Baryon Acoustic Oscillations and SDSS DR7

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Plan

- Introduction on BAOs
- BAO detection with classical χ^2 statistic
- Our new method for BAO detection
- Results on SDSS simulations
- Results on SDSS data (in progress)
- Conclusion

Introduction on Baryon Acoustic Oscillations

Baryon Acoustic Oscillations

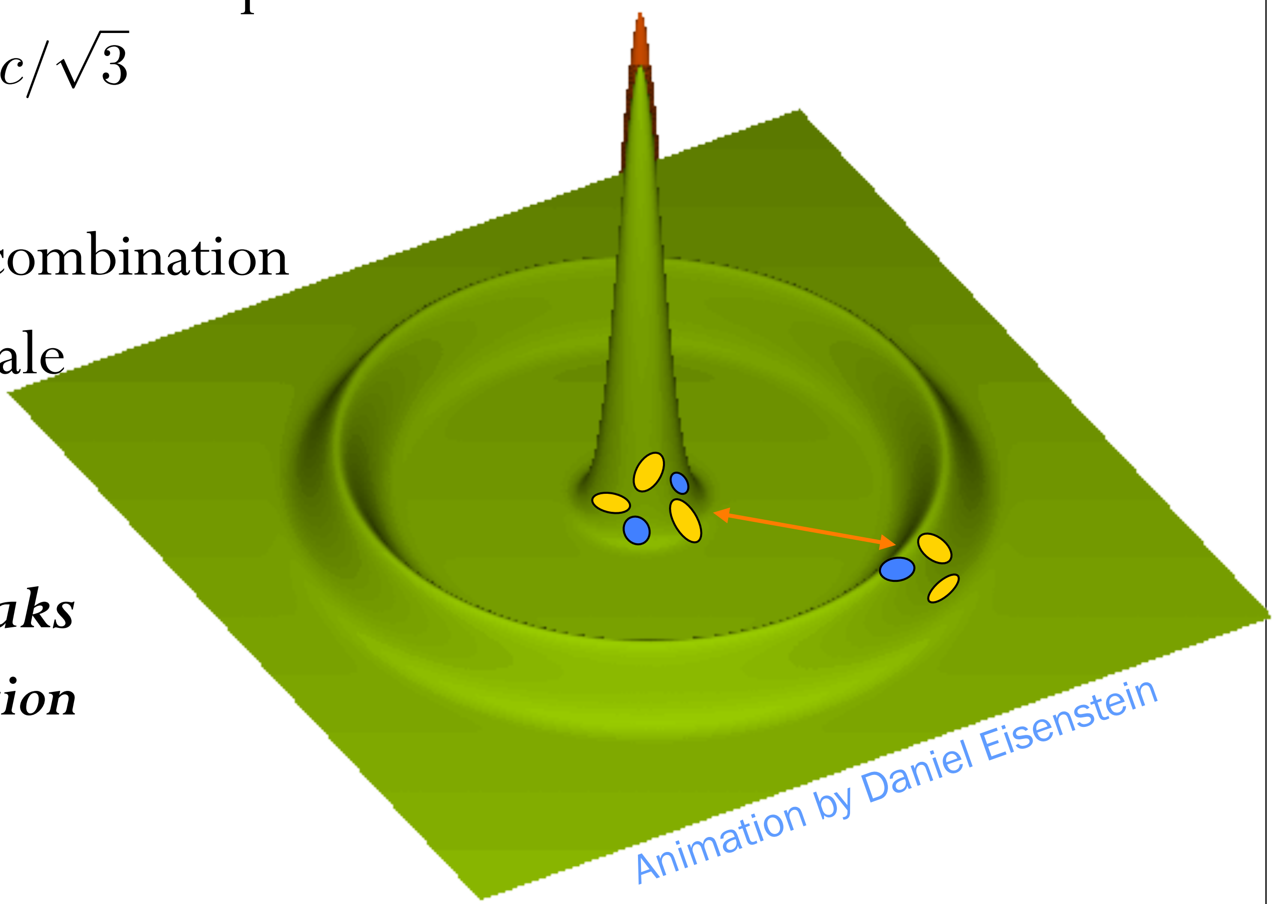
- Sound wave excited in the primordial plasma at speed $c/\sqrt{3}$
- Wave stops at recombination

at sound horizon scale

$r_s \approx 150$ Mpc

Galaxies form in peaks

- ***Excess of correlation***



BAOs as standard ruler in galaxy surveys (I)

- In reality waves originate from everywhere and superpose
- Only **1%** statistical effect
- Can only be seen statistically

