The Fundamental Plane in 3D from 6dF and SAMI

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&

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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 ~500,00 redshifts and ~50,000 Fundamental Plane distances and peculiar velocities, starting 2016

Chris Springob

Christina Magoulas

Lisa Fogarty

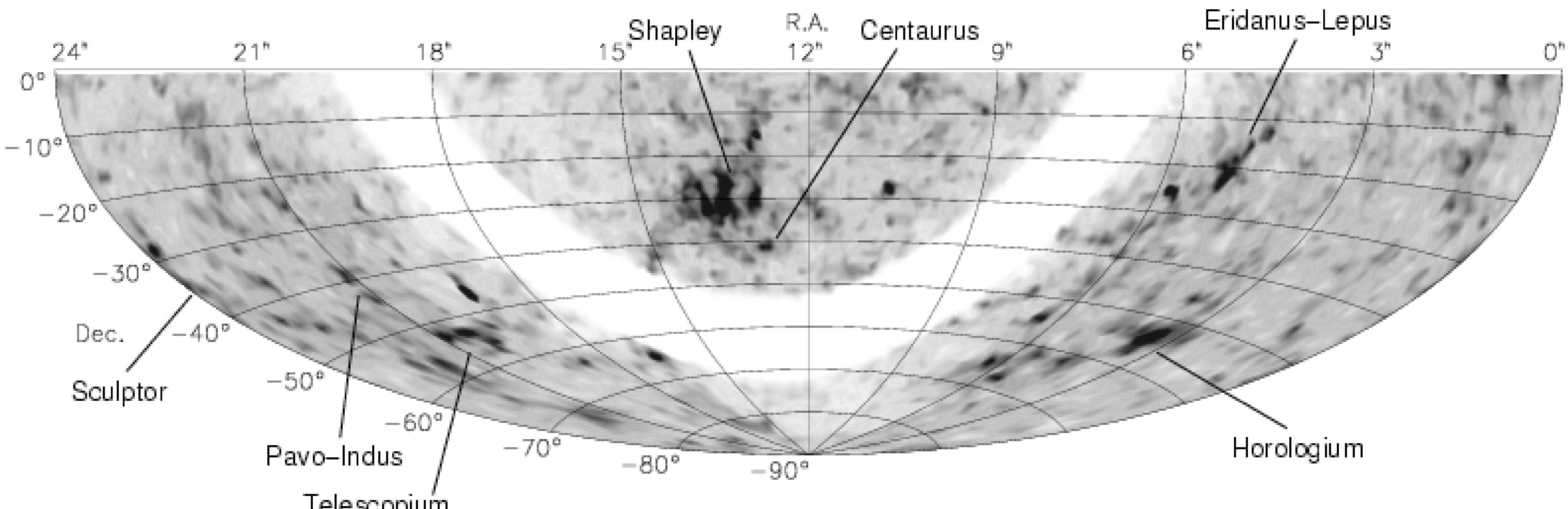
Nic Scott

Also many other members of the 6dFGS, SAMI and Taipan survey teams!

6dF Galaxy Survey

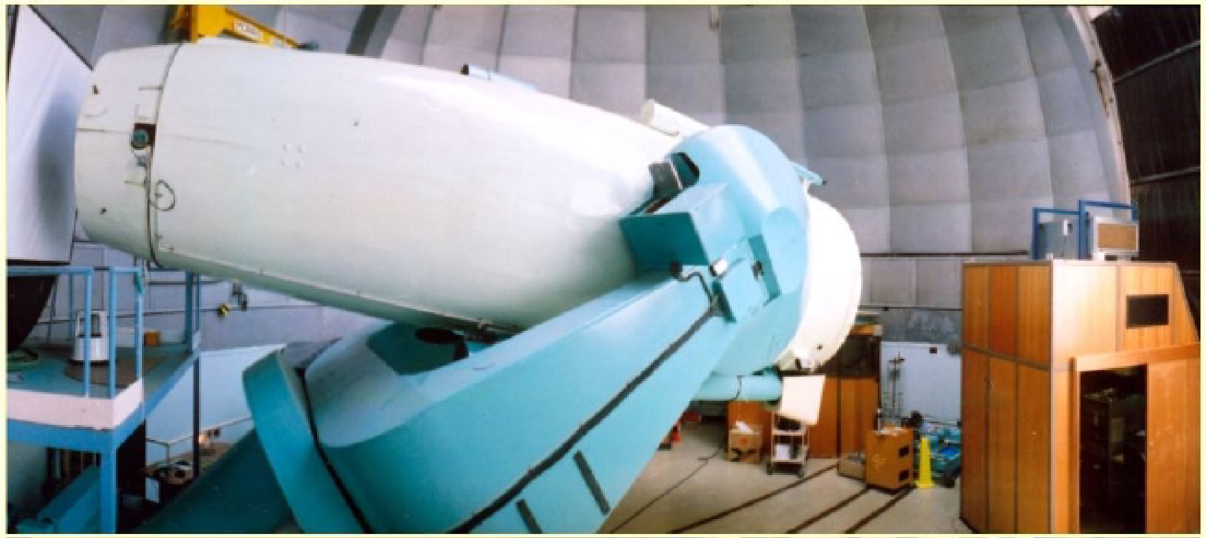
- The 6dFGS is a combined redshift and peculiar velocity survey designed to map the large-scale density and velocity fields in nearby universe
- Sample: NIR-selected galaxies from the 2MASS survey with K<12.65 (similar limits in b, r, J, H)
- Area: 17000 deg^2 of southern hemisphere excl. ±10° about the Galactic plane (δ<0°, |b|>10°)

