# The Fundamental Plane, Stellar Populations, and Environment

## Results from the 6dF Galaxy Survey

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# Some things we know…

- Some of the things we know (or think we know) about stellar populations in early-type galaxies, the Fundamental Plane and the effects of environment…
  - The stellar populations are mostly old or very old, though with exceptions, and sometimes with a 'frosting' of young stars
  - The stellar populations are generally metal-rich, with significantly enhanced $\alpha$-element abundances
  - There are strong trends of age, metallicity and $\alpha$-enhancement with velocity dispersion / $M_{star}$ / $M_{dyn}$ ($\sigma$ may be best predictor?)
  - Early-type galaxies (and bulges) form a Fundamental Plane in size/velocity dispersion/surface brightness ($\log R - \log\sigma - \log I$ ) space, with relatively small (15-20%) intrinsic scatter in R
  - Stellar populations properties and measures of environment (often ill-defined) show correlations, but they are entangled with mass-environment and morphology-environment correlations

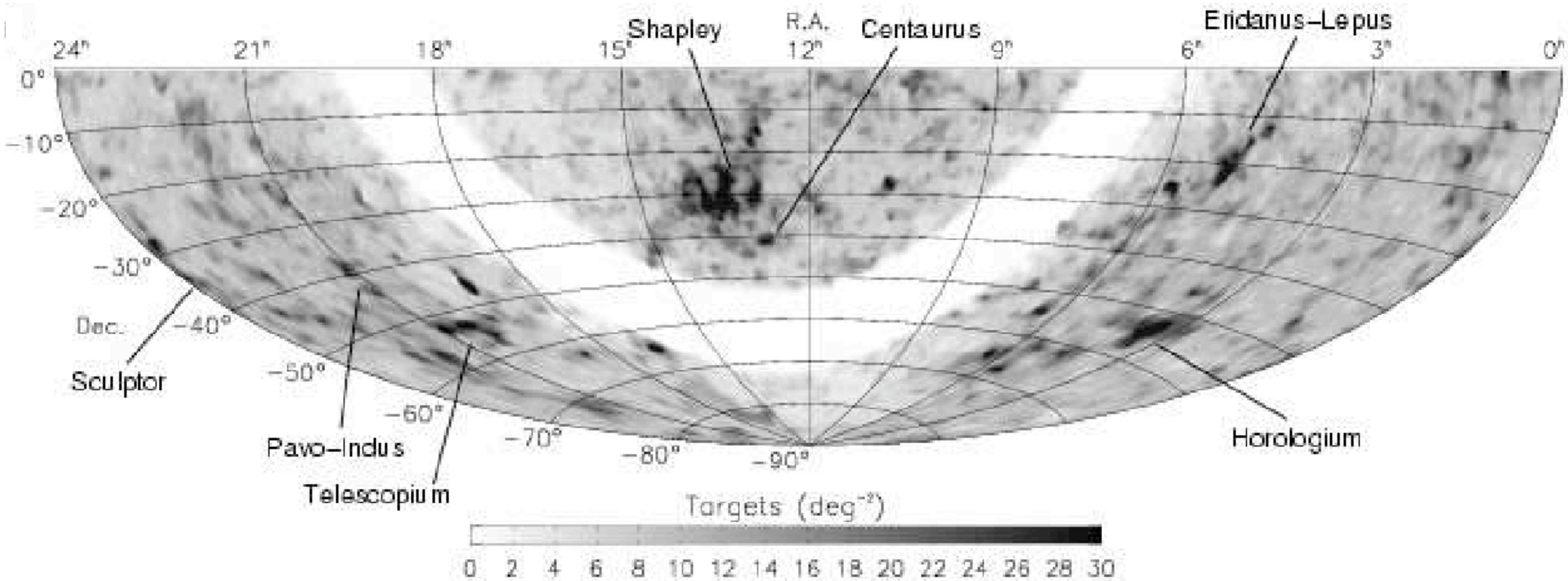
# Some things we don't know…

- Some of the (many) things we don't know (at least not well)…
  - What is the relation between stellar mass and dynamical mass, and how does this vary with parent halo mass & environment?
  - How do the observed trends in stellar populations vary with environment (NN/local density/cluster radius/cluster richness)?
  - What is origin of the 'tilt' of the FP and its variation with $\lambda$? How much is due to stellar population variations and how much is due to structural non-homology or variations in $M_{star}/M_{dark}$?
  - What is the origin of the scatter about the FP? Are there extra (hidden) parameters or is it due to the intrinsic stochasticity of galaxy formation? Is environment a factor?

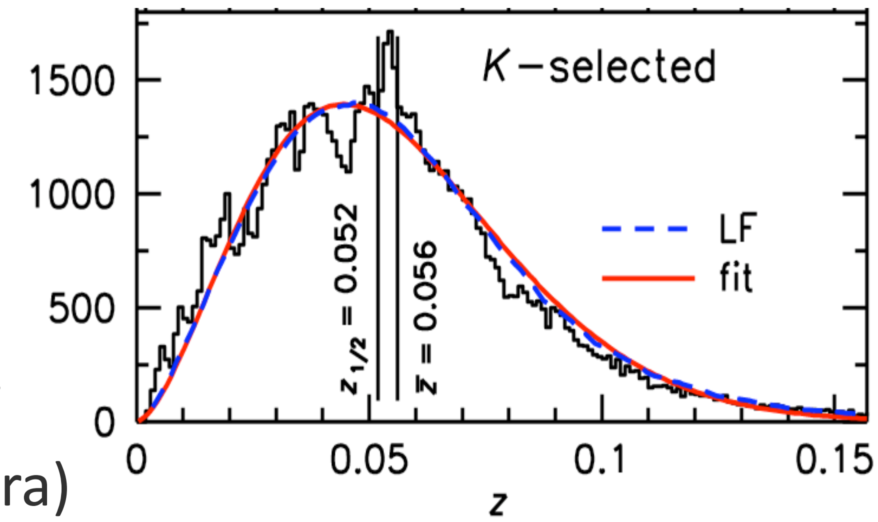
- A very large, uniform, stellar-mass-selected spectroscopic survey would surely help in answering these questions!

# The 6dF Galaxy Survey

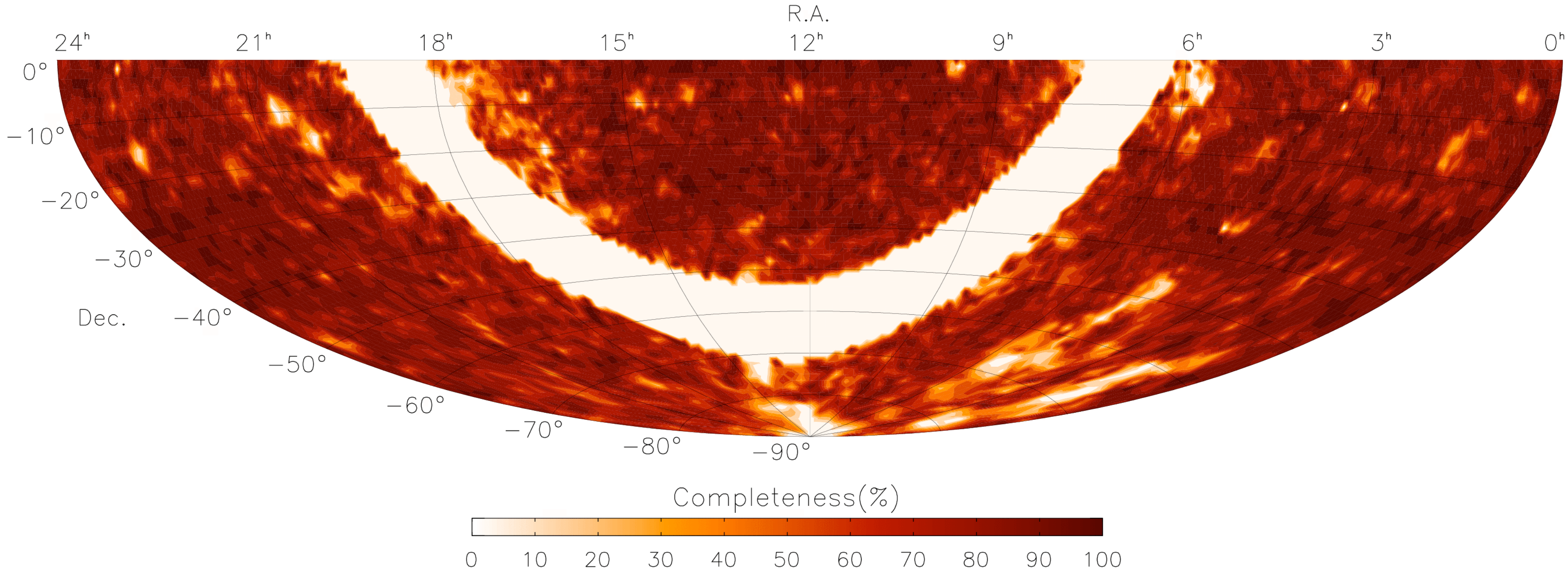
- Spectroscopic survey of southern sky with b>10° (17,000 $deg^2$)
- Primary sample from 2MASS with $K_{tot}$<12.75; also secondary samples with H<13.0, J<13.75, r<15.6, b<16.75 (SuperCosmos)
- The 6dFGS is both a redshift and a peculiar velocity survey
- FP distances and PVs for ~10,000 brightest early-type galaxies



# 6dFGS *z*-survey

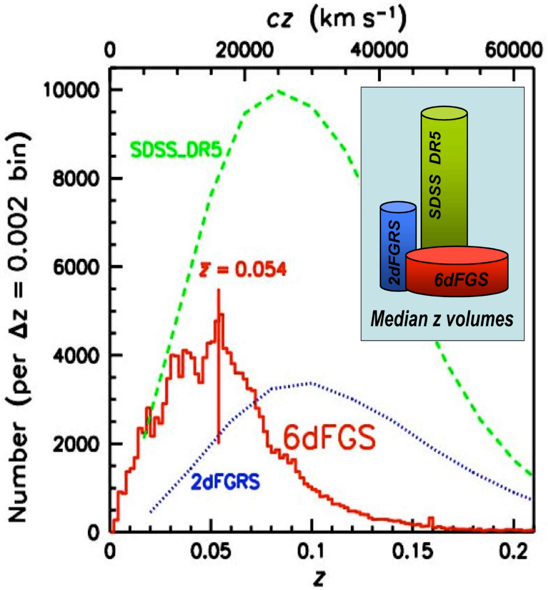


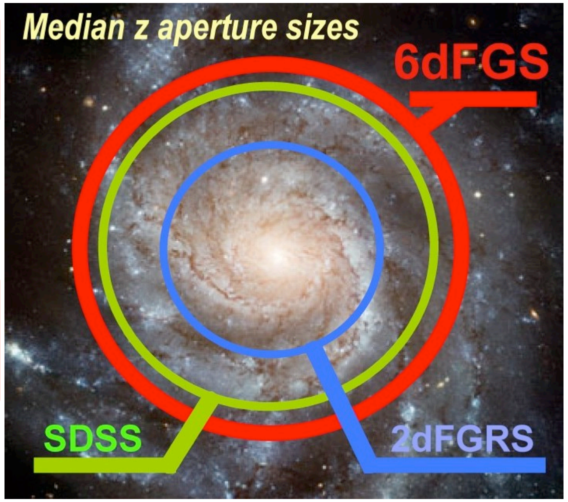

- Median redshift ~15,000 km/s
- Effective volume ~$2 \times 10^7$ $h^{-3}$ $Mpc^3$
- 125,000 redshifts (137,000 spectra)
- Primary sample mean completeness 88%; selection function is well-defined (depends on both position and magnitude)

