Testing gravity with Peculiar Velocity surveys

Cullan Howlett

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Contents

- Introduction to peculiar velocities for cosmology
- Measuring the velocity power spectrum
  - How do we do this?
  - Measurements with the 2MTF data
- The future of PV’s
  - TAIPAN survey
Galaxies are moving in two ways w.r.t. us:

1. Expansion of the universe

2. Motions due to ‘local’ large scale structure.

Courtois et. al., 2013

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Our galaxy is also moving -> CMB dipole.

\[(1 + z) = (1 + z_{\text{obs}}^p)(1 + \bar{z})(1 + z_p)\]
Galaxy redshifts are not a perfect proxy for distance! Annoying for measuring distances

...but great for testing gravity:

\[ \nabla \cdot \mathbf{v}(\mathbf{x}, a) = -aH(a)f(a)\delta(\mathbf{x}, a) \]
Redshifts are ‘easy’ to obtain.

Clustering of galaxies depends on galaxy bias, which is difficult to disentangle from growth rate.

Reid et. al., 2012
Direct measure of velocity field, independent of galaxy bias and ‘Hubble Flow’

...but large errors due to intrinsic scatter. Typically 20-30%

Empirical Distances Measurements

Hong et. al., 2014

Figure 4. Tully-Fisher relations for 2MTF galaxies by making a grid on the Tully-Fisher relation.
Empirical Distances Measurements

6dFGSv is largest homogenous dataset (8000 FP galaxies)

Magoulas et. al., 2012

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Using PV’s for Cosmology

Bulk Flow:
• Measure our motion w.r.t. observed galaxies and CMB

Sensitive to survey geometry, see Andersen, Davis and Howlett, 2016

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Using PV’s for Cosmology

Cosmography:
• Compare measured/reconstructed density and velocity fields

Springob et. al., 2014

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Velocity power spectrum:

• Look at correlation between galaxy velocities and positions and compare to theory

\[ P_{uu}^{AA}(k, \mu) = (aH\mu)^2 k^{-2} f^2 D_{u,A}^2 P_{\theta\theta}(k), \]

Direct measurement of growth rate
In linear theory, galaxy velocities should be drawn from a multivariate Gaussian with variance related to the velocity power spectrum.

\[
\mathcal{L} = \frac{1}{|2\pi C^{(v)}|^{1/2}} \exp \left( -\frac{1}{2} \sum_{m,n} S_m(\mathbf{x}, t) C_{mn}^{(v)-1} S_n(\mathbf{x}, t) \right)
\]

\[
C_{mn}(\mathbf{x}_m, \mathbf{x}_n) = \frac{a^2 H^2(a) f^2(a)}{2\pi^2} \int dk P_{\theta\theta}(k, a) W(\mathbf{x}_m, \mathbf{x}_n, k)
\]
Figure 1. Distribution of 2MTF galaxies in Galactic latitude ($\varpi$) and longitude ($\lambda$), shown in an Aitoff projection. Galaxies are color-coded by redshift.

Springob et al., 2015
Problem: Theory is Gaussian, but errors are non-Gaussian.

Solution: Change theory to a variable with Gaussian errors. In this case $\log(D_z/D_{\text{True}})$.
Problem: Non-linearities bias results.

Solution: Grid data to suppress non-linear structure or model non-linearities:

\[ C_{mn}(\mathbf{x}_m, \mathbf{x}_n) = \frac{a^2 H^2(a) f^2(a)}{2\pi^2} \int dk P_{\theta\theta}(k, a) W(\mathbf{x}_m, \mathbf{x}_n, k) \Gamma^2(k) \]

\[ C_{mn}(\mathbf{x}_m, \mathbf{x}_n) = \frac{a^2 H^2(a) f^2(a)}{2\pi^2} \int dk P_{\theta\theta}(k, a) W(\mathbf{x}_m, \mathbf{x}_n, k) D_u^2(k, \sigma_u) \]
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Next Step: Apply to 2MTF data!
### The Future of PV’s*

#### WALLABY+WNSHS
- HI survey using ASKAP complemented by Westerbork/FAST.
- Total ~500,000 expected redshift and 45,000 TF measurements.
- Full Sky (except very close to the galactic plane)
- bias = 0.7
- 20% distance error
- Z < 0.25

#### TAIPAN
- Spectroscopic survey on UK-Schmidt Telescope with new robotic fibre positioner.
- ~1,000,000 redshifts with 100,000 FP distances.
- Dec < 10° (except b < |10°|). Total area = 20,000 sq. deg.
- bias = 1.2
- 20% distance error
- Z < 0.4 (0.1)

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*In Australia

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The Taipan survey

TAIPAN uses a new 150-fibre robot positioner and spectrograph on the UKST. Commissioning starts in just a few months.

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Science Goals:

- Measure $H_0$ to 1% and growth rate to 5%
- Create the most extensive map of the local universe to date
- Explore galaxy evolution as a function of mass and environment. Significant overlap with WALLABY.

2 photometric catalogues will ultimately be used for target selection, gives 2 samples: Priority Science (Y1) and Final (Y4).
- Gives excellent constraints on short timescale.
The Taipan survey

BAO not relevant for this talk, but if interested come find me later!
The Taipan survey

Credit: Chris Blake

BAO not relevant for this talk, but if interested come find me later!