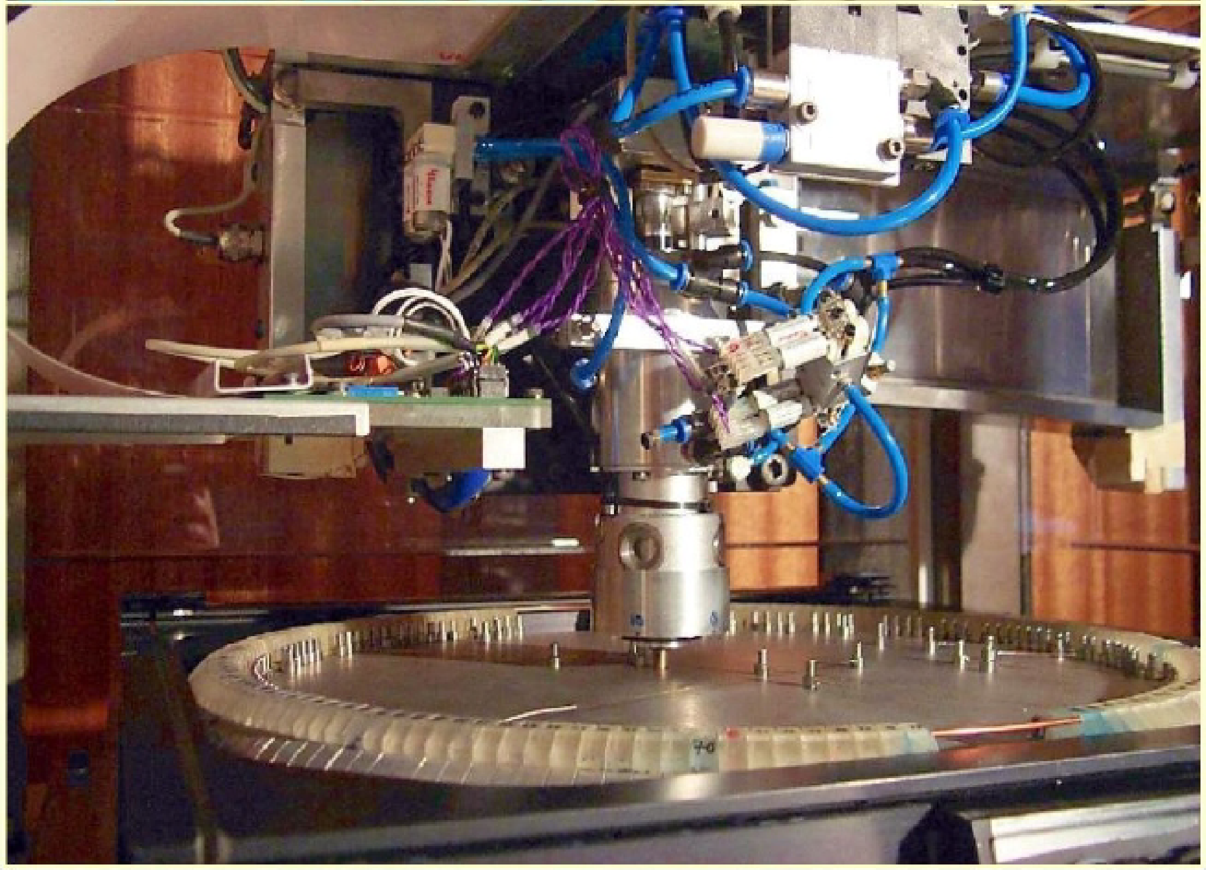
Magnitude limits	$K \leqslant 12.65$
	$H \leqslant 12.95$
	$J \leqslant 13.75$
	$r_F \leqslant 15.60$
	$b_J \leqslant 16.75$
Sky coverage (sr)	5.2
Fraction of sky	41%
Extragalactic sample, N	125 071
Median redshift, $z_{\frac{1}{2}}$	0.053
Volume V in $[0.5z_{\frac{1}{2}}, 1.5z_{\frac{1}{2}}]$ $(h^{-3}\,\mathrm{Mpc}^3)$	2.1×10^7
Sampling density at $z_{\frac{1}{2}}$, $\bar{\rho} = \frac{2N}{3V}$ $(h^3\,\mathrm{Mpc}^{-3})$	4×10^{-3}
Fibre aperture ($''$)	6.7
Fibre aperture at $z_{\frac{1}{2}}$ $(h^{-1}\,\mathrm{kpc})$	4.8



6dF Galaxy Survey

- Observations used the 6-degree Field (6dF) multi-object fibre spectrograph on the UK Schmidt Telescope over the period 2001-2006





6dFGS Fundamental Plane

- 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, σ 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 $r = a\,s + b\,i + c$ where $r = \log(R_e)$, $s = \log(\sigma)$ 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 (σ_0) from 6dFGS;
  - all early-type galaxies in 6dFGS with $z<0.055$, $\sigma_0>112$ km/s;
  - and comprises a total of ~9000 galaxies

Modelling the 6dFGS FP

- 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

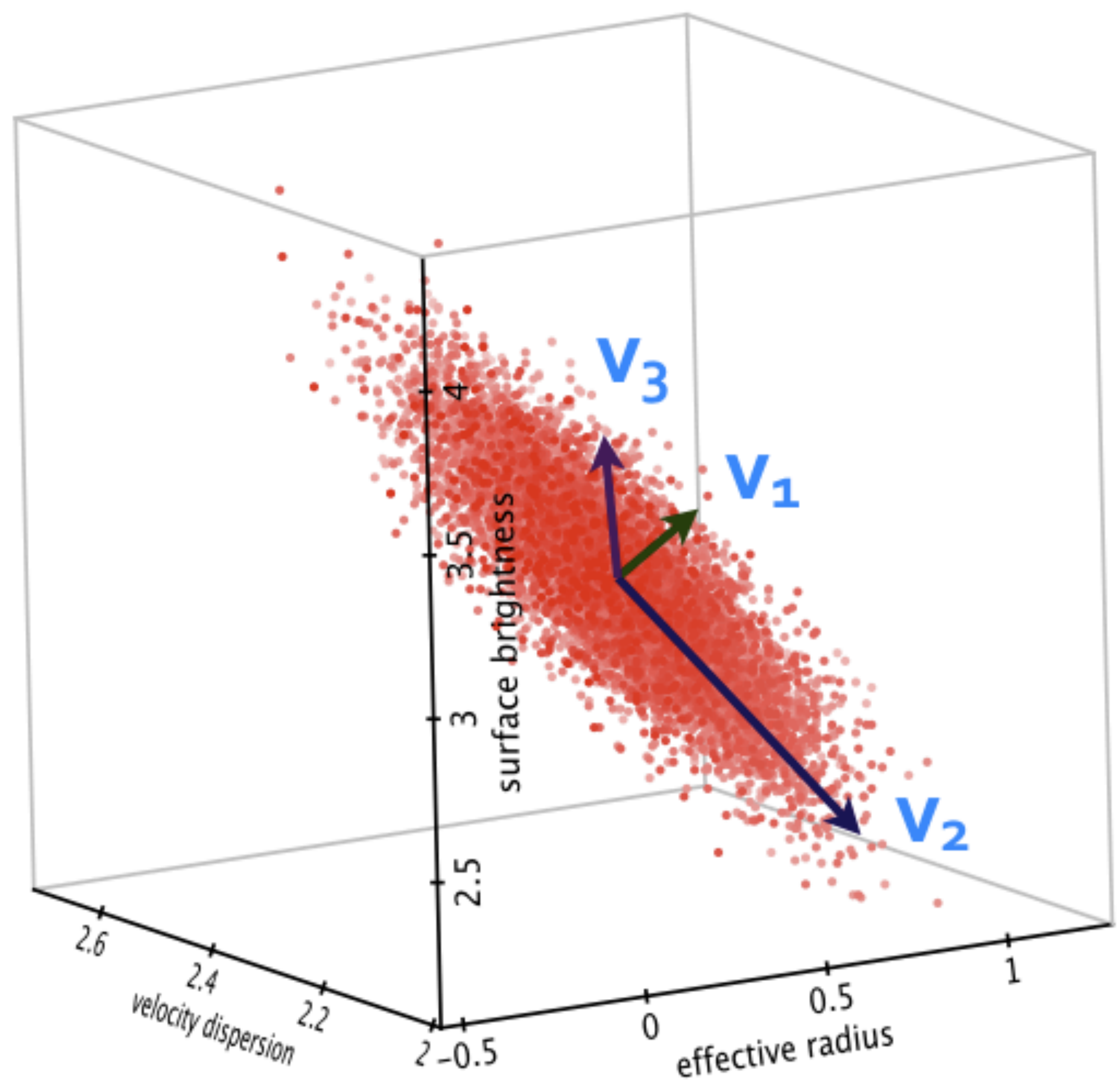
- The model is defined by the coefficients of the FP (*a, b, c*), and by the centroid (*r, s, i*) and dispersion (σ_1, σ_2, σ_3) of the 3D Gaussian

