Structure, dynamics and stellar populations in early-type galaxies

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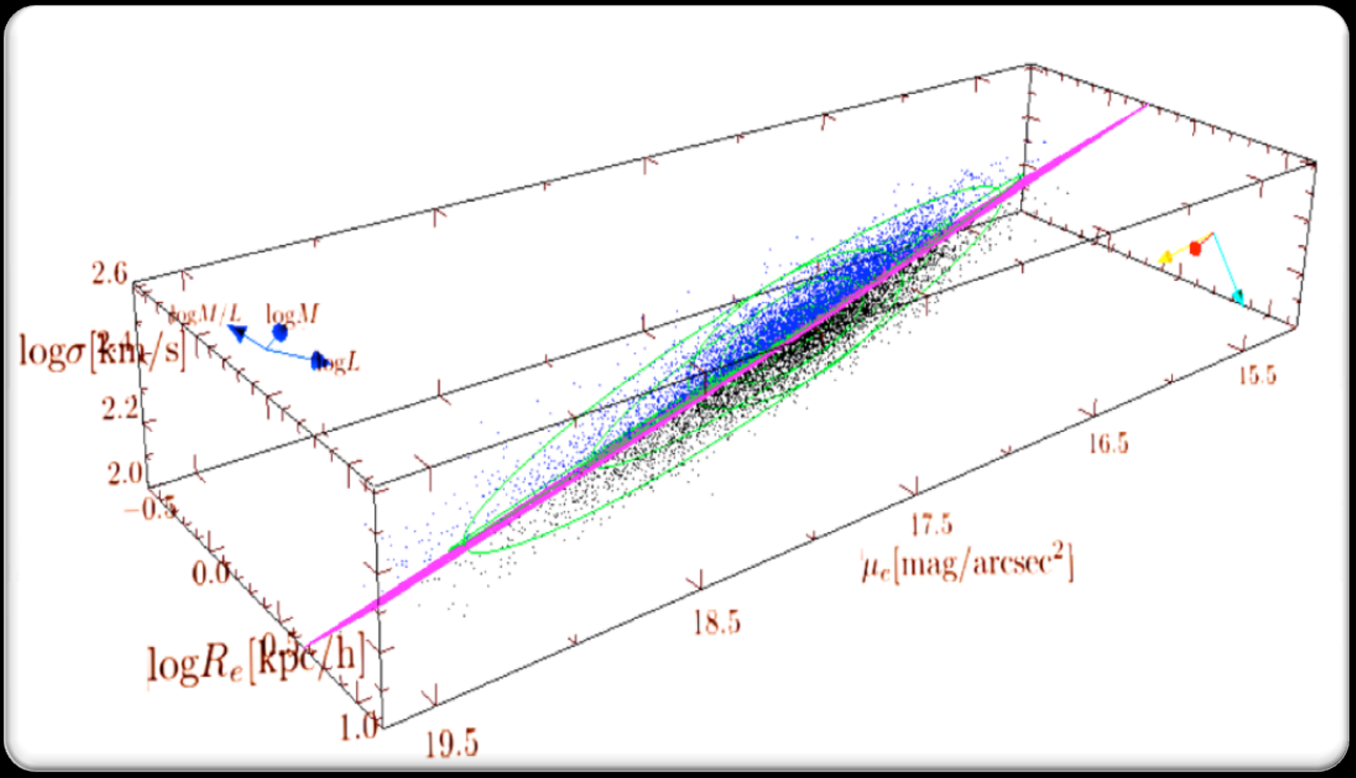

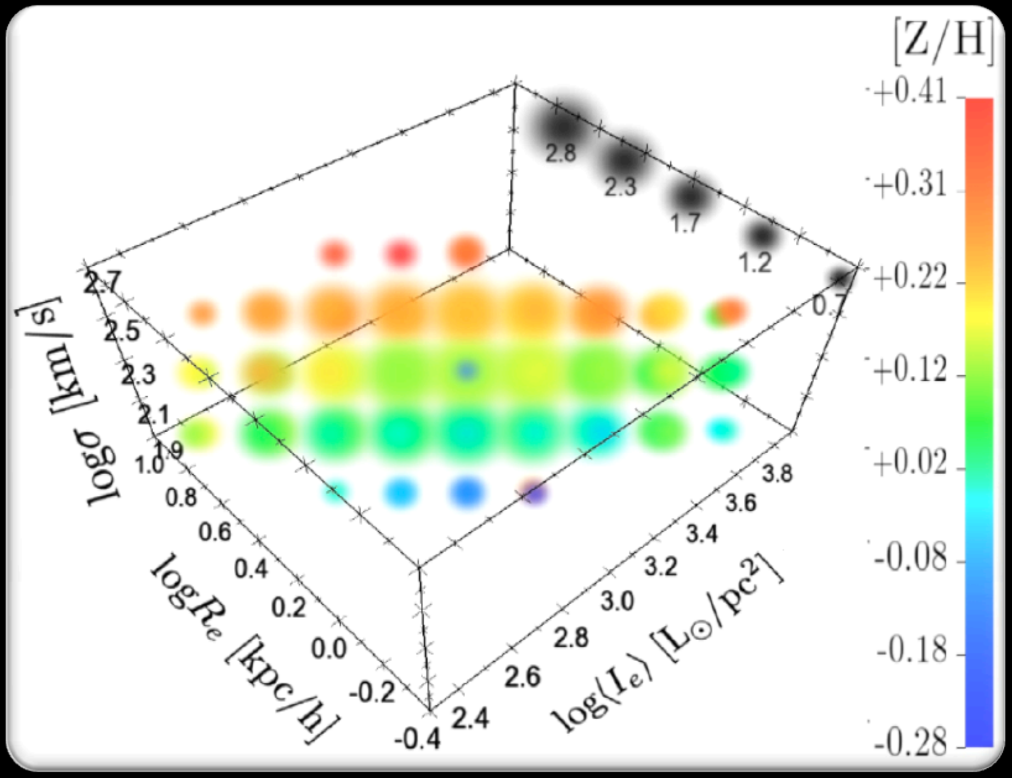

Galaxy Formation, Durham, 20 July 2011

Australian Government
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Motivation and outline

- The Fundamental Plane (FP) relates the dynamical and structural properties of early-type (i.e. bulge-dominated) galaxies

- Stellar population variations can cause scatter about the FP, obscuring these relations and limiting the use of the FP as a distance estimator

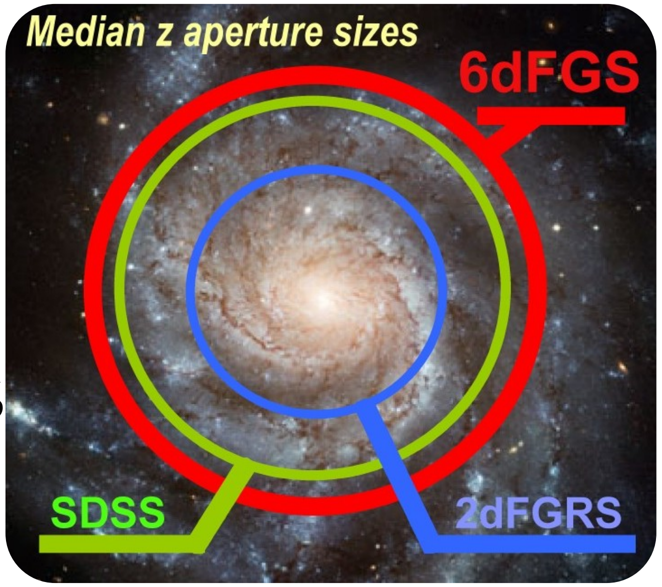
- Conversely, trends in the FP with stellar population can reveal clues linking the *structural* & *stellar* assembly histories of early-type galaxies

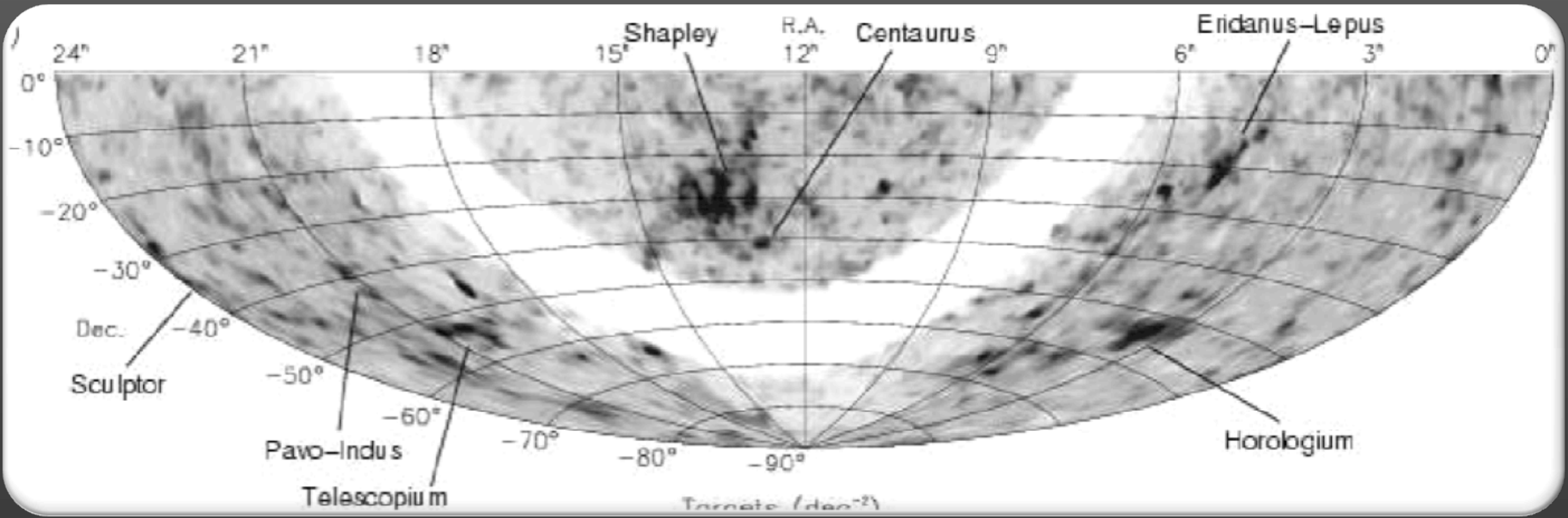
- We explore these issues with the 6dF Galaxy Survey, which measures FP and stellar population parameters for large NIR-selected samples