  → require large survey volume

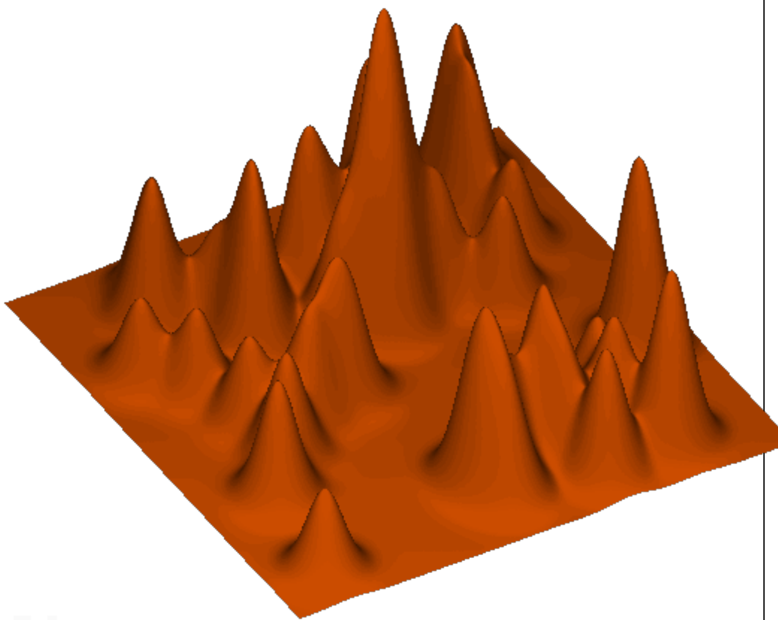


Figure from Daniel Eisenstein

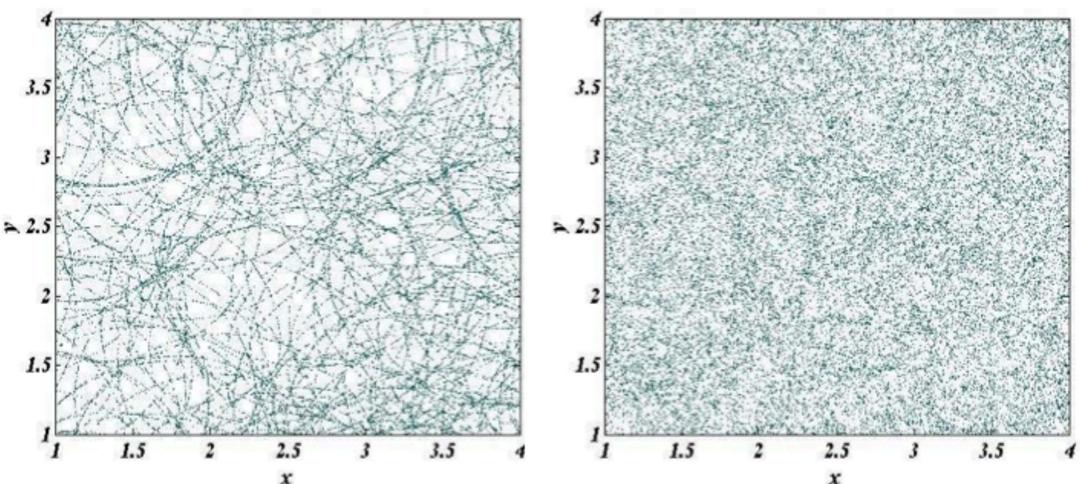
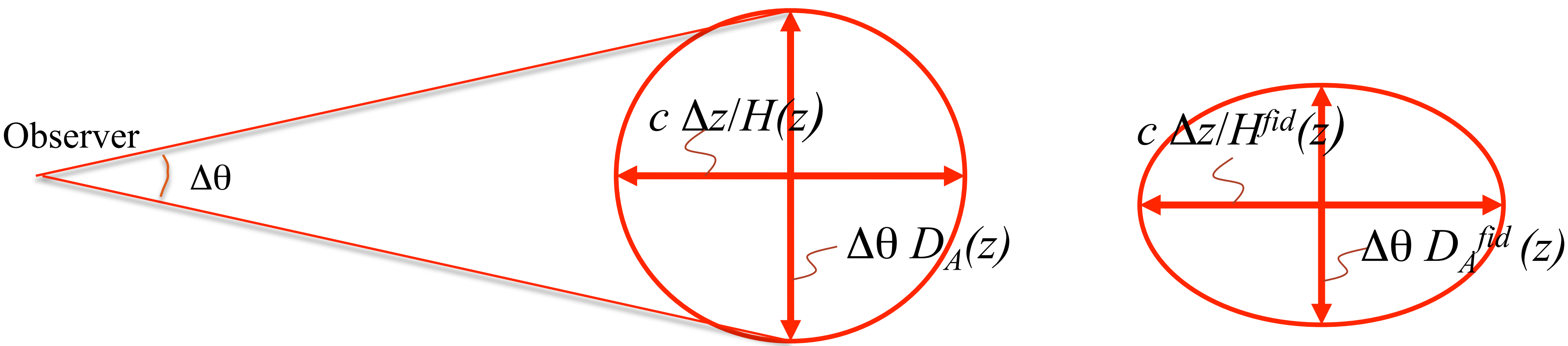


Figure from Bassett & Hlozek (2009)

BAOs as standard ruler in galaxy surveys (II)

- Galaxy surveys are redshift surveys → one **assumes a fiducial cosmology** to convert to 3D volume

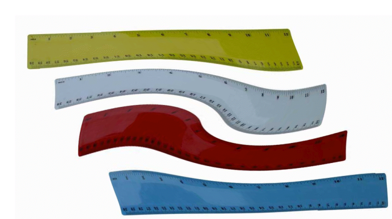


Circular object when fiducial cosmology is correct

Wrong size and shape when fiducial cosmology is wrong

- BAOs give a **standard ruler** (known real size)

→ they show how incorrect the fiducial cosmology is



BAOs in correlation function ξ(r)

