The Fundamental Plane in 3D from 6dF and SAMI

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&

the 6dFGS, SAMI and Taipan teams

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Motivation

- In broad terms, the Fundamental Plane (FP) provides...
  1. clues for understanding the formation and subsequent evolution of early-type galaxies (ETGs); and
  2. distance estimates, and so peculiar velocities, an independent probe of structure at low redshifts leading to improved cosmological constraints with fewer degeneracies.

- 3D spectroscopy can explore how the FP can be brought closer to the virial plane, and how the FP scatter can be reduced, by...
  1. using optimized ways of measuring FP parameters;
  2. including additional parameters characterizing the galaxies’ stellar populations or kinematic morphologies; and
  3. applying appropriate selection criteria for galaxy samples.
Fundamental Plane surveys

- **6dF Galaxy Survey**: properties of the Fundamental Plane from ~9000 early-type galaxies

- **SAMI survey**: preliminary results on the Fundamental Plane from 3D spectroscopy with the first ~100 early-type galaxies from the SAMI pilot survey

- **Taipan survey**: planned survey of ~500,000 redshifts and ~50,000 Fundamental Plane distances and peculiar velocities, starting 2016

*Also many other members of the 6dFGS, SAMI and Taipan survey teams!*
6dF Galaxy Survey

- The 6dFGS is a combined redshift and peculiar velocity survey designed to map the large-scale density and velocity fields in nearby universe.

- Sample: NIR-selected galaxies from the 2MASS survey with $K<12.65$ (similar limits in $b$, $r$, $J$, $H$).

- Area: 17000 deg$^2$ of southern hemisphere excl. ±10° about the Galactic plane ($\delta<0°$, $|b|>10°$).

### Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude limits</td>
<td>$K \leq 12.65$</td>
</tr>
<tr>
<td></td>
<td>$H \leq 12.95$</td>
</tr>
<tr>
<td></td>
<td>$J \leq 13.75$</td>
</tr>
<tr>
<td></td>
<td>$r_F \leq 15.60$</td>
</tr>
<tr>
<td>Sky coverage (sr)</td>
<td>5.2</td>
</tr>
<tr>
<td>Fraction of sky</td>
<td>41%</td>
</tr>
<tr>
<td>Extragalactic sample, $N$</td>
<td>125 071</td>
</tr>
<tr>
<td>Median redshift, $z_{1/2}$</td>
<td>0.053</td>
</tr>
<tr>
<td>Volume $V$ in $[0.5z_{1/2}, 1.5z_{1/2}]$ ($h^{-3}$ Mpc$^3$)</td>
<td>$2.1 \times 10^7$</td>
</tr>
<tr>
<td>Sampling density at $z_{1/2}$</td>
<td>$\frac{2N}{3V}$ ($h^3$ Mpc$^{-3}$)</td>
</tr>
<tr>
<td>Fibre aperture ($''$)</td>
<td>6.7</td>
</tr>
<tr>
<td>Fibre aperture at $z_{1/2}$ ($h^{-1}$ kpc)</td>
<td>4.8</td>
</tr>
</tbody>
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6dF Galaxy Survey

- Observations used the 6-degree Field (6dF) multi-object fibre spectrograph on the UK Schmidt Telescope over the period 2001-2006
The Fundamental Plane is the empirically observed relation...

\[
\log(R_e) = a \log(\sigma) + b \log(I_e) + c
\]

where \( R_e \) is the half-light radius in kpc, \( \sigma \) is the stellar velocity dispersion in km/s and \( I_e \) is the surface brightness in \( L_\odot/pc^2 \).

For convenience, we write the Fundamental Plane as

\[
r = a \ s + b \ i + c \quad \text{where} \quad r = \log(R_e), \ s = \log(\sigma) \ \text{and} \ i = \log(I_e)
\]

The Fundamental Plane (FP) subsample of the 6dFGS uses...

- J, H, K photometric parameters \( (R_e, I_e) \) from 2MASS;
- redshifts and central velocity dispersions \( (\sigma_0) \) from 6dFGS;
- all early-type galaxies in 6dFGS with \( z<0.055, \sigma_0>112 \text{ km/s}; \)
- and comprises a total of \( \sim9000 \) galaxies
We model the FP as a 3D Gaussian in \((r,s,i)\) space; for high-mass ETGs, this is an excellent empirical match to observed distribution.

The model is defined by the coefficients of the FP \((a, b, c)\), and by the centroid \((r, s, i)\) and dispersion \((\sigma_1, \sigma_2, \sigma_3)\) of the 3D Gaussian.

