

Constraining spatial curvature with large scale structure

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from Bel, Larena, Maartens, Marinoni and Pérenon, JCAP 2022

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GDR CoPhy

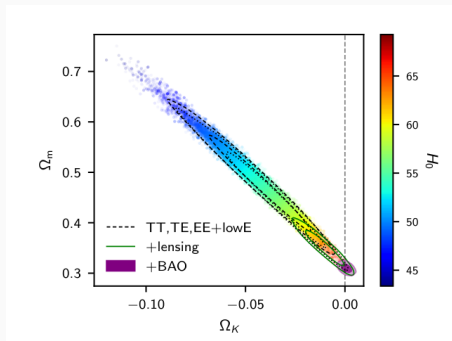
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Introduction

Evidence for spatial curvature?



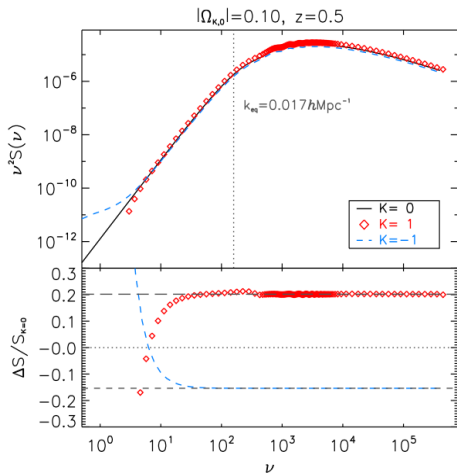
[Planck 2018 results]

- Planck PS alone favours $K > 0$
- H_0 tension worsen
- Degenerate with "lensing problem" ($A_L > 1$)
- Goes away with other probes
- But are combinations legit? [Handley, PRD, 2021]

- $\Omega_{K,0} \simeq 0$ is NOT $K = 0$
- Profound implications
- $\Omega_{K,0}$ nuisance parameter in Λ CDM

Large-scale structure observables in curved space

Real space power spectrum



Spectrum of Laplace-Beltrami operator:

$$\nabla^2 Q_{lm} = -k^2 Q_{lm}$$

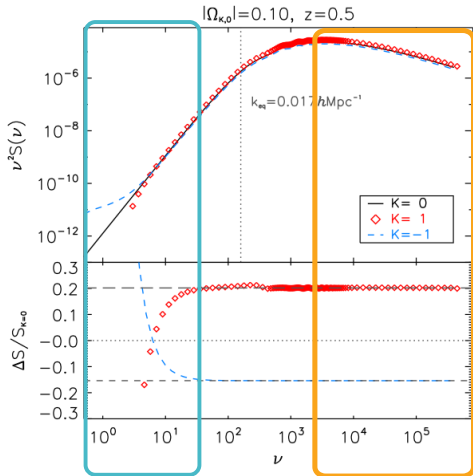
with $Q_{lm} = X_l(\nu, \chi) Y_{lm}(\theta, \phi)$

$$\nu = k/H_0 \text{ if } K = 0$$

$$\nu = \sqrt{\frac{k^2}{H_0^2 |\Omega_{K,0}|} - K} \text{ if } K \neq 0$$

$$S(\nu) = \frac{1}{2\pi^2} \int d\Omega^2 d\chi \xi(\chi) \frac{S_K(\chi) \sin(\nu\chi)}{\nu}$$

Real space power spectrum



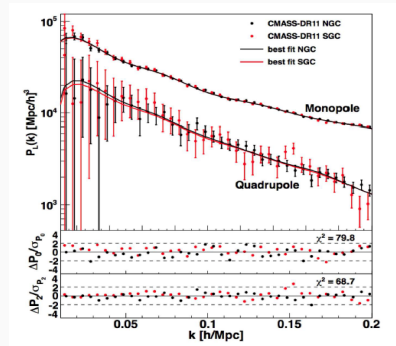
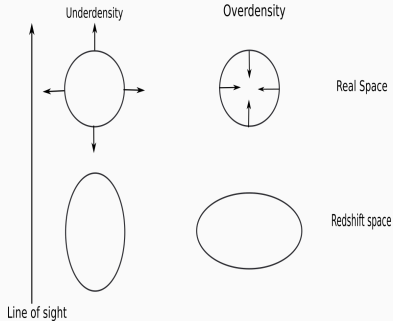
$$\nu = k/H_0 \text{ if } K = 0$$

$$\nu = \sqrt{\frac{k^2}{H_0^2 |\Omega_{K,0}|} - K} \text{ if } K \neq 0$$

$$D(z) \neq D_{K=0}(z)$$

$$\nu^2 S(\nu) = \frac{\nu(\nu^2 - 4K)^2}{\nu^2 - K} T^k(k, \eta) \zeta(k)$$

Clustering observables: Redshift space distortions



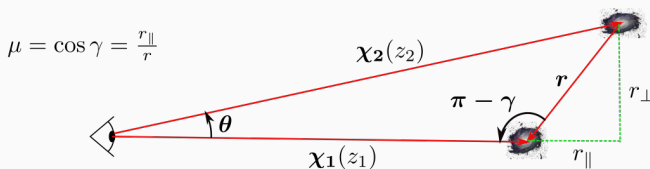
[Beutler et al, MNRAS, 2014]