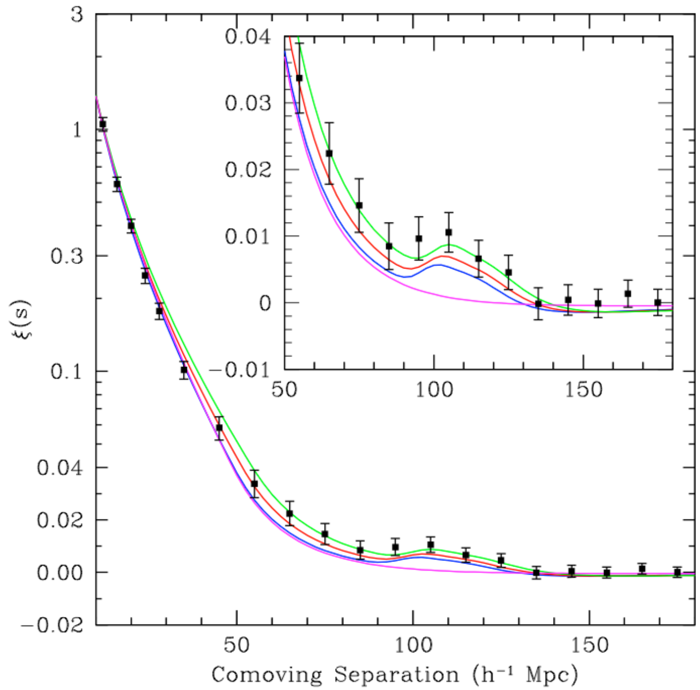
- We consider 3 parameters in our analysis:
  - Matter density $\Omega_m h^2$
    - horizon at matter-radiation equality
    - amplitude of BAO peak
  - Effect of wrong fiducial cosmology
    ≈ dilation factor $\alpha = D_V / D_V^{fid}$

$$D_V(z) = \left[D_M(z)^2 \frac{cz}{H(z)} \right]^{1/3}$$

  - Effect of σ_8 and galaxy bias
    ≈ amplitude factor b^2

→ **Detection of BAOs at expected scale confirms ΛCDM model**

→ **BAOs constrain α with standard ruler property**

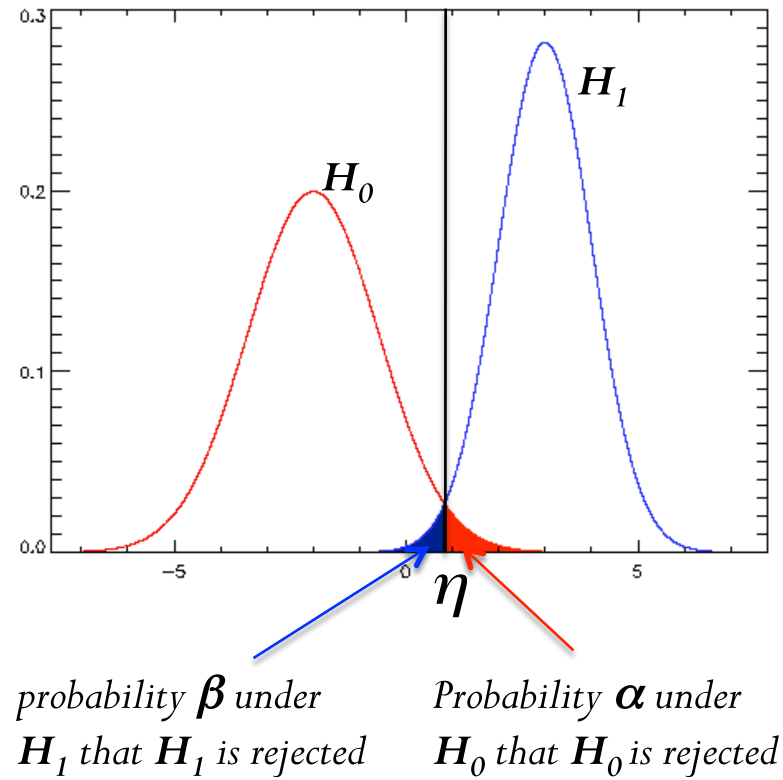


Different ξ curves with $\Omega_m h^2 = 0.12, 0.13, 0.14$ (green, red, blue) and non physical no-BAO model (pink) (Eisenstein et al. 2005)

I) BAO detection with classical χ^2 method

Statistical Hypothesis testing

- Test between 2 hypotheses $\boldsymbol{H_0}$ and $\boldsymbol{H_1}$ from a measurement X using a test statistics $t(X)$



- Statistical test of size α
  - *If* $t(X) > \eta$ *then accept* H_1
  - *If* $t(X) \leq \eta$ *then accept* H_0

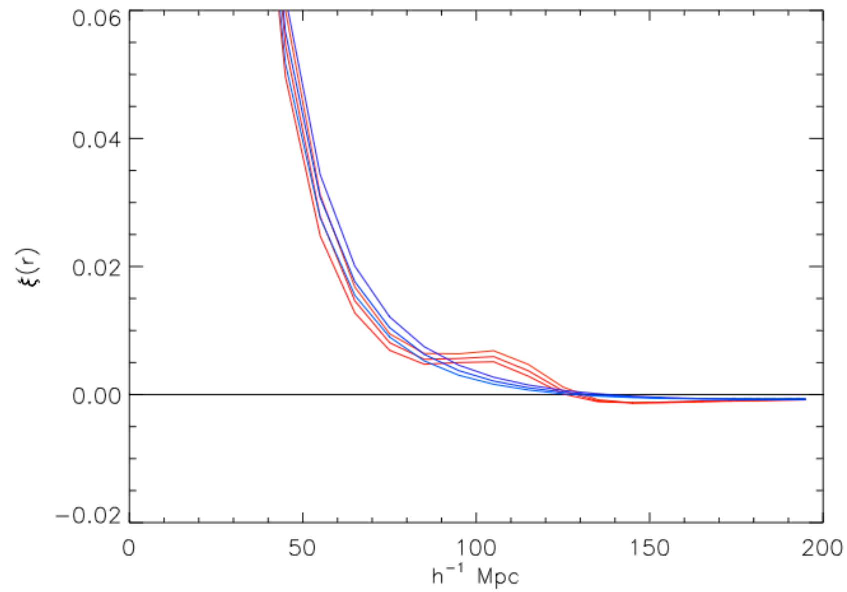
- More common in cosmology:

probability under H_0 that $t(X)$ > observed value

BAO detection with classical χ^2 method (I)