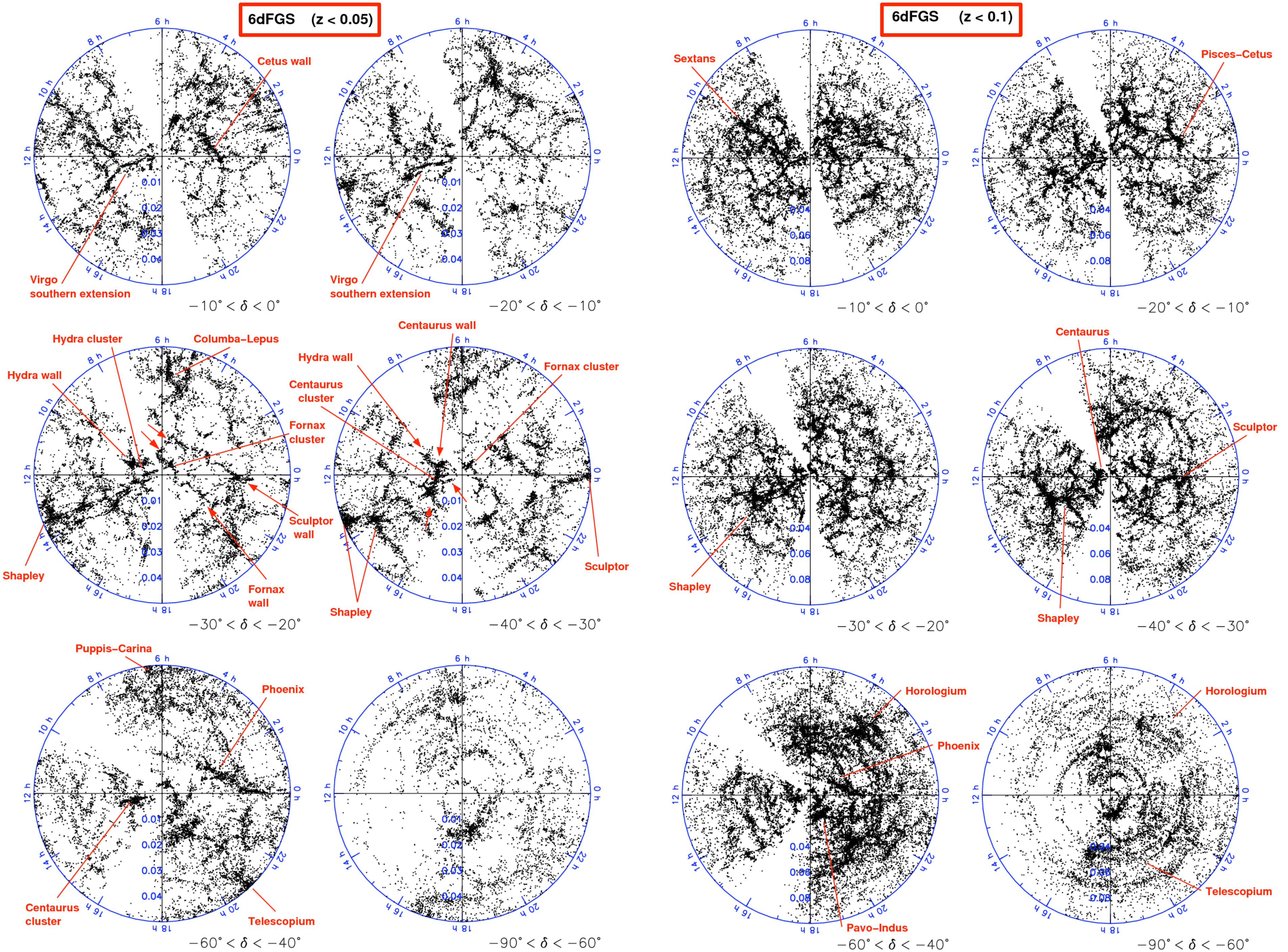


# Comparison of surveys

| | 6dFGS | 2dFGRS | SDSS-DR7 |
|---|---|---|---|
| Magnitude limits | $K \leqslant 12.65$ | $b_J \leqslant 19.45$ | $r \leqslant 17.77$ |
| | $H \leqslant 12.95$ | | (Petrosian) |
| | $J \leqslant 13.75$ | | |
| | $r_F \leqslant 15.60$ | | |
| | $b_J \leqslant 16.75$ | | |
| Sky coverage (sr) | 5.2 | 0.5 | 2.86 |
| Fraction of sky | 41% | 4% | 23% |
| Extragalactic sample, $N$ | 125 071 | 221 414 | 644 951 |
| Median redshift, $z_{\frac{1}{2}}$ | 0.053 | 0.11 | 0.1 |
| Volume $V$ in $[0.5z_{\frac{1}{2}}, 1.5z_{\frac{1}{2}}]$ $(h^{-3}\,\mathrm{Mpc}^3)$ | $2.1 \times 10^7$ | $1.7 \times 10^7$ | $7.6 \times 10^7$ |
| Sampling density at $z_{\frac{1}{2}}$, $\bar{\rho} = \frac{2N}{3V}$ $(h^3\,\mathrm{Mpc}^{-3})$ | $4 \times 10^{-3}$ | $9 \times 10^{-3}$ | $6 \times 10^{-3}$ |
| Fibre aperture ($''$) | 6.7 | 2.0 | 3.0 |
| Fibre aperture at $z_{\frac{1}{2}}$ $(h^{-1}\,\mathrm{kpc})$ | 4.8 | 2.8 | 3.9 |

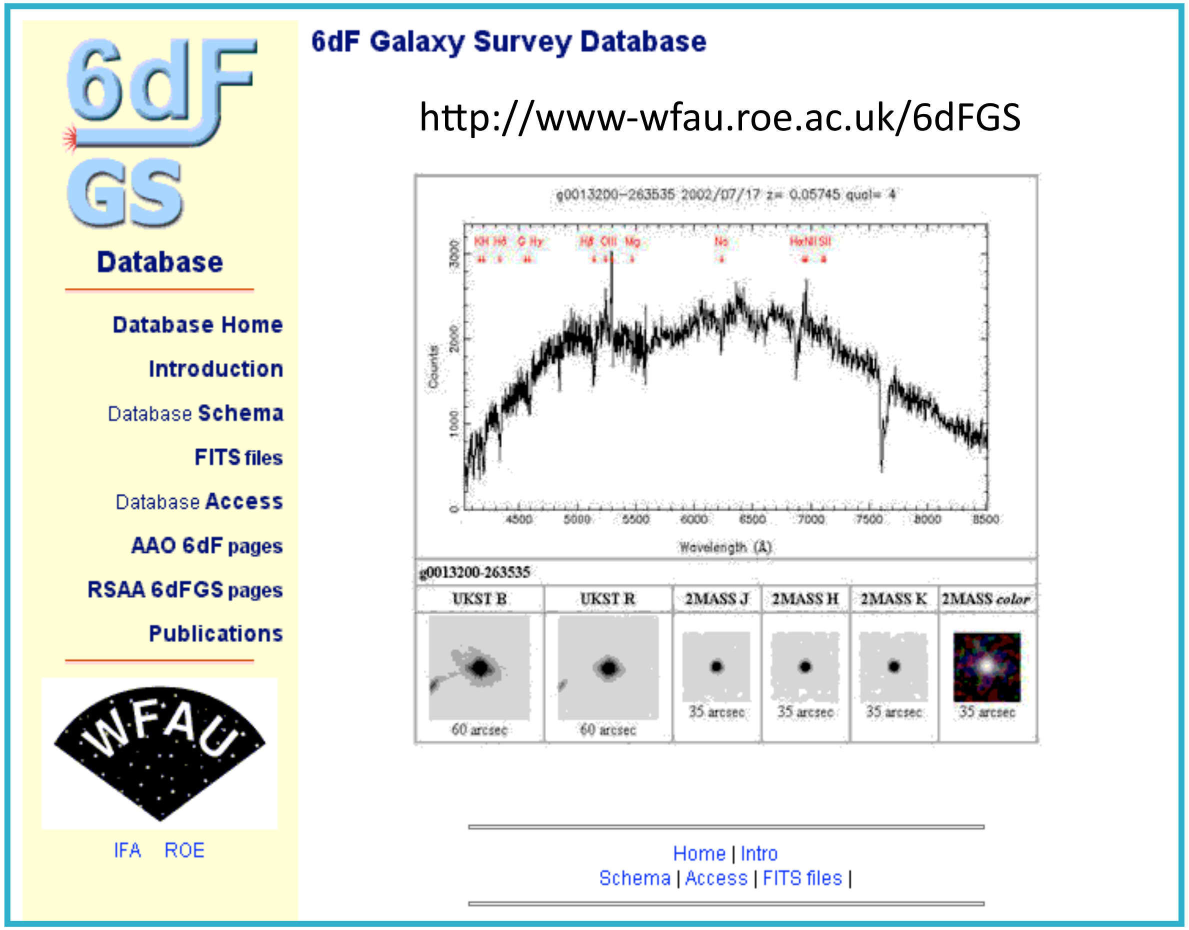



6dFGS (z < 0.05)
6dFGS (z < 0.1)
Cetus wall
Virgo southern extension
−10° < δ < 0°
−20° < δ < −10°
Sextans
Pisces−Cetus
Hydra cluster
Columba−Lepus
Hydra wall
Fornax cluster
Sculptor wall
Fornax wall
Shapley
Centaurus wall
Centaurus cluster
Sculptor
Centaurus
−30° < δ < −20°
−40° < δ < −30°
Puppis−Carina
Phoenix
Telescopium
Horologium
Pavo−Indus
−60° < δ < −40°
−90° < δ < −60°