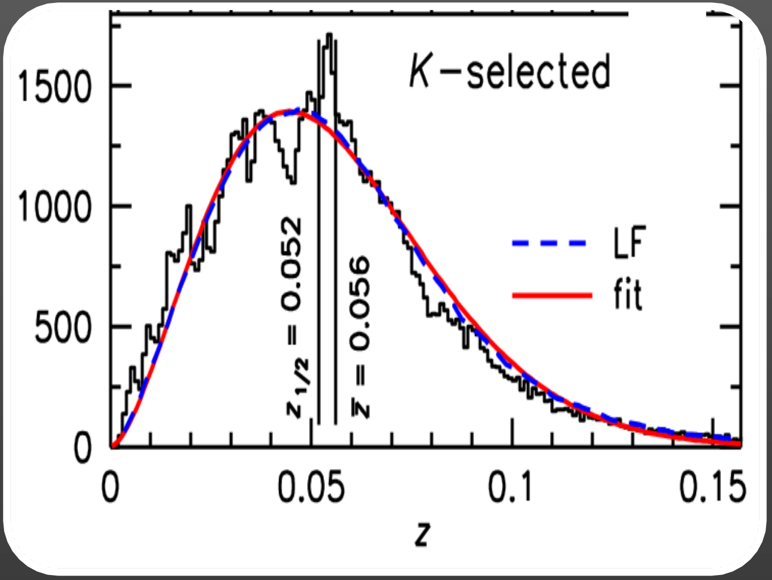
- We determine the variations in stellar populations in FP space, and examine: (i) the implications for the merger histories of galaxies; (ii) whether SP trends drive FP variations with galaxy morphology & cluster richness; & (iii) prospects for improving FP distance estimates

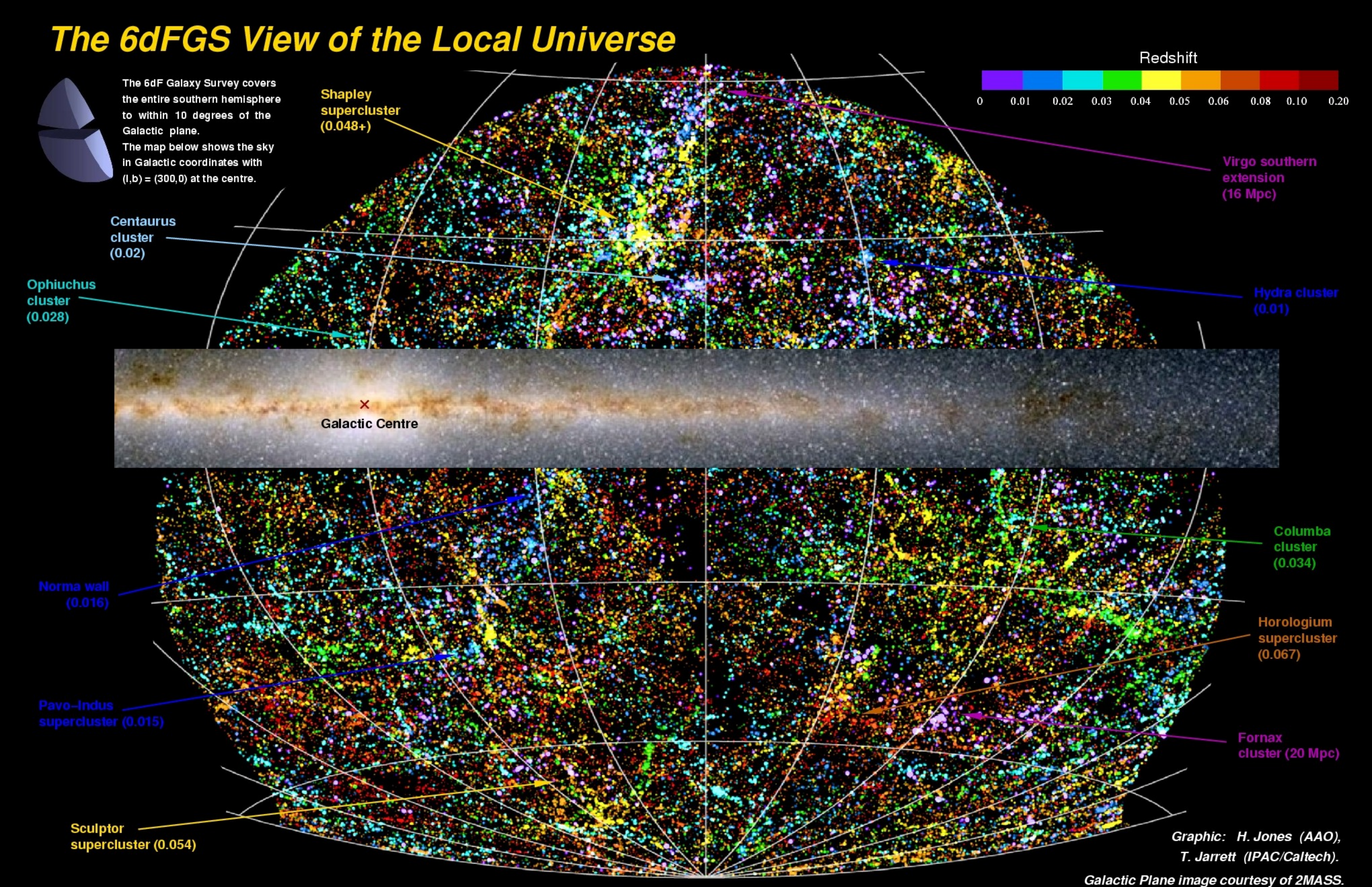
The 6dF Galaxy Survey – a brief introduction

- NIR-selected using 2MASS down to K = 12.65
- *z*-survey: 137000 spectra and 125000 redshifts
- *v*-survey: 10000 FP peculiar velocities; also ages, metallicities and [α/Fe] for 7000 galaxies
- 17000 deg^2 (δ<0°,|b|>10°) to <cz>≈16500 km/s
- Fibre aperture = 6.7 arcsec ≈ 7 kpc at <cz>









Beutler et al., *6dFGS: Baryon Acoustic Oscillations & the Local Hubble Constant,* astro-ph/1106.3366

The 6dF Galaxy Survey: The Fundamental Plane of Early-Type Galaxies

[*in prep.*]

Christina Magoulas[1], Christopher M. Springob[2], Matthew Colless[2], D. Heath Jones[2,3], Lachlan Campbell[4], John Lucey[5]

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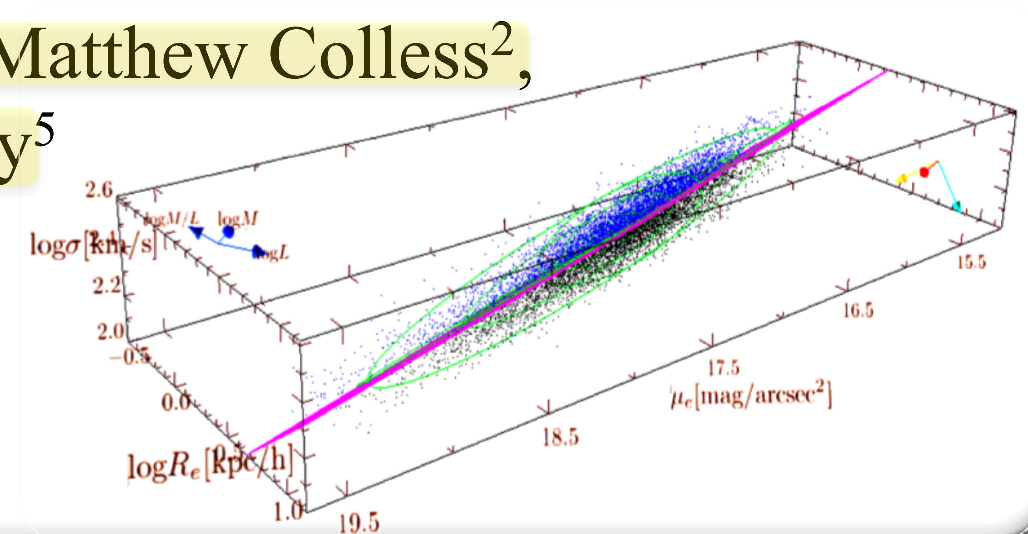

Stellar Population Trends Across and Through the 6dFGS Fundamental Plane

[*submitted*]

Christopher M. Springob[1], Christina Magoulas[2], Rob Proctor[3], Matthew Colless[1], D. Heath Jones[1,4], Chiaki Kobayashi[5], Lachlan Campbell[5,6], John Lucey[7], & Jeremy R. Mould[2,8]