- If measurement is the correlation function: $\hat{\xi} = (\hat{\xi}_i)_{1 \leq i \leq n}$

$$\mathcal{H}_0 : \exists \theta \in \Theta \text{ s.t. } \hat{\xi} \sim \mathcal{N}\left(\xi_{noBAO,\theta}, C\right)$$
$$\mathcal{H}_1 : \exists \theta \in \Theta \text{ s.t. } \hat{\xi} \sim \mathcal{N}\left(\xi_{BAO,\theta}, C\right)$$



- Define the χ^2 statistics (equivalent to likelihood)

$$\chi^2_{BAO,\theta} = \left\langle \hat{\xi} - \xi_{BAO,\theta}, C^{-1}(\hat{\xi} - \xi_{BAO,\theta}) \right\rangle \qquad \mathcal{L}_{BAO,\theta}(\hat{\xi}) \propto \exp\left(-\frac{1}{2}\chi^2_{BAO,\theta}\right)$$
$$\chi^2_{noBAO,\theta} = \left\langle \hat{\xi} - \xi_{noBAO,\theta}, C^{-1}(\hat{\xi} - \xi_{noBAO,\theta}) \right\rangle \qquad \mathcal{L}_{noBAO,\theta}(\hat{\xi}) \propto \exp\left(-\frac{1}{2}\chi^2_{noBAO,\theta}\right)$$

BAO detection with classical χ^2 method (II)

- The test statistic $\Delta\chi^2$ is a generalized likelihood ratio

$$\begin{aligned}\Delta\chi^2 &= \min_\theta \chi^2_{noBAO,\theta} - \min_\theta \chi^2_{BAO,\theta} \\ &= -2\left[\max_\theta \ln\left(\mathcal{L}_{noBAO,\theta}\right) - \max_\theta \ln\left(\mathcal{L}_{BAO,\theta}\right)\right] \\ &= -2\ln\left[\frac{\max_\theta \mathcal{L}_{noBAO,\theta}}{\max_\theta \mathcal{L}_{BAO,\theta}}\right]\end{aligned}$$

- Large values of $\Delta\chi^2$ favor H_1

→ significance is probability under H_0 that $\Delta\chi^2$ > observed value

- Given some assumptions:

$$\Delta\chi^2 \leq X^2 \text{ with } X \sim \mathcal{N}(0,1) \text{ under } \mathcal{H}_0$$

- Significance can be estimated as $P(X^2 > \Delta\chi^2)$, i.e. as $\sqrt{\Delta\chi^2}.\sigma$

BAO detection with classical χ^2 method (III)

- Problems:
  - Assumptions of the method are wrong: $\sqrt{\Delta\chi^2}.\sigma$ overestimates the significance

	χ_1^2	$\Delta\chi^2$
$P(X \geq 1.0)$	$0.32\ (1\sigma)$	$0.39\ (0.85\sigma)$
$P(X \geq 2.25)$	$0.13\ (1.5\sigma)$	$0.18\ (1.35\sigma)$
$P(X \geq 4.0)$	$4.5 \times 10^{-2}\ (2\sigma)$	$6.8 \times 10^{-2}\ (1.8\sigma)$
$P(X \geq 6.25)$	$1.2 \times 10^{-2}\ (2.5\sigma)$	$2.1 \times 10^{-2}\ (2.3\sigma)$
$P(X \geq 9.0)$	$2.7 \times 10^{-3}\ (3\sigma)$	$4.3 \times 10^{-3}\ (2.85\sigma)$

  - The method cannot work for model-dependent covariance matrix:

$$\mathcal{H}_0 : \exists \theta \in \Theta \text{ s.t. } \hat{\xi} \sim \mathcal{N}\left(\xi_{noBAO,\theta}, C_{noBAO,\theta}\right)$$
$$\mathcal{H}_1 : \exists \theta \in \Theta \text{ s.t. } \hat{\xi} \sim \mathcal{N}\left(\xi_{BAO,\theta}, C_{BAO,\theta}\right)$$

II) Our new method for BAO detection

Our new method for BAO detection (I)

- New procedure to estimate significance, which works in all cases
  - We generate realizations of every model $(\boldsymbol{H_0}, \theta)$

$$\hat{\xi} \sim \mathcal{N}\left(\xi_{noBAO,\theta}, C_{noBAO,\theta}\right)$$

  - This gives significance functions for individual model $(\boldsymbol{H_0}, \theta)$

$$P(\Delta\chi^2 \geq x \,|\, \mathcal{H}_0, \theta)$$

  - The significance is given by the "worst case" $\boldsymbol{H_0}$ model

$$p(x) = \max_{\theta \in \Theta} P(\Delta\chi^2 \geq x \,|\, \mathcal{H}_0, \theta)$$

Our new method for BAO detection (II)

- Change of the statistic
  - $\Delta\chi^2$ is not a generalized likelihood ratio for model-dependent covariance matrix

$$\mathcal{L}_{BAO,\theta} \propto |C_{BAO,\theta}|^{-1/2}\, e^{-\frac{\chi^2_{BAO,\theta}}{2}}$$

$$\mathcal{L}_{noBAO,\theta} \propto |C_{noBAO,\theta}|^{-1/2}\, e^{-\frac{\chi^2_{noBAO,\theta}}{2}}$$