# 6dFGS database: www.aao.gov.au/6dFGS

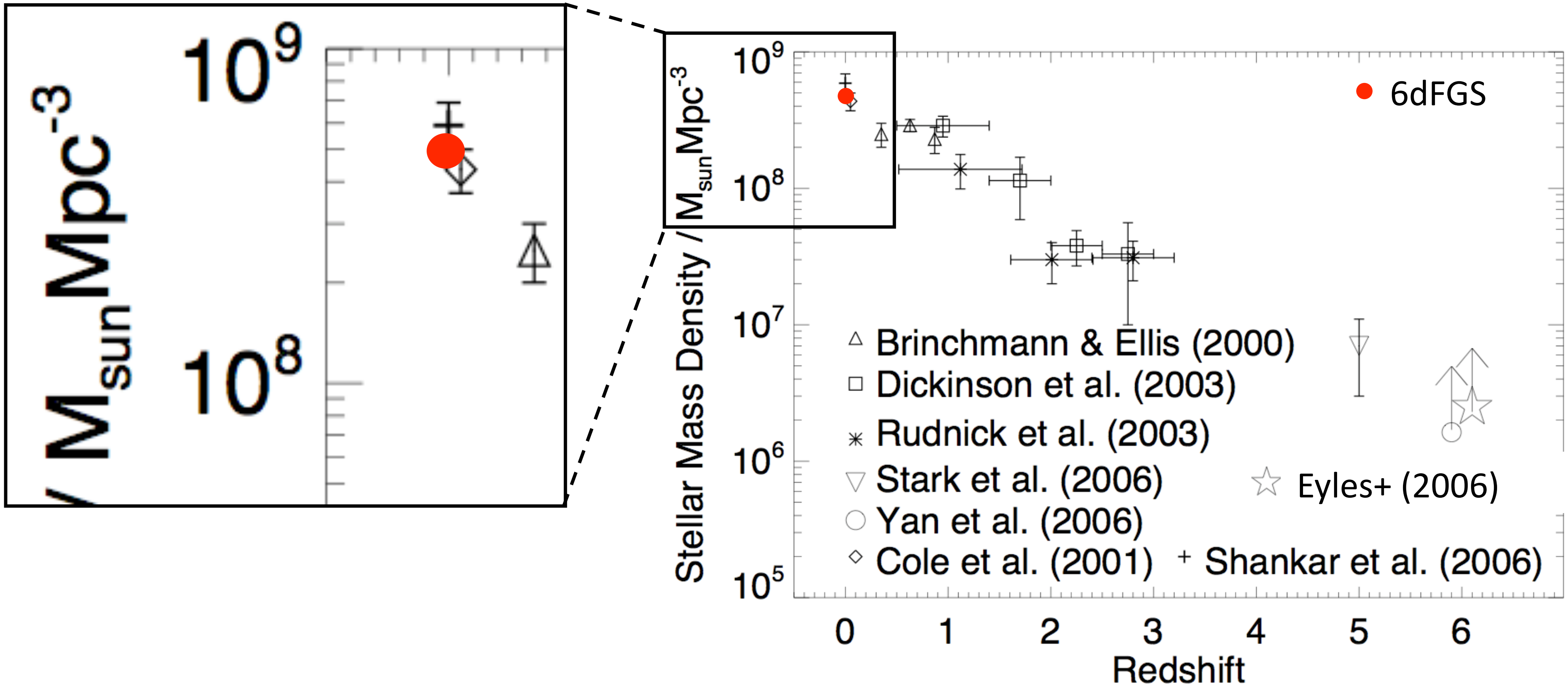
- Final Data Release
  - **DR3 public 1 April 2009**
  - Complete <u>*z*-survey</u> data
  - 1464 fields, 137k spectra
  - 125k unique redshifts
  - Jones et al. (2009) – see astro-ph/0903.5451
- 6dFGS online database
  - Searchable via SQL queries or WWW form
  - Spectra and images in a multi-extension FITS file
  - Target catalogues are fully searchable online




- <u>*v*-survey</u> information for bright early-type galaxies (not yet public)…
  - >20k galaxies with Lick indices giving age, metallicity and α-enhancement
  - >10k galaxies with velocity dispersion, effective radius, surface brightness

# The present-day stellar mass density

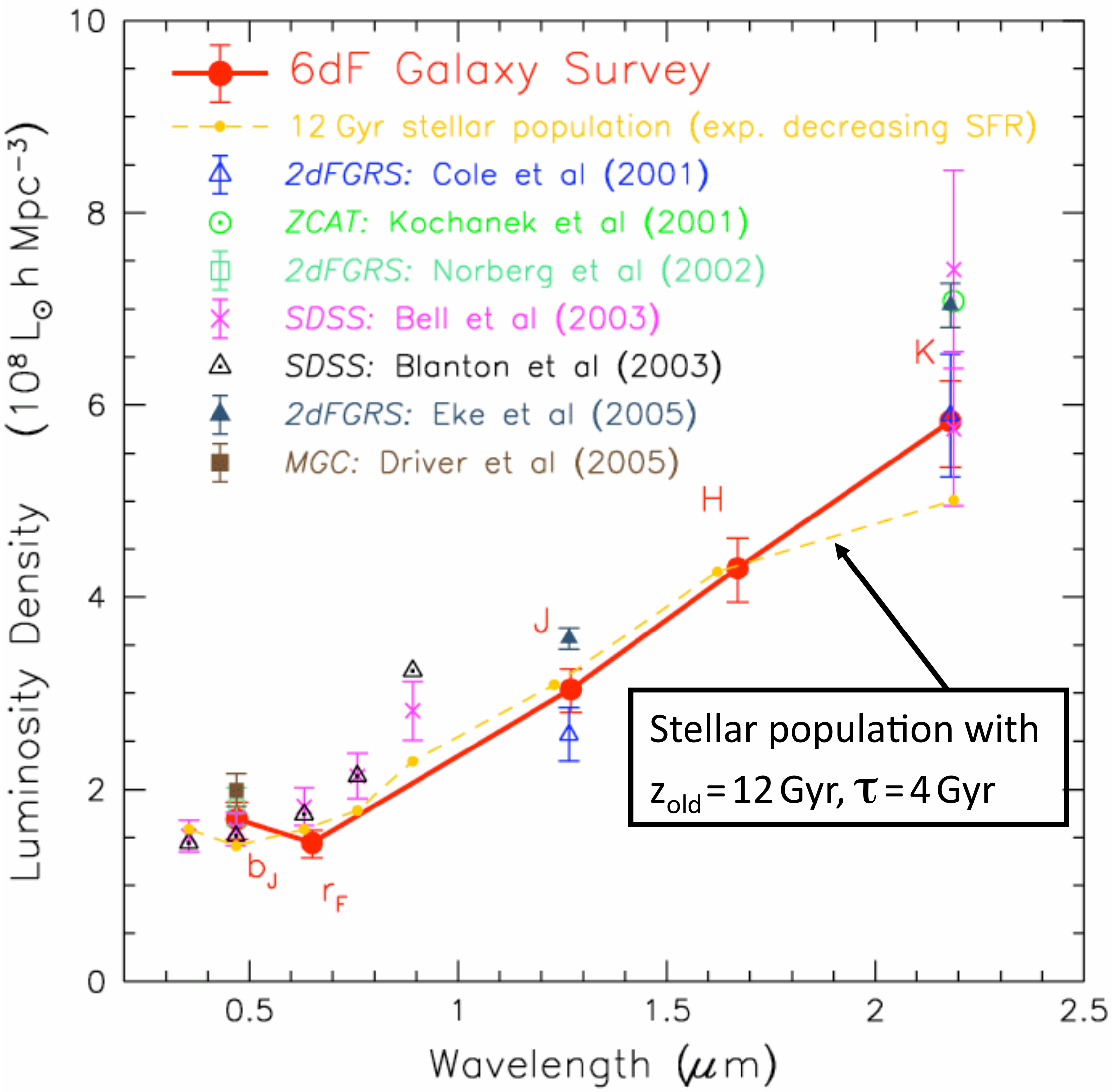
- The 6dFGS data provides (up to systematic errors in models) a very precise measurement of the present-day stellar mass density




- Stellar mass density is $\rho_\star = (5.00 \pm 0.11) \times 10^8\ h\ M_\odot\ Mpc^{-3}$ which corresponds to $\Omega_\star h = 0.00180 \pm 0.00004$ (statistical)

