The link between structure and kinematics in massive early-type galaxies from 6dFGS and SAMI

Matthew Colless
and the 6dFGS, SAMI & Taipan teams

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Relevant surveys

- **6dF Galaxy Survey**: properties of the Fundamental Plane and stellar populations from a low-redshift survey of ~9000 early-type galaxies

- **SAMI survey**: preliminary results on the Fundamental Plane and variants using 3D spectroscopy from a few hundred SAMI survey galaxies

- **Taipan survey**: planned survey, starting in mid 2016, of ~500,000 low-redshift galaxies, including ~50,000 ETGs with high S/N spectra to study stellar populations and the Fundamental Plane, and to measure distances and peculiar velocities

...plus many other members of the 6dFGS, SAMI & Taipan survey teams
The 6dFGS Fundamental Plane

- We model the FP as a truncated 3D Gaussian in \((\log R_e, \log \sigma, \log I_e) = (r, s, i)\) space; for high-mass ETGs, this is an excellent empirical match to the observed distribution.

- This model is specified by the coefficients of the FP \((a, b, c)\), and by the centroid \((\langle r \rangle, \langle s \rangle, \langle i \rangle)\) and dispersion \((\sigma_1, \sigma_2, \sigma_3)\) of the 3D Gaussian distribution.

- Fit with robust ML method that allows for errors (& correlations) and sample selection (& censoring).

- J-band FP from 8901 galaxies is:
  \[ R_e \propto \sigma_0^{1.53 \pm 0.03} I_e^{-0.89 \pm 0.01} \]

- The axes of the 3D Gaussian \((v_1, v_2, v_3)\) are defined as:
  \(v_1\) = through the plane \((r \uparrow, s \downarrow, i \uparrow)\)
  = short axis (normal to FP)
  \(\approx \log(M/L)\), i.e. mass-to-light ratio
  \(v_2\) = along the plane \((r \downarrow, \text{no} \ s, i \uparrow)\)
  = long axis
  \(\approx \log(L/R^3)\), i.e. luminosity density
  \(v_3\) = across the plane \((r \uparrow, s \uparrow, i \uparrow)\)
  = intermediate axis
3D Gaussian fit to FP

Observed J data
Mock J data
FP variations with morphology

- Morphologies based on visual inspection of NIR (2MASS) and optical (SSS) images
- Elliptical (E) and lenticular (S0) galaxies have very similar FPs
- The bulges of bulge-dominated spiral (Sp) galaxies...
  ... have an FP offset ⇒ 10% in distance
  ... within FP, are 35% larger on average
Correlations (red) between stellar population (SP) and FP parameters are consistent with well-known trends…

- All SP’s show clear trends with log $\sigma$
- Metallicity shows trends with log $R_e$
- There are weak or no trends with log $I_e$
FP variations with age & metallicity

Age variations

Variation in age is mainly through the FP (i.e. in $v_1$ direction)

Metallicity variations

Variation in metallicity is mainly across the FP (i.e. in $v_3$ direction)

FP variations with $[\text{Fe/H}]$ & $[\alpha/\text{Fe}]$

Variation in $[\text{Fe/H}]$ is mainly across the FP (i.e. in the $v_3$ direction)

Variation in $[\alpha/\text{Fe}]$ is both through and across the FP ($v_1$ & $v_3$ directions)

FP non-correlations & residuals

- No stellar population parameter has any significant trend with $v_2$, the long axis of the FP – i.e. no variation in stellar population with luminosity density.

- FP residuals correlate most strongly with age, which suggests age indirectly drives the correlations with environment, morphology, [Z/H] and [$\alpha$/Fe].
The SAMI survey

- SAMI galaxy survey aims to obtain 3D spectra for 3000 galaxies of all types, with a broad range in mass, and covering all environments
  - observations run from 2013 to 2016
  - currently data for ~1000 galaxies

- The targets for the SAMI survey were chosen to...
  - sample the full range of galaxy environments
  - cover a broad range in stellar mass
  - have sizes such that emission spectra can be obtained out to ~2$R_e$
  - have surface brightness sufficient to measure stellar kinematics to ~$R_e$
  - have a target density matched to SAMI IFU density
  - have the best ancillary data (opt/IR/UV/radio photometry, via GAMA)

See sami-survey.org and Allen et al. (2014, arXiv/1407.6068)
SAMI Fundamental Plane

- Preliminary Fundamental Plane for 74 ETGs from the SAMI pilot survey with $M_r < -20.25$ and within 1° of 3 clusters: A85, A168, A2399

- SAMI selection effects & sample biases not yet quantified, so focus on differential analyses

- FP comparison for central vs effective velocity dispersions – i.e. $\sigma_0 = \sigma(R_e/8)$ vs $\sigma_e = \sigma(R_e)$
  - expected offset (as $\sigma_0 > \sigma_e$)
  - very similar slopes (equally affected by selection effects)
  - marginally less scatter for FP($\sigma_e$) than FP($\sigma_0$)

- Consistent with previous findings: (e.g. Falcón-Barroso et al. 2011)
FP residual correlation with $\lambda_R$

- Are residuals from the FP (in $\log R_e$) correlated with kinematic morphology?

