Dynamical Constraints on the Galaxy–Halo Connection

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Objective

Use the relations between stellar mass, size and velocity to constrain the galaxy–halo connection under the abundance matching (AM) ansatz

Key questions:

1) Can the relations tell us the correlations of halo variables with galaxy variables besides stellar mass?
2) Are their scatters & other characteristics consistent with basic models of the galaxy–halo connection?
3) What do their normalisations say about halo density profiles?
4) Can they provide constraints on AM competitive and consistent with those from clustering?

Context

- Galaxy surveys tell us the relations between galaxy properties, and N-body simulations tell us the relations between halo properties. However, the link between them – the *galaxy–halo connection* – is not clear.
- One approach uses *empirical models*, which parameterize the relations between galaxy and halo properties. We can constrain these relations by directly comparing mock and real galaxy catalogues.
- One such model is *halo abundance matching (AM)* – roughly, associate the n[th] most massive galaxy within a given volume with the n[th] most massive halo. Along with assumptions about halo density profiles and the dependence of other galaxy variables (e.g. size and type) on halo properties, this determines the internal motions of model galaxies.
- Hence we make predictions for the *Tully–Fisher relation* ($M_* – V_{rot}$ in spirals; TFR), *Faber–Jackson relation* ($M_* – \sigma$ in ellipticals; FJR), *Fundamental Plane* ($M_* – \sigma – R$ in ellipticals; FP) and *mass discrepancy–acceleration relation* ($V^2_{tot}(r)/V^2_{bar}(r) – a(r)$; MDAR).
- By studying summary statistics of these relations, we learn the correlations of the galaxy–halo connection.

Methods

We map assumptions about the galaxy–halo connection onto statistics describing the TFR, FJR, FP and MDAR. We ask whether these statistics are compatible between theory and data, and hence constrain the model. Technically, this is *approximate Bayesian computation*.

- Assign stellar mass to each halo in an N-body sim by AM.
- Assign size to each galaxy, either 1) to match the mass–size relation by construction, 2) according to the angular-momentum partition model of Mo, Mao & White 1998 (MMW), or 3) using a toy model that correlates size with halo concentration.
- Assign a density profile to the halo & baryonic matter. Model halo response to galaxy formation.
- Allow for the possibility of morphology selection effects.
- Deduce rotation curve/velocity dispersion profile of each model galaxy, and hence generate mock TFR/FJR/FP/MDAR datasets. Calculate for each one a set of characteristic statistics (e.g. slope, intercept & scatter of a power-law fit), and compare the values in the data.
- Establish goodness of fit using the distance between the observed values and the centres of the mock data distributions. Explore model parameter space by Markov Chain Monte Carlo.

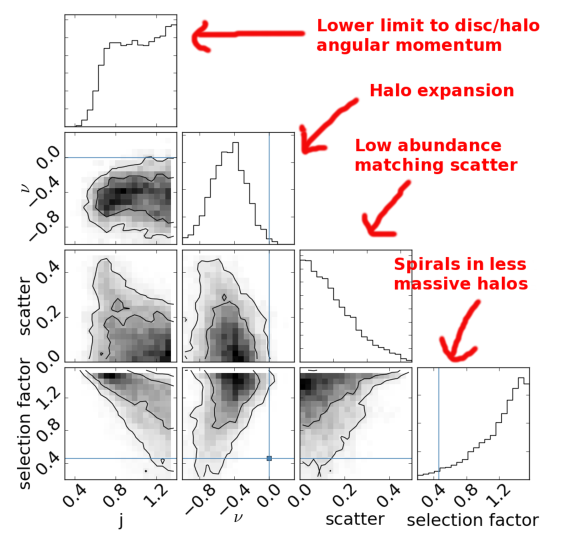
Observations and Simulations

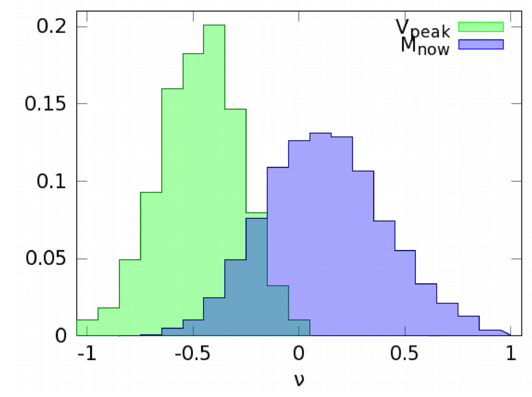
TFR: Pizago et al. 2007
FJR & FP: Nasa Sloan Atlas (www.nsatlas.org)
MDAR: Lelli, McGaugh & Schombert, 2016 (astroweb.cwru.edu/SPARC)
N-body boxes: Skillman et al., 2014 (darksky.slac.stanford.edu)

