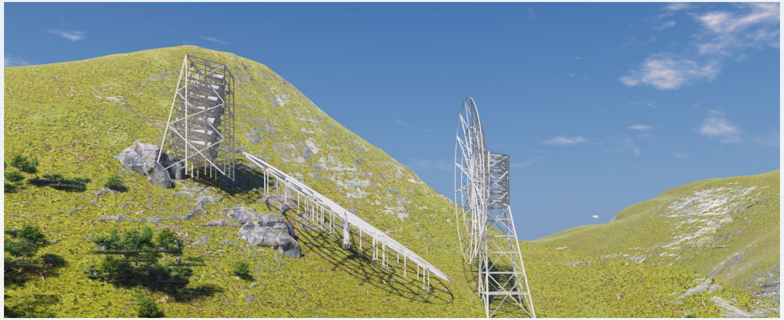


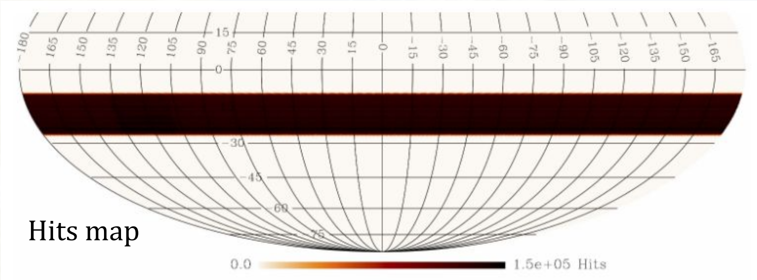
The BINGO telescope

The BINGO telescope: general information

- Transit telescope
- Optical design with 40-m diameter paraboloid primary dish and 34-m diameter hiperboloid secondary dish
- 28 horns in Phase 1
- Coverage: ~ 5324 square deg (⅛ of the sky)
- Declination: ~-25 deg
- Angular resolution: 40 arcmin
- Frequency range: 980 to 1260 MHz ($0.127 < z < 0.449$)

tomographic approach

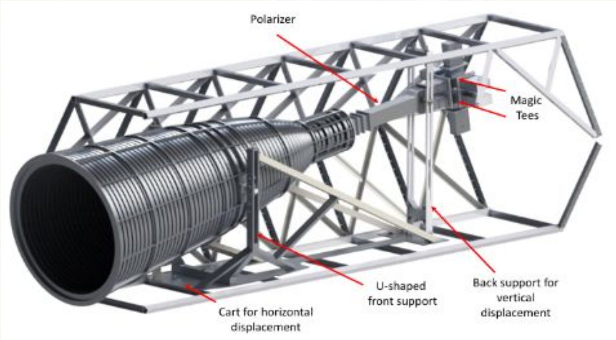




[II: C. A. Wuensche et al. 2107.01634]

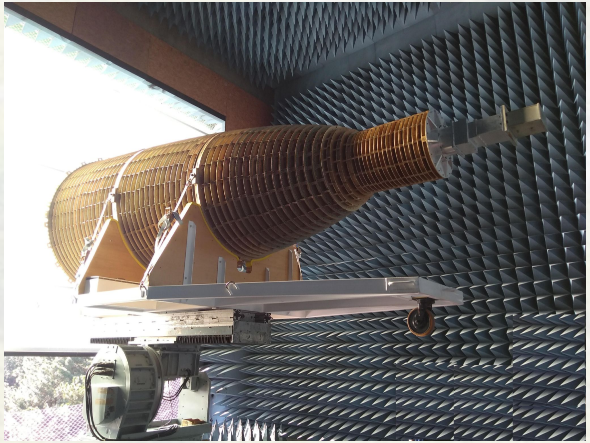
*See the BINGO project papers I to VII (A&A, vol 664, A14-A20) and VIII (CPN et al. 2207.12125) for a complete description of the instrument and scientific goals.

The BINGO telescope: general information



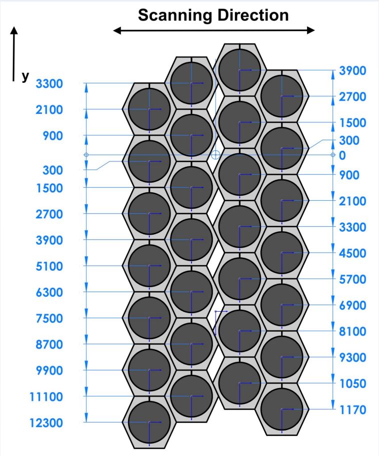
[II: C. A. Wuensche et al. 2107.01634]
[IV: Liccardo et al. 2107.01636]

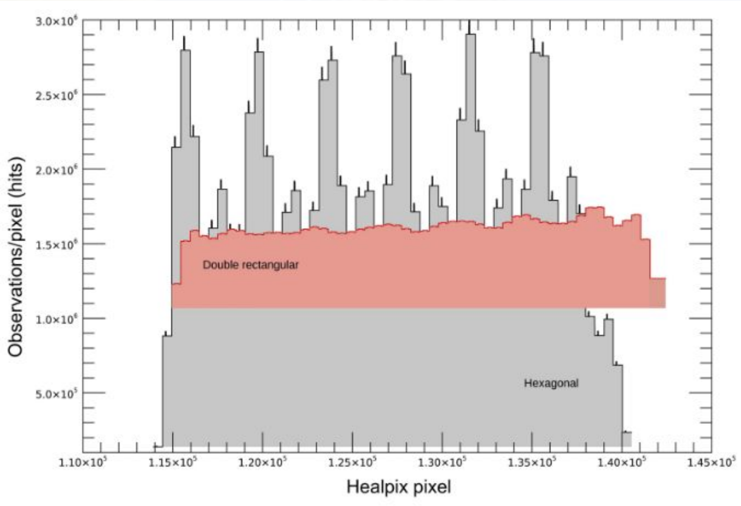
Feed horn:
- Aluminium,
- 800 kg,
- ~1.7 m diameter,
- 4.9 m length.



