Constrained Local Universe Simulations

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(thanks to Alejandro Benitez-Llambay, Stefan Gottlöber, Yehuda Hoffman, Noam Libeskind, Julio Navarro, Jenny Sorce, Brent Tully, Gustavo Yepes)
Modelling the Local Group in a LCDM environment

- How to set up constrain Gaussian Random Fields
- Constrained Local UniversE Simulations (CLUES)
  - HI distribution in the (simulated) Local Group
- Applications
  - Effects of environment
  - Vast Planes of Satellites
  - Cosmic web stripping
Constrained Simulations (from thesis J. Sorce)

Constraints from Observations

Reconstruction

Realizations

Initial Conditions

Constrained Simulation of Evolution
1D example - constraints

Motivation

Production Method

Constrained Simulation Results

Overview

Wiener-Filter or Reconstruction Technique

From Doumler's Thesis

Wiener-Filter = Linear Minimal Variance Estimator (valid down to $2 \leq 1 \text{Mpc}$) using noisy, sparse data and a model (Zaroubi et al. 1995)

Example:

$$v_{x}(X) = \sum_{i=1}^{n} v_{x}(X) C_{i} \sum_{j=1}^{n} C_{i} C_{j} \neq 1 (C_{j})$$

Jenny Sorce (AIP)

From Cosmicflows to CLUES

2015
1D example - mean field

Motivation

Production Method

Constrained Simulation Results

Overview

Wiener-Filter or Reconstruction Technique

From Domluer's Thesis

Wiener-Filter

reconstruction = Linear Minimal Variance Estimator

(\text{valid down to } 2 \text{ h } \neq 1 \text{ Mpc}) \text{ using noisy, sparse data and a model (Zaroubi et al. 1995)}

Example:

$$v_{\text{WF}}(x) = \sum_{i=1}^{n} \bar{v}_{x}(x) C_i \sum_{j=1}^{n} C_j$$

\[Jenny \text{ Sorce (AIP) From Cosmicflows to CLUES 2015 18]
1D example - reduced power spectrum realization

Motivation 1. Production Method 2. Constrained Simulation Results Overview

Constrained Realization Technique

From Doumler's Thesis

Constrained Realizations

\[ \text{Wiener-Filter + Random Realization to} \]

\[ \text{compensate for the missing Power Spectrum} \]

\[ \text{Ho\textsuperscript{man} & Ribak 1991} \]

Example:

\[ v_{\text{CR}}(x) = v_{\text{RR}}(x) + \sum_{i=1}^{n} \sum_{j=1}^{n} (C_i \times C_j) \]

\[ j \neq i \]

\[ (C_j \neq 0) \]

Jenny Sorce (AIP) From Cosmicflows to CLUES 2015
1D example - constrained random field

From Doumler's Thesis

Constrained Realization Technique

\[ v_{CR}(x) = v_{RR}(x) + n_{i} \sum_{j=1}^{i} C_{ij} \]

Hoffman & Ribak, 1991
Example Virgo (12 realizations)
Example Virgo (12 realizations)

$z=5$
Example Virgo (12 realizations)

\[ z = 2 \]
Example Virgo (12 realizations)
Example Virgo (12 realizations)
Example Virgo (12 realizations)

$z = 0$
Example Virgo (12 realizations)
Reconstruction and Resampling of Density Fields

• constraining Gaussian random fields  
  (Hoffman & Ribak, 1991)

• radial velocity field (MARK III, Willick et al., 1997,  

• nearby cluster positions (Reiprich & Böhringer, 2002)

• 2MASS galaxy distribution

• reconstruct the underlaying density field

• create a Gaussian representation of this density field
Distribution of Phases

Hot Gas
T > 10^5 K

Cold Gas
T < 10^5 K

HI

2-phase model by C. Scannapieco

Nuza et al., 2014
Gas distribution in Local Group galaxies

Figure 15. Gas density (upper panels), H\textsubscript{i} column density (middle panels) and temperature (lower panels) maps for the M31\textsubscript{c}/MW\textsubscript{c} system. Each row shows three perpendicular projections of the corresponding quantity, in order to highlight the three-dimensional distributions. The virial radii of M31\textsubscript{c} and the MW\textsubscript{c} are indicated by the solid and dashed circles, respectively. Prominent neutral gas features are indicated (see text).

Rate of \( \sim 0.05 - 0.1 \) \( \text{M}_\odot \text{yr}^{-1} \) for distances smaller than \( r \sim 70 \) kpc, as indicated by the corresponding dotted lines (see the caption of Fig. 14).

In the case of hot gas, our simulated galaxies show a clear transition scale, located at about 100−120 kpc from the galactic centres, below (above) which hot gas is being ejected (accreted). This is an indication of the strength of the supernova-driven winds, which weaken with increasing radius. The precise values of the net infall rates depend on the particular galaxy considered. For instance, in the case of M31\textsubscript{c}, we found accretion (ejection) of hot gas \( \lesssim 7 \) \( \text{M}_\odot \text{yr}^{-1} \) (\( \lesssim 2 \) \( \text{M}_\odot \text{yr}^{-1} \)) above (below) the transition scale, whereas, for the MW\textsubscript{c}, the rates (both for accretion and ejection) are more modest, namely, \( \lesssim 1 \) \( \text{M}_\odot \text{yr}^{-1} \) (see dot-dashed lines in the bottom panels of Fig. 14). The net accretion rates of all material (neutral+cold+hot) at the virial radius of the galaxies are about 6−8 \( \text{M}_\odot \text{yr}^{-1} \).