Results I. The Tully–Fisher Relation

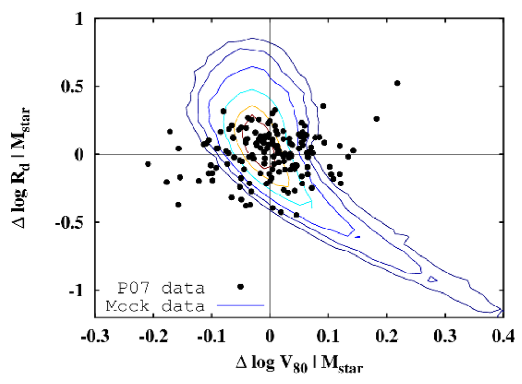
- Need halo expansion
- Small scatter in galaxy–halo connection
- Spirals occupy less massive halos than ellipticals
- Disk and halo specific angular momentum *not* proportional

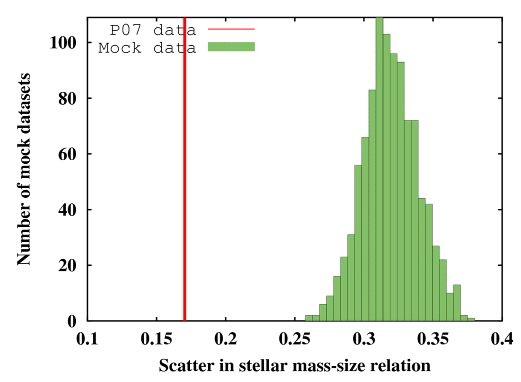
Posteriors of model parameters after fitting to the slope, intercept and scatter of the TFR





v=1: adiabatic contraction.
v=0: no effect of galaxy formation on halo profile.
v<0: halo expansion.
Realistic AM models prefer v<0.

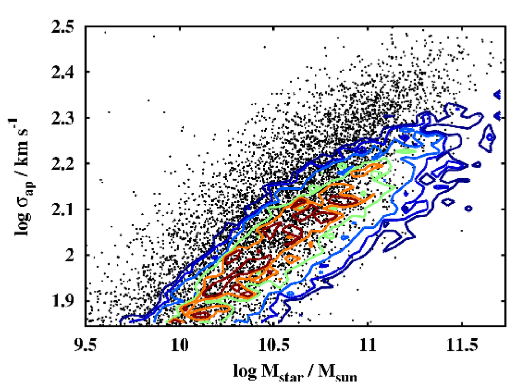




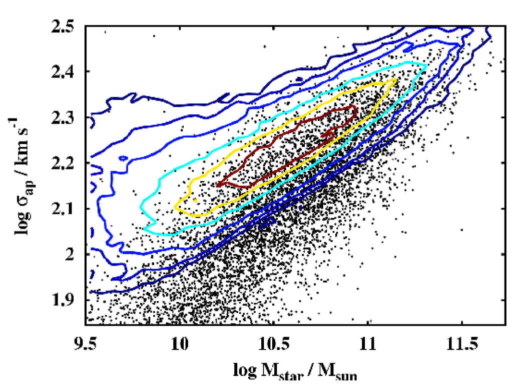
Setting disk and halo specific angular momentum proportional produces a strong anticorrelation between velocity and size residuals (left), and too large a scatter in sizes (right).

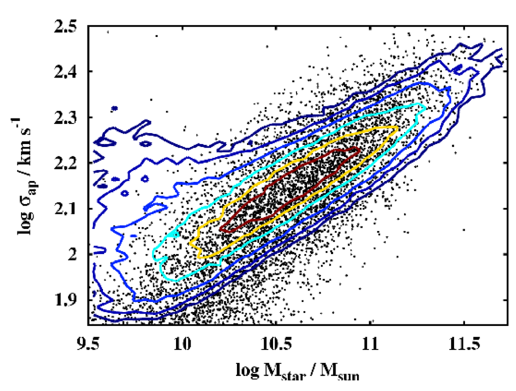
Results II. The Faber–Jackson relation and Fundamental Plane

- Need halo expansion
- FJR slope argues for non-universal IMF
- Matching FP tilt requires radial orbit anisotropy
- Predicted FP scatter too large



Comparison of predicted and observed FJR. Left: A baryon-only model underpredicts σ at high M_*. Bottom left: An AM model with halo contraction normalises the FJR too high. Bottom right: Halo expansion produces correct normalisation.