*Details about optical design [III: F. Abdalla et al. 2107.01635]:
See João Alberto's talk!

Double rectangular arrangement





The BINGO telescope: scientific goals

- Cosmology:
  - BAO measurements
  - Redshift space distortion
  - Constrain cosmological models

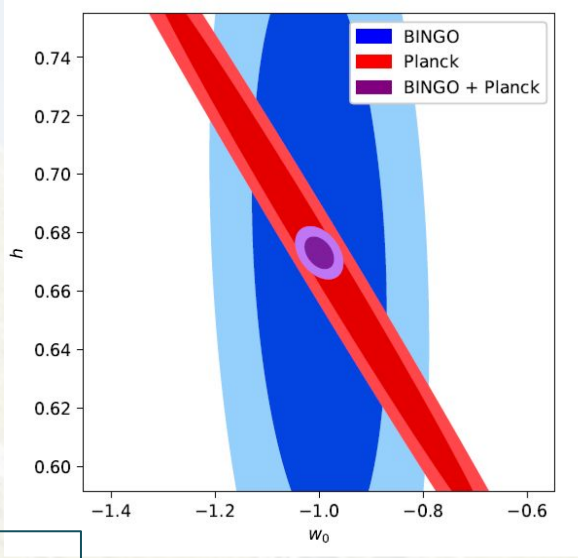
- Astrophysics:
  - Fast radio bursts (FRB) [dos Santos et al., in prep.] and transient phenomena
  - Galactic science
  - Extragalactic science

[I: E. Abdalla et al. 2107.01633]

ΛCDM: h and $\Omega_c h^2$ with 25% improvement.

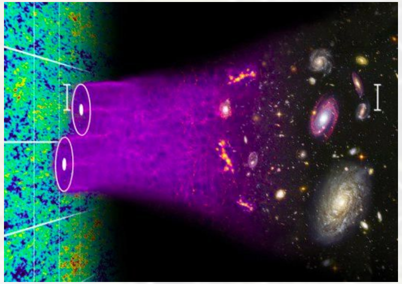
wCDM: precision of 1.1% and 3.3% for h and w_0.

[VII: A. Costa et al. 2107.01639]



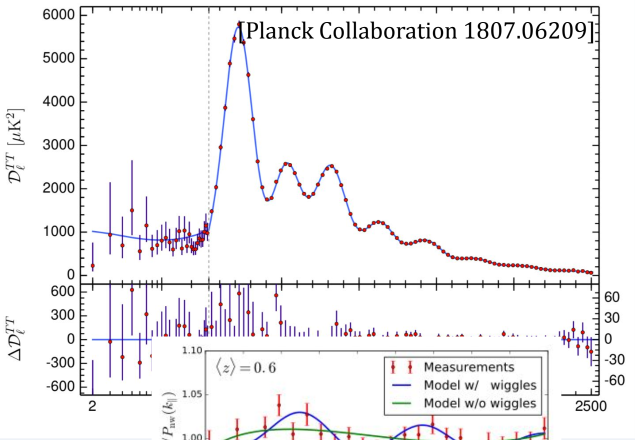
*For MCMC analyses with BINGO:
See Pablo Motta's poster!

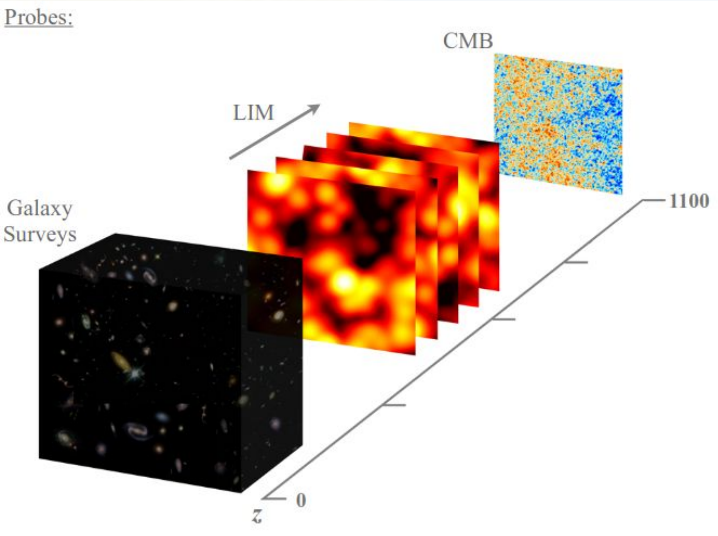
Baryon acoustic oscillations (BAO)



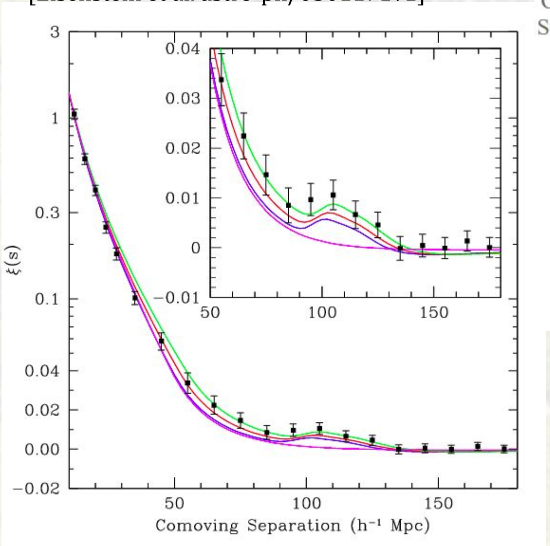
[sdss3.org/surveys/boss.php;
C. Blake and S. Moorfield]