In the next section we compare our predictions for the accretion rates of cold and neutral material with observations. Unfortunately, there are no available observational estimates on the hot gas accretion, as well as on the ejection rates, but, in relation to the latter, our results above indicate that outflowing material might be present near the virial radius of galaxy-sized haloes, although at low densities.

5.4 Cold and H\textsubscript{i} gas accretion rates

5.4.1 Comparison with observations

Observational estimates of the gas accretion rates on to the Milky Way galaxy are done using the cold and neutral gas density and temperature measurements. Nuza et al., 2014
HI column density as seen from the quasi-Sun

Nuza et al., 2014
Planes of Satellites
Milky Way – Vast Polar Orbiting structure (VPOS)

\[ c/a \sim 0.15 \]
\[ \Delta_{\text{rms}} = 24 \text{kpc} \]

Metz, Kroupa & Libeskind 2007
Pawlowski & Kroupa 2013

Pawlowski et al 2012
Metz, Kroupa & Jerjen 2007
Kroupa, Theis, Boily 2005

Kunkel & Demers 1975
Lynden-Bell 1976, 1982
Lynden-Bell & Lynden Bell 1982

Sloan Digital Sky Survey (SDSS)
Andromeda — 2 planes, one co-rotating.

Ibata et al 2013, Conn et al 2013, Shaya & Tully 2013
Centaurus A Planes


36 galaxies in total, 29 with distances
16 in plane 1
11 in plane 2
2 not in either
7 without distances of which +4 could be Plane 1 and +2 in plane 2

<table>
<thead>
<tr>
<th></th>
<th>Plane 1 (all)</th>
<th>Plane 1 (good)</th>
<th>Plane 2 (all)</th>
<th>Plane 2 (good)</th>
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<tbody>
<tr>
<td>$a_{\text{rms}}$</td>
<td>397 kpc</td>
<td>346 kpc</td>
<td>413 kpc</td>
<td>250 kpc</td>
</tr>
<tr>
<td>$b_{\text{rms}}$</td>
<td>287 kpc</td>
<td>203 kpc</td>
<td>200 kpc</td>
<td>236 kpc</td>
</tr>
<tr>
<td>$c_{\text{rms}}$</td>
<td>79 kpc</td>
<td>73 kpc</td>
<td>48 kpc</td>
<td>47 kpc</td>
</tr>
<tr>
<td>$c/a$</td>
<td>0.2</td>
<td><strong>0.21</strong></td>
<td>0.12</td>
<td><strong>0.19</strong></td>
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<tr>
<td>$b/a$</td>
<td>0.72</td>
<td><strong>0.60</strong></td>
<td>0.50</td>
<td>0.95</td>
</tr>
<tr>
<td>$c/b$</td>
<td>0.28</td>
<td>0.36</td>
<td>0.24</td>
<td>0.2</td>
</tr>
</tbody>
</table>
“Local” velocity field, from cosmic-flows-2

“Local Filament” stretched by Virgo

Laterally squashed by a “mini-repeller”

e₁ sheet normal, points to the local void

e₃ filament axis, points to Virgo

Libeskind et al 2015
Alignment of satellite planes w.r.t. the shear field

$\hat{n}$ sheet normal, points to the local void

$e_1$ sheet normal, points to the local void

$e_3$ filament axis, points to Virgo

$$\begin{bmatrix} 0 & \frac{1}{2}(\frac{\partial v_x}{\partial y} - \frac{\partial v_y}{\partial x}) & \frac{1}{2}(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}) \\ \frac{1}{2}(\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}) & 0 & \frac{1}{2}(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}) \\ \frac{1}{2}(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}) & \frac{1}{2}(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}) & 0 \end{bmatrix}$$
Alignment of satellite planes w.r.t. the shear field

2 planes in CenA are well aligned
2 planes in M31 are well aligned

\[
\begin{bmatrix}
0 & \frac{1}{2}(\frac{\partial v_x}{\partial y} - \frac{\partial v_y}{\partial x}) & \frac{1}{2}(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}) \\
-\frac{1}{2}(\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}) & 0 & \frac{1}{2}(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}) \\
-\frac{1}{2}(\frac{\partial v_z}{\partial x} - \frac{\partial v_x}{\partial z}) & \frac{1}{2}(\frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z}) & 0
\end{bmatrix}
\]
MW plane is off by ~38 deg, appears to have been torqued about the e₂ axis
Summary of Local Volume Planes

4 out 5 satellite planes are well aligned with shear field!
Haloes with Mass $\sim 1-5 \times 10^{13}$

Nothing bigger than itself within 3Mpc

Lets test for:

- Two halos $r \sim 1$Mpc
- Nothing else $r < 1$Mpc
- Nothing $M > M_{\text{Virgo}}$ within $d \sim 10$Mpc

"Local Group" pairs

Cen A analogues

Libeskind et al 2015

Isolated Massive

Less massive partner, not as well aligned
Summary

- Considerable progress in the recent years w.r.t formation of disk galaxies/Hubble sequence
  - Realistic subgrid models of ISM + feedback are crucial
- CLUES: cosmological simulations of the Local Group environment
  - Properties of Milky Way and nearby galaxies may be substantially affected by the special local environment
  - Cosmic web may provide a natural explanation for alignments of satellites