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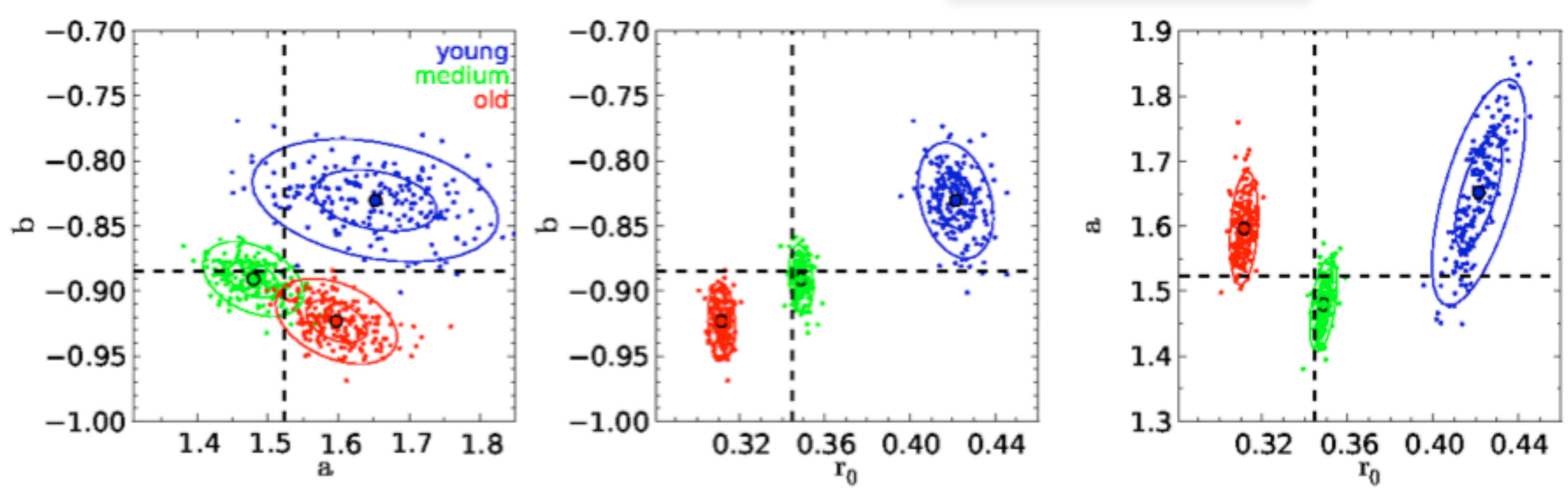

The 6dF Galaxy Survey: The Fundamental Plane of Early-Type Galaxies

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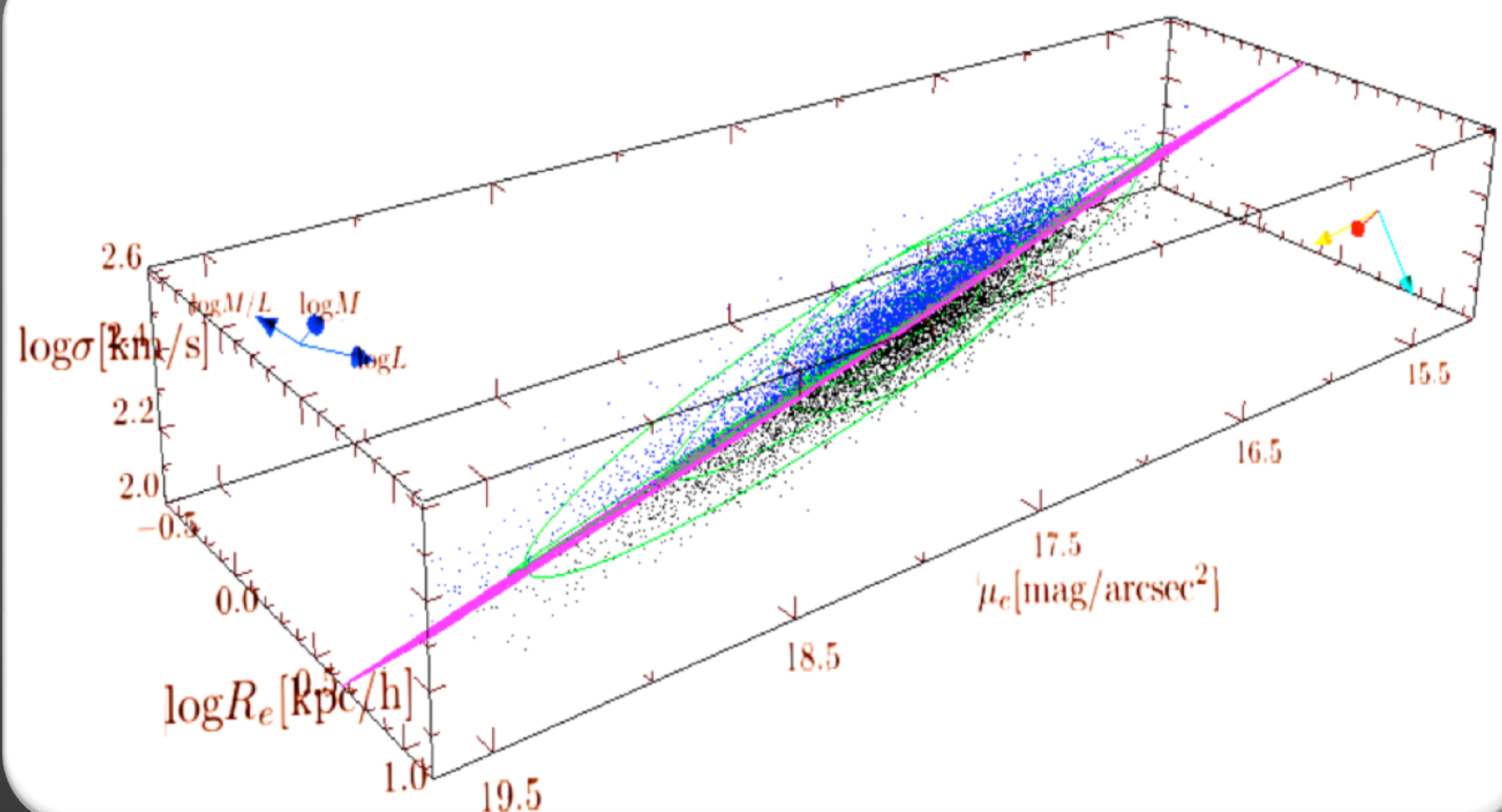
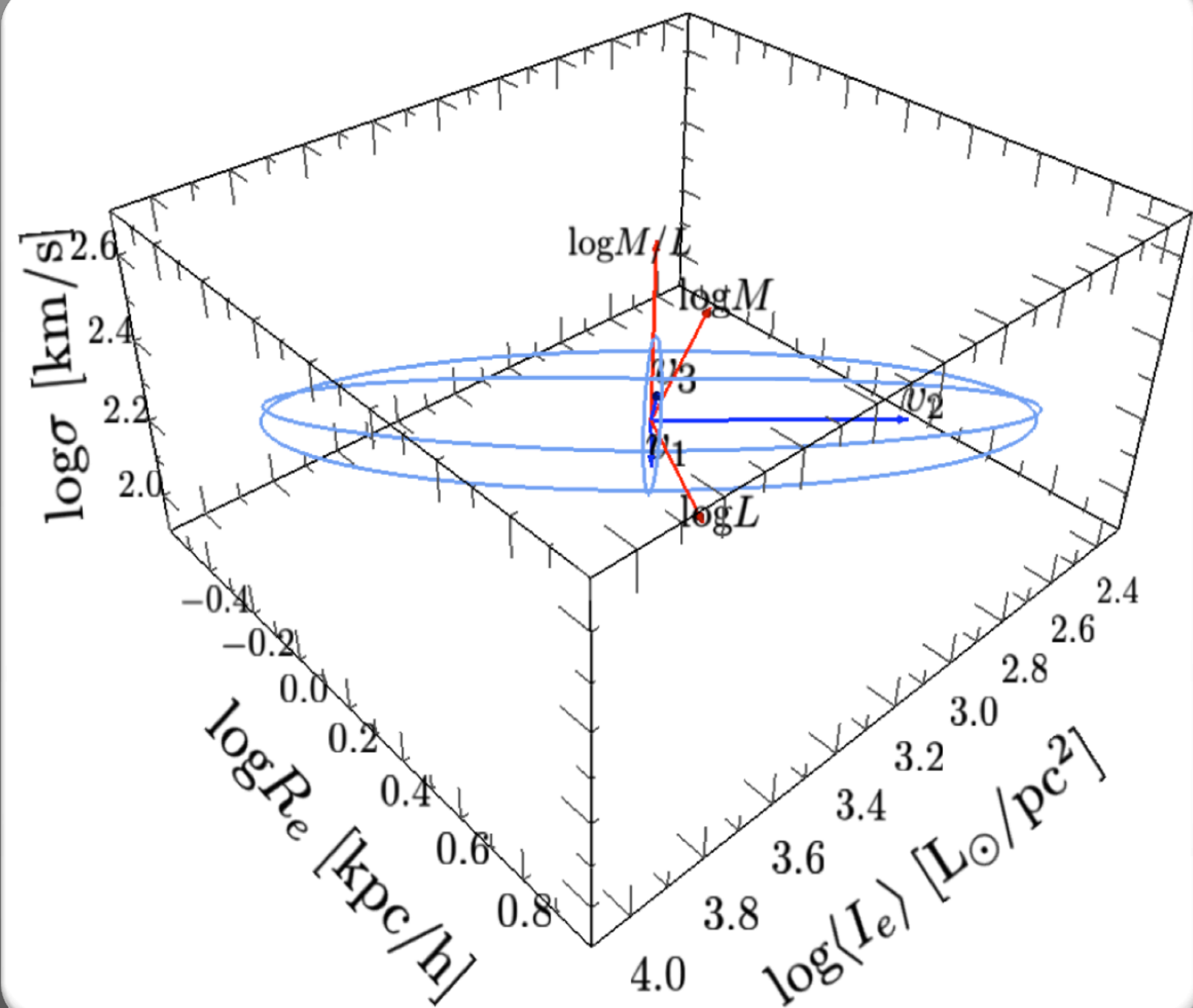
Fit the Fundamental Plane as 3D Gaussian distribution using maximum likelihood.