$$\frac{\Delta\rho}{\bar{\rho}} \propto \frac{\Delta T}{T_0}$$

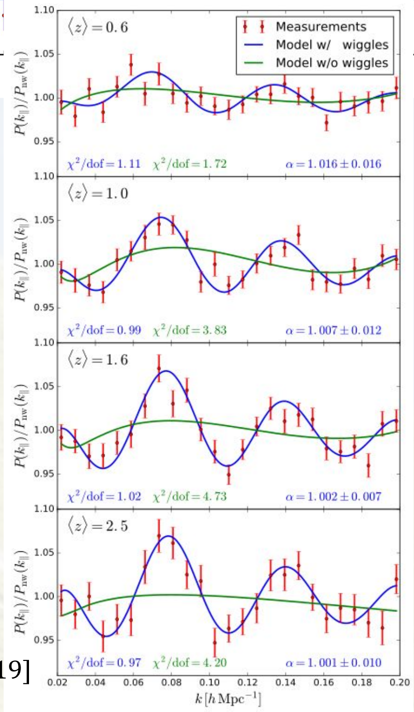




[Eisenstein et al. astro-ph/0501171v1]



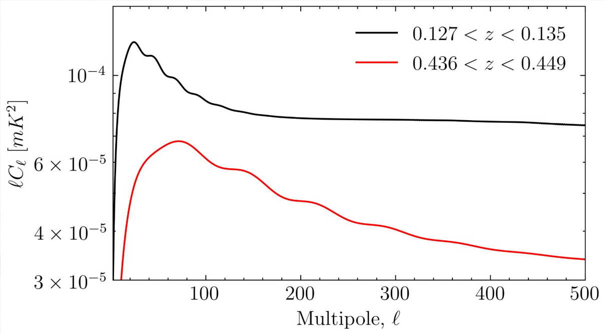
[Kovetz et al. 1903.04496]

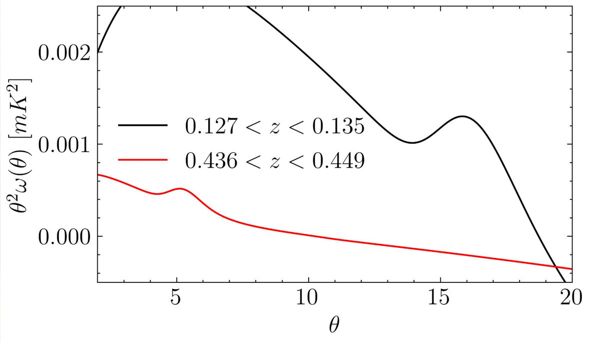


[Forecasting: 21cm for SKA
Villaescusa-Navarro et al. 1609.00019]

BAO measurements with BINGO simulations

[VIII: CPN et al. 2207.12125]





Clustering measurements:

- Angular power spectrum (APS, harmonic space): the pseudo-C_ℓ approach

$$C_\ell = \sum_{\ell'} \mathcal{M}^{-1}_{\ell\ell'} \hat{C}_{\ell'}$$

- Two-point angular correlation function (ACF; real space):

$$\hat{\omega}(\theta) = \frac{\sum_{ij} \delta T_i \delta T_j wt_i wt_j}{\sum_{ij} wt_i wt_j}$$

BINGO-like simulations

- 21 cm IM: **30 frequency bins*** [0.127 < z < 0.449],
  - 1500 FLASK log-normal realizations [Xavier et al. 1602.08503],
  - 100 Mocks constructed from N-body simulations [VI: J. Zhang et al. 2107.01638]

+

- Foreground contamination,

+

- Beam size (~40 arcmin),

+

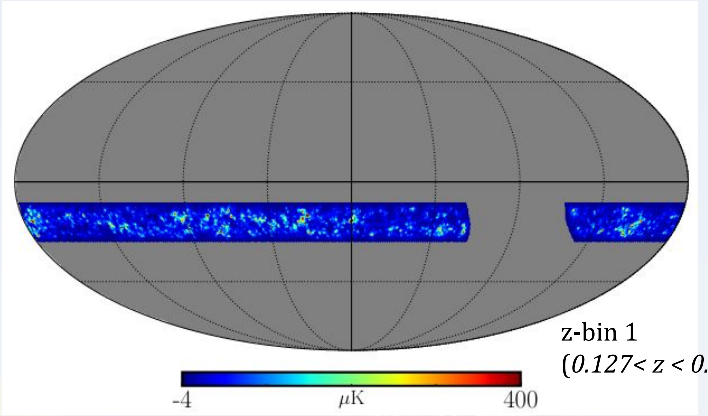
- Instrumental noise (white noise).

⇩

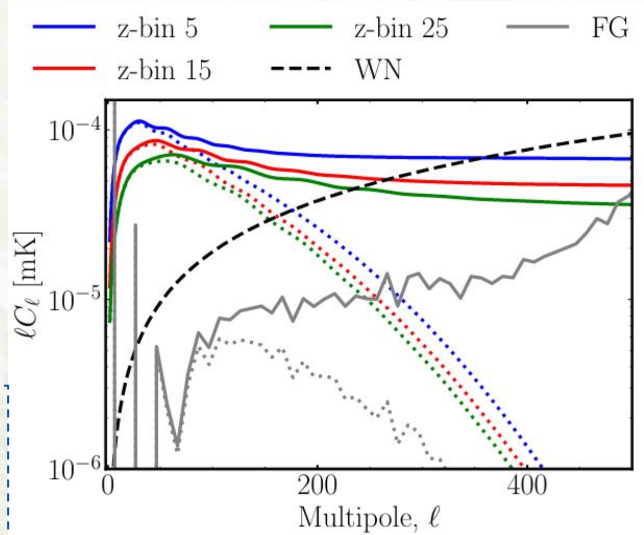
- Foreground cleaning.