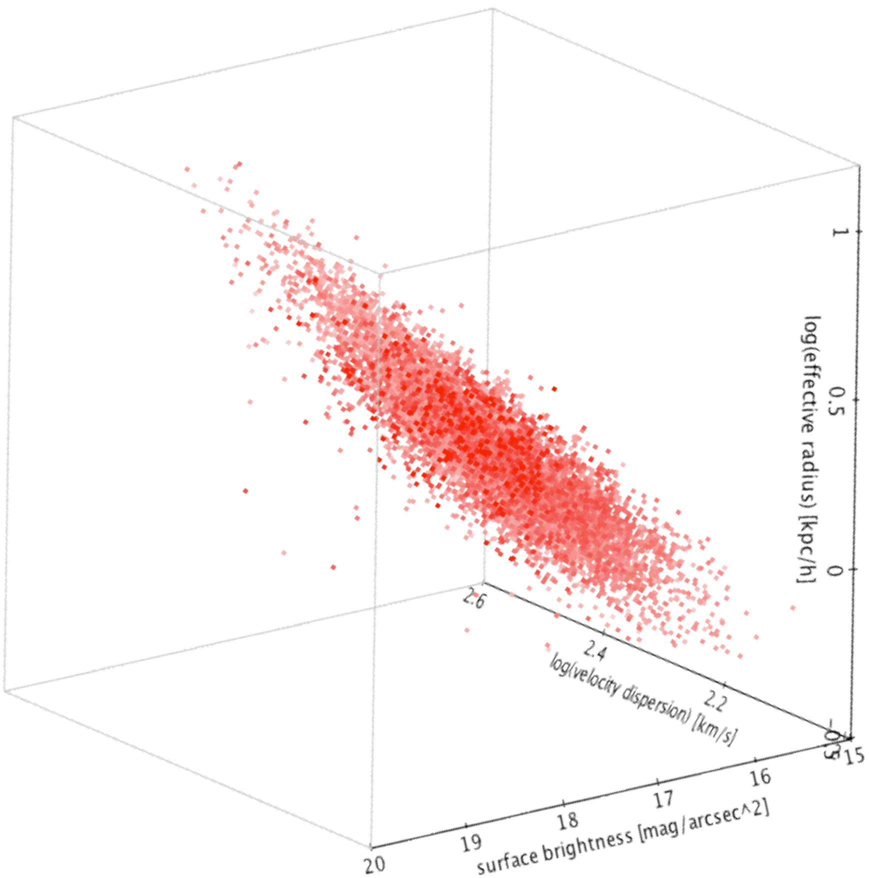
# Luminosity density in optical and NIR

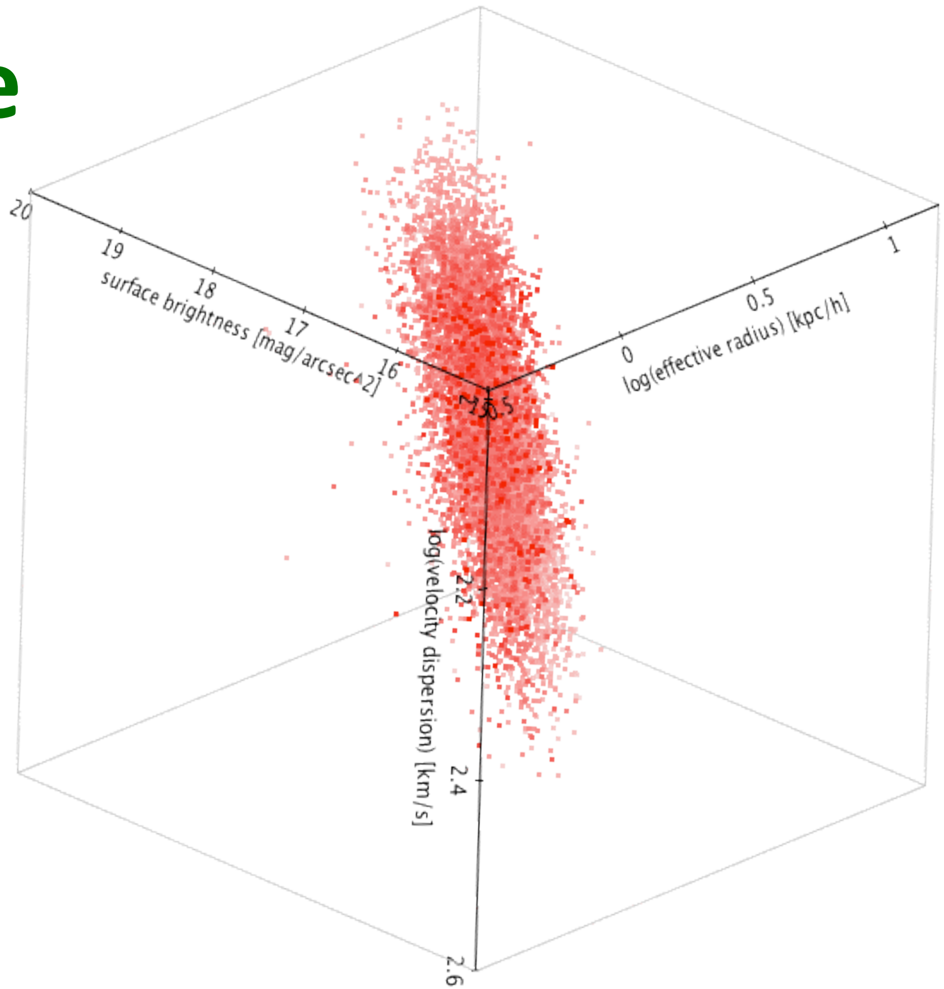
- The luminosity densities in optical and NIR estimated from 6dFGS are broadly consistent with the 2dFGRS and SDSS results
- K-band luminosity density lies at lower end of literature range
- From optical through NIR, the variation of luminosity density with wavelength is <u>consistent</u> with models for an old stellar population



# Fundamental Plane

- Edge-on projections of the 6dFGS Fundamental Plane (~10k galaxies, H band)

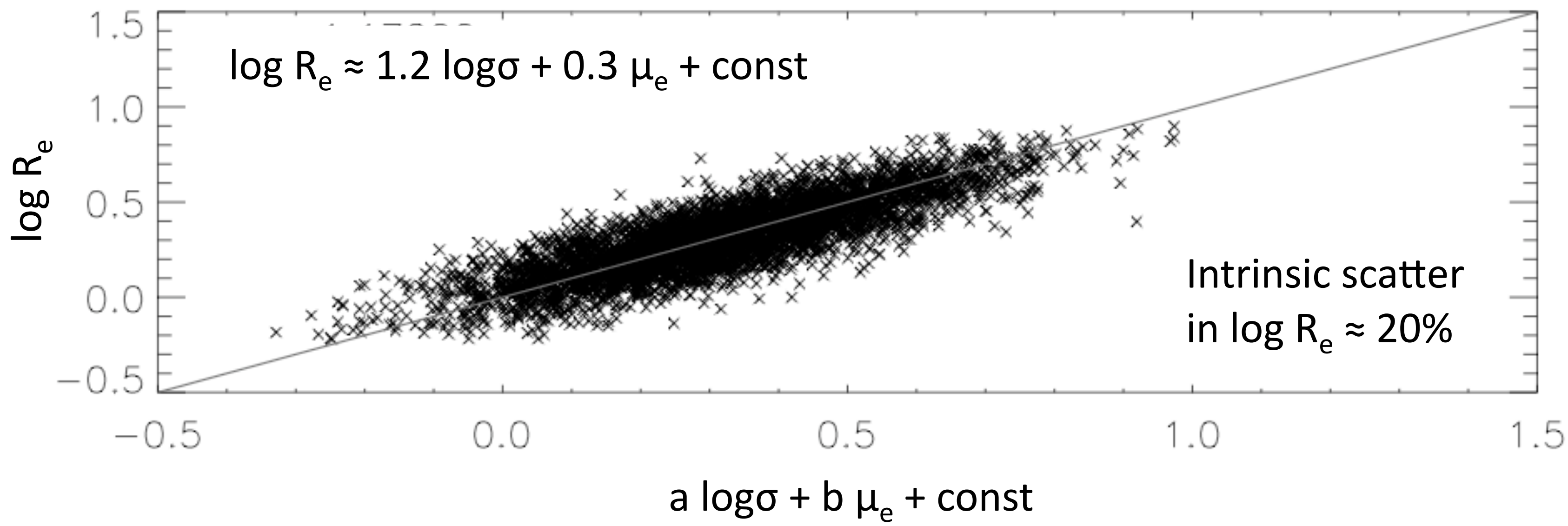


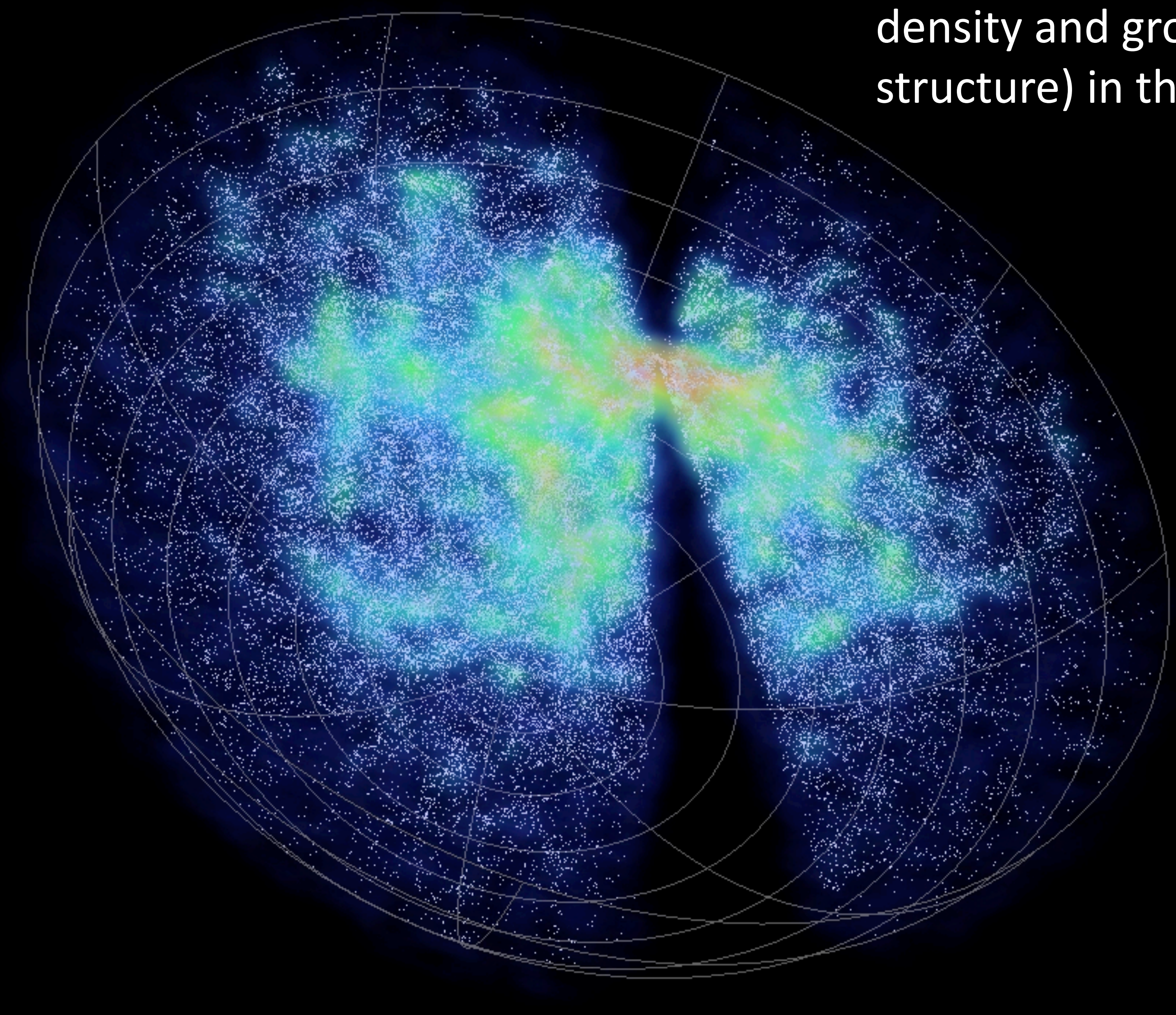

- Hint of curvature and twisting of the Fundamental Plane?
- Selection/bias effect? or real?