Synthetic parameter: $f\sigma_8$

Sensitive to normalisation of power spectrum

Clustering observables: Redshift space distortions

- 2PC function for $K \neq 0$ [Matsubara, ApJ, 2000]
- $\tilde{f}\sigma_8$ in **fiducial** cosmology
- Alcock-Paczynski corrections: $\tilde{\xi}_g(\tilde{r}, \tilde{\mu}) = \xi_g(r, \mu)$



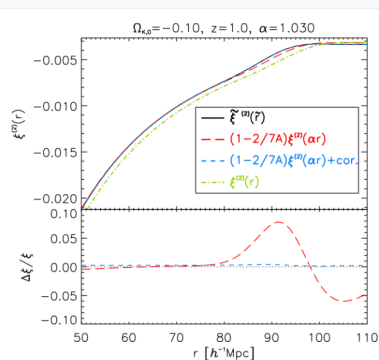
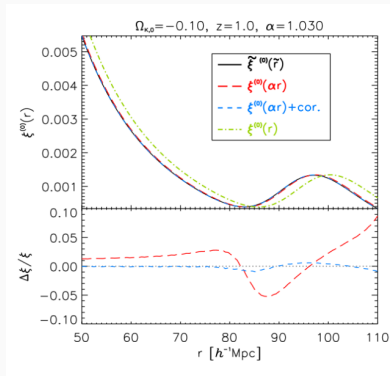
$$r_{\parallel} = \frac{\tilde{E}(z)}{E(z)} \tilde{r}_{\parallel} = \alpha_{\parallel} \tilde{r}_{\parallel}$$

$$r \simeq \alpha \tilde{r} = (\alpha_{\parallel} \alpha_{\perp}^2)^{1/3} \tilde{r}$$

$$r_{\perp} = \frac{D_A(z)}{D_A(z)} \tilde{r}_{\perp} = \alpha_{\perp} \tilde{r}_{\perp}$$

$$\tilde{\xi}^{(0)}(\tilde{r}) \simeq \xi^{(0)}(\alpha \tilde{r}) + Corr[\xi^{(2)}(\alpha \tilde{r}), \alpha_{\parallel}, \alpha_{\perp}]$$

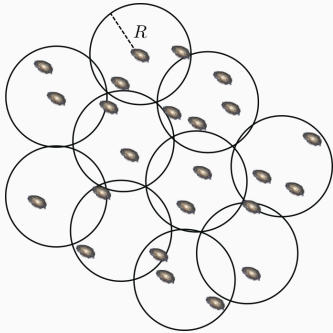
Redshift space distortions: Alcock-Paczynski corrections



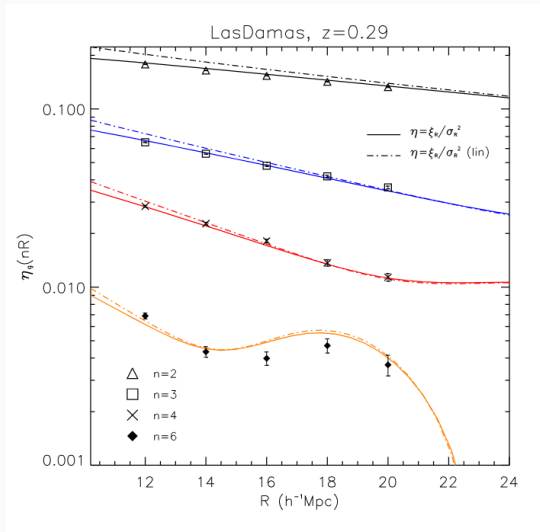
- $\tilde{f}\sigma_8 \simeq \left[\frac{5}{7} + \frac{2}{7} \frac{\tilde{E}(z)\tilde{D}_A(z)}{E(z)D_A(z)} \right] f\sigma_8 \neq \frac{\tilde{E}(z)\tilde{D}_A(z)}{E(z)D_A(z)} f\sigma_8$
- Large compilation of measurements: SDSS-IV, WiggleZ, BOSS DR12, Vipers etc.

