Refining Estimates of the Local Group Mass using Local Velocity Shear and ANN

M. McLeod\textsuperscript{1} \quad N. Libeskind\textsuperscript{2} \quad O. Lahav\textsuperscript{1} \quad Y. Hoffman\textsuperscript{3}

\textsuperscript{1}Department of Physics and Astronomy University College London
\textsuperscript{2}Leibniz-Insitut für Astrophysik Potsdam (AIP), Potsdam, Germany
\textsuperscript{3}Racah Institute of Physics, Hebrew University, Jerusalem, Israel

arXiv: 1606.02694
Galaxy Flows and LSS, July 2016
Outline

1. The Problem of the Local Group Mass
   - The Timing Argument

2. The Cosmic Environment and Velocity Shear
   - The Velocity Shear Tensor

3. Using Machine Learning with Simulations
   - ANN
   - The Small MultiDark Planck Simulation
   - Application to Simulations
   - Including Environmental Parameters
   - Physical Interpretation

4. Application to the Local Group

McLeod, Libeskind, Lahav, Hoffman
Cosmic Shear and the Local Group Mass
The Problem of the Local Group Mass

The Cosmic Environment and Velocity Shear

Using Machine Learning with Simulations

Application to the Local Group
The mass of the Local Group (LG) is very much still an open problem.

Dynamical arguments such as the Timing Argument have been – and still are – widely used.

Estimates are generally around $2 - 5 \times 10^{12} M_\odot$.
The Timing Argument

- Introduced by Kahn and Woltjer in 1959, it has been an enduring estimator for the LG mass.
- It assumes that the galaxy pair start with a separation $r = 0$ at time $t = 0$ in the early universe, and evolve according to the usual gravitation equation:

$$\frac{d^2r}{dt^2} = -\frac{GM}{r^2}$$

- This has a simple parametric solution which is fully determined by observation of $r$, $v_r$, and $t$. 

$\text{McLeod, Libeskind, Lahav, Hoffman}$

$\text{Cosmic Shear and the Local Group Mass}$
Extensions

- It has many extensions, such as the inclusion of a Cosmological Constant (Partridge, Lahav & Hoffman 2013; Binney & Tremaine)

\[
\frac{d^2r}{dt^2} = -\frac{GM}{r^2} + \frac{\Lambda c^2}{3} r
\]

- Other extensions include Angular Momentum, and including the LMC (Lynden-Bell 1981, Raychaudhury 1989, Einasto 1982...)

- All of these models make a number of idealised assumptions

- Can we look for additional physics beyond two-body interactions?
Outline

1. The Problem of the Local Group Mass
   - The Timing Argument

2. The Cosmic Environment and Velocity Shear
   - The Velocity Shear Tensor

3. Using Machine Learning with Simulations
   - ANN
   - The Small MultiDark Planck Simulation
   - Application to Simulations
   - Including Environmental Parameters
   - Physical Interpretation

4. Application to the Local Group
Velocity Shear

- The velocity shear tensor is calculated from the velocity field

\[ \Sigma_{ij} = -\frac{1}{2H_0} \left( \frac{\partial v_i}{\partial r_j} + \frac{\partial v_j}{\partial r_i} \right) \]

- It can act as a tracer of cosmic web structure
- Web structure is characterised by sign and magnitude of eigenvectors

Hoffman et al. 2012
Velocity Shear

- On the diagonal in the eigenvector frame
  \[ \Sigma_{xx} = -\frac{1}{H_0} \frac{\partial v_x}{\partial r_x} = \lambda_x \]

- It characterises quantitatively some of the local dynamics

- It gives us an idea of whether particles are tending to move together or apart

Hoffman et al. 2012
Outline

1. The Problem of the Local Group Mass
   • The Timing Argument

2. The Cosmic Environment and Velocity Shear
   • The Velocity Shear Tensor

3. Using Machine Learning with Simulations
   • ANN
     • The Small MultiDark Planck Simulation
     • Application to Simulations
     • Including Environmental Parameters
     • Physical Interpretation

4. Application to the Local Group
Artificial Neural Networks

- We require three data sets: a training set, a validation set, and a testing set.
- Each must be, as far as possible, representative of the population.
- ANN is trained on the training set until the error from the validation set is minimised to avoid overfitting.
- ANN may then be tested on the testing set not used during any training.