Study variations in the NIR Fundamental Plane with wavelength, morphology and group/cluster richness.



Principal axes of the 3D Gaussian Fundamental Plane with respect to the observed parameters

$r \equiv \log R_e, s \equiv \log \sigma, i \equiv \log \langle I \rangle_e$



Axis of 3D Gaussian		r	s	i
v_1	short axis = *through*	0.494	-0.752	0.437
v_2	long axis = *along*	0.663	0.000	-0.749
v_3	medium axis = *across*	0.563	0.659	0.498

$-v_1$ is ~mass-to-light ratio:

$$\log(M/L) = (r+2s) - (i+2r) = -r+2s-i$$

cf. $-v1 = 1.13r - 1.72s - I$

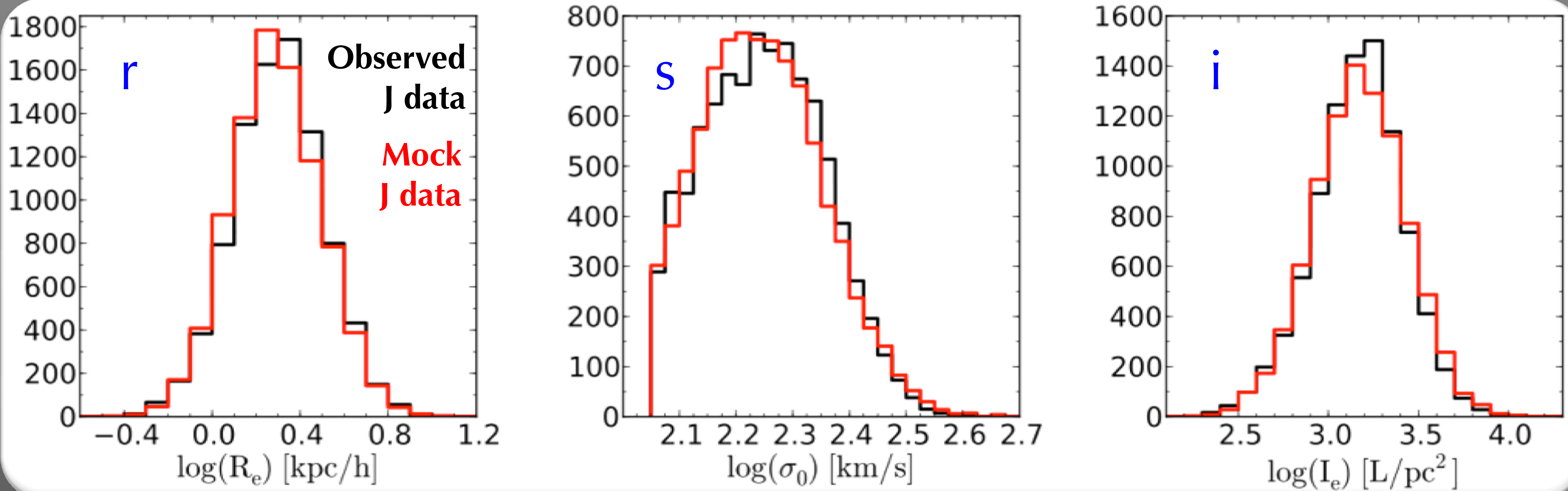
$-v_2$ is ~luminosity density:

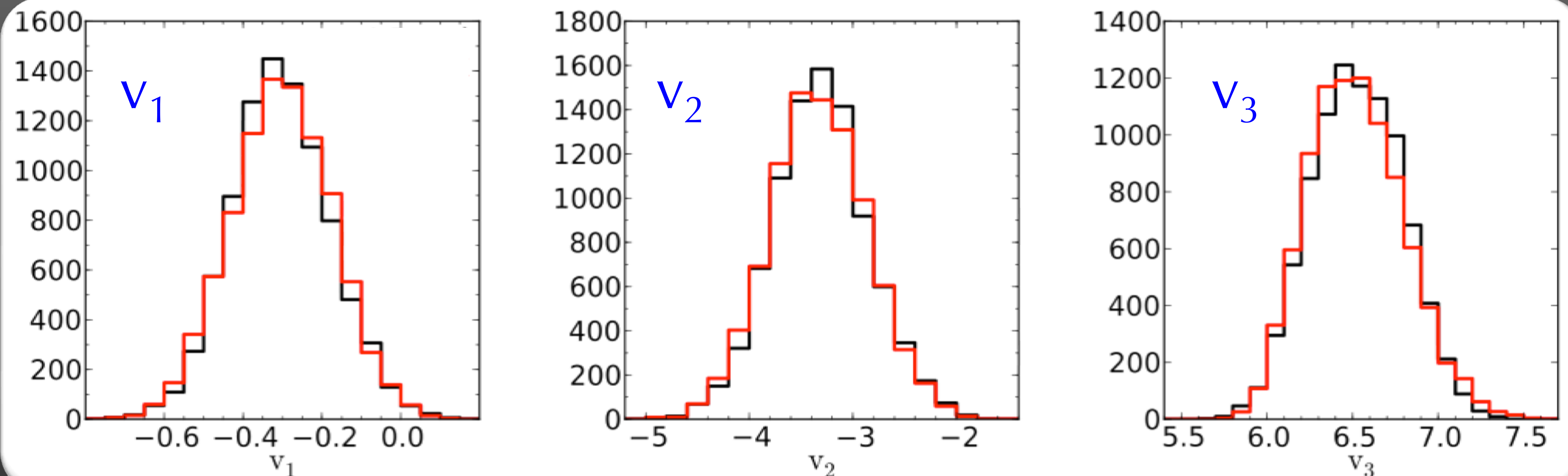
$$\log(L/R^3) = (i+2r) - (3r) = i-r$$

cf. $-v2 = i - 0.89r$

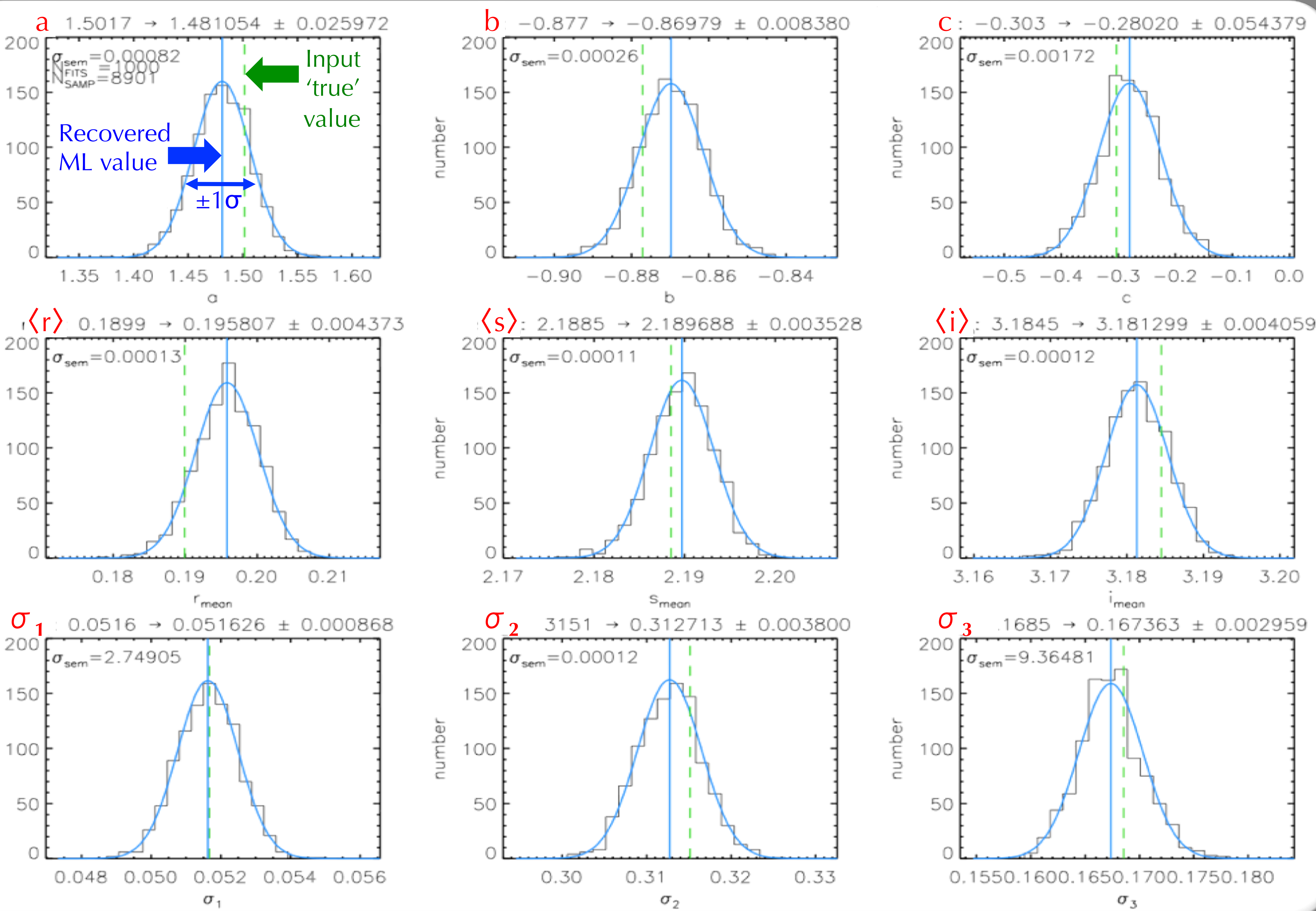
$-v_3$ is not special physically

A 3D Gaussian distribution is found, empirically, to be an excellent fit to the observed *bright end* (σ > 100 km/s) of the NIR Fundamental Plane



