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

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Outline

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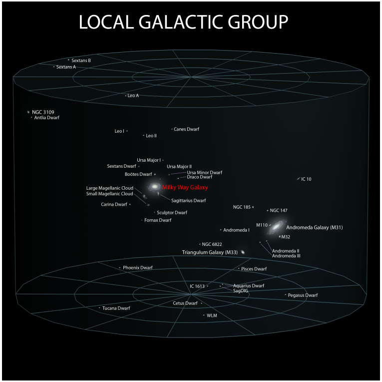
Estimating the Local Group Mass

- 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 $2 - 5 \times 10^{12} M_{\odot}$



Andrew Z. Colvin (Wikipedia)

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

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

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

Extensions

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

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

- 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?

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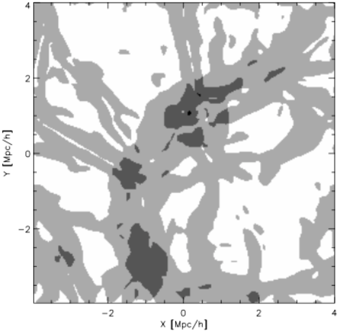
Velocity Shear

- 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



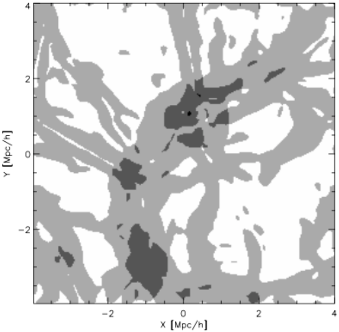
Hoffman et al. 2012

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

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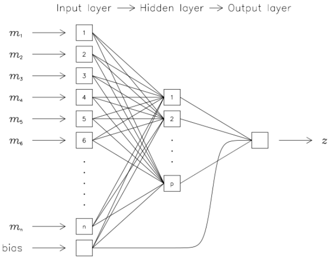
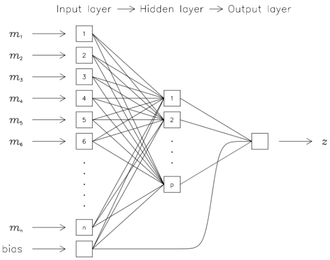
Artificial Neural Networks



Collister & Lahav 2004

- 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

Artificial Neural Networks



Collister & Lahav 2004

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

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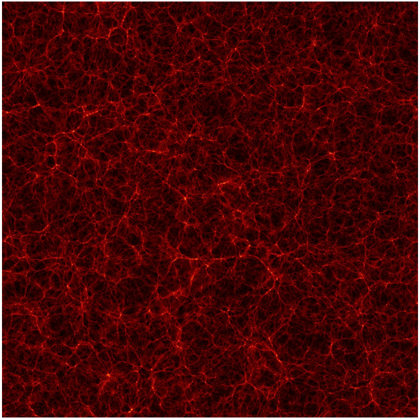
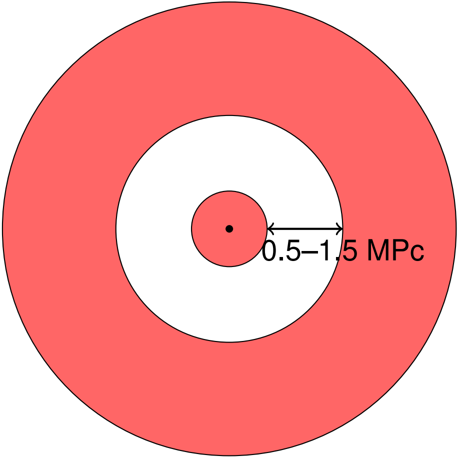
The Small MultiDark Planck Simulation



Stefan Gottlöber, IDL

- 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

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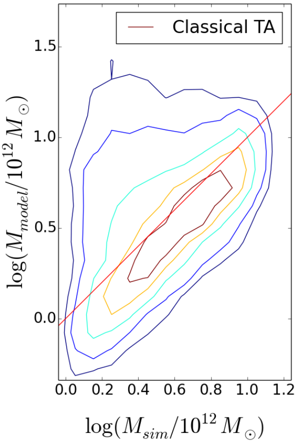
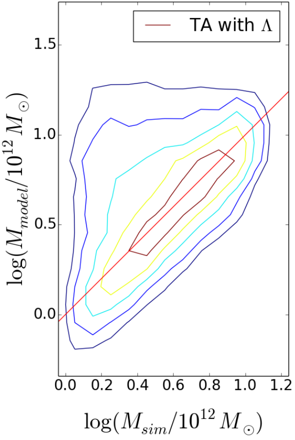
Applying the TA as a Benchmark