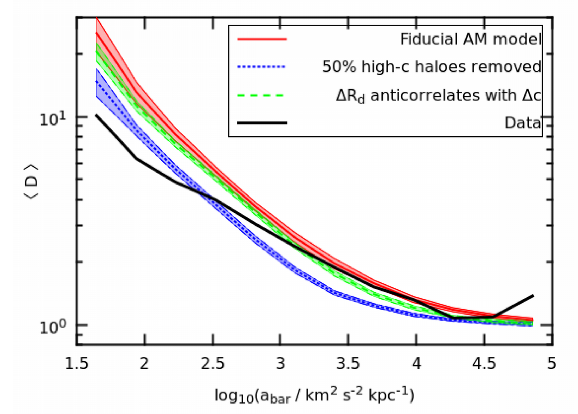


(α, AM scatter, ν, selection factor)	FP scatter	FP tilt
NSA data	0.158	-0.70
No-DM	0.053	-0.46
0.6, 0.16, 0.5, 1.4	0.252	-0.20
0.6, 0.4, 0.5, 1.4	0.269	-0.34
0.6, 0.16, -0.5, 1.4	0.256	-0.18
0.6, 0.16, 0.5, arctan(0.5)	0.234	-0.30
0.6, 0.16, -0.5, arctan(0.5)	0.232	-0.28
$\beta \sim \mathcal{N}(0.3, 0.35)$	0.264	-0.73
$\beta \sim \mathcal{N}(1.59 \log(M_*/M_\odot) - 17.6, 0.35)$	0.205	-0.25

All AM models predict too high a scatter in the FP. Matching FP tilt requires a spread of radial orbit anisotropies between model galaxies.

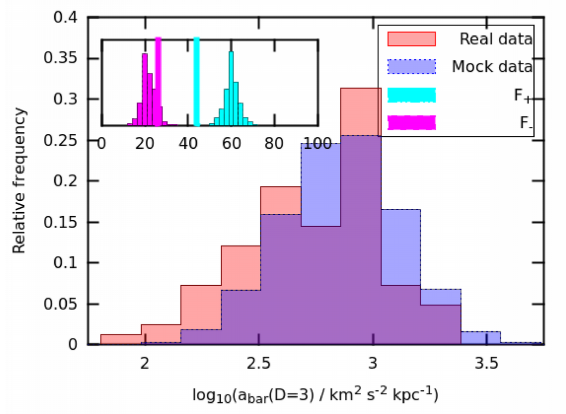
Results III. The Mass Discrepancy–Acceleration Relation

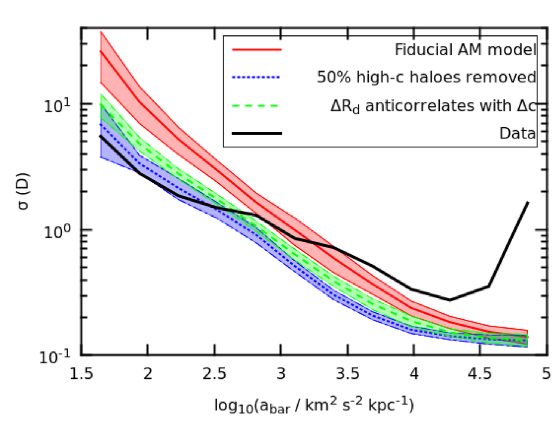
- Shape and high-acceleration behaviour matched
- "Acceleration scale" accounted for
- Normalisation and scatter too high at low acceleration
- Evidence for anticorrelation of R_{eff} with c at fixed M_*

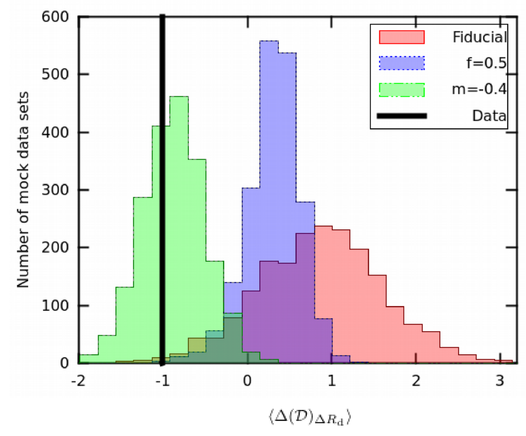


The MDAR describes the local connection of dark to visible mass. AM models readily match the shape and high-acceleration regime.

Galaxies are sometimes said to exhibit a "characteristic acceleration" at which the mass discrepancy consistently goes to ~1. This occurs too in AM mocks.







AM overpredicts the MDAR scatter at low-acceleration. This may indicate that MDAR samples occupy a biased subset of the overall halo population.

The relation favours an anticorrelation of galaxy size with halo concentration (or mass) at fixed M_*.

Conclusions

- Abundance matching (AM) provides a simple and powerful basis for modelling galaxy scaling relations, and naturally accounts for several of their important features.
- A *statistical* investigation of the relations between dynamical galaxy variables – the Tully–Fisher, Faber–Jackson and mass discrepancy–acceleration relations, and Fundamental Plane – enables goodness-of-fit testing and quantitative determination of galaxy formation parameters.
- This reveals a number of important aspects of the galaxy–halo connection: 1) Halo expansion, 2) Dependence of galaxy morphology on halo properties, 3) Anticorrelation of galaxy size with halo concentration at fixed stellar mass, 4) Galaxy size not set by simple proportionality between galaxy and halo specific angular momentum.
- It is challenging to account for the small scatter in the FP and MDAR. This may indicate correlations between galaxy and halo variables beyond the scope of standard AM, and/or significant selection effects.

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