- 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)

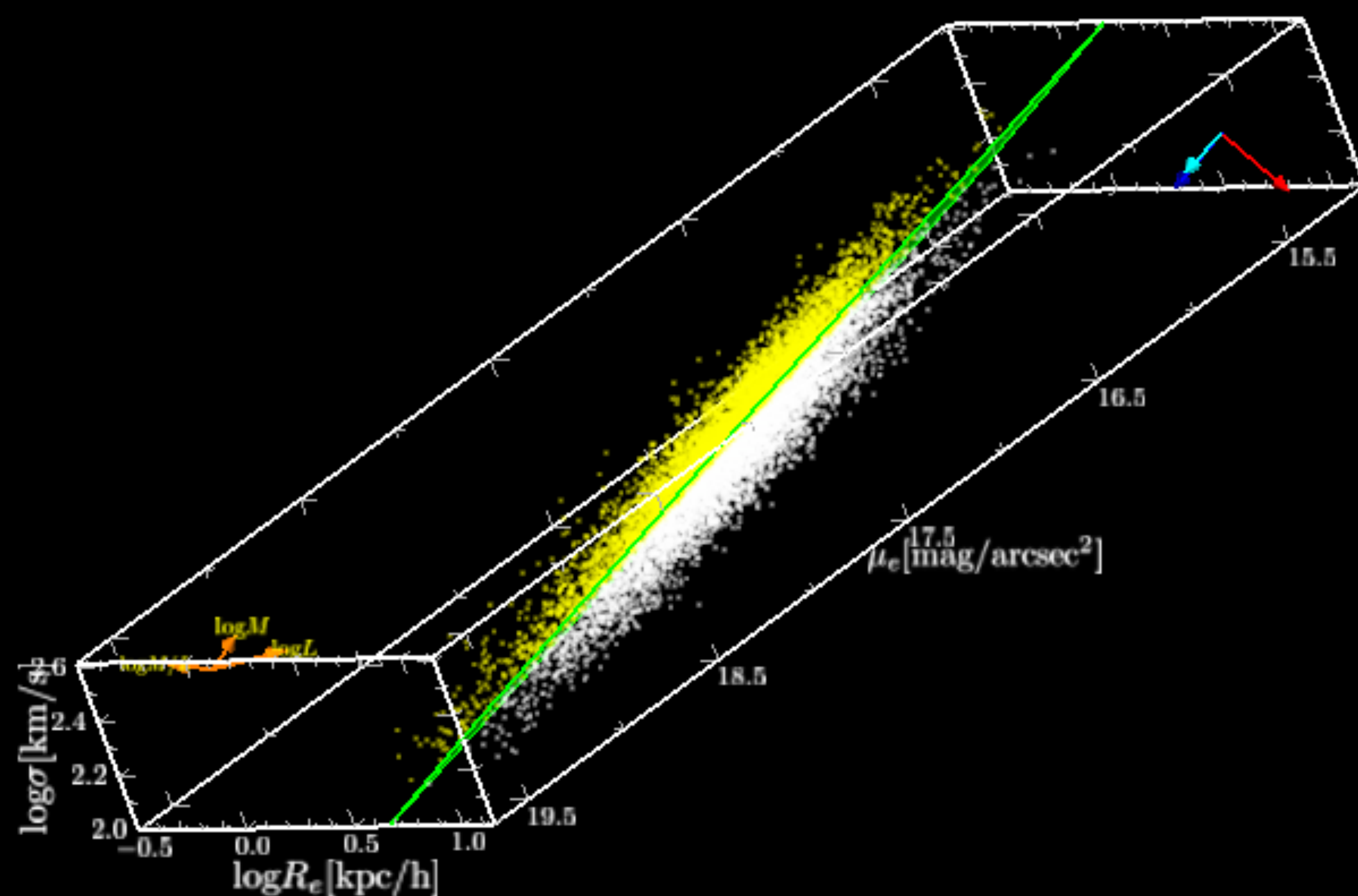
v_2 = along the plane ($r\downarrow$, no s, $i\uparrow$)
= long axis

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)