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)
- \(v_2\) = along the plane \((r \downarrow, \text{ no } s, i \uparrow)\) = long axis
- \(v_3\) = across the plane \((r \uparrow, s \uparrow, i \uparrow)\) = intermediate axis
Fitting the 6dFGS FP

- We fit a 3D Gaussian model to the FP using a comprehensive and robust maximum likelihood method that accounts for:
  - errors in all the observed quantities for each galaxy & their correlations
  - sample selection effects & censoring (redshift range, lower limit on velocity dispersion, bright & faint magnitude limits, outlier rejection)
Fitted FP parameters and trends

- In the J band (largest sample, smallest errors), the best-fit FP is
  \[ r = (1.52 \pm 0.03) \, s + (-0.89 \pm 0.01) \, i + (-0.33 \pm 0.05) \]
  with intrinsic dispersions in the three axes of (0.05, 0.32, 0.17)

- Best-fit 3D Gaussian is a good representation of observed \((r,s,i)\) distribution

- Small FP offsets are found between cluster & field galaxies and E/S0’s & spiral bulges

- The ‘intrinsic’ scatter about the FP is due largely to the effect of stellar population age variations on M/L; other trends may be driven by indirect correlations with age
FP scatter and distance errors

- The scatter about the FP in \( r \equiv \log(R_e) \) translates into the uncertainty in individual distances and peculiar velocities.
- The total scatter in \( r \) is given by the quadrature sum of the observational errors and the intrinsic scatter in \( r \) about the FP.
- The inferred intrinsic scatter of the FP in distance is \( \sim 23\% \).

\[
\sigma_r^2 = \Delta r^2 - (a.\Delta s)^2 - \Delta X_{FP}^2
\]

- Computing the distance errors from the posterior probability distributions, and including the effects of sampling biases, the rms distance error for galaxies in the 6dFGS sample is \( 26\% \).

- Why \( 26\% \) rather than canonical \( 20\% \)? Factors are: low S/N of \( \sigma \) measurements, steep NIR FP slope, inclusive morphological sample(?), careful error analysis, allowance for sampling biases.
The SAMI instrument

- SAMI is a multi-IFU spectrograph at the AAT 3.9m prime focus
  - 13 hexabundle IFUs deployed over a 1° diameter field
  - Each IFU is ~15” in diameter, with 61 x 1.6” fibres
  - SAMI feeds the double-beam AAOmega spectrograph
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 have data for >600 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 $\sim 2R_e$
  - have surface brightness sufficient to measure stellar kinematics to $\sim R_e$
  - have a target density matched to SAMI IFU density
  - have the best ancillary data (opt/IR/UV/radio photometry, via GAMA)

- For more on the SAMI survey (sami.survey.org), see talks by Lisa Fogarty, Iraklis Konstantopoulos, Nic Scott & James Allen
SAMI pilot survey data for ETGs

- SAMI pilot survey: a precursor to the SAMI galaxy survey
  - it comprises observations of 3 clusters: A85, A168 & A2399
  - 106 galaxies with $M_r<-20.25$ in $1^\circ$ fields were observed
  - we examine the 74 morphological ETGs with good pilot survey data

![Image of kinematic maps and velocity distributions](image-url)
Preliminary Fundamental Plane for 74 early-type galaxies from 3 clusters

SAMI selection effects and sample biases are not yet quantified, so current focus is on differential analyses

First comparison: central versus effective velocity dispersions in the FP – i.e. $\sigma_0 = \sigma(R_e/8)$ vs $\sigma_e = \sigma(R_e)$.
Comparing \( \text{FP}(\sigma_0) \) and \( \text{FP}(\sigma_e) \), we find:

- the expected offset (because \( \sigma_0 > \sigma_e \))
- very similar slopes (equally affected by selection effects)
- marginally less scatter for \( \text{FP}(\sigma_e) \) than \( \text{FP}(\sigma_0) \)

Broadly 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?

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

- We find a mild negative correlation: the 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 (2.3σ) FP zeropoint offset
- less FP scatter for SRs than FRs (11% versus 16%)

These results are consistent with those from a same-size SAURON sample of ETGs from lower-density environments (Falcón-Barroso et al. 2011)
The Taipan galaxy survey

- Taipan is a z+v-survey expanding 6dFGS by 4x in sample size & volume; with SDSS it will cover ~3/4 of sky
- Now refurbishing UKST & building new fibre positioner + spectrograph; Taipan survey planned to start in 2016
- Survey will measure ~500,000 redshifts and ~50,000 FP distances/peculiar velocities for galaxies to r≈17 (K≈14); <z> ≈ 0.08 and V_{eff} ≈ 0.23 h^{-3} \text{ Gpc}^3
- Lessons learned from SAMI will improve Taipan FP measurements (and distances) relative to 6dFGS
- Other Taipan improvements are:
  - more precise σ’s from higher spectral resolution at higher S/N
  - better R_e’s from higher spatial resolution imaging at higher S/N
  - expect distance errors of 15-20%