# Fundamental Plane fitting

- Fit the Fundamental Plane in $\log R_e - \log\sigma - \mu_e$ space with a 3D Gaussian distribution using maximum likelihood method:
  - Empirically, a 3D Gaussian is a better representation of the data than a uniformly populated plane with Gaussian scatter
  - ML fit allows for (possibly correlated) errors in all observables
  - ML fit incorporates selection effects (sample limits in velocity dispersion, magnitude, size, surface brightness and others)

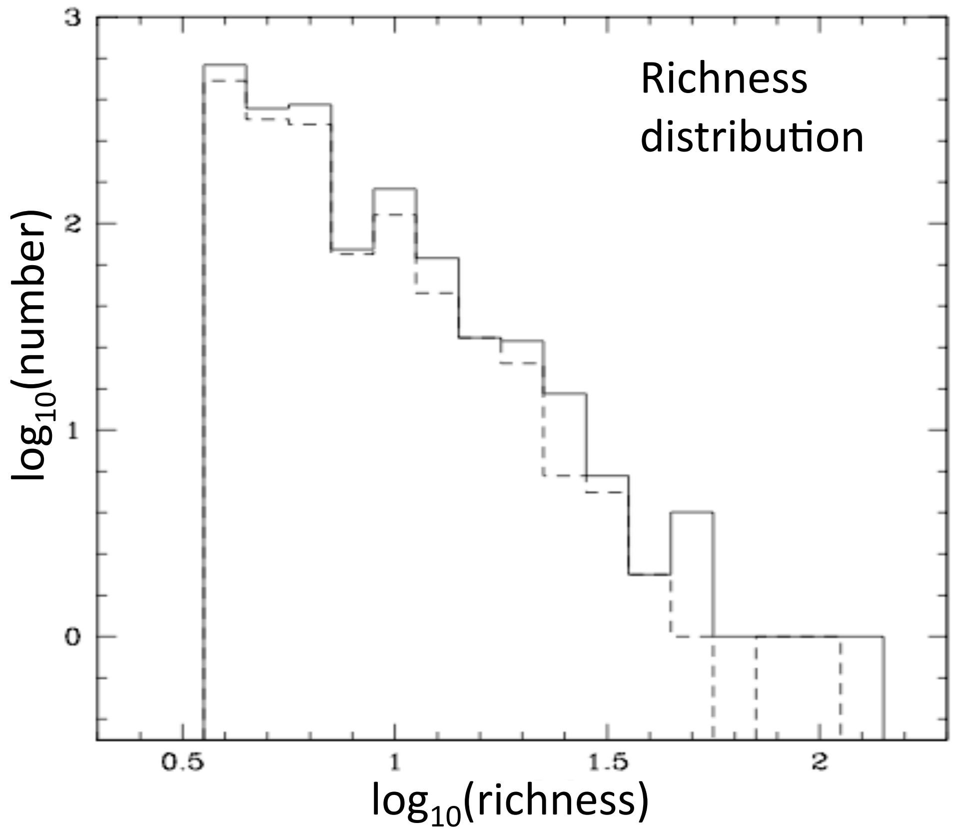


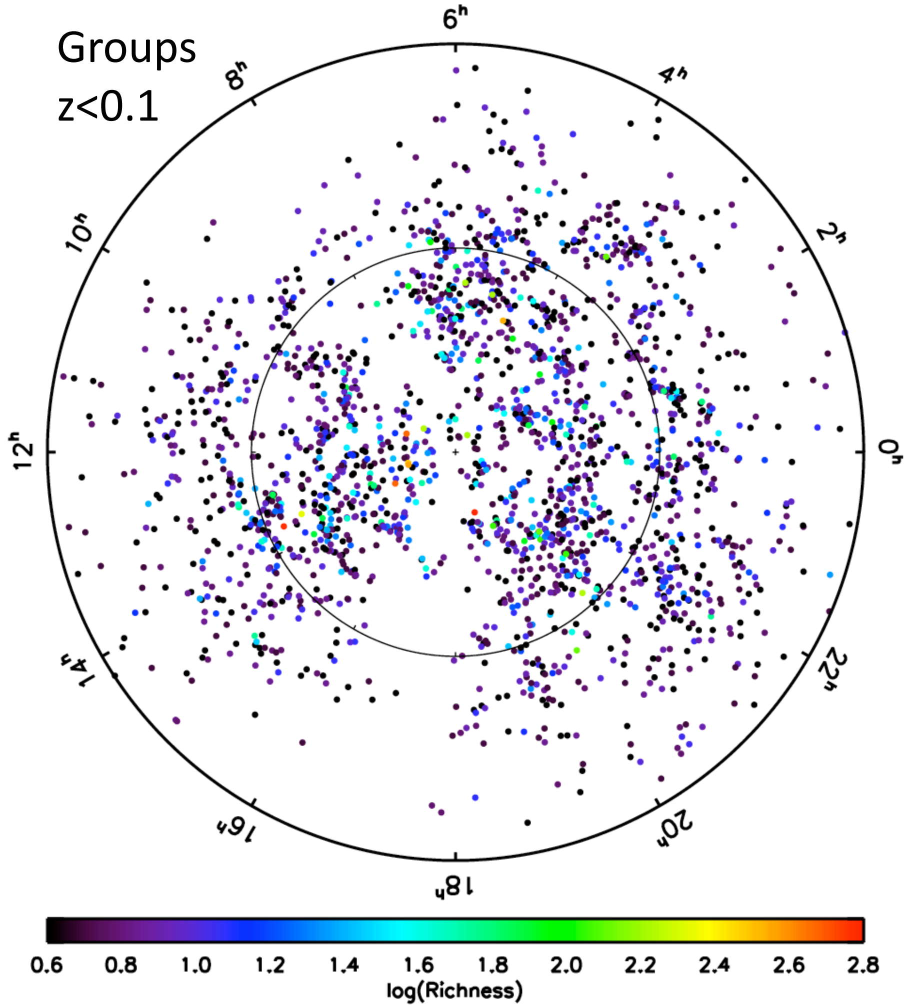
Environment (galaxy density and group structure) in the 6dFGS



# Cluster-finding

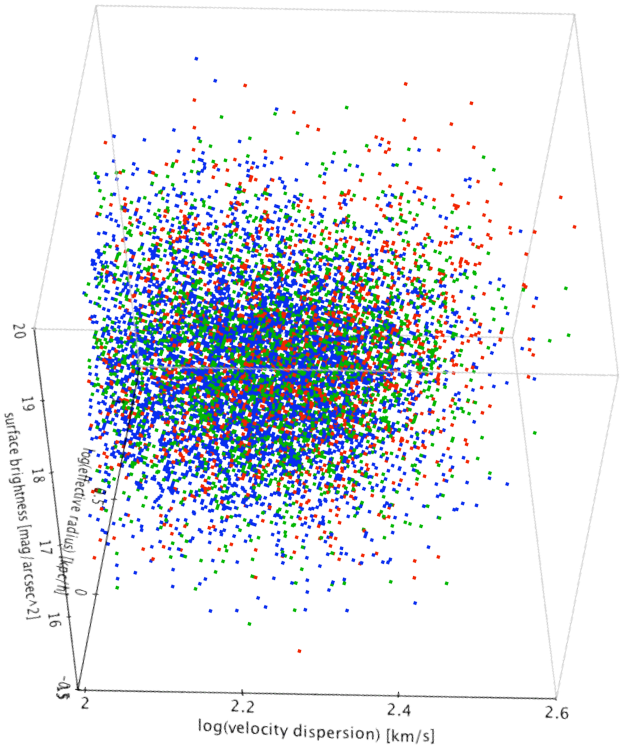
- Applies the percolation based cluster-finding code used to generate the 2PIGG group catalogue in 2dFGRS [Alex Merson]



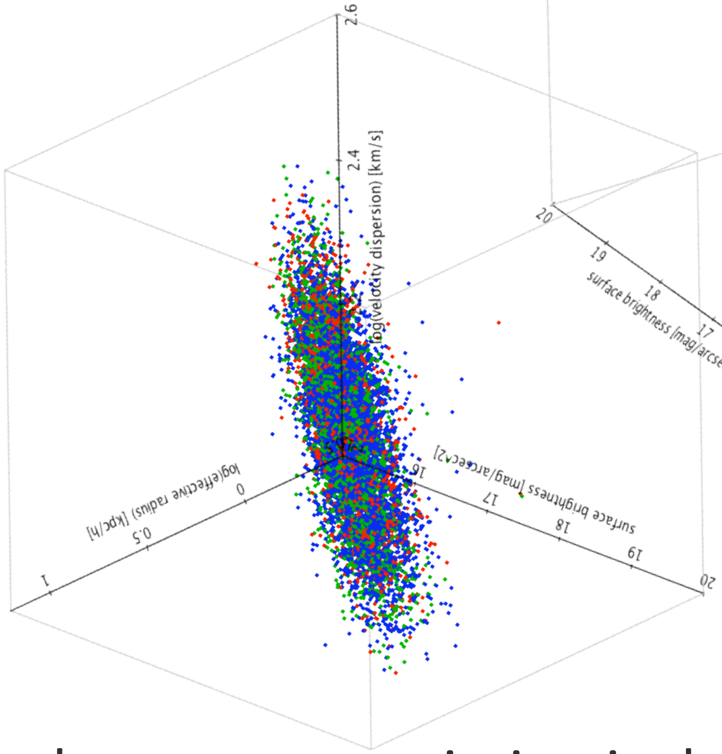



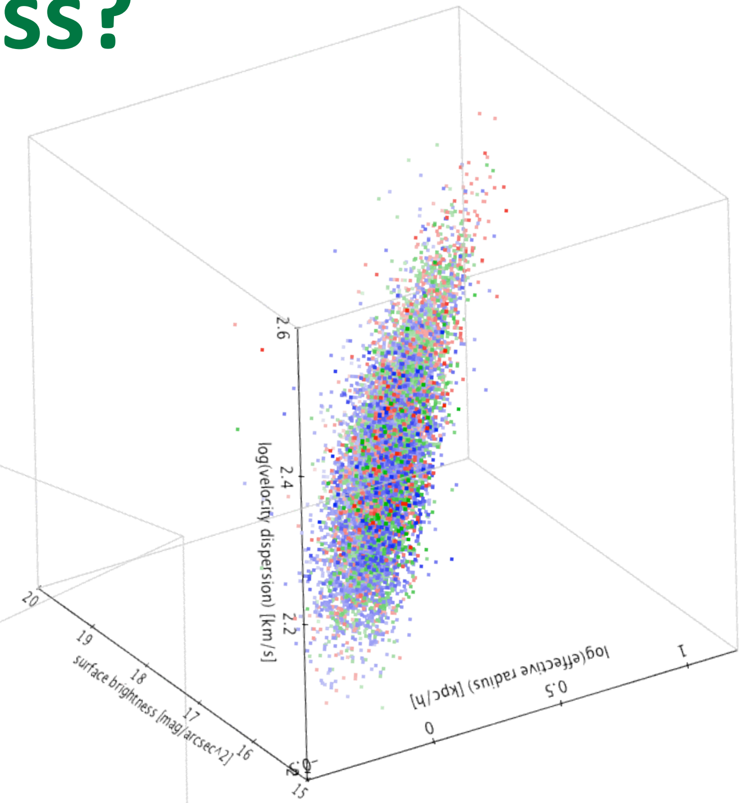

- Algorithm parameters (e.g. linking lengths) are calibrated via simulations to optimise cluster finding in the 6dFGS