*# of z-bins depends specially on the foreground cleaning process [E. Mericia et al. 2204.08112].
See Larissa Santos talk!

More about *component separation* in:
IV: V. Liccardo et al. 2107.01636,
V: K. Fornazier et al. 2107.01637,
A. Marins et al. in prep.

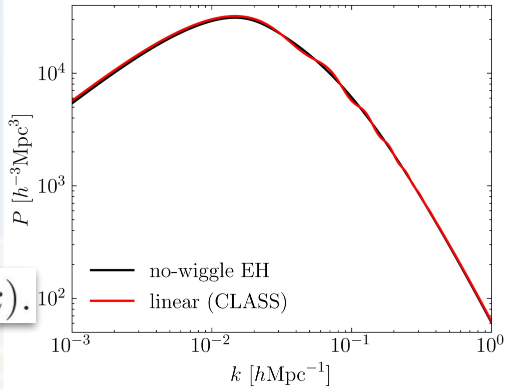


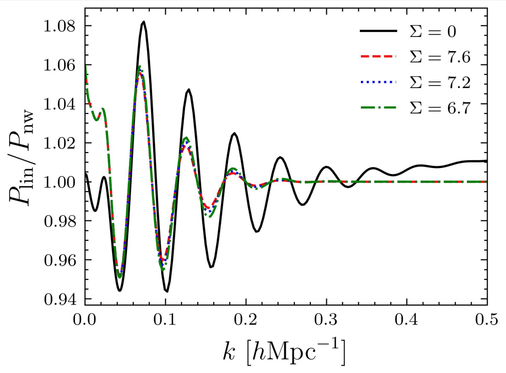
z-bin 1
(*0.127< z < 0.138*)



Modeling the BAO

$$P^{temp}(k) = [P^{lin}(k) - P^{nw}(k)]e^{-k^2\Sigma^2} + P^{nw}(k).$$





APS:

$$C(\ell) = B\,C^{temp}(\ell/\alpha) + \sum_q A_q\,\ell^q$$

ACF:

$$\omega(\theta) = B\omega^{temp}(\alpha\theta) + \sum_q \frac{A_q}{\theta^q}$$

where $\omega(\theta)$ and $C^{temp}(\ell)$ are related through:

$$\omega^{temp}(\theta) = \frac{1}{4\pi}\sum_\ell (2\ell+1)C^{temp}(\ell)P_\ell(\cos\theta)$$

BAO fitting using a MLE:

$$L \propto \exp(-\chi^2/2)$$

We do this by ***combining the redshift*** *bins!*

➢ $\lambda(\alpha, B, A_i)$

$$\alpha = \frac{(D_A(z)/r_d)}{(D_A(z)/r_d)_{fid}}$$

Shift parameter

[e.g., Camacho et al. 1807.10163, Chan et al. 1801.04390]