Clustering ratio

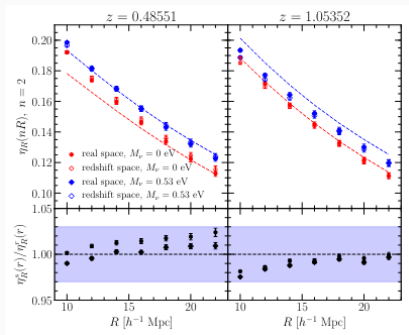
[Bel and Marinoni, A & A, 2014]



- $\eta_R(r) = \frac{\xi_R^{(0)}(r)}{\sigma_R^2}$
- Sensitive to shape of PS



- Insensitive to galaxy bias and large-scale RSD



[Zennaro et al, MNRAS, 2018]

- Simple Alcock-Paczynski corrections: $\tilde{\eta}_{\tilde{R}}(\tilde{r}) = \eta_{\alpha\tilde{R}}(\alpha\tilde{r})$
- Determined using BOSS DR7 and DR12

Results

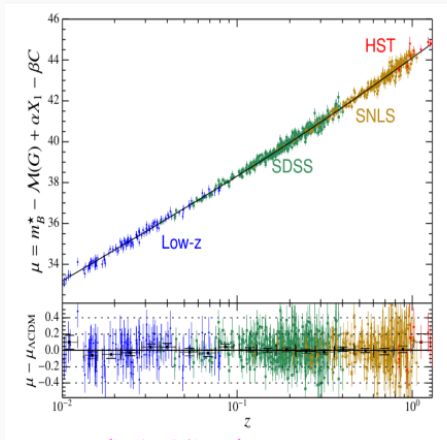
Parameters and priors

- Simple power-law primordial PS
- 7 cosmological parameters:
 $\{\Omega_{b,0}h^2, \Omega_{c,0}h^2, H_0, \tau, \ln(10^{10}A_s), n_s, \Omega_{K,0}\}$
- **BBN prior** on $\Omega_{b,0}h^2$ to get CMB-independent results

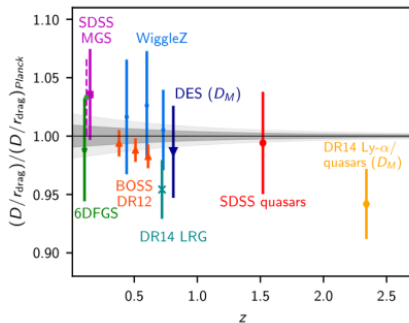
Parameter	Prior
$\Omega_{b,0}h^2$	[0, 100]
$\Omega_{c,0}h^2$	[0, 100]
H_0	[40, 100]
τ	[0, 0.2]
$\ln(10^{10}A_s)$	[0, 100]
n_s	[0.9, 1]
$\Omega_{K,0}$	[-0.2, 0.6]
$\Omega_{b,0}h^2$	$\mathcal{N}(0.0222, 0.0005^2)$
$\sigma_{8,0}$	[0.6, 1]
$\Omega_{m,0}$	[0, 1]

Geometric probes

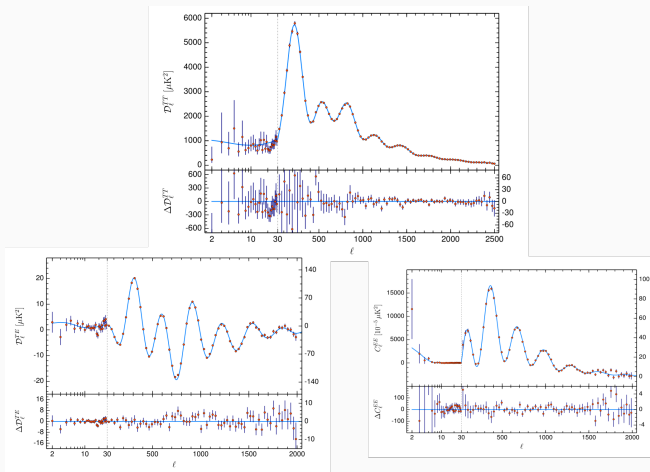
SN1a: JLA



BAO: Planck likelihood



[Planck results, 2018]



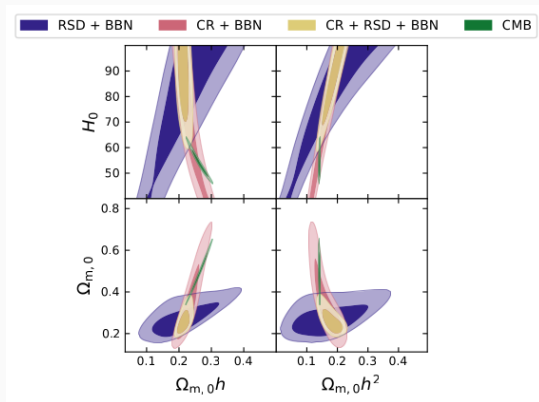
- $A_L = 1$ (degenerate with curvature and not physical)