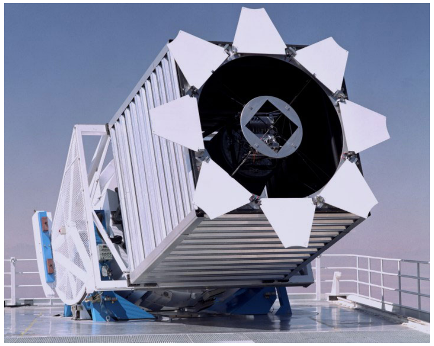
  - We use Δl instead of $\Delta\chi^2$ to keep a generalized likelihood ratio

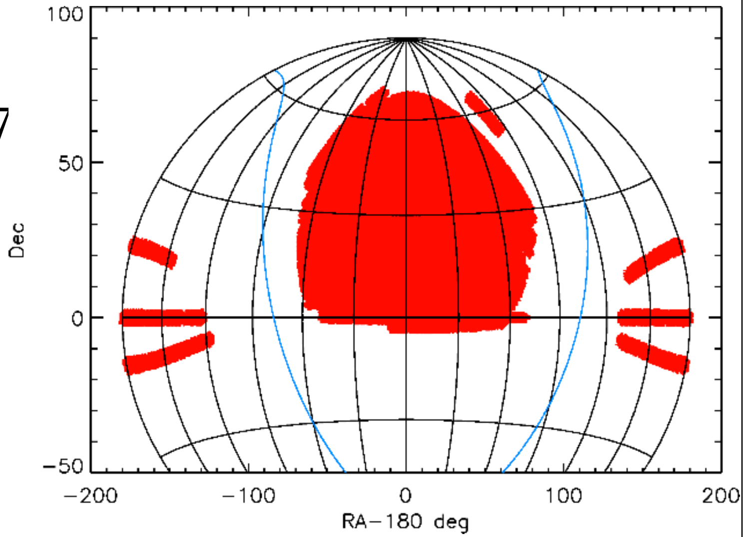
$$\begin{aligned}
\Delta l &= \min_{\theta} l_{noBAO,\theta} - \min_{\theta} l_{BAO,\theta} \\
l_{BAO,\theta} &= \chi^2_{BAO,\theta} + \ln|C_{BAO,\theta}| \\
l_{noBAO,\theta} &= \chi^2_{noBAO,\theta} + \ln|C_{noBAO,\theta}|
\end{aligned}$$

III) Results on SDSS simulations

SDSS LRG survey

- 8 year program with 2.5m telescope at Apache point (New Mexico)
- SDSS DR7, last release of SDSS II
- Sample that we use (Kazin et al. 2010)
  - Spectroscopic LRG sample with 105k galaxies
  - Quasi volume-limited up to z=0.36
  - Magnitude-limited for 0.36<z<0.47
- SDSS DR9 publicly released in July 2012





Description of the simulations (I)

- Simple Gaussian realizations (Gaussian assumption well verified with LN realizations)

$$\hat{\xi} \sim \mathcal{N}\left(\xi_{noBAO,\theta}, C_{noBAO,\theta}\right)$$
$$\hat{\xi} \sim \mathcal{N}\left(\xi_{BAO,\theta}, C_{BAO,\theta}\right)$$

- Models of correlation function:

$$\xi_{BAO,\theta}(r) = b^2\, \xi_{BAO,\Omega_m h^2}(\alpha\, r)$$
$$\xi_{noBAO,\theta}(r) = b^2\, \xi_{noBAO,\Omega_m h^2}(\alpha\, r)$$

- Covariance matrix:
  - Case 1: Constant covariance matrix C
  - Case 2: Simple example of Model-dependent covariance matrix

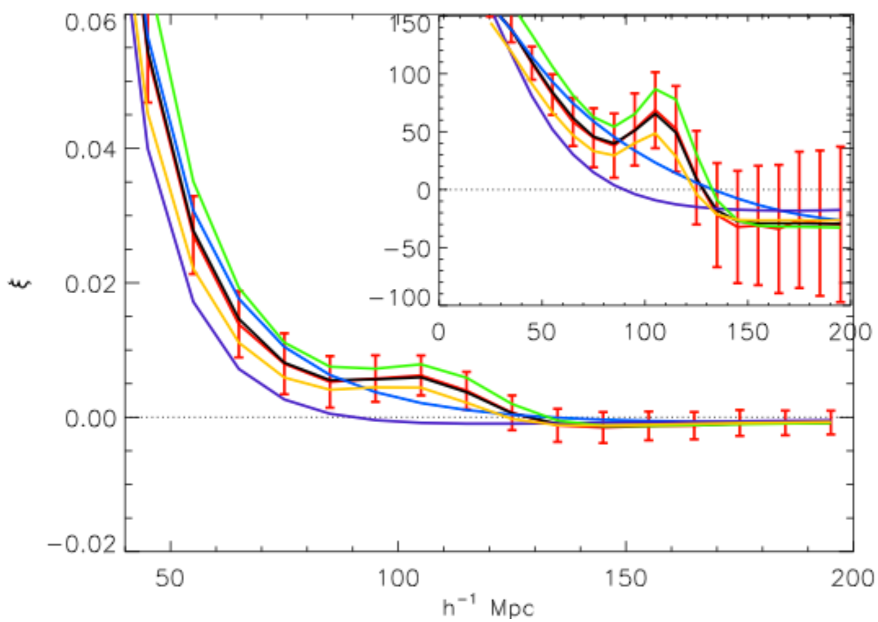
$$C_{noBAO,\theta} = C_{BAO,\theta} = \left(\frac{b}{b_0}\right)^4 C$$

- Where does the covariance matrix C come from ?