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Can forecast the precision on parameters using:

\[ F_{ij} = \frac{1}{2} \int \frac{d^3 x d^3 k}{(2\pi)^3} \text{Tr} \left[ \mathbf{C}^{-1} \frac{\partial \mathbf{C}}{\partial \theta_i} \mathbf{C}^{-1} \frac{\partial \mathbf{C}}{\partial \theta_j} \right] \]

**PV Forecasts**

**Single Dataset:**

\( \mathbf{C} \) is a matrix of power spectra. For PV surveys we can use density, velocity and cross

\[
\mathbf{C}(r, k, \mu) = \begin{pmatrix}
P_{gg}^{AA}(k, \mu) + \frac{1}{n_g^A(r)} & P_{ug}^{AA}(k, \mu) \\
P_{gu}^{AA}(k, \mu) & P_{uu}^{AA}(k, \mu) + \frac{(\sigma_u^A(r))^2}{n_u^A(r)}
\end{pmatrix}
\]
PV Forecasts

Can forecast the precision on parameters using:

\[ F_{ij} = \frac{1}{2} \int \frac{d^3 x d^3 k}{(2\pi)^3} \ Tr \left[ C^{-1} \frac{\partial C}{\partial \theta_i} C^{-1} \frac{\partial C}{\partial \theta_j} \right] \]

Two Datasets:

\( C \) is a matrix of power spectra. For PV surveys we can use density, velocity and cross

\[
\begin{bmatrix}
P^{AA}_{gg}(k, \mu) + \frac{1}{\bar{n}_A(r)} & P^{AA}_{ug}(k, \mu) & P^{AB}_{gg}(k, \mu) & P^{AB}_{gu}(k, \mu) \\
P^{AA}_{gg}(k, \mu) & P^{AA}_{uu}(k, \mu) + \frac{(\sigma^A_u(r))^2}{\bar{n}_A^2(r)} & P^{AB}_{uu}(k, \mu) & P^{AB}_{tu}(k, \mu) \\
P^{BA}_{gg}(k, \mu) & P^{BA}_{uu}(k, \mu) & P^{BB}_{gg}(k, \mu) + \frac{1}{\bar{n}_B(r)} & P^{BB}_{gu}(k, \mu) \\
P^{BA}_{gg}(k, \mu) & P^{BA}_{uu}(k, \mu) & P^{BB}_{uu}(k, \mu) + \frac{(\sigma^B_u(r))^2}{\bar{n}_B^2(r)} & P^{BB}_{tu}(k, \mu)
\end{bmatrix}
\]
Forecasts

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% Error on $f\sigma_8$

- 6dFGS
- TAIPAN-Y1
- TAIPAN-FINAL
### Forecasts

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Parameters</th>
<th>$f\sigma_8$</th>
<th>$\beta$</th>
<th>$r_g$</th>
<th>$\sigma_u$</th>
<th>$\sigma_g$</th>
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</thead>
<tbody>
<tr>
<td>TAIPAN</td>
<td>$f\sigma_8$, $\beta$</td>
<td>2.3</td>
<td>2.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td></td>
<td>$f\sigma_8$, $\beta$, $r_g$, $\sigma_u$, $\sigma_g$</td>
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<td>2.3</td>
<td>12.1</td>
<td>6.8</td>
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<td>WALLABY + WNSHS</td>
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<td>3.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td></td>
<td>$f\sigma_8$, $\beta$, $r_g$, $\sigma_u$, $\sigma_g$</td>
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<td>0.3</td>
<td>6.8</td>
<td>12.9</td>
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<tr>
<td>TAIPAN +</td>
<td>$f\sigma_8$, $\beta$</td>
<td>1.8</td>
<td>2.2</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>WALLABY + WNSHS</td>
<td>$f\sigma_8$, $\beta$, $r_g$, $\sigma_u$, $\sigma_g$</td>
<td>2.8</td>
<td>3.0</td>
<td>3.1</td>
<td>1.1, 0.3</td>
<td>10.9, 6.4</td>
</tr>
</tbody>
</table>

Amazing constraints on the growth rate from TAIPAN, WALLABY+WNSHS and their combination!

3% Measurement from the combo, including all nuisance parameters.

We also extend our forecasts to incorporate primordial non-Gaussianity, velocity bias, scale dependent bias and zero-point offset (not in this talk, but please talk to me later!)
Forecasts

WALLABY+WNSHS
TAIPAN – Y1
TAIPAN – Y4

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Peculiar velocities have great potential for cosmology, both separately and in combination with RSD.

Measuring the velocity power spectrum can give a scale-dependent measurement of the growth rate without effects of galaxy bias.

Currently testing this with 2MTF. Results for data soon!!

TAIPAN and WALLABY+WNSHS will be AMAZING for growth rate. Combining redshifts and PV’s these can give 3% measurement! But we’ll have to worry about systematics like velocity bias. TAIPAN is also great for BAO!

Could extend forecast method to look at momentum field and modified gravity parameters.

**Forecast paper published: Howlett, Staveley-Smith and Blake, 2016 (ArXiv:1609.08247)**