Datasets: Consistency in Λ CDM

- Which datasets can be combined?
- Deviance Information Criterion

Λ CDM model		
Comparison	$\log_{10} I$	Agreement/Disagreement
CR + BBN vs RSD + BBN	1.35	strong agreement
SN Ia vs RSD + BBN	0.48	inconclusive
SN Ia vs CR + BBN	0.14	inconclusive
BAO vs CR + BBN	0.07	inconclusive
BAO vs RSD + BBN	0.04	inconclusive
CMB vs CR + BBN	-0.28	inconclusive
CMB vs SN Ia	-0.7	substantial
CMB vs BAO	-2.14	decisive disagreement
CMB vs RSD + BBN	-2.75	decisive disagreement

Clustering alone at $z < 2$

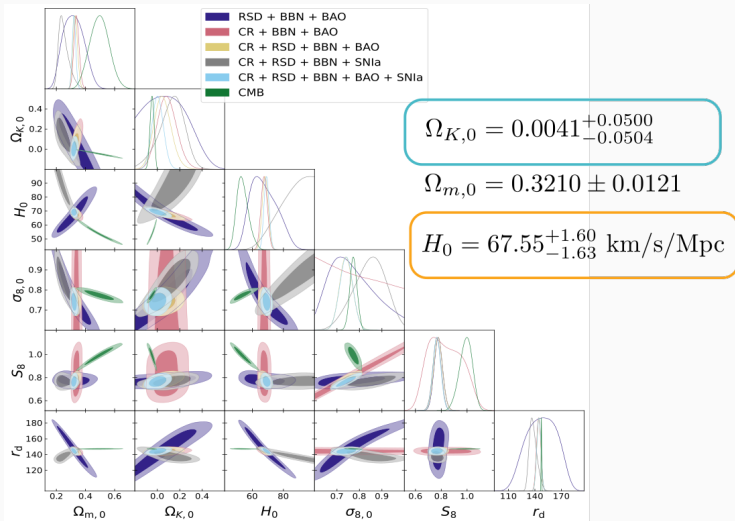


- $H_0 > 0.62$
- CR x RSD
- $\Omega_{m,0} = 0.26 \pm 0.04$ even without BBN prior on $\Omega_{b,0}h^2$

$\Omega_{K,0}$ unconstrained

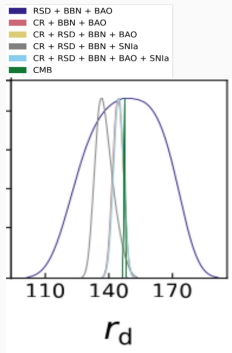
- CR sensitive to shape of PS but sampled scales too small
- RSD: degeneracy shift in PS/A_s

Clustering + Geometric probes



- Flat Λ CDM okay without CMB
- H_0 tension persists

Clustering + Geometric probes

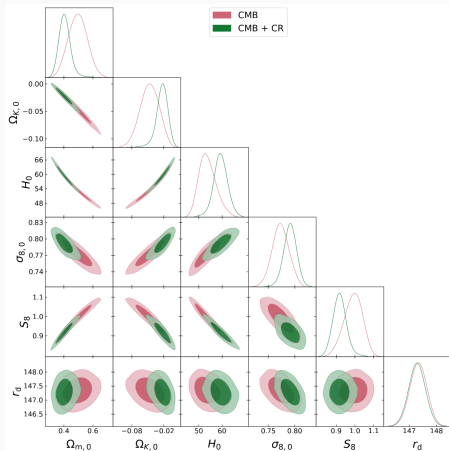


- CR + RSD
- Only BAO with r_d free param
- CMB independent estimate of sound horizon scale
- Strongly depends on BBN prior on $\Omega_{b,0}h^2$

$$r_d = 144.50^{+2.33}_{-2.35} \text{ Mpc}$$

- Agrees with base Λ CDM

Clustering + CMB



$K\Lambda$ CDM model

Comparison	$\log_{10} I$	Agreement/Disagreement
CR + BBN vs RSD + BBN	1.35	strong agreement
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SN Ia vs CR + BBN	0.14	inconclusive
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CMB vs CR + BBN	-0.28	inconclusive
CMB vs SN Ia	-0.7	substantial
CMB vs BAO	-2.14	decisive disagreement
CMB vs RSD + BBN	-2.75	decisive disagreement

- Only CR compatible with CMB
- $\Omega_{K,0} = -0.023 \pm 0.010$
- CR brings $K = 0$ into agreement with CMB at 2σ

Conclusion

Conclusion

- New, theoretically motivated Alcock-Paczynski prescription for RSD and CR in curved space
- Low- z clustering alone to constraint background params:
 - $H_0 > 62 \text{ km/s/Mpc}$
 - $\Omega_{m,0} = 0.26 \pm 0.04$
- CMB-independent test of flatness:

$$\Omega_{K,0} = 0.0041^{+0.0500}_{-0.0504} .$$

- CR + CMB compatible with $K = 0$