Description of the simulations (II)

- We use lognormal simulations of the SDSS DR7 LRG sample **to obtain a reasonable covariance matrix *C***

- We obtain covariance matrix *C* as the empirical covariance matrix of 2000 lognormal simulations



Average significance for BAO detection under H_1

- Comparison of 3 methods:
  - Classical χ^2 method with estimate $\sqrt{\Delta\chi^2}.\sigma$
  - Rigorous estimate with $\Delta\chi^2$
  - Rigorous estimate with Δl (our new method)

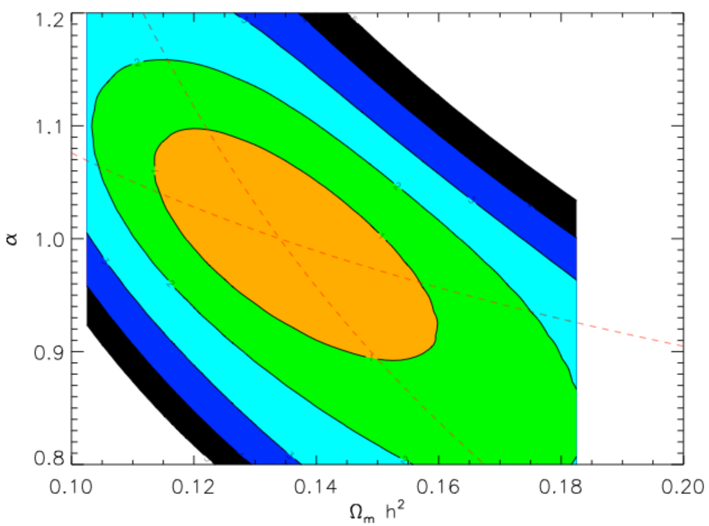
	Classical χ^2 method (wrong)	**$\Delta\chi^2$ statistic with correct significance**	**Δl method**
Constant covariance matrix	2.21σ	2.0σ	2.0σ
Model-dependent covariance matrix	2.32σ	1.59σ	1.96σ

Effect of model-dependent covariance matrix in constraints

- Cosmological parameter constraints

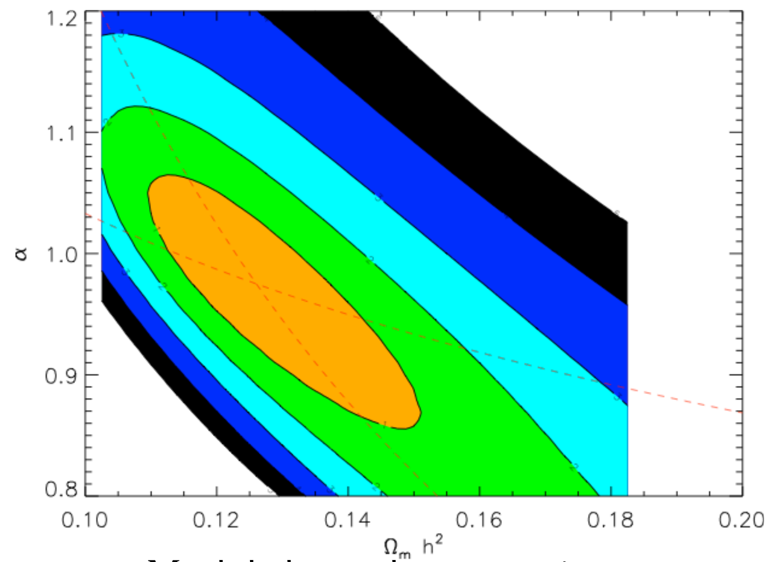
$$p(\Omega_m h^2, \alpha \,|\, \hat{\xi}) \propto \int \mathcal{L}_{BAO,(\Omega_m h^2, \alpha, B)} dB$$

- Example with expected correlation from simulations



Constant covariance

$$\alpha = 0.995 \pm 0.070$$
$$\Omega_m h^2 = 0.134 \pm 0.015$$



Model-dependent covariance

$$\alpha = 0.976 \pm 0.070$$
$$\Omega_m h^2 = 0.126 \pm 0.014$$

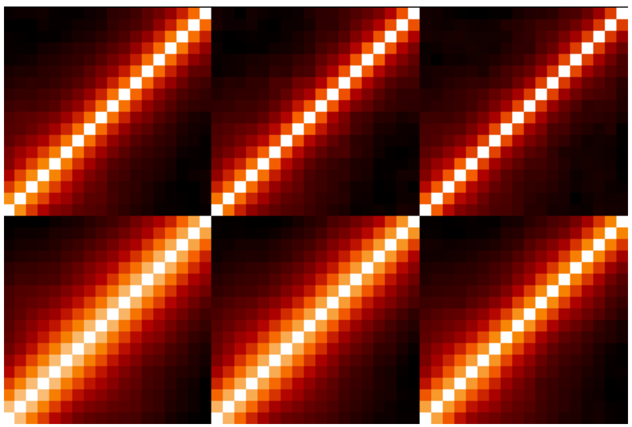
Results on SDSS data (work in progress)