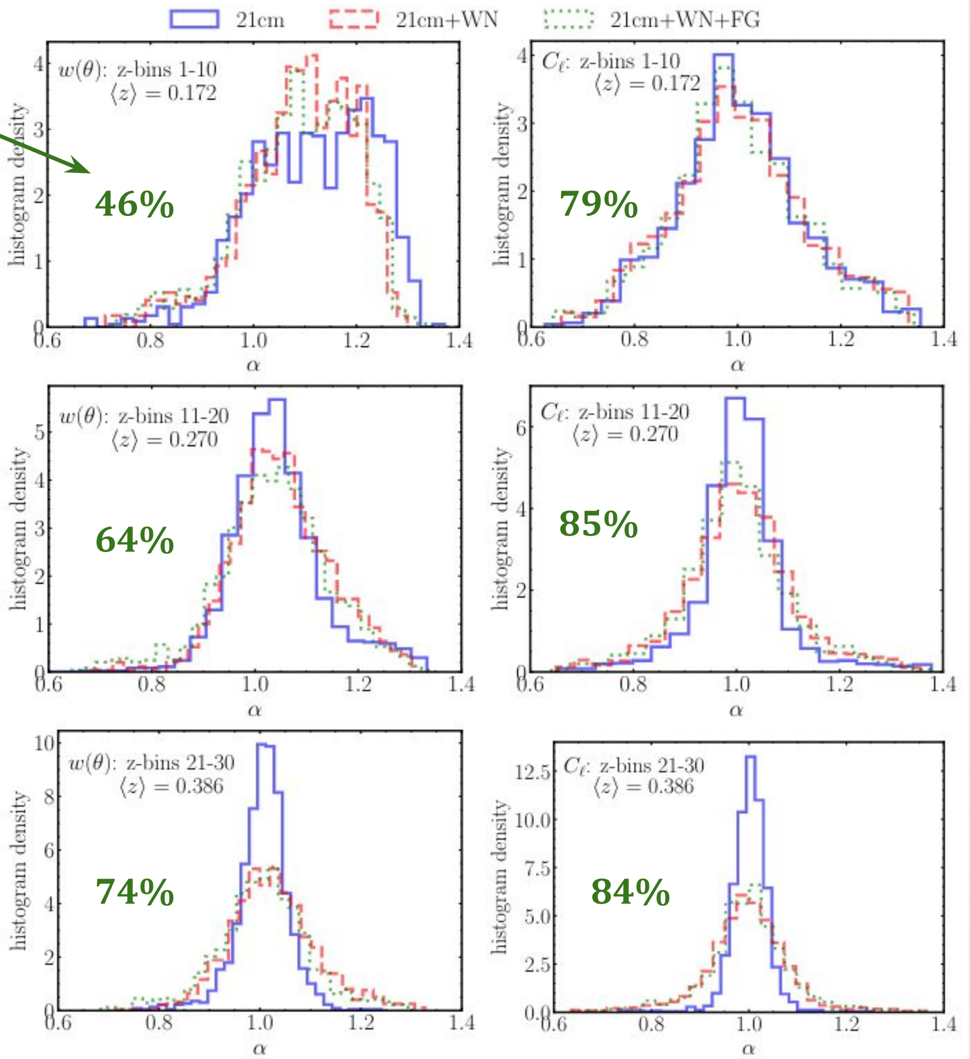
Fitting results

- Fiducial configuration:
  - Joint analyses of N_z = *10, 10, 10* consecutive z-bins,
  - *Δℓ = 10 and Δθ = 0.5 deg.*
  - A_q parameters for C_ℓ and ω(θ) templates: q = −1, 0, 1, 2 and q = 0, 1, 2, respectively.

\+ **Robustness tests.**

Results can be improved by the choice of an "optimal configuration" for each redshift interval.

Detection (fid. conf.)



Detection criterium: 0.8 < α < 1.2

Conclusions

[VIII: CPN et al. 2207.12125]

- The two ***clustering estimators*** show better results at higher redshifts, but present different ***sensitivities*** to each ***redshift range***.

- ***Intermediate*** and ***higher redshifts*** are the most promising in measuring the BAO scale.

- The ***APS*** estimator provides ***slightly better estimates***, with smaller uncertainties and larger ***probability of detection*** of the BAO signal, achieving $\gtrsim 90\%$ at higher redshifts.

- The presence of thermal ***noise*** increases the error bars (~ 2.2x) on the α parameter, specially for the APS, while ***foreground residual*** do not seem to have a significant impact to the analyses.

- Even including some realistic systematic effects, ***our results indicate that BINGO has the potential to detect BAO in its redshift range during its Phase 1 (5-year) operation***.

To do:

- Simulations: Realistic beams, polarization leakage, *1/f* noise, …
- Analyses: alternative foreground cleaning method, z-bins, and fitting method, test reconstruction process …

Thank you!!

https://bingotelescope.org/

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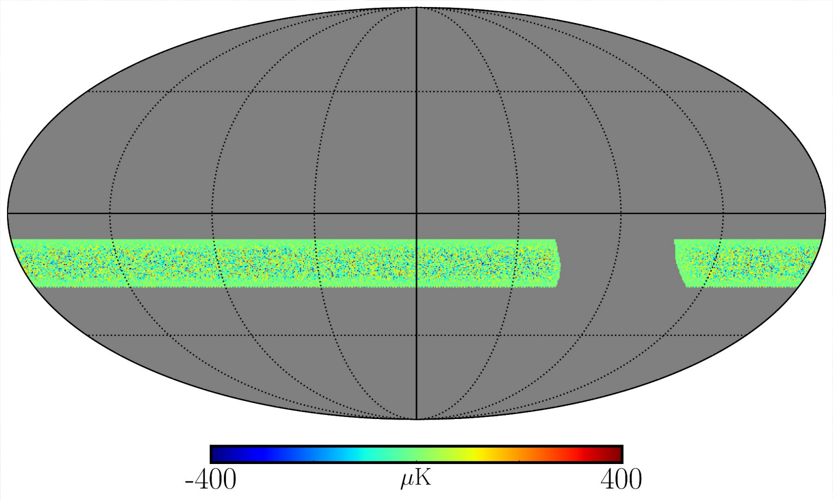
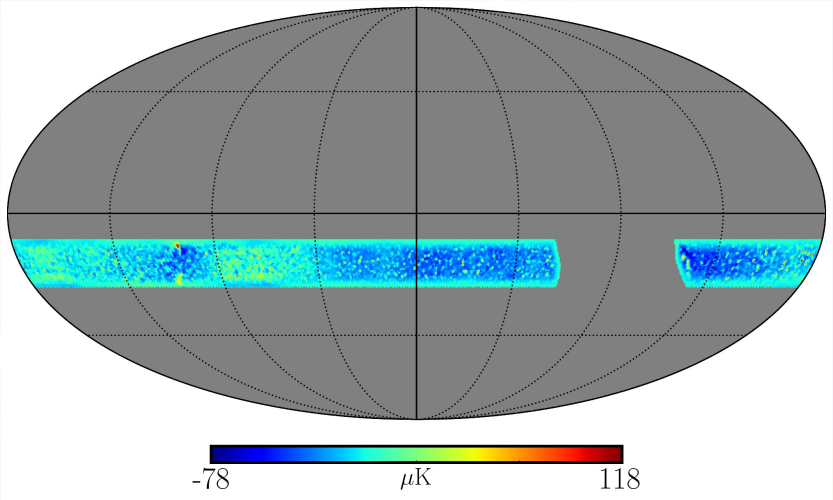
Extra slides:

White noise and foreground residual





Fitting results

$\omega(\theta)$

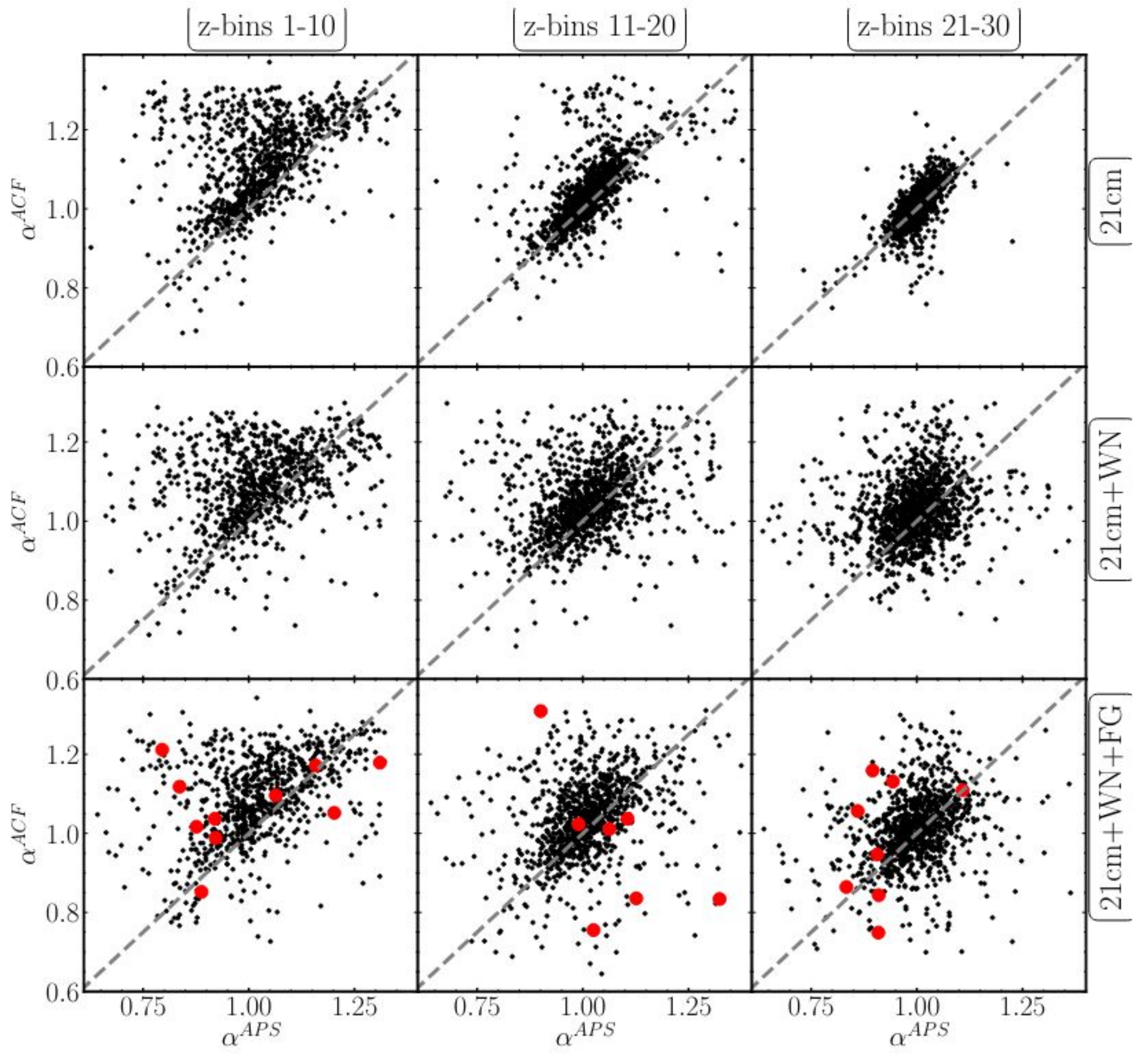
Tests	z-bins	$\langle\alpha\rangle$	$\langle\sigma_\alpha\rangle$	σ_{68}	σ_{std}	$\langle\chi^2\rangle$/dof (χ^2_{red})	N_s (%)	N_d (%)	Mean
21 cm only									
Fid. config.	1–10	1.1158	0.1427	0.1209	0.1166	122.49/123 (1.00)	65.27	45.73	1.0067 ± 0.2433
	11–20	1.0426	0.0977	0.0775	0.0923	76.84/70 (1.10)	81.00	75.00	1.0082 ± 0.1014
	21–30	1.0060	0.0565	0.0425	0.0514	69.54/61 (1.14)	92.60	92.00	1.0076 ± 0.0507
+ white noise									
Fid. Config.	1–10	1.0906	0.1619	0.1042	0.1066	122.05/123 (0.99)	58.73	48.60	1.0070 ± 0.2915
	11–20	1.0524	0.1213	0.0924	0.0948	76.34/70 (1.09)	80.53	73.80	1.0107 ± 0.1470
	21–30	1.0267	0.0932	0.0807	0.0883	67.88/61 (1.11)	89.60	85.13	1.0070 ± 0.0989
+ white noise + foreground residuals									
Fid. Config. ($\Delta\theta = 0.50°$;	1–10	1.0897	0.1624	0.1123	0.1118	122.42/123 (1.00)	57.07	46.27	0.9952 ± 0.3270
$q = 0, 1, 2$)	11–20	1.0362	0.1267	0.0969	0.1070	76.60/70 (1.09)	70.20	63.93	0.9989 ± 0.1546
	21–30	1.0074	0.1006	0.0809	0.0930	68.37/61 (1.12)	78.00	73.53	0.9965 ± 0.1039
$\Delta\theta = 0.25°$	11–20	1.0370	0.1307	0.0999	0.1054	166.28/180 (0.92)	71.67	64.87	1.0135 ± 0.2560
	21–30	1.0063	0.1034	0.0842	0.0970	154.15/164 (0.94)	76.67	72.33	0.9826 ± 0.1394
$\Delta\theta = 0.40°$	1–10	1.0888	0.1647	0.1100	0.1157	155.02/165 (0.94)	57.73	46.60	1.0034 ± 0.3245
	11–20	1.0375	0.1298	0.0969	0.1054	100.85/98 (1.03)	72.00	65.20	0.9981 ± 0.1597
	21–30	1.0160	0.0998	0.0833	0.0982	90.00/86 (1.05)	78.80	73.07	0.9976 ± 0.1065
$q = 0, 1$	1–10	1.1687	0.1299	0.1092	0.1117	130.45/133 (0.98)	37.40	18.73	0.9894 ± 0.3321
	11–20	1.0364	0.1294	0.1022	0.1070	85.43/80 (1.07)	70.00	63.60	0.9955 ± 0.1521
	21–30	1.0068	0.1005	0.0823	0.0951	78.36/71 (1.10)	85.80	80.67	1.0023 ± 0.0989
$q = -1, 0, 1, 2$	1–10	1.0790	0.1813	0.1432	0.1269	114.55/113 (1.01)	34.93	26.47	1.0015 ± 0.3270
	11–20	1.0344	0.1307	0.0963	0.1018	67.38/60 (1.12)	70.53	65.20	1.0047 ± 0.1521
	21–30	1.0200	0.0954	0.0801	0.0895	58.92/51 (1.14)	85.87	82.20	1.0096 ± 0.1014
$q = -2, 0, 1$	1–10	1.0995	0.1657	0.1046	0.1039	216.71/123 (1.76)	14.20	11.33	0.9952 ± 0.7275
	11–20	1.0444	0.1214	0.0839	0.0904	146.87/70 (2.10)	39.87	37.73	0.9989 ± 0.1648
	21–30	1.0178	0.0963	0.0790	0.0891	101.07/61 (1.67)	63.87	61.07	0.9965 ± 0.1065