3D Visualization with S2PLOT by C.Fluke

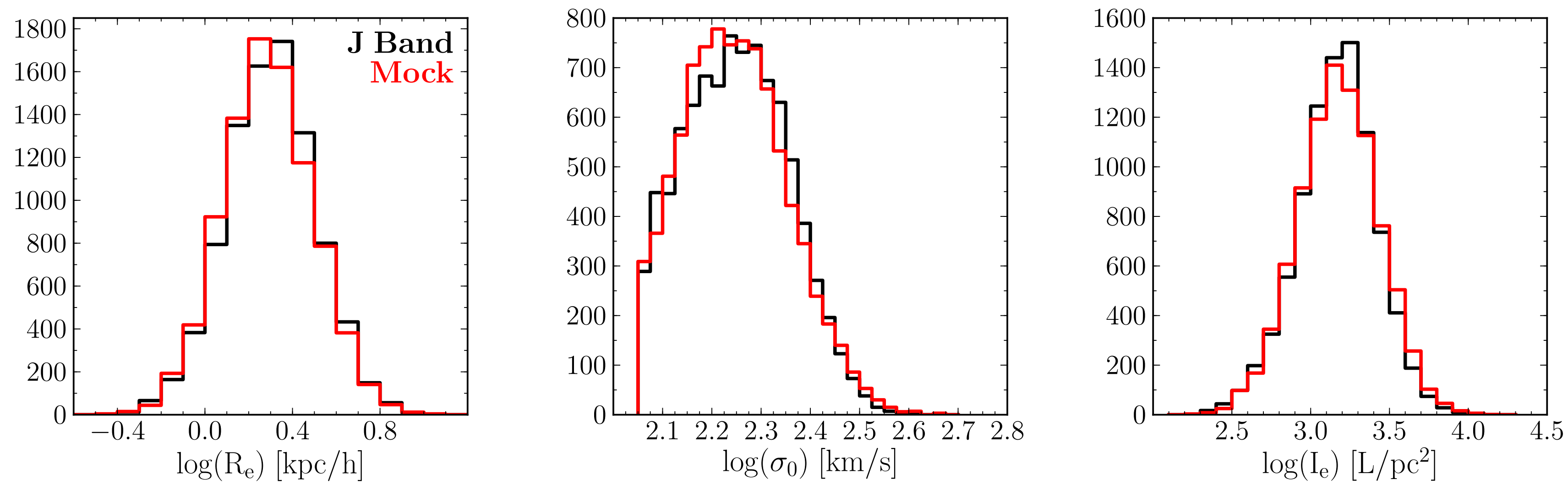
Fitted FP parameters and trends

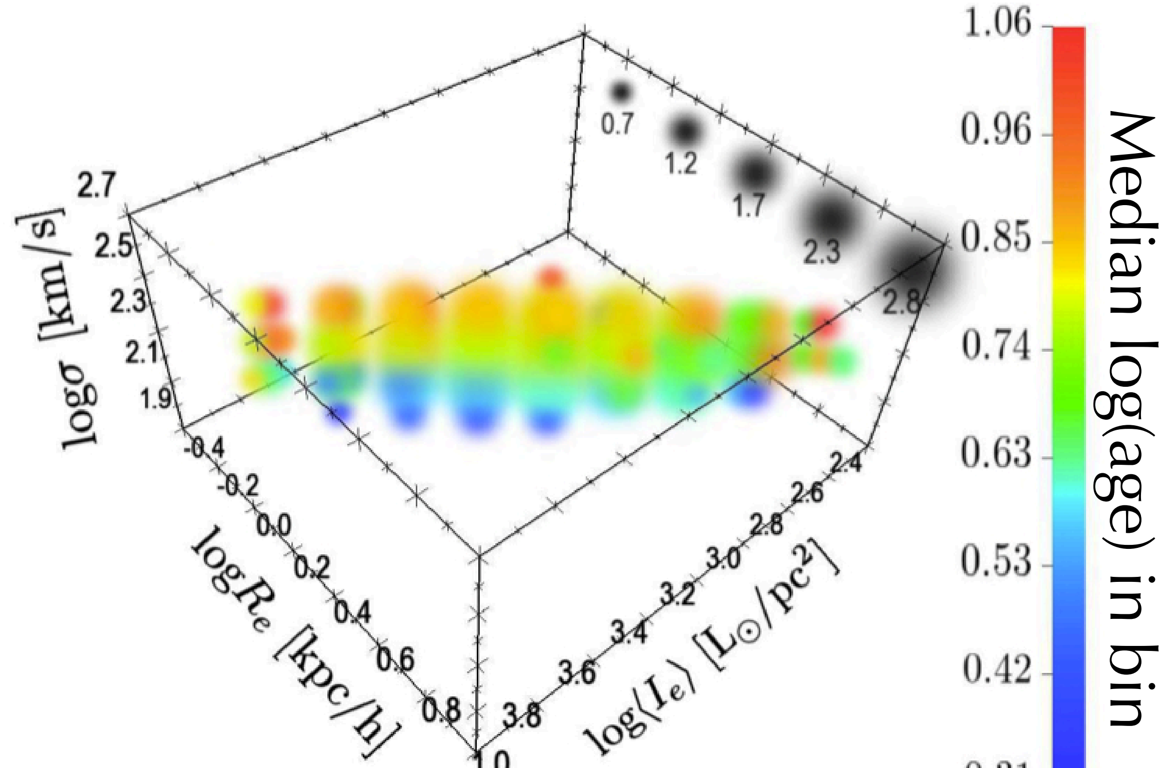
- In the J band (largest sample, smallest errors), the best-fit FP is

$$r = (1.52 \pm 0.03)\ s + (-0.89 \pm 0.01)\ i + (-0.33 \pm 0.05)$$

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*) dist^n
- 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 ~23%

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

Photometric error
$\Delta X_{FP} = 3\%$

Intrinsic r error
$\sigma_r = 23\%$

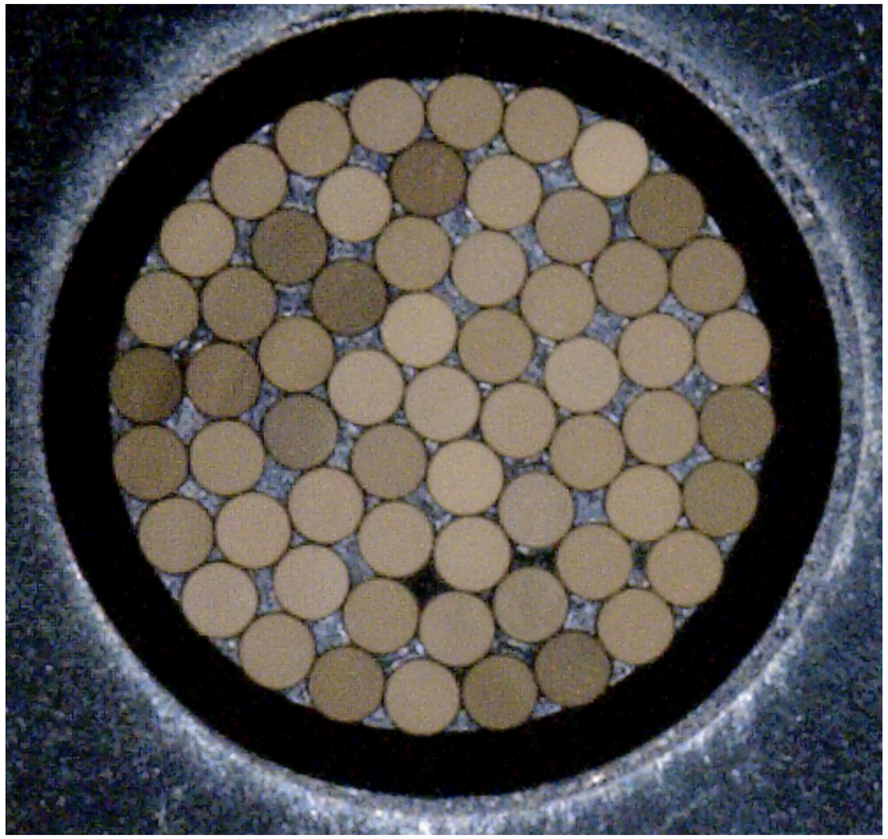
Total scatter in r
$\Delta r = 29\%$

FP slope x obs error in s
$a.\Delta s = 1.5 \times 12\% = 18\%$

- 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 σ 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