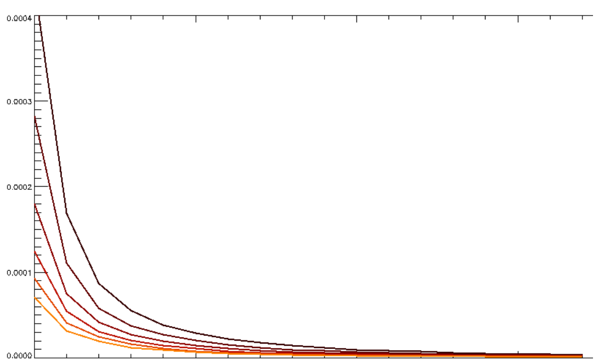
New procedure for simulations

- **New procedure to compute model-dependent C_θ**
  - Generate 2000 simulations for each value $\Omega_m h^2=0.08, 0.105, 0.13, 0.155, 0.18$
  - Geometric parameter α taken into account by introducing a selection function ϕ_α $(0.8< \alpha <1.2)$
  - b is well approximated by a factor b^4 in the covariance matrix
    - when changing b_1=2.5 to b_2=3.0 we find that $(b_2/b_1)^4 C_1$ is 10 times closer to C_2 than C_1

Structure of the covariance matrix

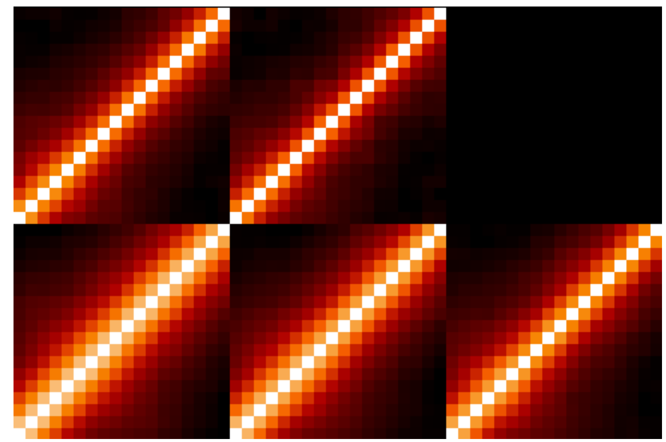
Effect of α

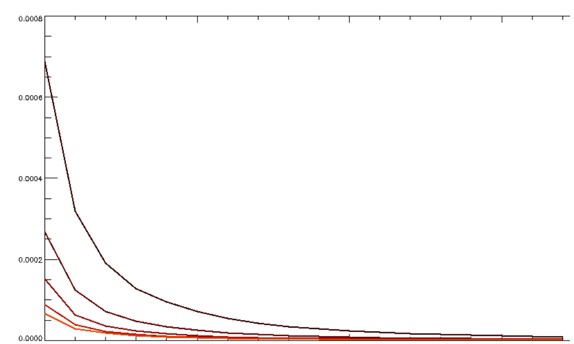




- Only the diagonal of C is really affected

Effect of $\Omega_m h^2$

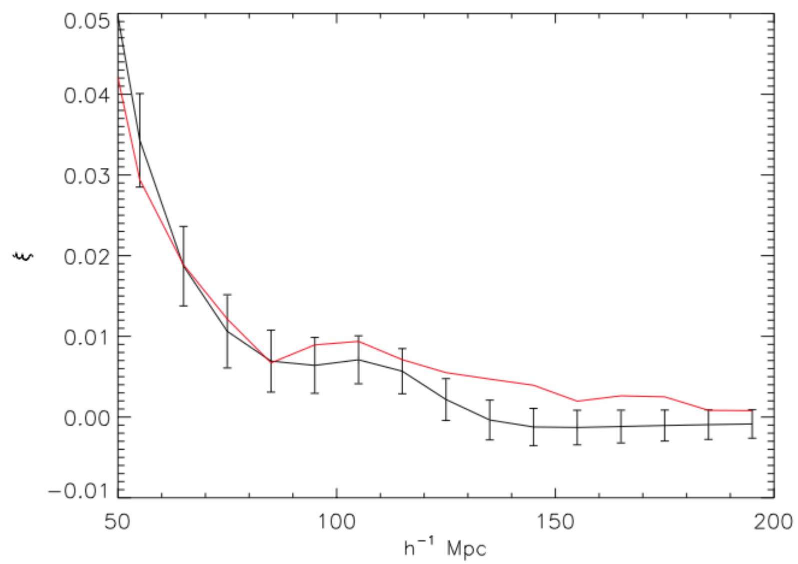




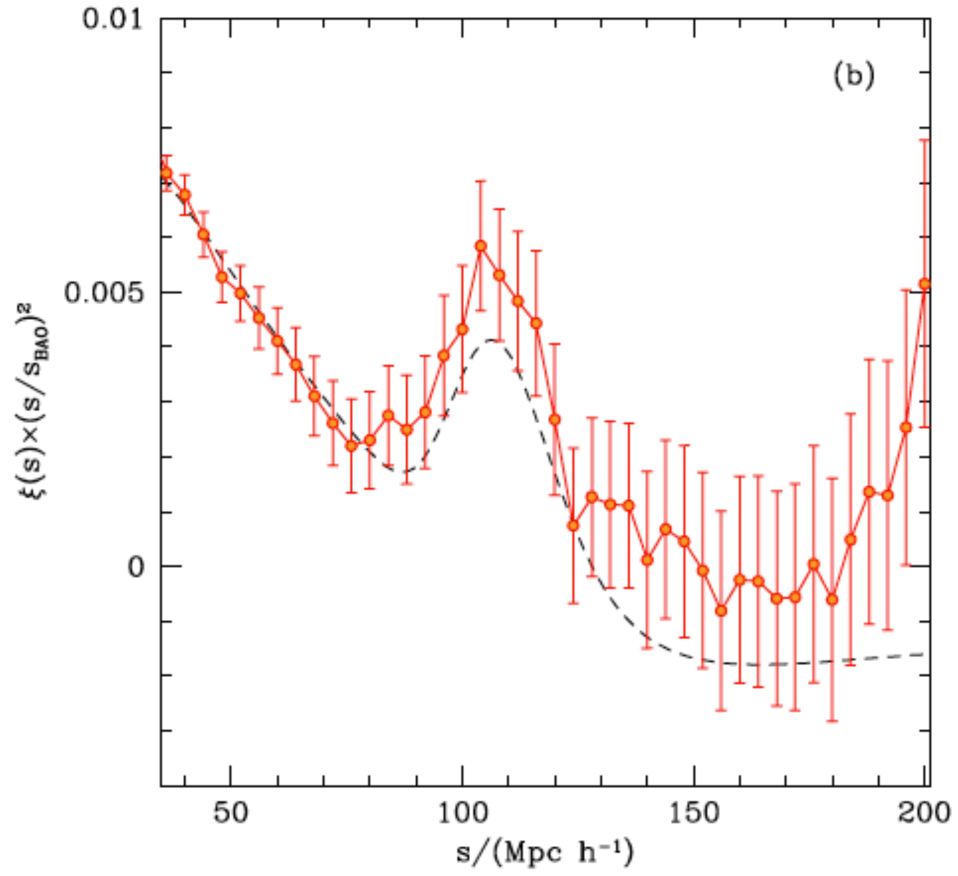
- The whole covariance matrix is affected by variations of $\Omega_m h^2$