# FP variation with richness?



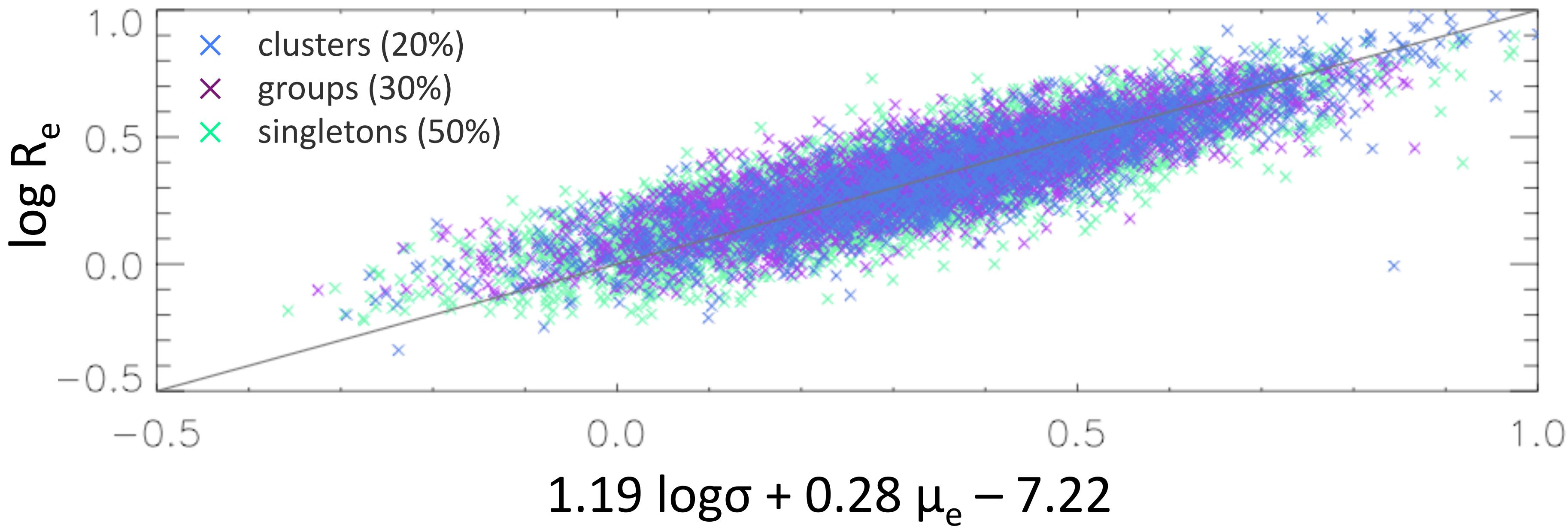

- clusters (top 20%)
- groups (mid 30%)
- singletons (50%)




- <u>Within</u> the FP, the only apparent variation is that the biggest and most massive galaxies are in the richest clusters

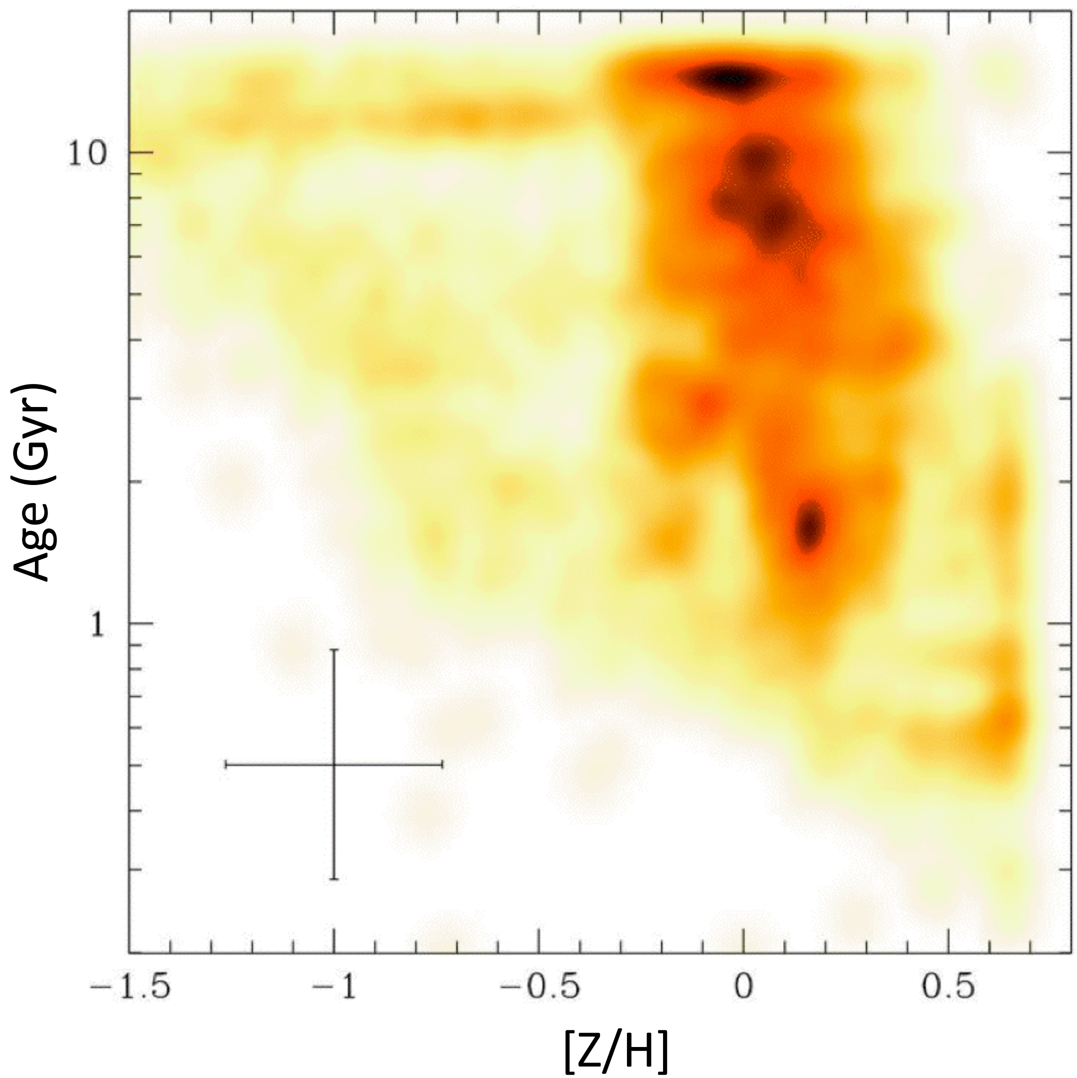
# FP variation with richness?




- In terms of the fitted parameters of the FP itself, there appears to be no significant variation over the whole range in richness
- Next step: break these samples down further into age subsets, as there is evidence that age correlates with deviations from the FP (e.g. Graves et al. astro-ph/0903.3603)

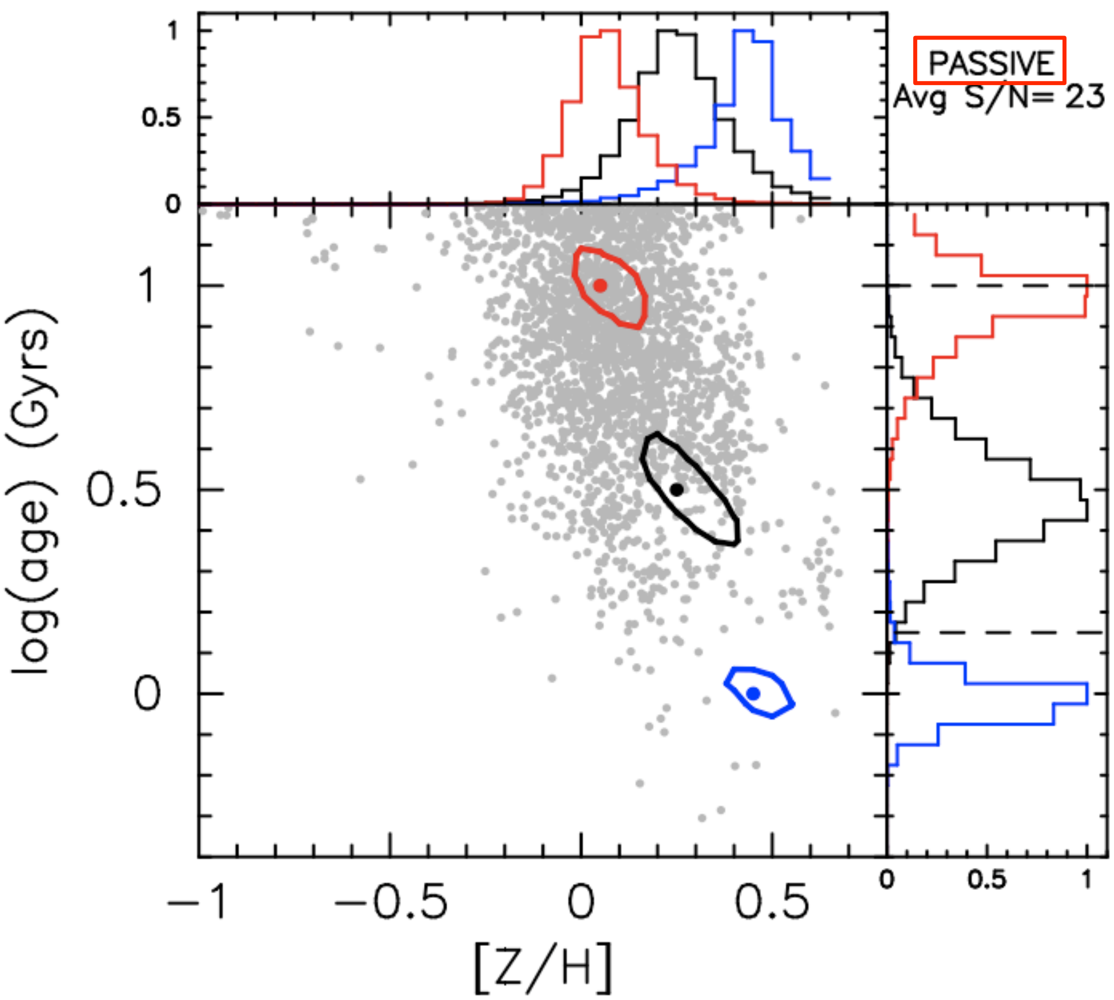
# Galaxy ages and metallicities

- For the 7000 DR2 galaxies there are Lick indices giving ages, metallicities and α-enhancements (based on fits to Thomas & Maraston SSP models)
- The distribution over age and metallicity shows…
  - Most galaxies have –0.2<[Z/H]<0.3
  - The youngest galaxies have higher minimum metallicities
  - The least metal-rich galaxies have older minimum ages