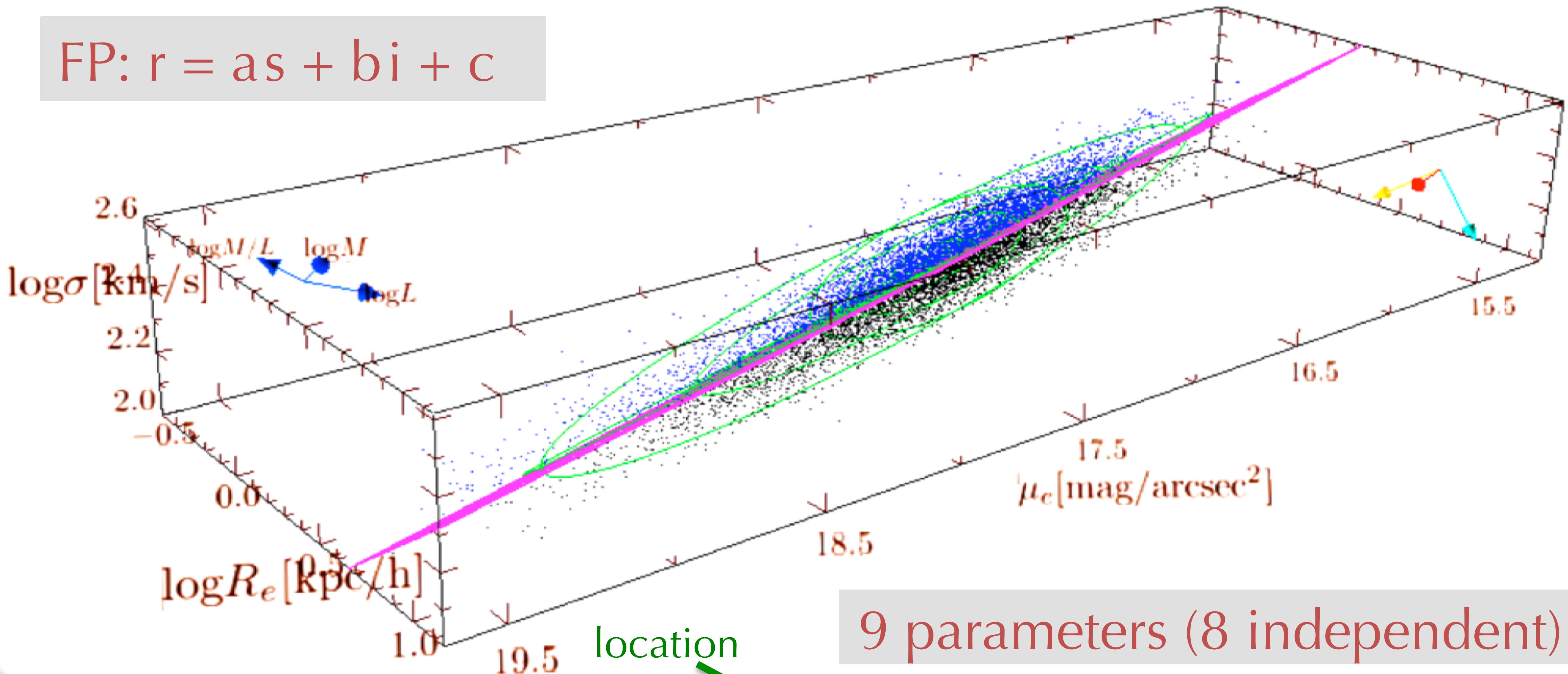


ML method recovers mock FP accurately and precisely



The J-band Fundamental Plane for 8901 early-type galaxies

FP: r = as + bi + c



9 parameters (8 independent)

N_g	a	b	c	$\bar{r}$	$\bar{s}$	$\bar{i}$	σ_1	σ_2	σ_3	σ_r
8,901	1.502	-0.877	-0.303	0.190	2.189	3.185	0.0517	0.3151	0.1686	0.13
	da	db	dc	$d\bar{r}$	$d\bar{s}$	$d\bar{i}$	$d\sigma_1$	$d\sigma_2$	$d\sigma_3$	
	0.026	0.008	0.054	0.004	0.003	0.004	0.0009	0.0038	0.0029	

slope & offset (a, b, c) — location ($\bar{r}$, $\bar{s}$, $\bar{i}$) — scatter (σ_1, σ_2, σ_3)

Stellar Population Trends Across and Through the 6dFGS Fundamental Plane

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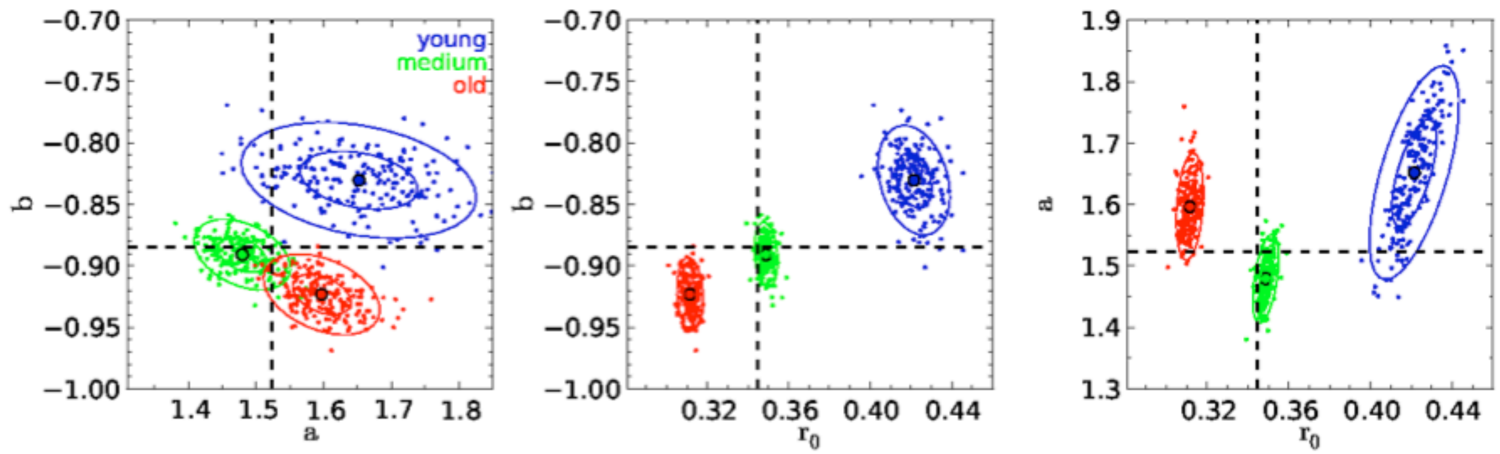


[1] Stellar population parameters (age, metallicity, [α/Fe]) for 7143 galaxies with FP parameters

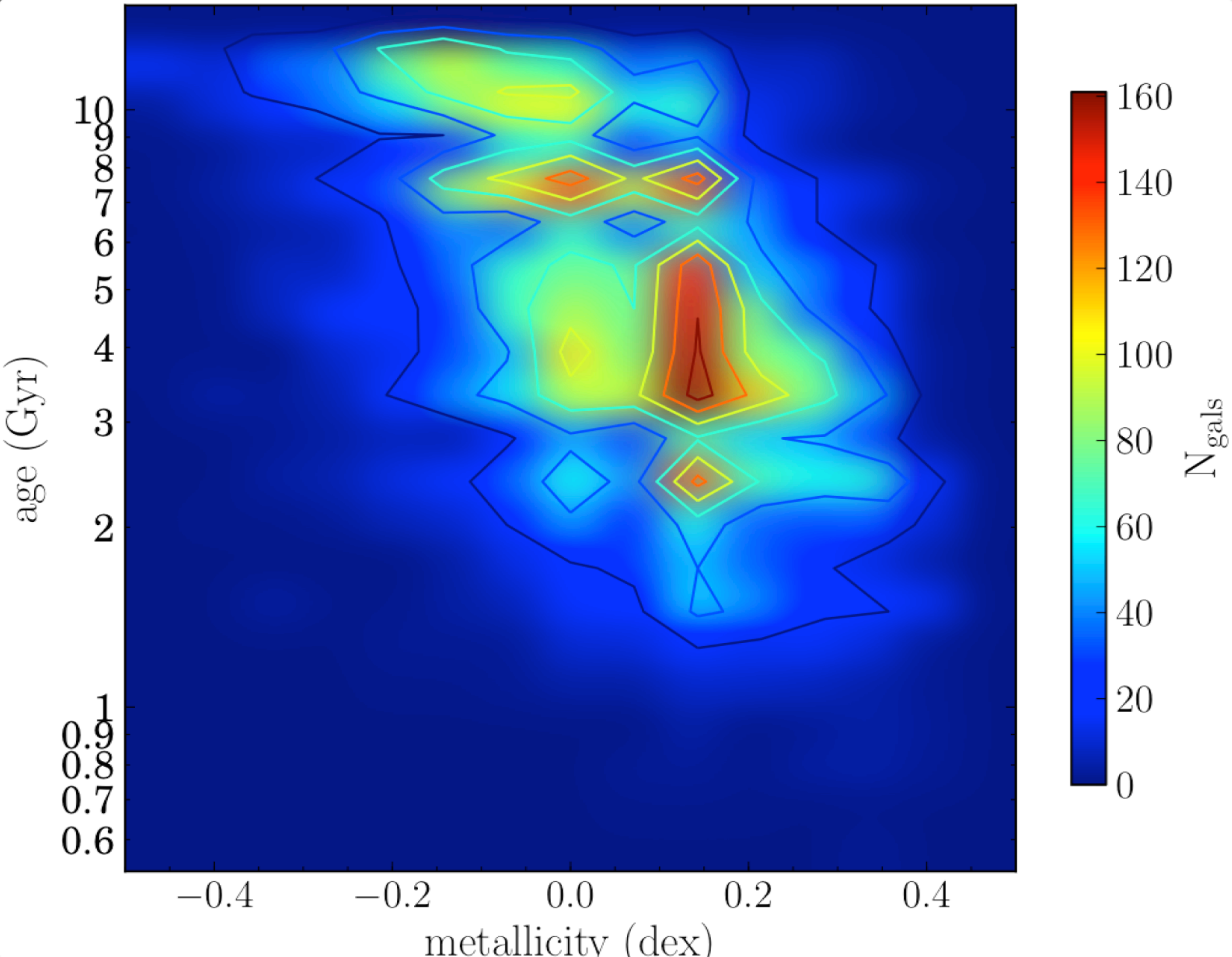
[3] SP parameters vary with v_1 (*through* FP) and v_3 (*across* FP), but not with v_2 (*along* FP ~ L/R_e^3)