- In particular, are they correlated with specific angular momentum?

$$\lambda_R = \frac{\langle R|V| \rangle}{\langle R\sqrt{V^2 + \sigma^2} \rangle}$$

- Find a mild negative correlation – Spearman rank correlation statistic is $-0.19$ (significant at 90% confidence level)
Residual correlations: FR vs SR

- Do FP residual distributions differ for the two identified kinematic classes, the fast and slow rotators?
  - Slow rotators are classified using the criterion $\lambda_R < k \varepsilon^{1/2}$ (with $k=0.31$ at $R_e$)

- For the small pilot survey sample (60 FRs + 14 SRs) we find:
  - a marginally significant (2.3$\sigma$) FP zeropoint offset
  - less FP scatter for SRs than FRs (11% versus 16%)

- Consistent with results from a same-size SAURON ETG sample from lower-density environments (Falcón-Barroso et al. 2011)
Generalized scaling relations

- How can we generalize (and tighten) the Fundamental Plane?

- One important improvement is the Mass Plane, using stellar/dynamical masses to reduce scatter due to M/L and/or dynamical non-homology

- A more ambitious generalization is to try to unify the Fundamental Plane for early-type galaxies and the Tully-Fisher relation for late-type galaxies

- This could proceed via detailed morphology-dependent mass modeling; but an alternative is to seek to identify generalized measures of internal dynamics that achieve much the same effect more simply

- Cortese et al. (2014, ApJ, 795, 37) use SAMI to examine the applicability of the $S_{0.5}$ parameter, which combines pressure support from velocity dispersion ($\sigma$) and rotational support from circular velocity ($V_{rot}$)…

$$S_{0.5} = \sqrt{0.5 V_{rot}^2 + \sigma_e^2}$$

…as suggested by Weiner et al. (2006) and explored by, amongst others, Kassin et al. (2007) and Zaritsky et al. (2008)
Scaling relation sample

- Use SAMI observations of 250 galaxies in GAMA fields having sizes 2.5″ (median seeing FWHM) < 2R_e < 14.7″ (fibre bundle diameter)

- Stellar velocities measured with pPXF, gas velocities with LZ-IFU; then require >80% of spaxels within R_e have velocity errors < 20 km/s (gas) and 50 km/s (stars)

- Resulting sample is 235 individual galaxies: 193 with gas kinematics (blue), 105 with stellar kinematics (red), and 62 with both (black)
Dynamical support measure

- Measure $V_{\text{rot}} = \frac{V_{90} - V_{10}}{2(1+z)\sin i}$ where $\cos i = \sqrt{\frac{(b/a)^2 - q_0^2}{1-q_0^2}}$ and $q_0=0.2$

- Measure $\sigma$ as spaxel average within $R_e$ (without luminosity weighting)

- Unlike $V_{\text{rot}}$ or $\sigma$, $S_{0.5} = \sqrt{0.5V_{\text{rot}}^2 + \sigma_e^2}$ recovers nearly the same value regardless of whether the circular velocity and dispersion are determined from a galaxy’s stars or its gas (and similar results for $S_K$ with $K \approx 0.3-1.0$)
A unified scaling relation

- We construct the scaling relation of stellar mass ($M_\star$) with dynamical support ($S_{0.5}$) for 235 SAMI galaxies of all morphological types over $8.5<\log(M_\star/M)<11$, independent of the component (star/gas) is used to measure $\sigma_e$ and $V_{\text{rot}}$

- $M_\star-S_{0.5}$ is as least as tight as any other dynamical scaling relation ($\sim 0.1\text{dex}$)

- The $M_\star-S_{0.5}$ relation significantly improves on the canonical $M_\star-V_{\text{rot}}$ & $M_\star-\sigma$ relations: no sample selection needed, and stellar & gas kinematics can be used simultaneously (asymmetric drift accounted by combining $V_{\text{rot}}$ & $\sigma$)

A baryonic scaling relation?

- The $M_\star-S_{0.5}$ relation appears steeper for $M_\star<10^{10} M_\odot$; if we only fit massive galaxies, low-mass systems appear systematically below the relation.

- This non-linearity likely reflects that observed in the $M_\star-\sigma$ relation, but may relate to the similar feature in the stellar mass Tully-Fisher relation (McGaugh et al. 2000), which disappears in the baryonic Tully-Fisher relation.

- At present, the absence of cold gas measurements prevents examination of the ‘baryonic $S_{0.5}$ relation’ for the SAMI sample.

- However, if UV & optical properties used to predict total gas content, the residuals about the linear fit vary with gas fraction roughly as expected if $S_{0.5}$ is linearly related to total baryonic mass.
The Taipan Survey

- Planned southern hemisphere z+v-survey with UKST; 4x sample size/volume of 6dFGS; with SDSS it will cover $\sim \frac{3}{4}$ of sky; with LAMOST may complete whole sky
- Now refurbishing UKST & building new fibre positioner & spectrograph; Taipan survey planned to start mid-2016
- Survey will measure $\sim 500,000$ redshifts and $\sim 50,000$ FP distances & peculiar velocities for galaxies to $r \approx 17$ ($K \approx 14$) $\Rightarrow <z> \approx 0.08$ & $V_{\text{eff}} \approx 0.23 \ h^{-3} \ Gpc^3$
- Lessons learned from 6dFGS/SAMI will improve Taipan FP distances and velocities relative to 6dFGS
- Other Taipan improvements are:
  - more precise $\sigma$'s from higher S/N and spectral resolution
  - better $R_e$'s from higher spatial resolution imaging at higher S/N
  - smaller distance errors ($\leq 20\%$)