BAO detection in SDSS DR7 LRG

- We can observe the BAO peak
- However it is not well localized:
  - very weak BAO detection $\Delta\chi^2$=0.92 (but in agreement with expectation under H_1 : $\Delta\chi^2$ = 7.5 +/- 8.9)
  - real significance with $\Delta\chi^2$ and Δl ??

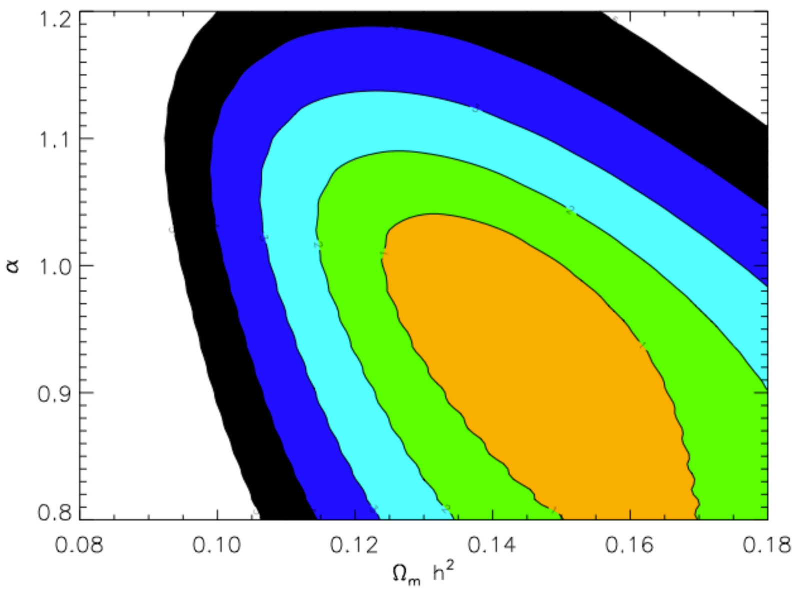


Correlation in BOSS DR9

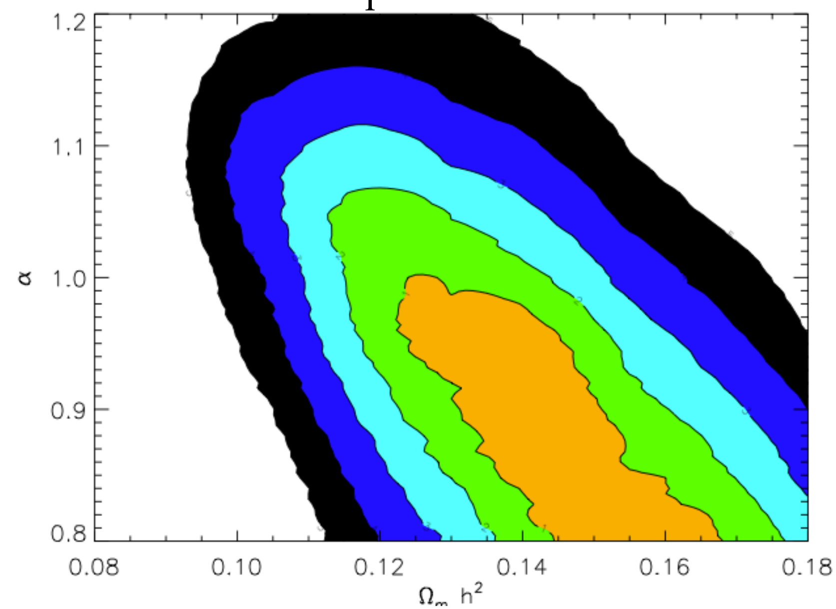


Parameter constraints with SDSS DR7 LRG

Constant covariance



Model-dependent covariance



- Constraints are **tighter** with model-dependent covariance matrix
- **No shift** in the maximum likelihood

Conclusions

Conclusions

- New method for BAO detection (Δl method)
  - Rigorous
  - Works even with model-dependent covariance matrix

- New procedure for obtaining realistic model-dependent covariance matrix

- Consequence of model-dependent covariance matrix for SDSS DR7 LRG sample
  - Does not change much BAO detection → weak signal
  - Seems to tighten cosmological constraints