Collister & Lahav 2004
Artificial Neural Networks

- Function is built as a non-linear composition of sigmoid functions
- Nodes have values $u^k_i$ which are calculated from nodes of previous layer
- $u^{k+1}_j = \sum_i w^{k}_{ij} g(u^k_i)$
- $g(u^k_i) = \frac{1}{1+\exp(-u^k_i)}$
- Cost function
  $$\sum (x^i_{\text{ANN}} - x^i_{\text{test}})^2 + \sum (\alpha w^i_{jk})^2$$

Collister & Lahav 2004
Outline

1. The Problem of the Local Group Mass
   - The Timing Argument

2. The Cosmic Environment and Velocity Shear
   - The Velocity Shear Tensor

3. Using Machine Learning with Simulations
   - ANN
   - The Small MultiDark Planck Simulation
     - Application to Simulations
     - Including Environmental Parameters
     - Physical Interpretation

4. Application to the Local Group
The Small MultiDark Planck Simulation

- Box size of 400 Mpc / h
- $3840^3$ particles
- Particle mass of $9.63 \times 10^7 M_\odot / h$
- Force resolution 1.5 kpc / h
- Halos are identified using a Friends-of-Friends algorithm (Knebe et al. 2011)
Selecting Galaxy Pairs

- Candidates selected with $5 \times 10^{11} M_\odot \leq M \leq 10^{13} M_\odot$
- If another halo of mass $> 10^{12}$ is between 1.5–3 Mpc away, discard
- If another halo of mass $> 10^{11}$ is within 0.5 Mpc, discard
- If another candidate halo is between 0.5–1.5 Mpc away, accept the pair
- 30,190 halo pairs

Candidates selected with $5 \times 10^{11} M_\odot \leq M \leq 10^{13} M_\odot$
- If another halo of mass $> 10^{12}$ is between 1.5–3 Mpc away, discard
- If another halo of mass $> 10^{11}$ is within 0.5 Mpc, discard
- If another candidate halo is between 0.5–1.5 Mpc away, accept the pair
- 30,190 halo pairs
1. The Problem of the Local Group Mass
   - The Timing Argument

2. The Cosmic Environment and Velocity Shear
   - The Velocity Shear Tensor

3. Using Machine Learning with Simulations
   - ANN
   - The Small MultiDark Planck Simulation
   - Application to Simulations
     - Including Environmental Parameters
     - Physical Interpretation

4. Application to the Local Group

McLeod, Libeskind, Lahav, Hoffman
Cosmic Shear and the Local Group Mass
Applying the TA as a Benchmark

- Calculate mass from \((r, v_r)\) using the TA with \(\Lambda\) for each pair in the sample
- r.m.s scatter = 0.43
- Pearson product-moment correlation coefficient = 0.32
Applying the TA as a Benchmark

Calculate mass from \((r, v_r)\) using the TA with \(\Lambda\) for each pair in the sample

- r.m.s scatter = 0.43
- Pearson product-moment correlation coefficient = 0.32
Applying the ANN with \((r, v_r)\)

- Calculate mass from \((r, v_r)\) using the ANN for each pair in the testing set
- \(\text{r.m.s scatter} = 0.24\) (56% of TA result)
- \(\text{Pearson product-moment correlation coefficient} = 0.53\) (1.65 times the TA result)
Applying the ANN with \((r, v_r)\)