Fitting results

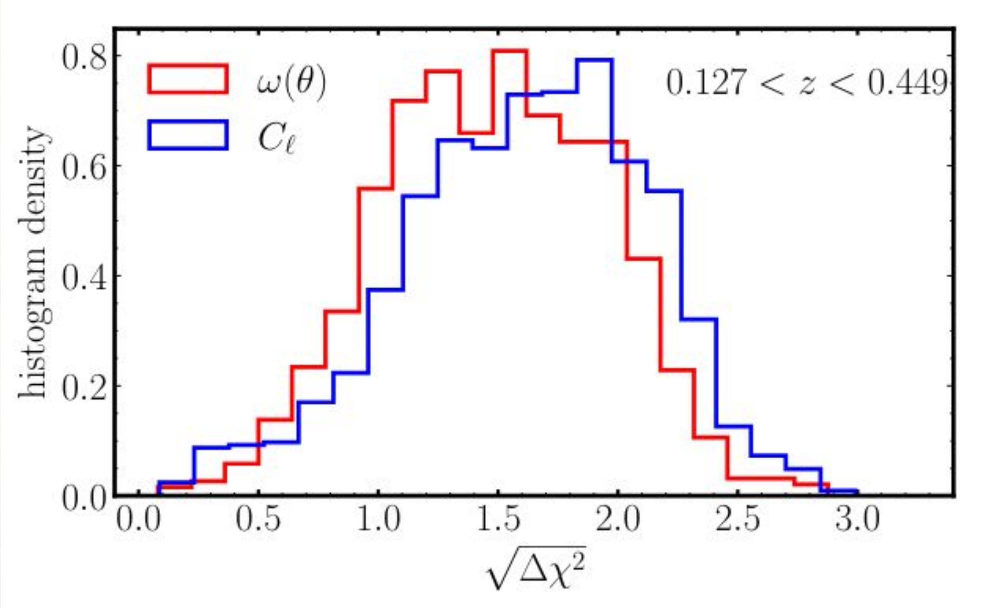
C_ℓ

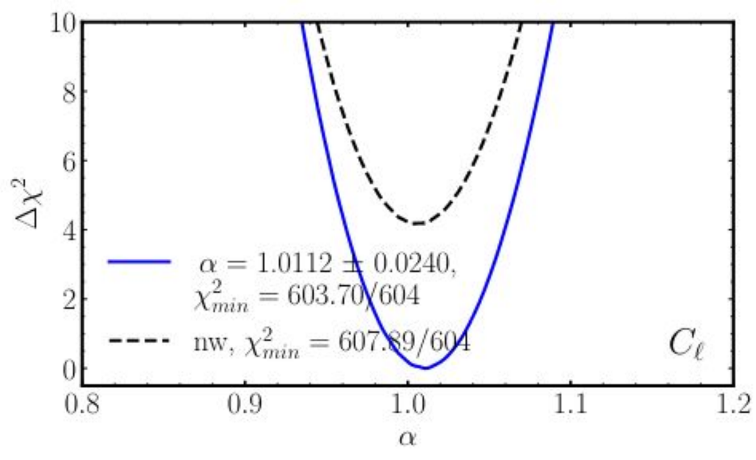
Tests	z-bins	$\langle\alpha\rangle$	$\langle\sigma_\alpha\rangle$	σ_{68}	σ_{std}	$\langle\chi^2\rangle$/dof	N_s (%)	N_d (%)	Mean
21 cm only									
Fid. config.	1–10	1.0061	0.0594	0.1200	0.1243	102.14/100 (1.02)	93.73	84.20	1.0012 ± 0.0608
	11–20	1.0083	0.0316	0.0616	0.0889	185.70/207 (0.90)	92.87	87.73	1.0062 ± 0.0304
	21–30	1.0024	0.0178	0.0318	0.0399	244.17/295 (0.83)	92.93	92.27	1.0028 ± 0.0152
+ white noise									
Fid. config.	1–10	1.0041	0.0653	0.1311	0.1311	102.12/100 (1.02)	92.33	79.20	0.9915 ± 0.0684
	11–20	1.0057	0.0410	0.0929	0.1092	185.46/207 (0.91)	90.87	83.27	1.0036 ± 0.0406
	21–30	0.9965	0.0322	0.0707	0.0897	242.42/295 (0.82)	91.60	86.87	0.9999 ± 0.0304
+ white noise + foreground residual									
Fid. Config. ($\Delta\ell$ = 10; $q = -1, 0, 1, 2$)	1–10	1.0009	0.0659	0.1257	0.1274	102.23/100 (1.02)	90.47	78.87	0.9925 ± 0.0684
	11–20	1.0012	0.0418	0.0888	0.1063	185.53/207 (0.90)	92.47	84.77	0.9985 ± 0.0431
	21–30	0.9975	0.0323	0.0701	0.0890	242.88/295 (0.82)	88.13	83.73	1.0012 ± 0.0304
$\Delta\ell$ = 15	11–20	1.0070	0.0474	0.1002	0.1154	108.96/108 (1.01)	92.87	83.00	1.0016 ± 0.0482
	21–30	1.0015	0.0345	0.0685	0.0867	157.06/168 (0.93)	94.47	90.40	1.0020 ± 0.0355
$\Delta\ell$ = 20	1–10	1.0299	0.0724	0.1293	0.1128	27.24/17 (1.60)	96.87	87.80	1.0346 ± 0.0760
	11–20	1.0199	0.0476	0.1088	0.1117	76.90/71 (1.08)	94.60	86.93	1.0117 ± 0.0456
	21–30	1.0009	0.0366	0.0726	0.0912	116.66/117 (1.00)	96.20	91.47	0.9975 ± 0.0355
$q = 0, 1$	1–10	1.0523	0.0682	0.1307	0.1334	119.73/120 (1.00)	62.73	50.80	1.0985 ± 0.0735