[2] Derive directional derivatives of SP parameters in FP space; find variations with all of σ, R_e, I_e & δ_{FP}

[4] Relate this result to merger histories: lower luminosity densities ⇒ more mergers

[5] Can (some of) these trends be used to reduce the scatter in the FP?

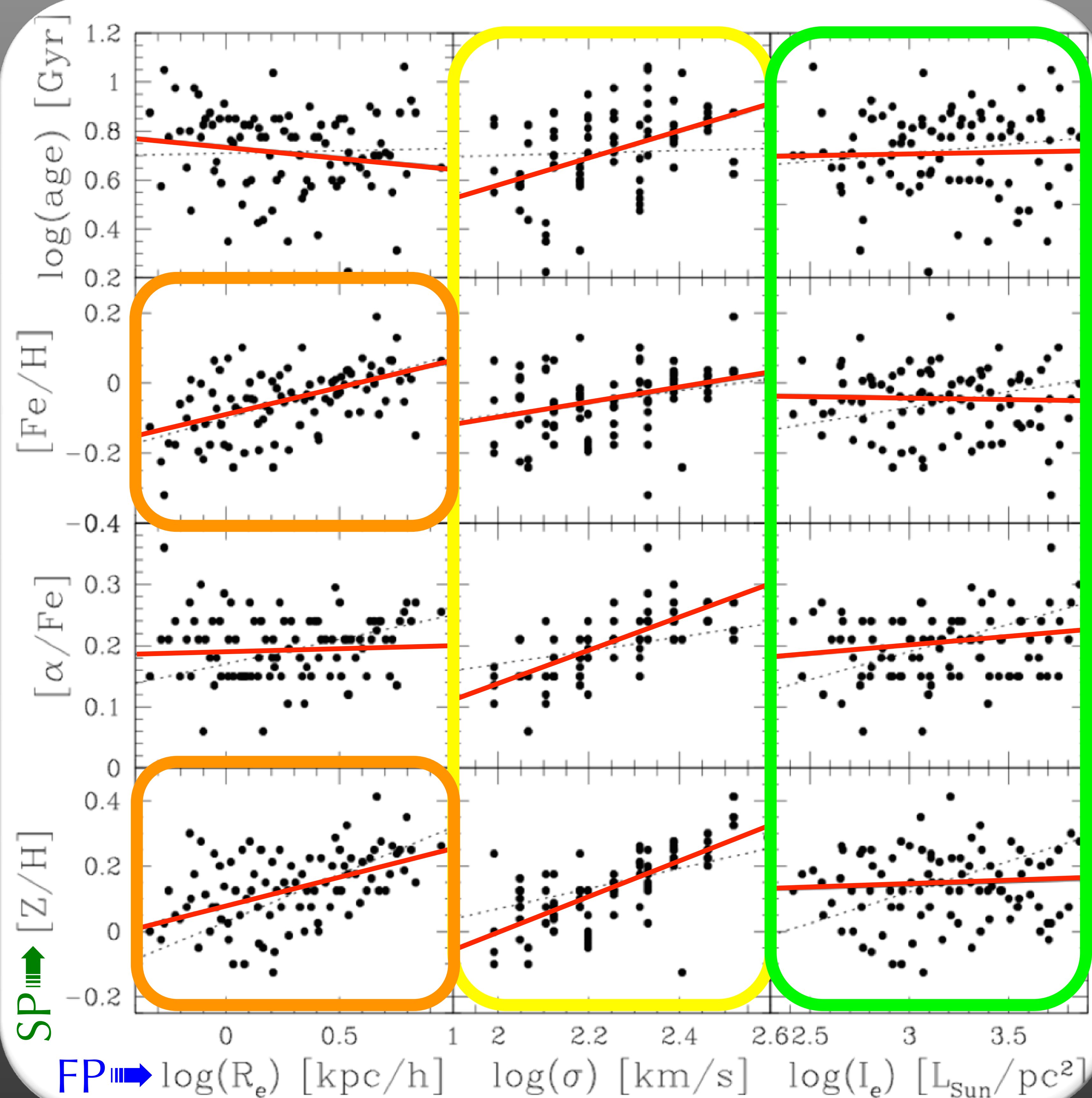
Age-metallicity distribution for 7143 early-type galaxies



Pair-wise correlations between stellar population parameters and Fundamental Plane parameters

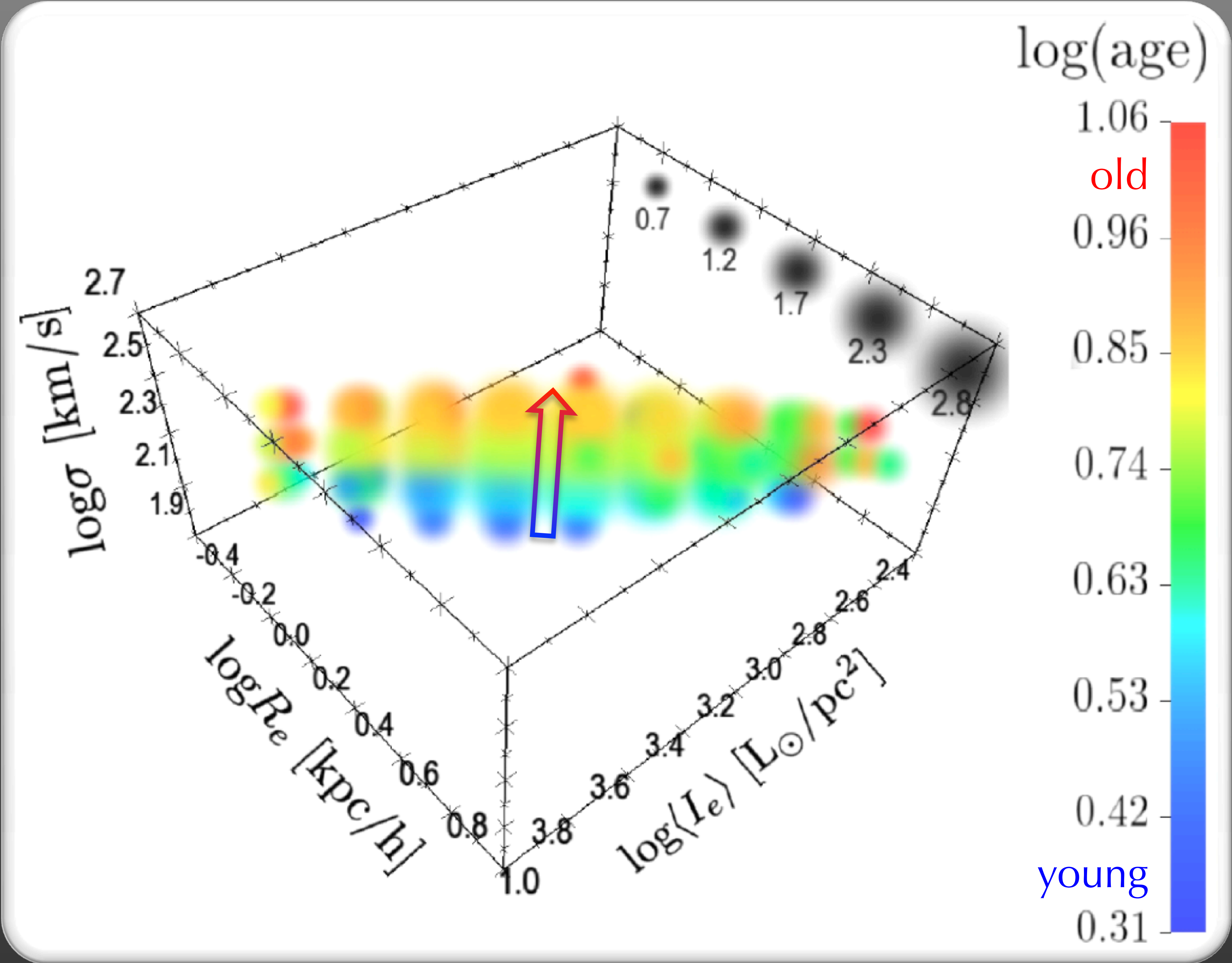
Correlations (in red) are consistent with well-known trends:

- All SP's show clear trends with log σ
- Metallicity shows trends with log R_e
- There are weak or no trends with log I_e



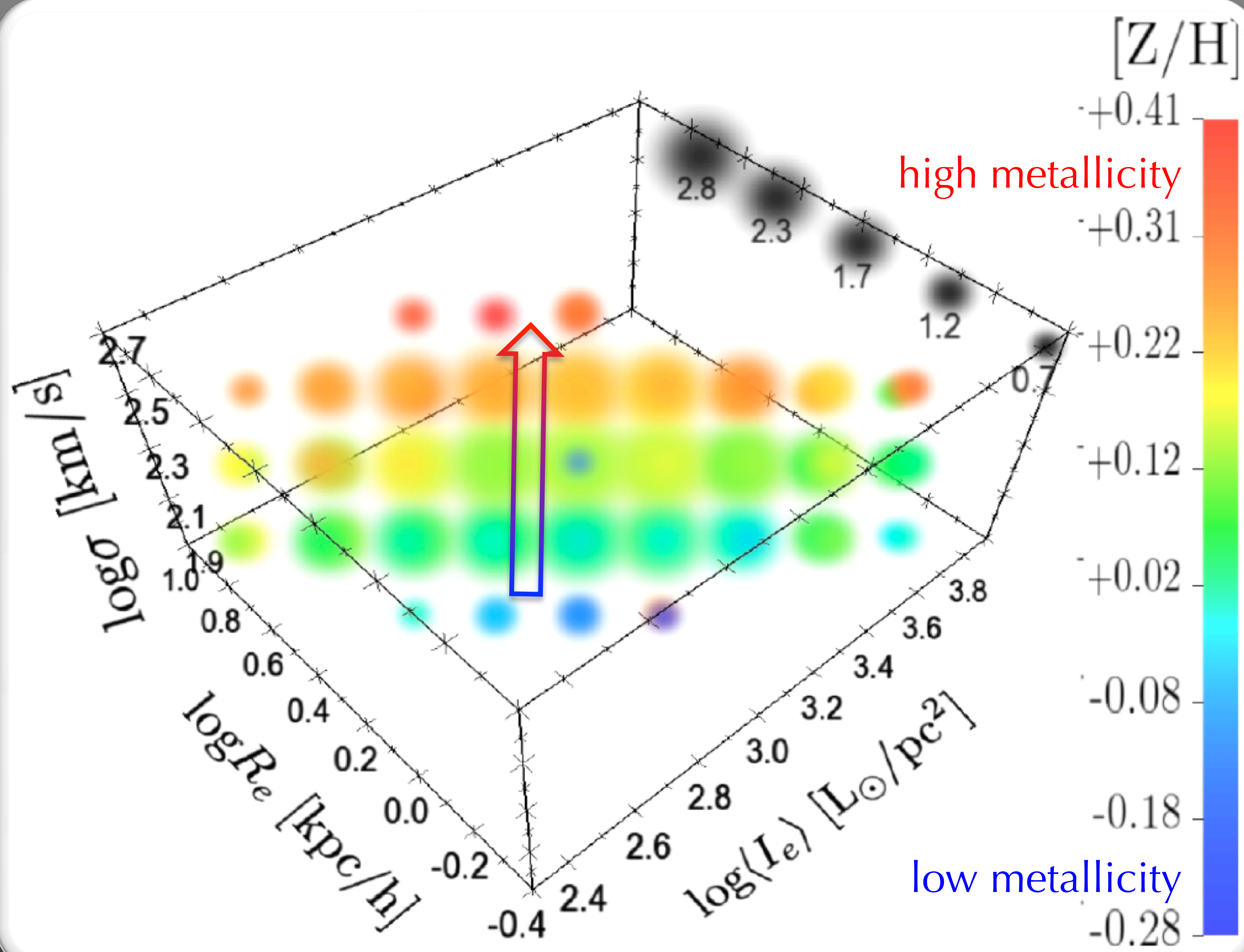
Age trend in the Fundamental Plane

The variation in age is mainly *through* the FP (i.e. in v_1 direction)



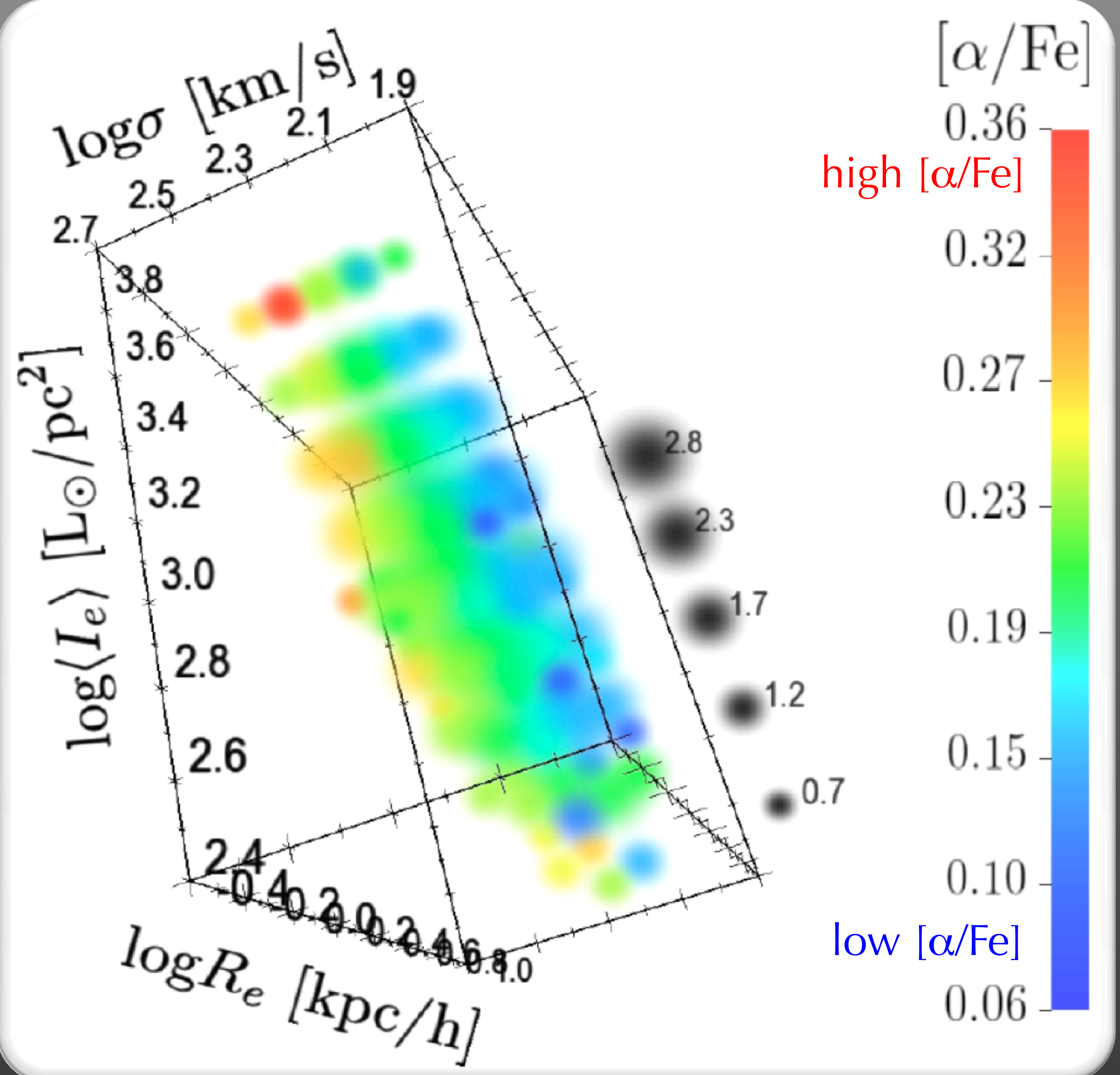
[Z/H] trend in the Fundamental Plane

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



[α/Fe] trend in the Fundamental Plane

Variation of [α/Fe] runs both *through* and *across* the FP (i.e. in a combination of the v_1 and v_3 directions)



Directional derivatives of stellar population parameters w.r.t. the FP principal axes, the FP observables, and M, L and M/L

Stellar population parameter

	..........Age..........			........Metallicity........			.....Over-abundance.....		
FP parameter	$\nabla_{\hat{\mathcal{F}}} A$	ϵ	χ	$\nabla_{\hat{\mathcal{F}}}[Z/H]$	ϵ	χ	$\nabla_{\hat{\mathcal{F}}}[\alpha/Fe]$	ϵ	χ
v_1	**-1.47**	**0.12**	**12.25**	0.07	0.13	0.54	**-0.24**	**0.05**	**4.80**
v_2	-0.04	0.04	1.00	0.05	0.03	1.67	-0.01	0.01	1.00
v_3	0.08	0.09	0.89	**0.46**	**0.04**	**11.50**	**0.16**	**0.02**	**8.00**
r	**-0.70**	**0.08**	**8.75**	**0.32**	**0.07**	**4.57**	-0.03	0.03	1.00
s	**1.16**	**0.11**	**10.55**	0.25	0.10	2.50	**0.29**	**0.04**	**7.25**
i	**-0.57**	**0.08**	**7.13**	**0.22**	**0.06**	**3.67**	-0.02	0.03	0.67
m	**0.32**	**0.05**	**6.92**	**0.16**	**0.04**	**3.87**	**0.11**	**0.02**	**6.44**
l	**-0.39**	**0.04**	**11.01**	**0.17**	**0.03**	**5.65**	-0.02	0.01	1.19
$m-l$	**0.60**	**0.04**	**14.51**	-0.01	0.04	0.18	**0.11**	**0.02**	**6.96**

