What do large-scale structure have to tell us about spatial curvature?

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

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String-Cosmo day

APC, Paris

Particules, Astroparticules, Cosmologie: Théorie
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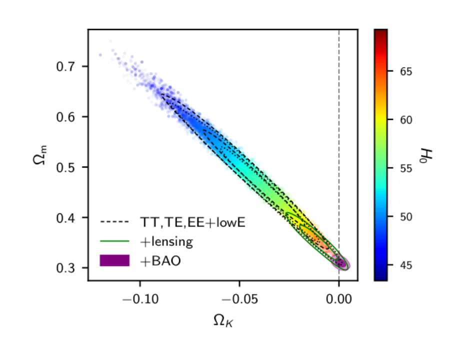
Introduction

Evidence for spatial curvature?



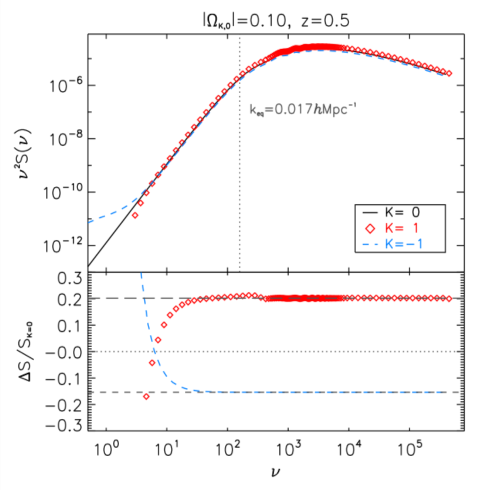
[Planck 2018 results]

- 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 ΛCDM

Large-scale structure observables in curved space

Real space power spectrum



Spectrum of Laplace-Beltrami operator:

$$\nabla^2 \mathcal{Q}_{lm} = -k^2 \mathcal{Q}_{lm}$$

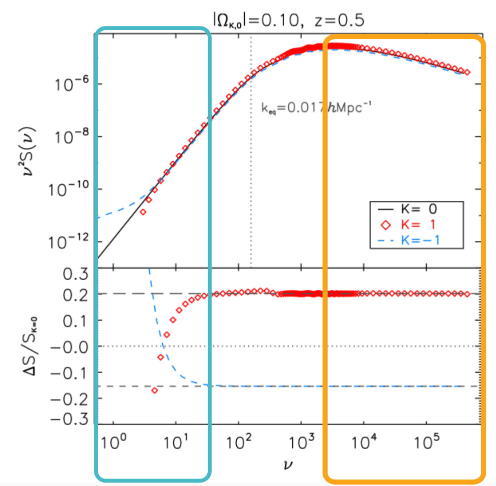
with $\mathcal{Q}_{lm} = X_l(\nu, \chi) Y_{lm}(\theta, \phi)$

$\nu = k/H_0$ if $K = 0$

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

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

Real space power spectrum



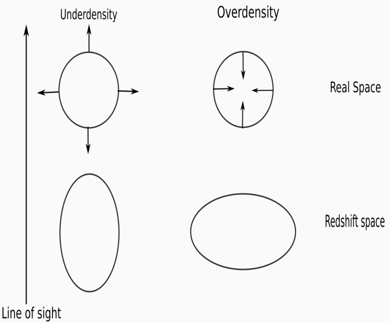
$$\nu = k/H_0 \text{ if } K = 0$$

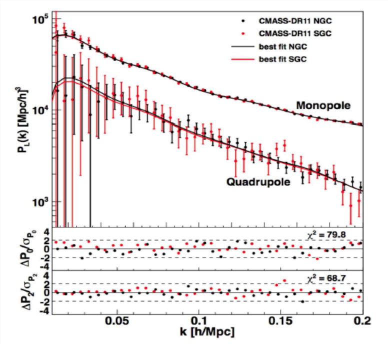
$$\nu = \sqrt{\frac{k^2}{H_0^2 \left|\Omega_{K,0}\right|} - K} \text{ if } K \neq 0$$

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

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

Clustering observables: Redshift space distortions





[Beutler et al, MNRAS, 2014]