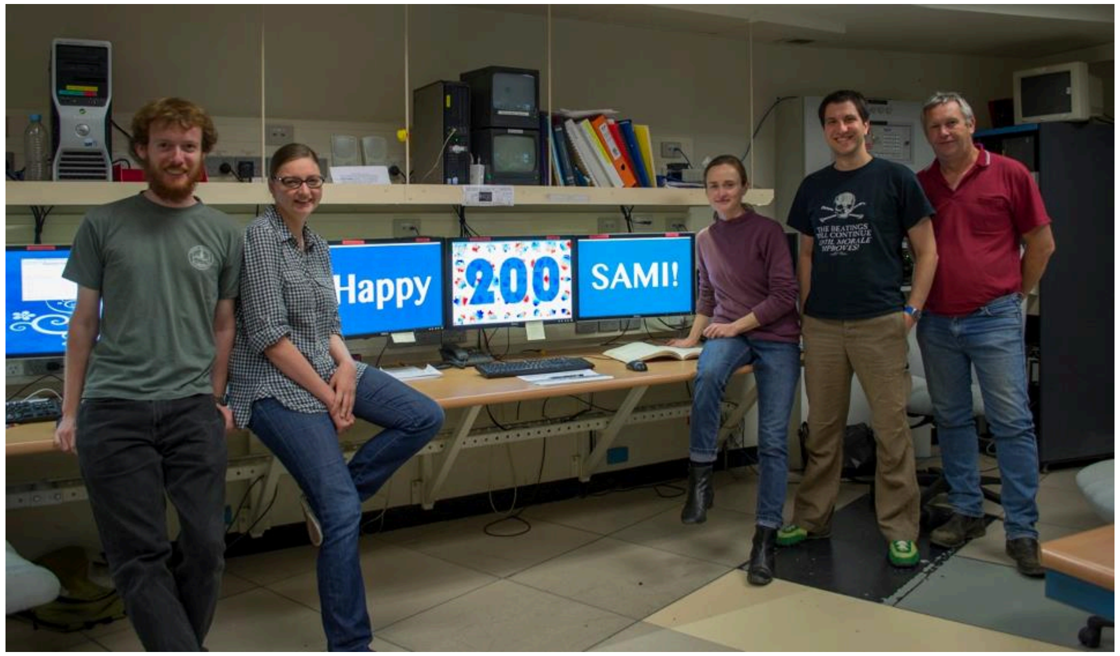


  - SAMI feeds the double-beam AAOmega spectrograph

The SAMI survey

sami galaxy survey

- ❑ 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

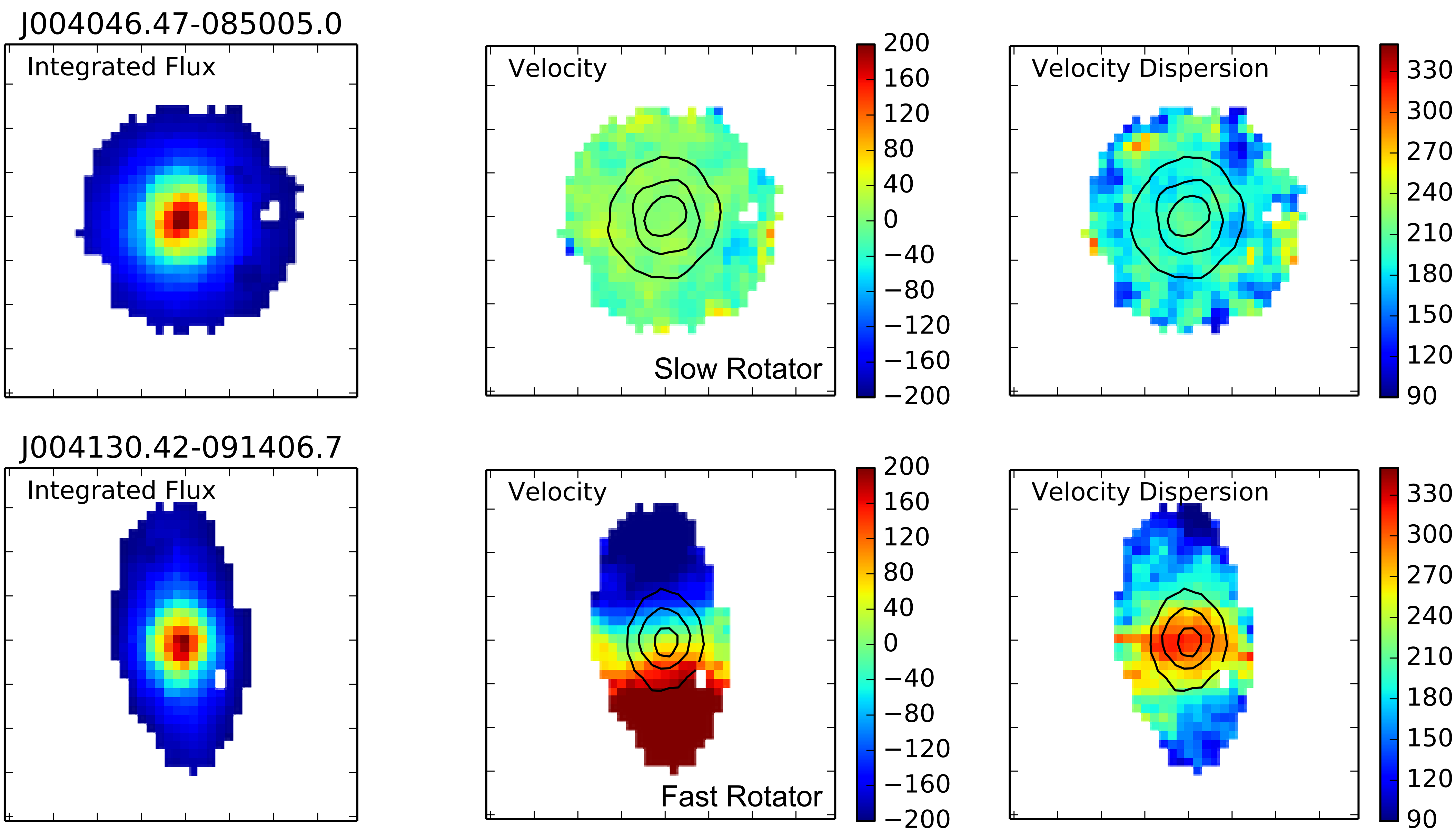


- ❑ The targets for the SAMI survey were chosen to…
  - sample the full range of galaxy environments
  - cover a broad range in stellar mass
  - have sizes such that emission spectra can be obtained out to ~2R_e
  - have surface brightness sufficient to measure stellar kinematics to ~R_e
  - have a target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