- Results are quantitatively better but the scatter plot looks unsatisfactory.
- Contours are similar to TA but appear squashed.
- ANN estimate of mass appears 'capped' at a low mass.
- \((r, v_r)\) does not give enough information to rectify high mass estimates.
The Problem of the Local Group Mass
The Cosmic Environment and Velocity Shear
Using Machine Learning with Simulations
Application to the Local Group

ANN
The Small MultiDark Planck Simulation
Application to Simulations
Including Environmental Parameters
Physical Interpretation

ANN with Velocity Shear

- Include as inputs $(r, v, \lambda_i, |\cos(\theta_i)|)$
- r.m.s. scatter = 0.21 and correlation = 0.63
- Results are quantitatively and qualitatively better than before
- ANN estimate of mass no longer suffers from strict cap
- Shear is providing important information in understanding ‘outlier’ systems

---

McLeod, Libeskind, Lahav, Hoffman
Cosmic Shear and the Local Group Mass
Outline

1. The Problem of the Local Group Mass
   - The Timing Argument

2. The Cosmic Environment and Velocity Shear
   - The Velocity Shear Tensor

3. Using Machine Learning with Simulations
   - ANN
   - The Small MultiDark Planck Simulation
     - Application to Simulations
     - Including Environmental Parameters
     - Physical Interpretation

4. Application to the Local Group

Shear eigenvector $\lambda_2$ is varied from -0.15 (expanding) to +0.15 (collapsing)

The same observed parameters $r = 770$ kpc, $v = -130$ km s$^{-1}$ are used

System is totally aligned with the direction $e_2$

Bulk motion affects our apparent dynamics
Alignment of the Binary with the Shear Eigenvectors

- Shear eigenvalues remain constant
  \[ \lambda_1 = 0.15, \lambda_2 = 0, \lambda_3 = -0.15 \]
- The same observed parameters \( r = 770 \text{ kpc}, v = -130 \text{ km s}^{-1} \) are used
- System is rotated from total alignment with \( e_3 \) to \( e_2 \), and from \( e_2 \) to \( e_1 \)
- The effect we see depends on which eigenvector we are aligned with, and to what extent
Observations of the Local Group

- Observations of the relative motion and separation of MW and M31 are required.
- van der Marel (2012) gives a relative motion consistent with a purely radial orbit.
- Libeskind et al. (2015) reconstruct the velocity field from the CF2 survey to obtain a measure of shear.

Libeskind et al. 2015
Observations of the Local Group

- $r = 770 \pm 30$ kpc,
  $v_r = -109.4 \pm 4.4$ km s$^{-1}$,
  $v_t = 17 \pm 17$ km s$^{-1}$

- $\lambda_{1,2} > 0$ and $\lambda_3 < 0$
  suggest that LG lies in a filament, with strong
  expansion pointing towards Virgo

- Alignment of $r$ is close to
  perpendicular to $e_1$, and
  lies between $e_2$ and $e_3$

Libeskind et al. 2015
The Mass of the Local Group

<table>
<thead>
<tr>
<th></th>
<th>TA</th>
<th>ANN (r,v)</th>
<th>ANN (shear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>4.7$^{+0.7+3.9}_{-0.6}$</td>
<td>3.6$^{+0.3+1.4}_{-0.3}$</td>
<td>4.9$^{+0.8+1.3}_{-0.8}$</td>
</tr>
</tbody>
</table>

- Application of the ANN with no shear information is hindered by mass capping.
- ANN with shear produces a better estimate for simulation masses.
- ANN with shear produces a slightly boosted estimate compared to the TA.
- This is on the higher end of typical mass estimates for the LG.
Summary

- Using ANN can reduce the scatter compared to traditional analytic Timing Argument
- r.m.s. scatter is reduced by over 50% and correlation coefficient is almost doubled
- The method is flexible enough to explore new physics such as the effects of environmental parameters

Future Work
- Further exploration of parameter space to improve estimates
- Exploration in non-ΛCDM cosmologies
- Connecting the ANN with a physical model of the effect