Unveiling the Cosmic Web
with
Bayesian Perturbation Theory

Francisco-Shu Kitaura

Leibniz Institute for Astrophysics (AIP)
Karl-Schwarzschild fellow

February 21, 2012

Cosmic Flow in the Rainforest, 21/02/12, Australia
Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

→ sparse, noisy and incomplete sample
→ matter field $\delta_M$?
→ pec. vel. field $\mathbf{v}$?
→ grav. pot. $\Phi_{\text{Grav}}$?
→ power-spectrum/BAO $P(k)$?
→ joint statistical analysis is necessary!
→ as precise as possible!
(enviromental studies, constrained simulations)
Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

\[ X \text{ [Mpc/h]} \]
\[ Z \text{ [Mpc/h]} \]

→ sparse, noisy and incomplete sample
→ matter field \( \delta_M \)?
→ pec. vel. field \( \mathbf{v} \)?
→ grav. pot. \( \Phi_{\text{Grav}} \)?
→ power-spectrum/BAO \( P(k) \)?
→ joint statistical analysis is necessary!
→ as precise as possible!
(eniromental studies, constrained simulations)
Bayes theorem: the posterior

\[ P(s|d, p) = \frac{P(s|p)P(d|s, p)}{\int ds \ P(s|p)P(d|s, p)}, \]  

→ can we characterise the matter field and its biased tracers in a statistical way? (beyond the Wiener-filter)
Bayes theorem: the posterior

\[ P(s|d, p) = \frac{P(s|p)P(d|s, p)}{\int ds P(s|p)P(d|s, p)}, \]  

\[ (1) \]

\[ \rightarrow \] can we characterise the matter field and its biased tracers in a statistical way? (beyond the Wiener-filter)
Bayes theorem: the posterior

Lognormal-Poisson model

\[
P(\Phi | \mathbf{N}, \mathbf{S}) \propto G(\Phi)
\times \prod_k \left( \frac{w_k \tilde{N} (1 + b (\exp (\Phi_k + \mu) - 1)))}{N_k} \exp \left( -w_k \tilde{N} (1 + b (\exp (\Phi_k + \mu) - 1)) \right) \right)\frac{N_k}{N_k!},
\]

FK & Enßlin 2008
FK, Jasche & Metcalf 2010
How good is the lognormal approximation?

FK & Angulo 2011
Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

Francisco-Shu Kitaura
Bayesian perturbation theory
Velocity reconstruction with LPT

FK, Angulo, Hoffman & Gottlöber 2011
Bayesian approach
**Velocity reconstruction**
Bayesian reconstruction of the LSS

Francisco-Shu Kitaura

Bayesian perturbation theory
Bayesian approach

Velocity reconstruction

Bayesian reconstruction of the LSS

Francisco-Shu Kitaura

Bayesian perturbation theory
Bayesian approach

Velocity reconstruction
Bayesian reconstruction of the LSS

Francisco-Shu Kitaura

Bayesian perturbation theory
Bayesian approach

Velocity reconstruction

Bayesian reconstruction of the LSS

Francisco-Shu Kitaura

Bayesian perturbation theory
Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

Francisco-Shu Kitaura
Bayesian perturbation theory
$r_s = 5 \, h^{-1} \text{Mpc}$

- LIN
- LOG-2LPT
- 2LPT

\[ P_{\text{rec}}(k) / P_{\text{Nbody}}(k) \]

$k \ [h \, \text{Mpc}^{-1}]$
Bayesian approach

Velocity reconstruction

Bayesian reconstruction of the LSS

Francisco-Shu Kitaura

Bayesian perturbation theory
Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

Francisco-Shu Kitaura
Bayesian perturbation theory
Bayesian approach

Velocity reconstruction

Bayesian reconstruction of the LSS

Francisco-Shu Kitaura

Bayesian perturbation theory
Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

Francisco-Shu Kitaura  Bayesian perturbation theory
Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