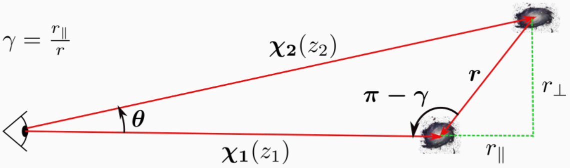
Synthetic parameter: $f\sigma_8$

Sensitive to normalisation of power spectrum

Clustering observables: Redshift space distortions

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

$$\mu = \cos\gamma = \frac{r_\parallel}{r}$$



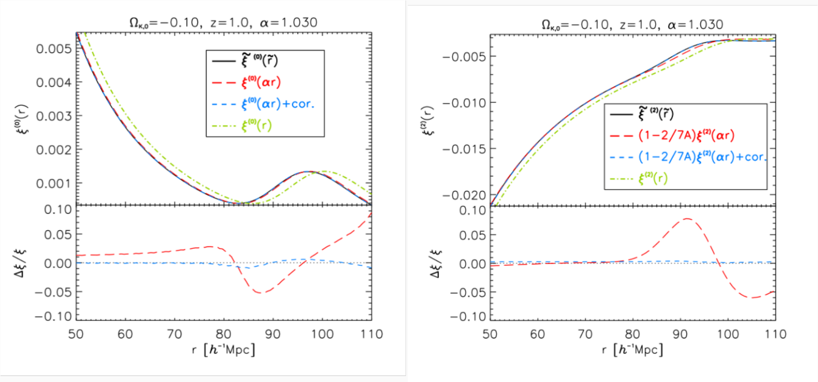
$$r_\parallel = \frac{\tilde{E}(z)}{E(z)}\tilde{r}_\parallel = \alpha_\parallel \tilde{r}_\parallel$$

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

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

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

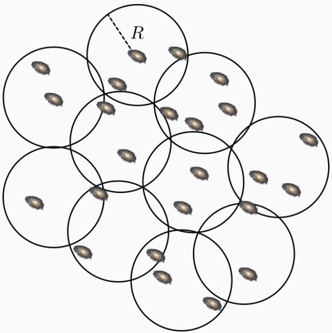
Redshift space distortions: Alcock-Paczynski corrections



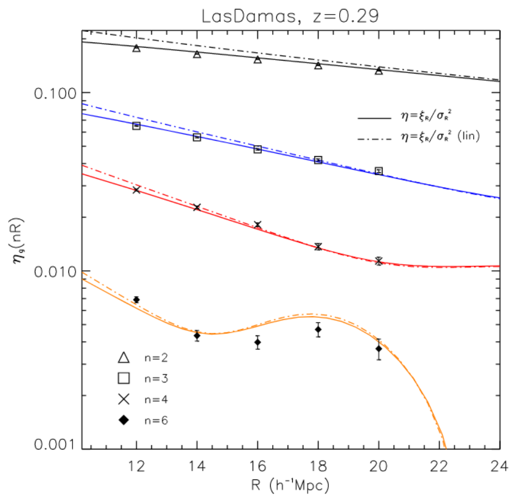
- $\widetilde{f\sigma_8} \simeq \left[\frac{5}{7} + \frac{2}{7}\frac{\tilde{E}(z)\tilde{D}_A(z)}{E(z)D_A(z)}\right] f\sigma_8 \neq \frac{\tilde{E}(z)\tilde{D}_A(z)}{E(z)D_A(z)} f\sigma_8$
- Large compilation of measurements: SDSS-IV, WiggleZ, BOSS DR12, Vipers etc.

Clustering ratio

[Bel and Marinoni, A & A, 2014]



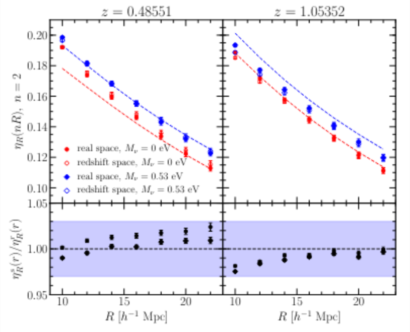
- $\eta_R(r) = \frac{\xi_R^{(0)}(r)}{\sigma_R^2}$
- Sensitive to shape of PS



Clustering ratio

[Bel and Marinoni, A & A, 2014]

- 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

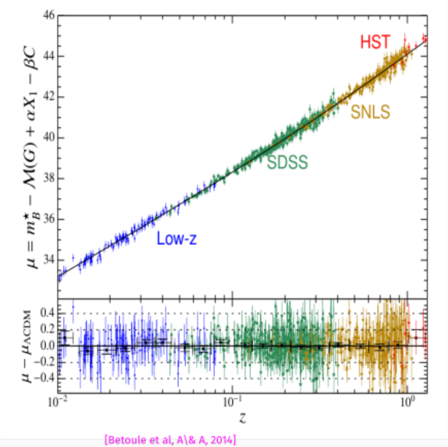
Parameters and priors

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

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

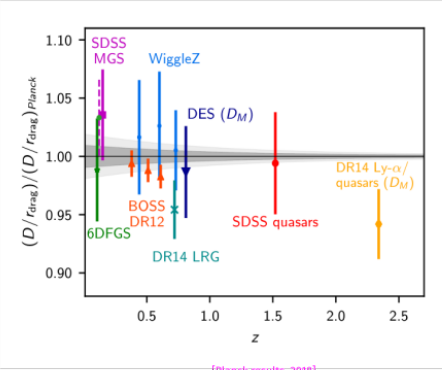
Geometric probes

SN1a: JLA



[Betoule et al, A\& A, 2014]