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

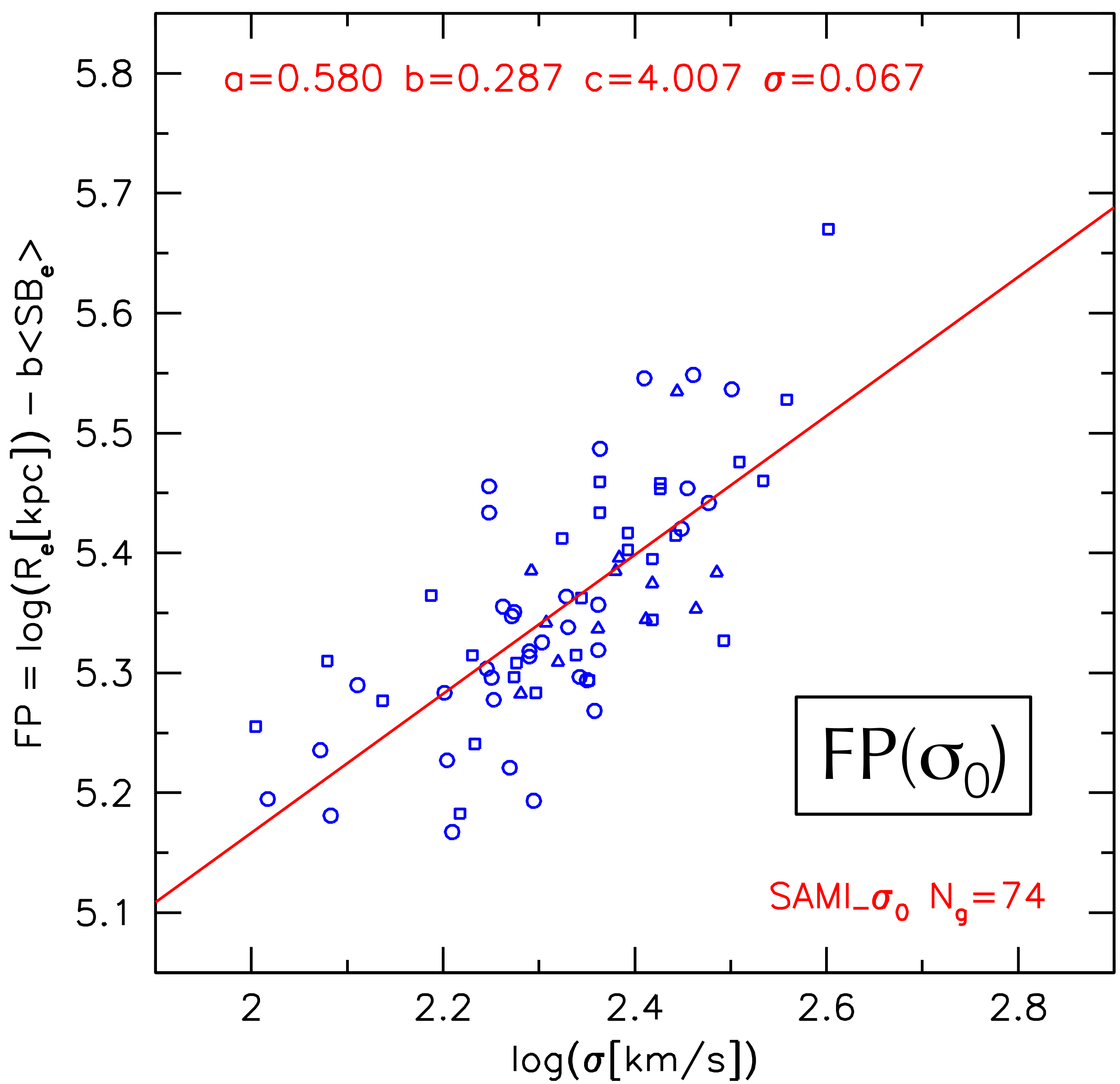
SAMI pilot survey data for ETGs

- 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° fields were observed
  - we examine the 74 morphological ETGs with good pilot survey data