FK, Gallerani & Ferrara 2011; FK 2011

\[ s^{(j+1)} \leftarrow P(s \mid v^{(j)}, S, d^z), \quad (3) \]
\[ S^{(j+1)} \leftarrow P(S \mid s^{(j+1)}), \quad (4) \]
\[ v^{(j+1)} \leftarrow P(v \mid s^{(j+1)}), \quad (5) \]

see also
FK & Enßlin 2008
FK, Jasche & Metcalf 2010
Jasche, FK, Wandelt & Ensslin 2010
Jasche & FK 2010
Bayesian reconstruction from a halo distribution at $z=0$
preliminary results FK & Angulo
Beyond the Lognormal Poisson model?
\[ P(\delta_M | \mathbf{N}, S, \ldots) \]

\[
\propto \left\{ \prod_l \frac{1}{1 + \delta_{Ml}} \exp \left( -\frac{1}{2} \sum_{ij} (\ln (1 + \delta_{Mi}) - \mu_i) S_{ij}^{-1} (\ln (1 + \delta_{Mj}) - \mu_j) \right) \right\}
\]

\[
\times \left\{ [1 + \frac{1}{3!} \sum_{i',j',k'} \langle \Phi_{i'}, \Phi_{j'}, \Phi_{k'} \rangle_c \sum_{ij} S_{ii'}^{-1/2} S_{jj'}^{-1/2} S_{kk'}^{-1/2} h_{ijk}(S^{-1/2} \Phi) + \ldots] \right\}
\]

\[
\times \left\{ \prod_k \sum_j (\delta^K_{k,j} - Q_{k,j}) w_j \bar{N}(1 + B(\delta_M)_j) \right\}
\]

\[
\times \left\{ \frac{\sum_l (\delta^K_{k,l} - Q_{k,l}) w_l \bar{N}(1 + B(\delta_M)_l) + \sum_m Q_{k,m} N^g_m}{N^g_k} \right\}^{N^g_k - 1}
\]

\[
\times \exp \left( -\sum_n (\delta^K_{k,n} - Q_{k,n}) w_n \bar{N}(1 + B(\delta_M)_n) - \sum_o Q_{k,o} N^g_o \right) \right\}, \quad (6)
\]

FK 2010,11

Francisco-Shu Kitaura Bayesian perturbation theory
Let us go back to the original problem.
Let us go back to the original problem.
Where does the matter come from which formed the structures we observe today?

\[ \delta(\{q\}) \sim P(\delta(\{q\})|\{x_G\}), \]  

(7)
FK tbs

\[
\delta(\{q\}) \sim P(\delta(\{q\})|\{q\}) \tag{8}
\]

\[
\{q\} \sim P(\{q\}|\{x_G\}, \delta(\{q\})). \tag{9}
\]
Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

Francisco-Shu Kitaura
Bayesian perturbation theory
\[
\begin{align*}
S(\delta(\{q\})) & \approx 0.02 \\
K(\delta(\{q\})) & \approx -0.08 \\
\langle \delta(\{q\}) \rangle & \approx 6 \times 10^{-6}
\end{align*}
\]
From real-space
From real-space

Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

Francisco-Shu Kitaura
Bayesian perturbation theory
From redshift-space

Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

Francisco-Shu Kitaura
Bayesian perturbation theory
From redshift-space

Francisco-Shu Kitaura

Bayesian approach
Velocity reconstruction
Bayesian reconstruction of the LSS

Bayesian perturbation theory
Future work?
Conclusions

- Reconstructions are necessary and useful!
- Statistical analysis required.
- We have shown how to undo (mitigate) the effects of gravitation beyond the Zeldovich approximation.
- We have developed a new high order time-reversal machine.
- We have tested higher order LPT to estimate peculiar motions from density fields.
- Now we are going for the data sets to measure BAOs cosmological parameters, make constrained simulations ...