	11–20	1.0558	0.0436	0.0788	0.0870	199.91/227 (0.88)	73.33	68.47	1.0626 ± 0.0431
	21–30	1.0279	0.0333	0.0517	0.0556	254.90/315 (0.81)	76.27	75.67	1.0294 ± 0.0330
$q = 0, 1, 2$	1–10	0.9995	0.0660	0.1236	0.1279	110.52/110 (1.00)	71.87	62.40	0.9935 ± 0.0684
	11–20	0.9912	0.0419	0.0858	0.1091	192.63/217 (0.89)	82.73	74.80	0.9960 ± 0.0406
	21–30	0.9958	0.0324	0.0637	0.0818	248.84/305 (0.82)	84.33	81.53	0.9987 ± 0.0304
$q = -2, 0, 1$	1–10	1.0161	0.0664	0.1324	0.1278	110.95/110 (1.01)	83.73	72.40	1.0113 ± 0.0684
	11–20	1.0162	0.0422	0.0864	0.1020	193.18/217 (0.89)	88.33	82.13	1.0164 ± 0.0431
	21–30	1.0097	0.0326	0.0691	0.0870	249.10/305 (0.82)	84.47	80.27	1.0131 ± 0.0304

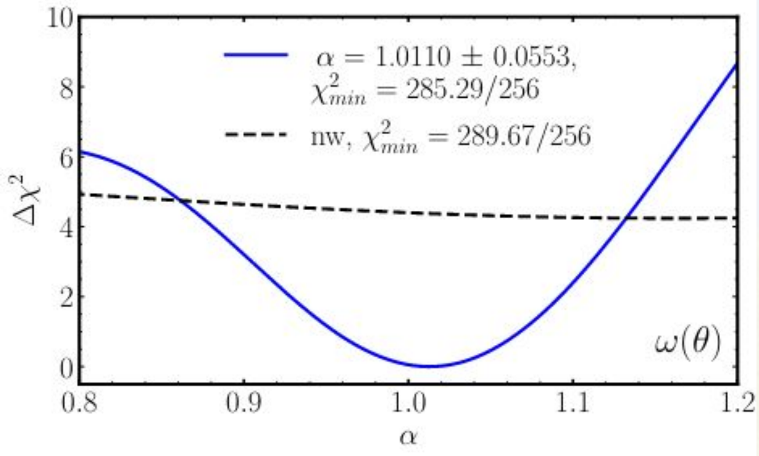
Fitting results



Significance







$$S = \sqrt{\Delta\chi^2} = \sqrt{\chi^2 - \chi^2_{nw}(\alpha_{bf})}$$

BAO analyses

#	$\bar{z}$	ℓ_{max}	$[\theta_{min}, \theta_{max}]$	#	$\bar{z}$	ℓ_{max}	$[\theta_{min}, \theta_{max}]$
1	0.131	141	[10.5, 21.0]	16	0.274	301	[5.0, 10.5]
2	0.140	141	[10.5, 20.0]	17	0.284	311	[4.5, 10.5]
3	0.148	151	[9.0, 18.5]	18	0.295	321	[4.5, 10.0]
4	0.157	161	[8.5, 17.5]	19	0.306	331	[4.0, 10.0]
5	0.166	181	[8.0, 17.0]	20	0.318	341	[4.0, 10.0]
6	0.175	201	[7.5, 16.0]	21	0.329	361	[4.0, 9.5]
7	0.184	211	[7.0, 15.5]	22	0.341	371	[3.5, 9.5]
8	0.194	231	[7.0, 15.0]	23	0.353	371	[3.5, 9.5]
9	0.203	251	[6.5, 14.0]	24	0.365	381	[3.5, 9.0]
10	0.213	251	[6.5, 13.5]	25	0.377	391	[3.0, 9.0]
11	0.222	271	[6.0, 13.0]	26	0.390	391	[3.0, 9.0]
12	0.232	271	[6.0, 12.5]	27	0.403	401	[3.0, 8.0]
13	0.242	271	[5.5, 11.5]	28	0.416	401	[3.0, 8.0]
14	0.252	281	[5.5, 11.5]	29	0.429	401	[2.5, 8.0]
15	0.263	291	[5.0, 11.0]	30	0.442	401	[2.5, 8.0]

$\ell_{min} = 32$