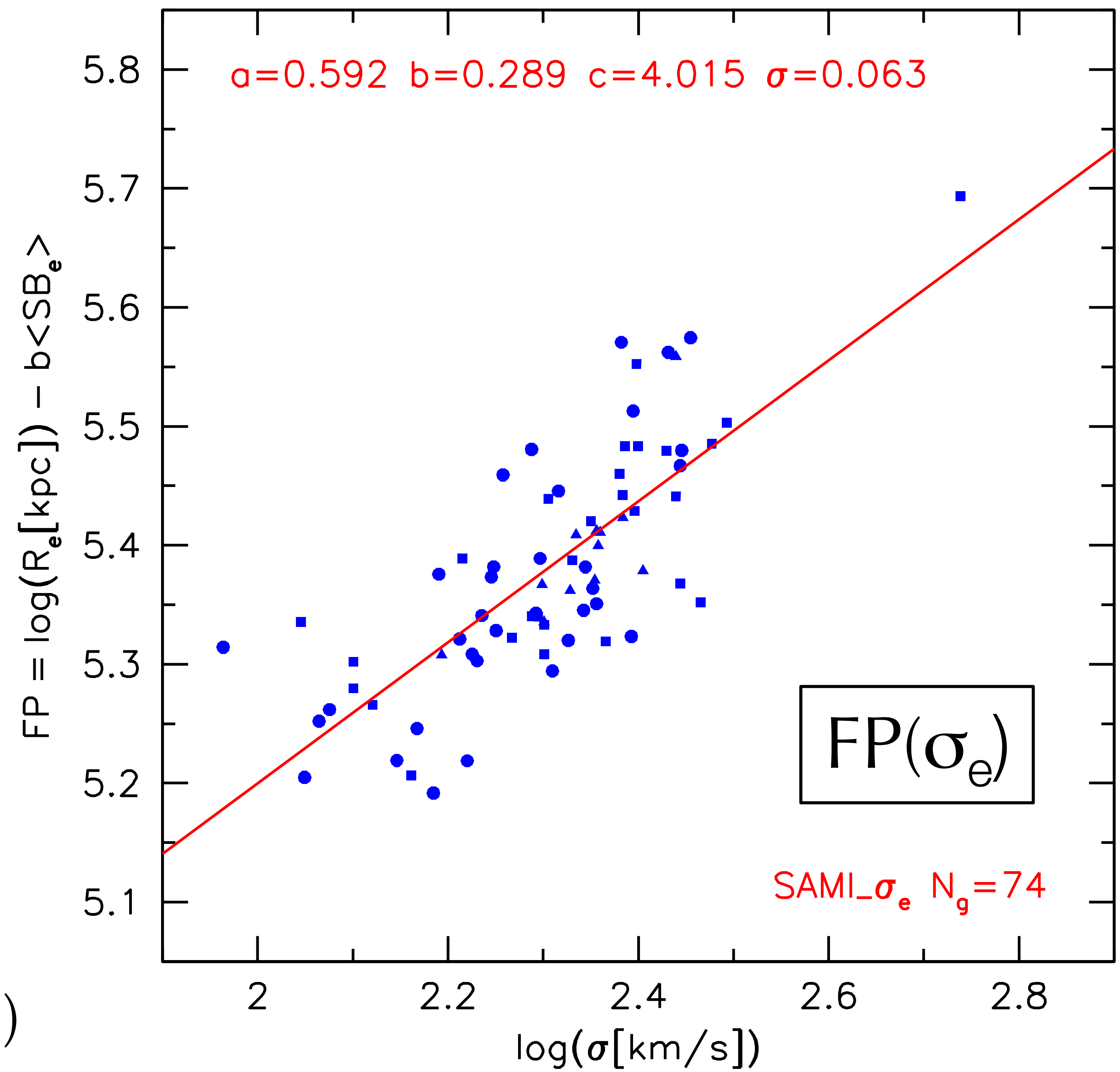
SAMI Fundamental Plane

- 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* $\sigma_e = \sigma(R_e)$.



SAMI Fundamental Plane

- Comparing FP(σ_0) and FP(σ_e), we find:
  - the expected offset (because $\sigma_0 > \sigma_e$)
  - very similar slopes (equally affected by selection effects)
  - marginally less scatter for FP(σ_e) than FP(σ_0)
- Broadly consistent with previous findings (e.g. Falcón-Barroso et al. 2011)