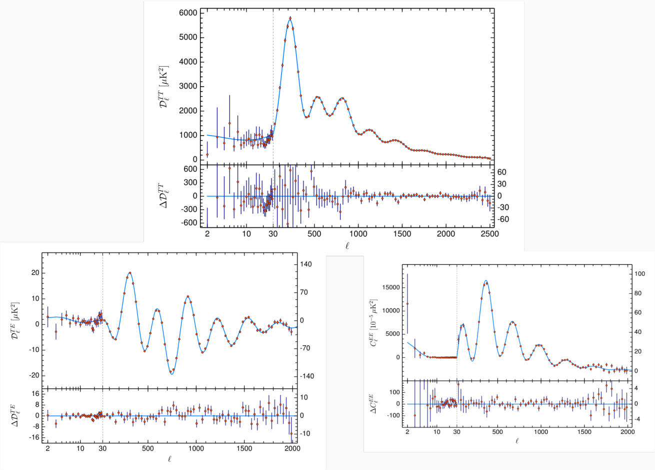
BAO: Planck likelihood



[Planck results, 2018]

CMB

[Planck results, 2018]



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

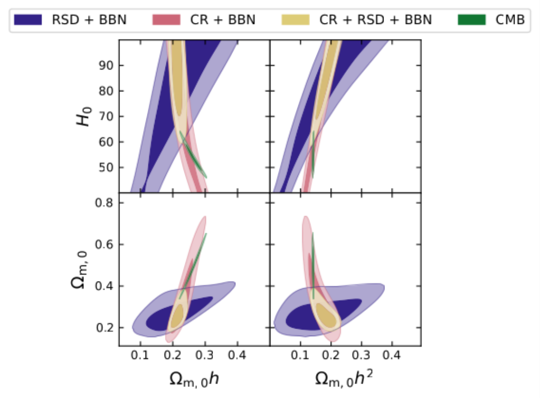
Datasets: Consistency in $K\Lambda CDM$

- Which datasets can be combined?
- Deviance Information Criterion

$K\Lambda$CDM model

Comparison	$\log_{10} I$	Agreement/Disagreement
CR + BBN vs RSD + BBN	1.35	strong agreement
SNIa vs RSD + BBN	0.48	inconclusive
SNIa 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 SNIa	−0.7	substantial
CMB vs BAO	−2.14	decisive disagreement
CMB vs RSD + BBN	−2.75	decisive disagreement

Clustering alone at $z < 2$

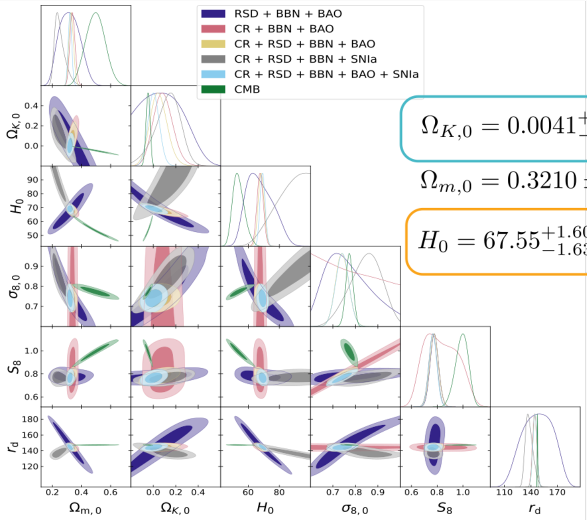


- $H_0 > 62$ km/s/Mpc
- CR x RSD
- $\Omega_{m,0} = 0.26 \pm 0.04$ even without BBN prior on $\Omega_{b,0}h^2$

$\Omega_{K,0}$ unconstrained

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

Clustering + Geometric probes



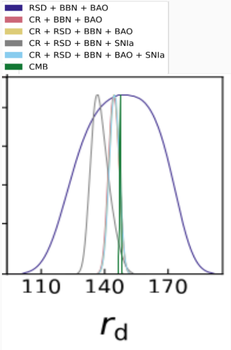
$$\Omega_{K,0} = 0.0041^{+0.0500}_{-0.0504}$$

$$\Omega_{m,0} = 0.3210 \pm 0.0121$$

$$H_0 = 67.55^{+1.60}_{-1.63}\ \mathrm{km/s/Mpc}$$

- Flat ΛCDM okay without CMB
- H_0 tension persists

Clustering + Geometric probes

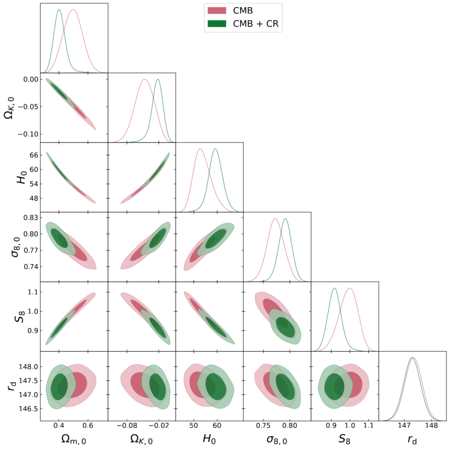


- CR + RSD
- Only BAO with r_d free param
- CMB independent estimate of sound horizon scale
- Strongly depends on BBN prior on $\Omega_{b,0}h^2$

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

- Agrees with base ΛCDM

Clustering + CMB



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- 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-Paczynki prescription for RSD and CR in curved space
- Low-z clustering alone to constrain background params:
  - $H_0 > 62$ 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 $K = 0$