- Calculate mass from (r, v_r) using the TA with Λ 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 Λ for each pair in the sample
- r.m.s scatter = 0.43
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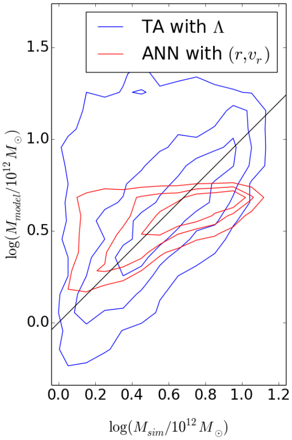
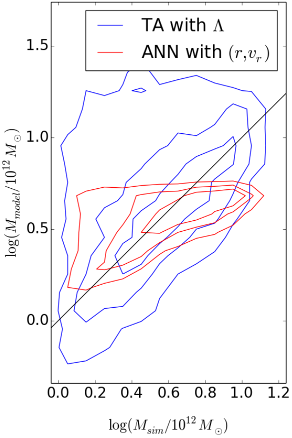
Applying the ANN with (r, v_r)



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

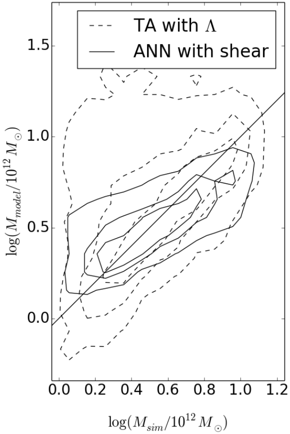
Applying the ANN with (r, v_r)



- 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

Outline

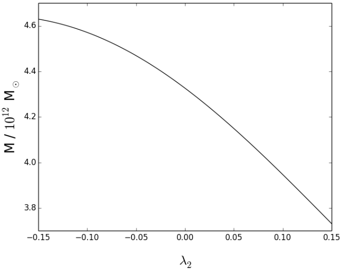
ANN with Velocity Shear



- 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

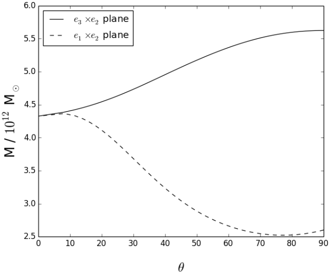
Outline

Magnitude of Shear Eigenvectors



- Shear eigenvector λ_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

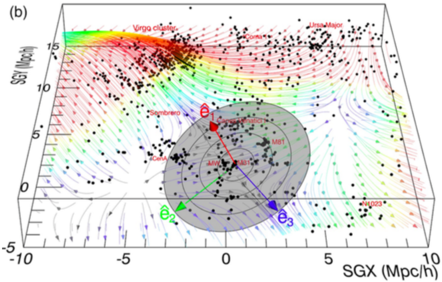
Alignment of the Binary with the Shear Eigenvectors



- Shear eigenvalues remain constant
- $\lambda_1 = 0.15$, $\lambda_2 = 0$, $\lambda_3 = -0.15$
- The same observed parameters r = 770 kpc, v = -130 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

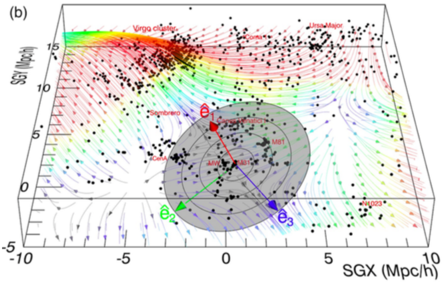
- Observations of the relative motion and separation of MW and M31 are required
- van der Marel (2012) gives a relative motion consistent with a purely radial orbit
- Libeskind et al. (2015) reconstruct the velocity field from the CF2 survey to obtain a measure of shear



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 ± 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

	TA	ANN (r,v)	ANN (shear)
Mass	$4.7^{+0.7+3.9}_{-0.6-2.4}$	$3.6^{+0.3+1.4}_{-0.3-1.4}$	$4.9^{+0.8+1.3}_{-0.8-1.4}$

- 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