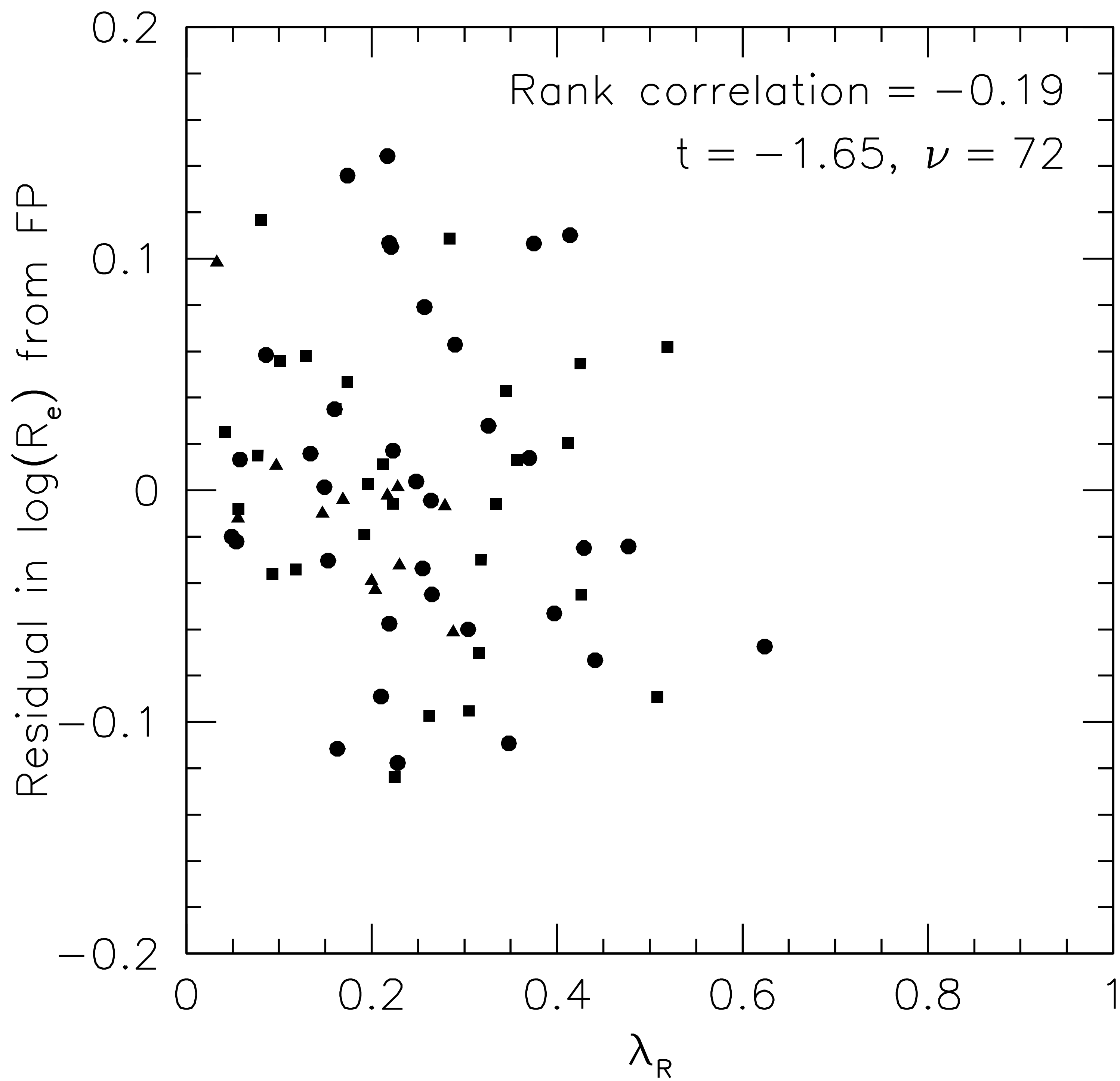


FP residual correlation with λ_R

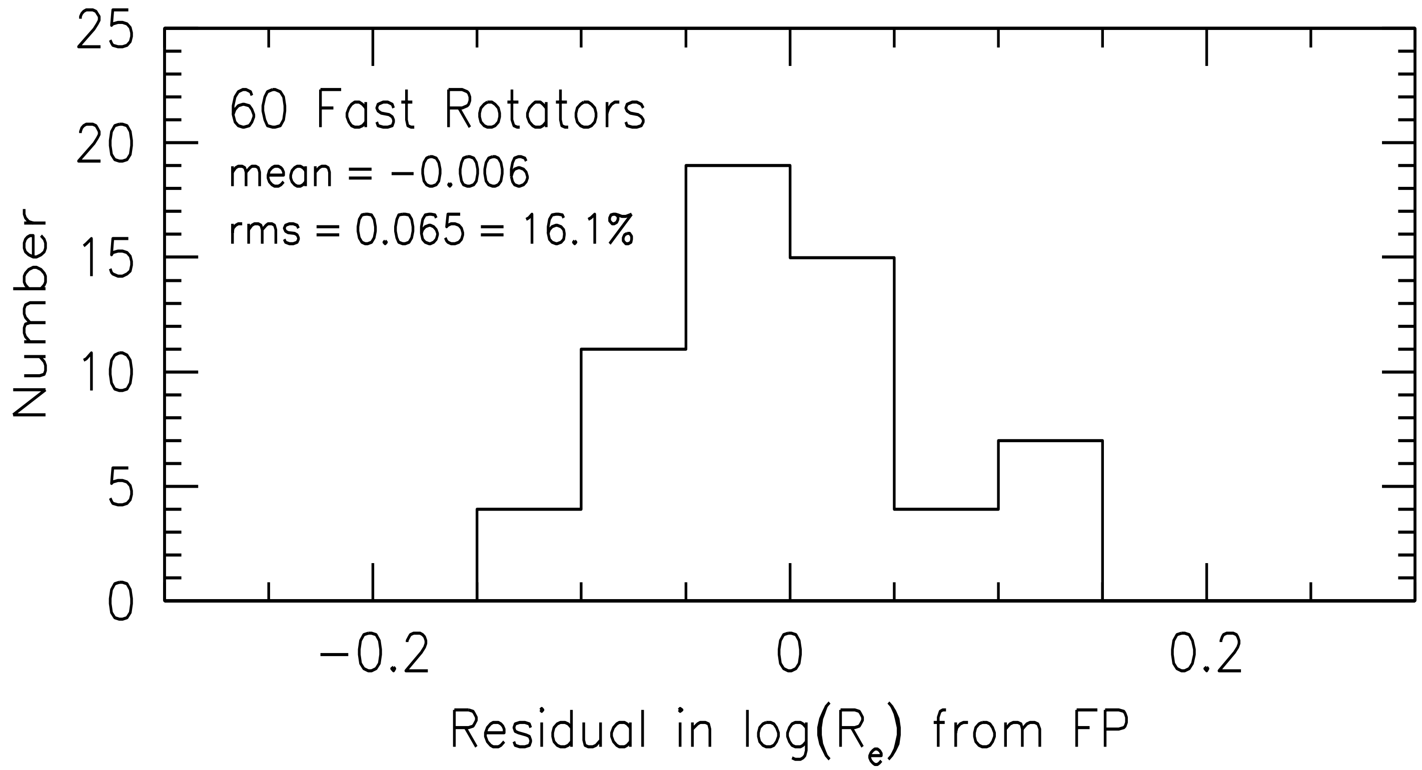
- Are residuals from the FP (in $\log R_e$) correlated with kinematic morphology?
- In particular, are they correlated with specific angular momentum?

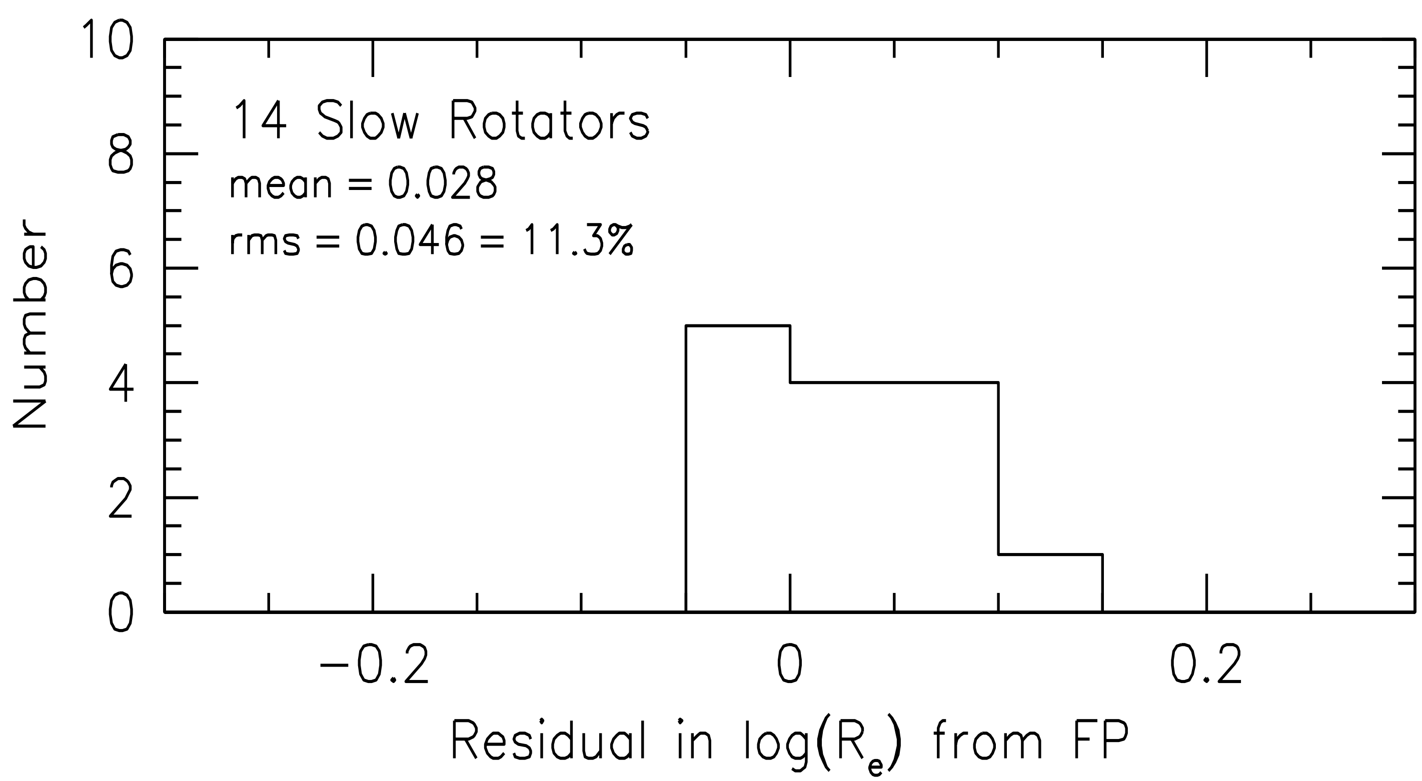
$$\lambda_R = \frac{\langle R|V|\rangle}{\langle R\sqrt{V^2+\sigma^2}\rangle}$$

- 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 $\lambda_R < k\boldsymbol{\varepsilon}^{1/2}$ (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 ~¾ 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); $\langle z \rangle \approx 0.08$ and $V_{eff} \approx 0.23\ h^{-3}\ Gpc^3$
- 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%