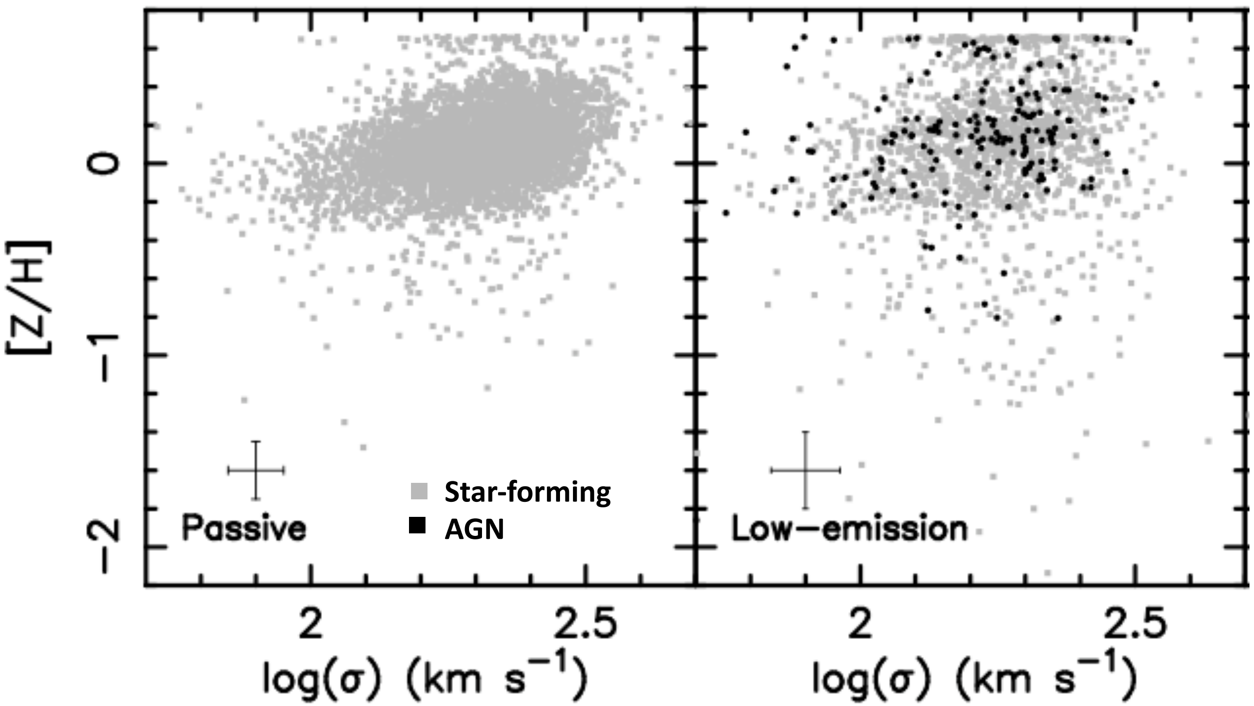


# Real effect or residual degeneracy?

- Estimate residual degeneracy using $10^6$ Monte-Carlo realisations of best-fit models with actual observed errors
- Residual degeneracy is present, but is much smaller than the age-metallicity trend that is observed
- The old passive galaxies used in the following analysis are clearly distinguished from their younger counterparts



# Metallicity and velocity dispersion

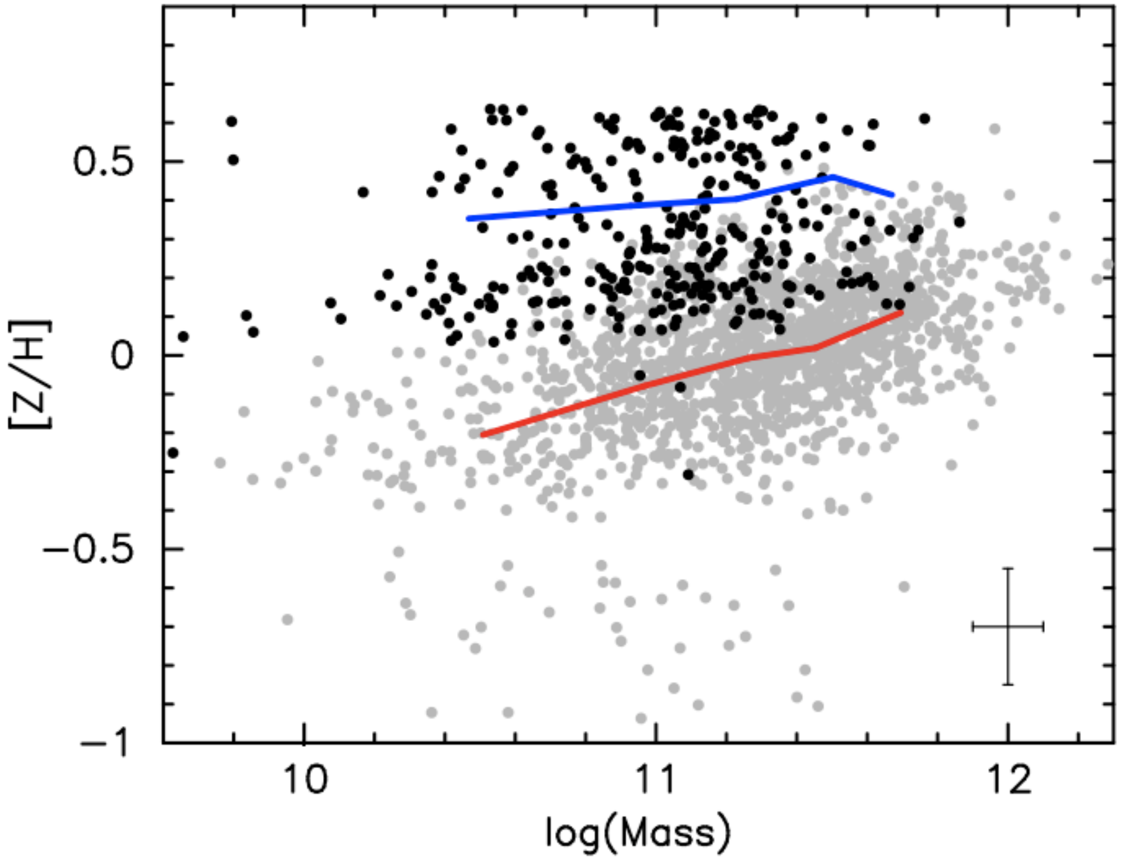



- Well-known strong correlation of increasing metallicity with increasing velocity dispersion for both passive galaxies and low-emission galaxies
- The age of the stellar populations shows a weaker correlation with velocity dispersion

# Mass-metallicity relations

- Metallicity versus dynamical mass…
  - >10 Gyr = grey
  - <1.5 Gyr = black

- Galaxies with old populations show strong correlation of mass and metallicity (projection of joint age–[Z/H]–σ relation), young galaxies do not




- N.B. 6dFGS spectra (and hence the estimated ages & metallicities) are 'central' rather than 'integrated' or 'total'

# The tilt of the Fundamental Plane

- The Virial Theorem predicts

$$\log r = 2 \log \sigma - \log \langle I \rangle + \text{constant}$$

where r = effective radius, $\sigma$ = velocity dispersion, $\langle I \rangle$ = mean S.B., and where it is assumed that M/L = constant ($M \propto \sigma^2 r$)

- Observations in the K band give

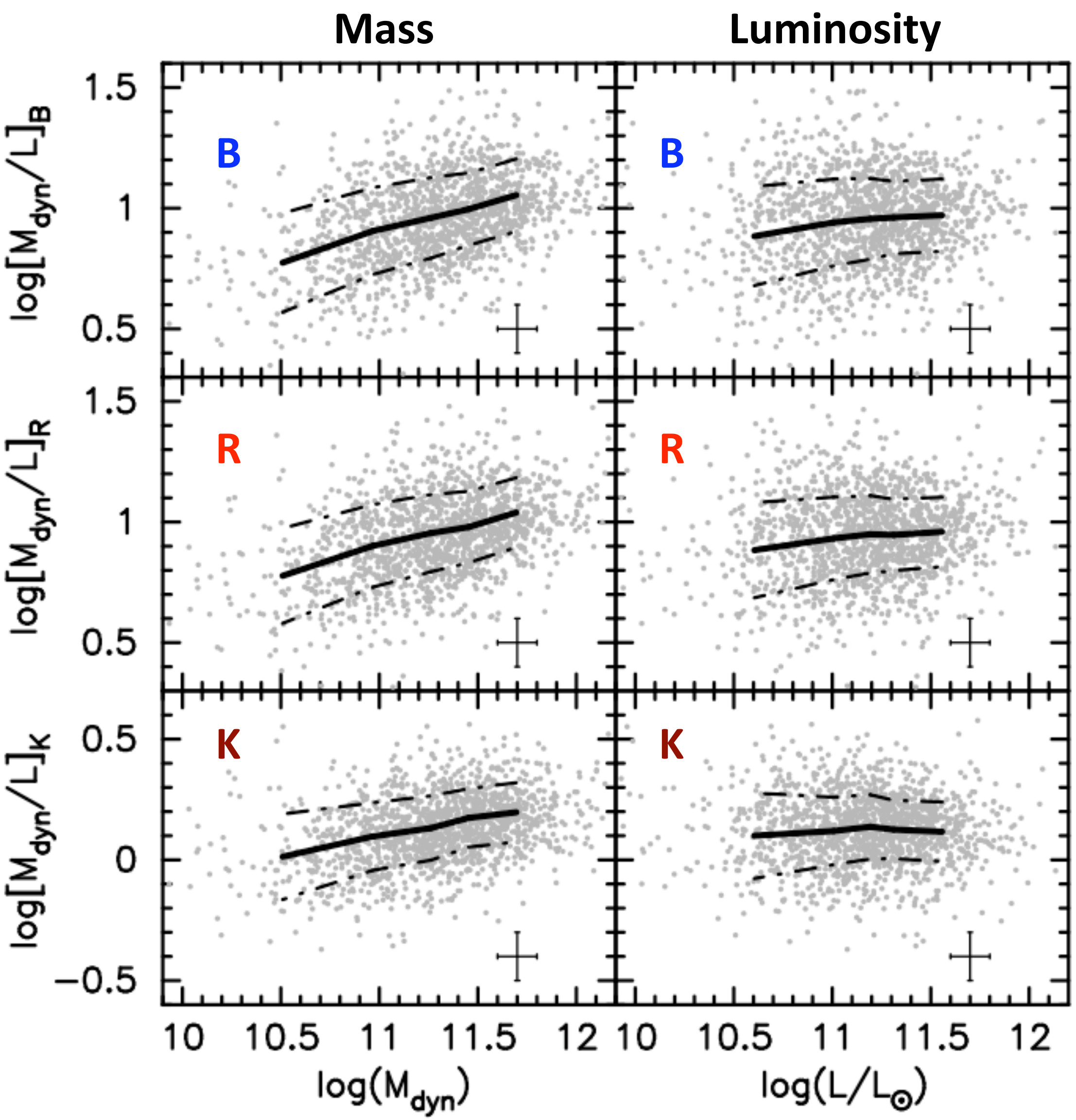
$$\log r = 1.45 \log \sigma - 0.85 \log \langle I \rangle + \text{constant} \quad (\text{scatter} \approx 15\text{-}20\%)$$

implying a 'tilt' relative to the virial FP corres. to $M/L \propto M^{0.15}$; this 'tilt' increases when the FP is measured in bluer bands

