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Bayesian cosmological reconstruction of matter fields, peculiar velocities and power-spectra

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Motivation

In the current cosmological picture, structures in the Universe have grown from tiny fluctuations through gravitational clustering. Non-linear processes of structure formation destroy the information about the origin of our Universe. This information is, however, still encoded in the large scales in which structures are close to the linear regime. In particular baryon-photon plasma oscillations can be detected in the large-scale structure (LSS) as remnants of the early Universe. Their characteristic scale is measurable as an oscillatory pattern in the matter power-spectrum which evolves in time in such a way that they can be used as standard rulers and to constrain cosmological parameters. They can also be used to study dark energy evolution. For these reasons it is especially interesting to have measurements of baryon-acoustic oscillations (BAOs) at different redshifts and with different matter tracers confirming the same underlying physics. However, astronomical data are plagued by many systematic uncertainties which make the extraction of such signals difficult: complex survey masking, bias of the matter tracer, redshift distortions caused by peculiar motions, etc. A statistical approach becomes necessary.

The Bayesian approach

Sampling the joint probability distribution of the 3D linear matter field $\boldsymbol{s}$, the quasi-nonlinear peculiar velocities $\boldsymbol{v}$ and the covariance (or power-spectrum) $\mathbf{S}$ from nonlinear data $\boldsymbol{d}$ $P(\boldsymbol{s},\boldsymbol{v},\mathbf{S}|\boldsymbol{d}^z)$ can be done using the Gibbs-sampling scheme (see Figures on the right)

$$\boldsymbol{s}^{(j+1)} \hookleftarrow P(\boldsymbol{s} \mid \boldsymbol{v}^{(j)}, \mathbf{S}, \boldsymbol{d}^z), \quad (1)$$

$$\mathbf{S}^{(j+1)} \hookleftarrow P(\mathbf{S} \mid \boldsymbol{s}^{(j+1)}), \quad (2)$$

$$\boldsymbol{v}^{(j+1)} \hookleftarrow P(\boldsymbol{v} \mid \boldsymbol{s}^{(j+1)}), \quad (3)$$

(1) Matter field reconstruction (Eq. 1)

This step is done with the Hamiltonian sampling method under the Gaussian prior assumption for the variable $\boldsymbol{s}$ and encoding the lognormal transformation between the linear and the nonlinear density fields in the likelihood (KJW10;JK10;KGF12). It yields an estimate of the linear component of the density field correcting for masking and noise. More complex prior distributions can be used expanding the lognormal approximation (K12).

(2) Power-spectrum sampling (Eq. 2)

The power-spectrum corresponding to $\boldsymbol{s}$ is consistently sampled with the inverse Gamma distribution function (KE08;Ketal09;JKWE10).

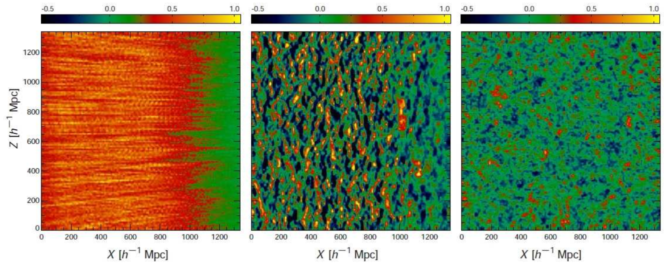
(3) Redshift distortions correction (Eq. 3)

The mapping between real- and redshift-space is done with linear Lagrangian perturbation theory (LPT) (KGF12). Extensions to higher orders are being investigated within the CLUeS project.

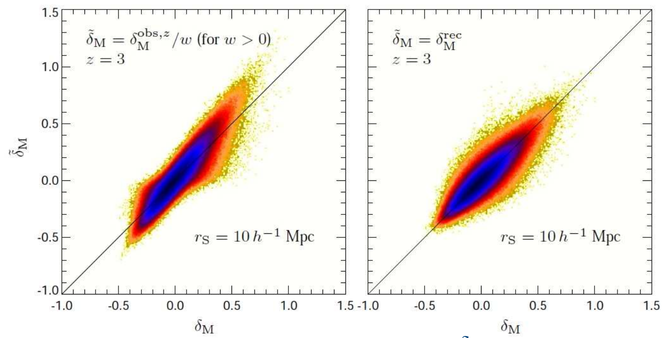
Summary

The Bayesian approach permits us to split a complex problem into simple ones which can be solved separately in an iterative fashion with conditional PDFs.We have shown that one can perform joint reconstructions of matter fields and power-spectra while correcting for redshift distortions in the quasi-nonlinear regime.

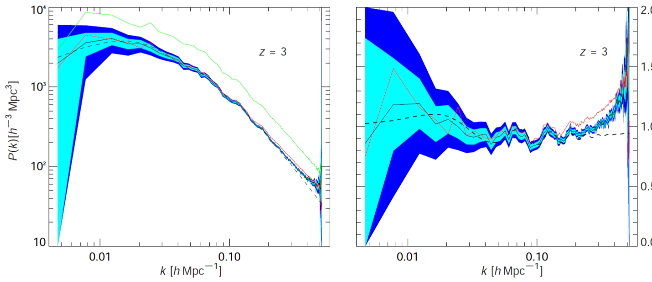
Test case: the Lyman alpha forest



Slices of $\sim$10 h^{-1}Mpc width with 1.34 h^{-1} Gpc side showing left panel: the completeness according to the distribution of about 130000 mock quasar spectra, middle panel: 10th sample of our reconstruction, right panel: sample 400 showing well balanced recovered densities.



Cell-to-cell correlation between the real density field $\delta_{\rm M}$ and the one in redshift-space including mask w effects and noise $\delta_{\rm M}^{{\rm obs},z}/w$ (middle panel), and the 2000th reconstructed sample $\delta_{\rm M}^{\rm rec}$ showing that the reconstructions are unbiased (note that different converged samples give extremely similar results). The different colours indicate the number density of cells for each overdensity bin. Low density values are represented by light and high values by dark colours.



Left panel: power-spectrum with 1 and 2 sigma contours (light and dark blue respectively). Black curve: mean of about 10000 samples. Red: power-spectrum of the N-body simulation in real-space. Green: same as red but in redshift-space. Dashed curve: linear theory. Right panel: same as left panel but divided by the fiducial power-spectrum without wiggles.

References

KE08: Kitaura & Enßlin, MNRAS, arxiv:0705.0429, 2008

Ketal09: Kitaura, Jasche, Li, Enßlin, Metcalf, Wandelt, Lemson & White, MNRAS, arxiv:0906.3978, 2009

KJM10: Kitaura, Jasche & Metcalf, MNRAS, arxiv:0911.1407, 2010

JKWE10: Jasche, Kitaura, Wandelt & Enßlin, MNRAS, arxiv:0911.2493, 2010

JK10: Jasche & Kitaura, MNRAS, arxiv:0911.2496, 2010

GKF11: Gallerani, Kitaura & Ferrara, MNRAS, arxiv:1011.6228, 2011

KGF12: Kitaura, Gallerani & Ferrara, MNRAS, arxiv:1011.6233, 2012

K12: Kitaura, MNRAS, arxiv:1012.3168, 2012