- The tilt in the FP could be produced by…
  - Trend in $M_{star}/M_{dark}$ due to variations with galaxy mass of the gas-to-star conversion efficiency, or the IMF, or the DM content
  - Non-homology due to varying 'concentration' with galaxy mass
- However, age and metallicity effects complicate interpretation

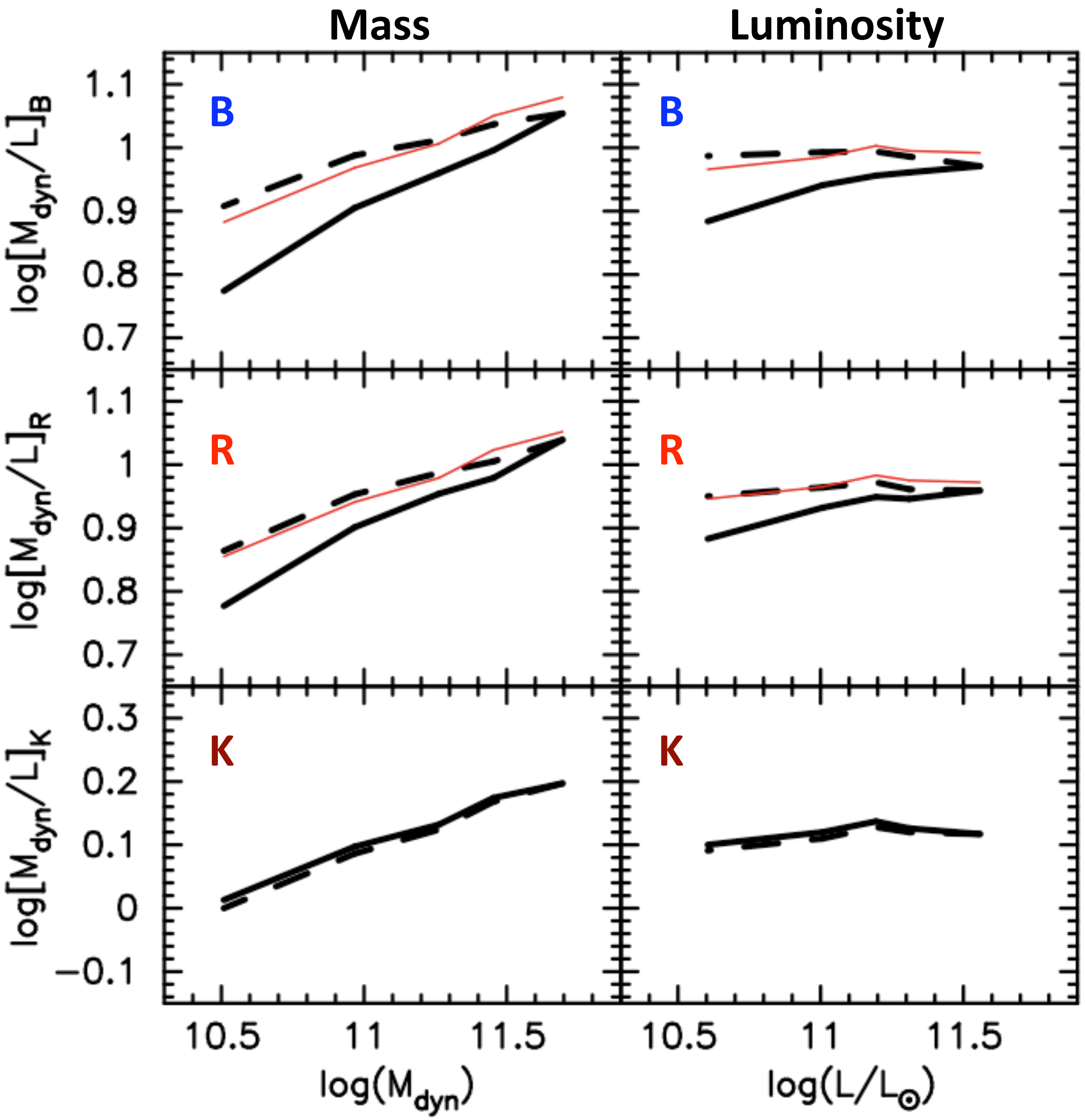
# M/L vs M for old galaxies

- Consider only old (>10 Gyr) galaxies and so eliminate age effects
- There is a trend in M/L with M, as suggested by FP fit
- The trend is steeper in bluer passbands
- The trend of M/L with luminosity is weaker than the trend with mass



# Allowing for metallicity (or $M/M_\star$ vs M)

- Use Bruzual & Charlot (2003) models to adjust the observed slopes (thick lines) for metallicity trend (dashed)
- L at each M is adjusted to corresponding L at a fixed common [Z/H]; this is the same as computing $M/M_\star$
- Slope of M/L (or $M/M_\star$) with M or L (thin red line) is now <u>identical</u> at all λ
- Conclusion: for <u>old</u> galaxies, the variation in the FP with λ is entirely explained by the metallicity-mass relation

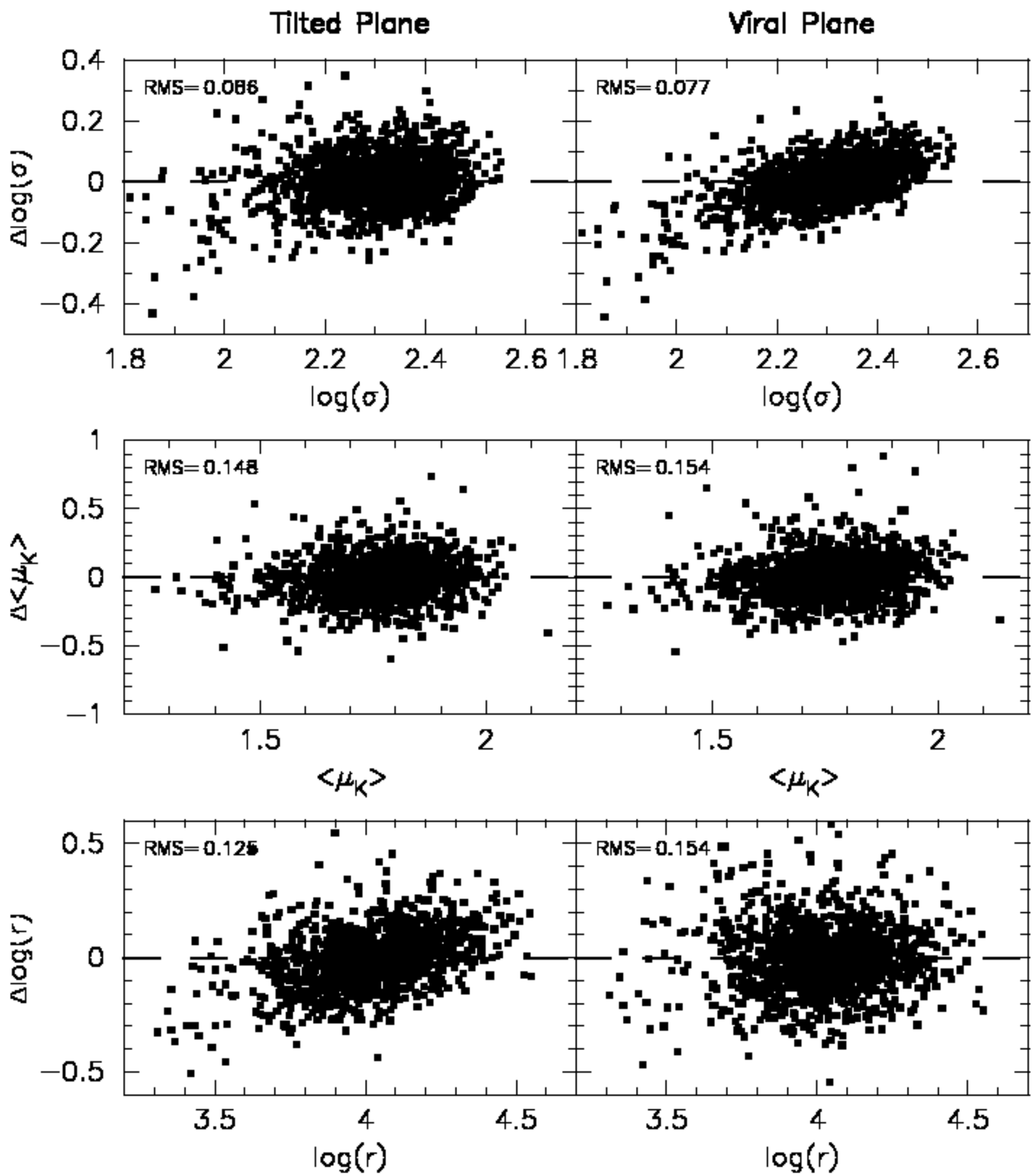


# Conclusions

- 6dFGS is ideal for studying galaxy properties & environment…
  - Provides ~10k early-type galaxies for studying the Fundamental Plane
  - Recover standard NIR FP fit and scatter – also hints of curvature/twisting
- Group/cluster richness has little or no effect on FP…
  - Percolation-based group/cluster catalogue for 6dFGS (like 2PIGG)
  - Fitting to subsamples of isolated/poor group/cluster galaxies shows no evidence of significant variations in the FP
- Mass-metallicity-age relations…
  - There is a <u>strong</u> (weak) mass-metallicity relation in <u>old</u> (young) galaxies
  - This implies an age/metallicity/mass manifold (not simply a plane)
- Mass-to-light ratios for <u>old</u> galaxies…
  - Allowing for mass-metallicity relation, no trend in M/L with either M or L
  - Equivalent to saying that $M/M_\star$ is independent of M and L
  - So star-formation <u>efficiency</u> in old galaxies is independent of halo mass

# Inconsistency?

- Observed variation of adjusted M/L (or $M/M_\star$) with mass: $M/L \propto M^{0.142}$
- But M/L is independent of luminosity, which is odd, as $M/L \propto M^{\alpha} \Rightarrow M/L \propto L^{\beta}$ where $\beta=\alpha/(1-\alpha)$
- So $\alpha = 0.14 \ \Rightarrow \ \beta = 0.17$, whereas we observe $\beta \approx 0$
- To explain this apparent inconsistency we need a more detailed model for the full 3-D distribution in $\log R_e - \log \sigma - \mu_e$ space
- Residuals to both planes show trends, so 'FP' may be curved or twisted



# 6dFGS web pages - http://www.aao.gov.au/6dFGS