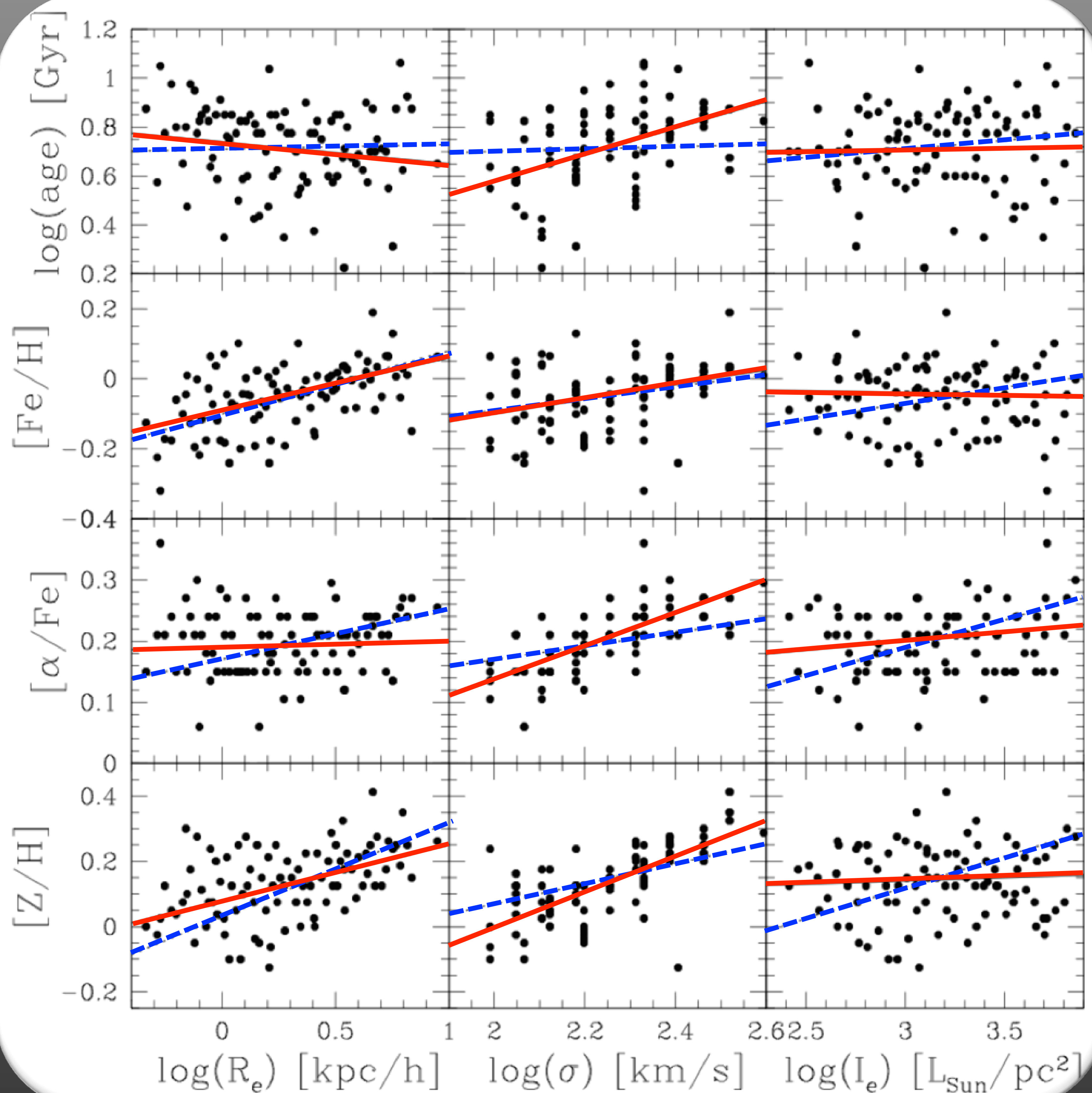
Significant trends (in **bold**) have χ>5 (i.e are significant at >5-sigma): e.g. age with v_1, metallicity with v_3 and over-abundance with both v_1 and v_3.

Can use the 3D directional derivatives to predict the 2D pair-wise correlations between the stellar population parameters and the FP parameters.

2D correlations between stellar population parameters and Fundamental Plane parameters

Predicted correlations based on directional partial derivatives (blue) are generally consistent with – but not identical to – the observed correlations (red)

The 2D correlations are projections of more complex 3D correlations



Directional derivatives of stellar population parameters w.r.t. the FP principal axes, the FP observables, and M, L and M/L

	Stellar population parameter								
	..........Age..........			.........Metallicity.........			.....Over-abundance.....		
FP parameter	$\nabla_{\hat{\mathcal{F}}} A$	ϵ	χ	$\nabla_{\hat{\mathcal{F}}}[Z/H]$	ϵ	χ	$\nabla_{\hat{\mathcal{F}}}[\alpha/Fe]$	ϵ	χ
v_1	**-1.47**	**0.12**	**12.25**	0.07	0.13	0.54	**-0.24**	**0.05**	**4.80**
v_2	-0.04	0.04	1.00	0.05	0.03	1.67	-0.01	0.01	1.00
v_3	0.08	0.09	0.89	**0.46**	**0.04**	**11.50**	**0.16**	**0.02**	**8.00**
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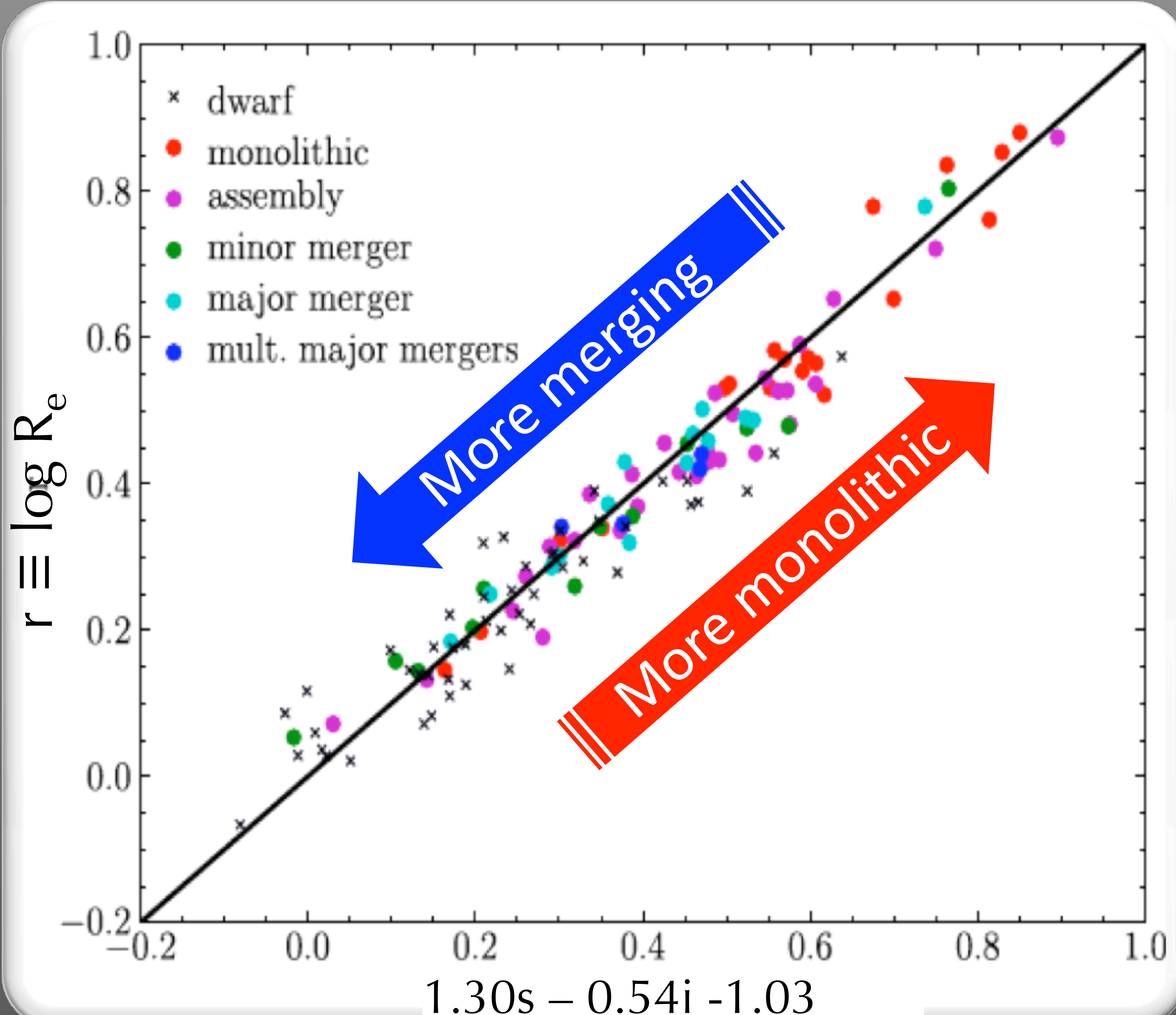
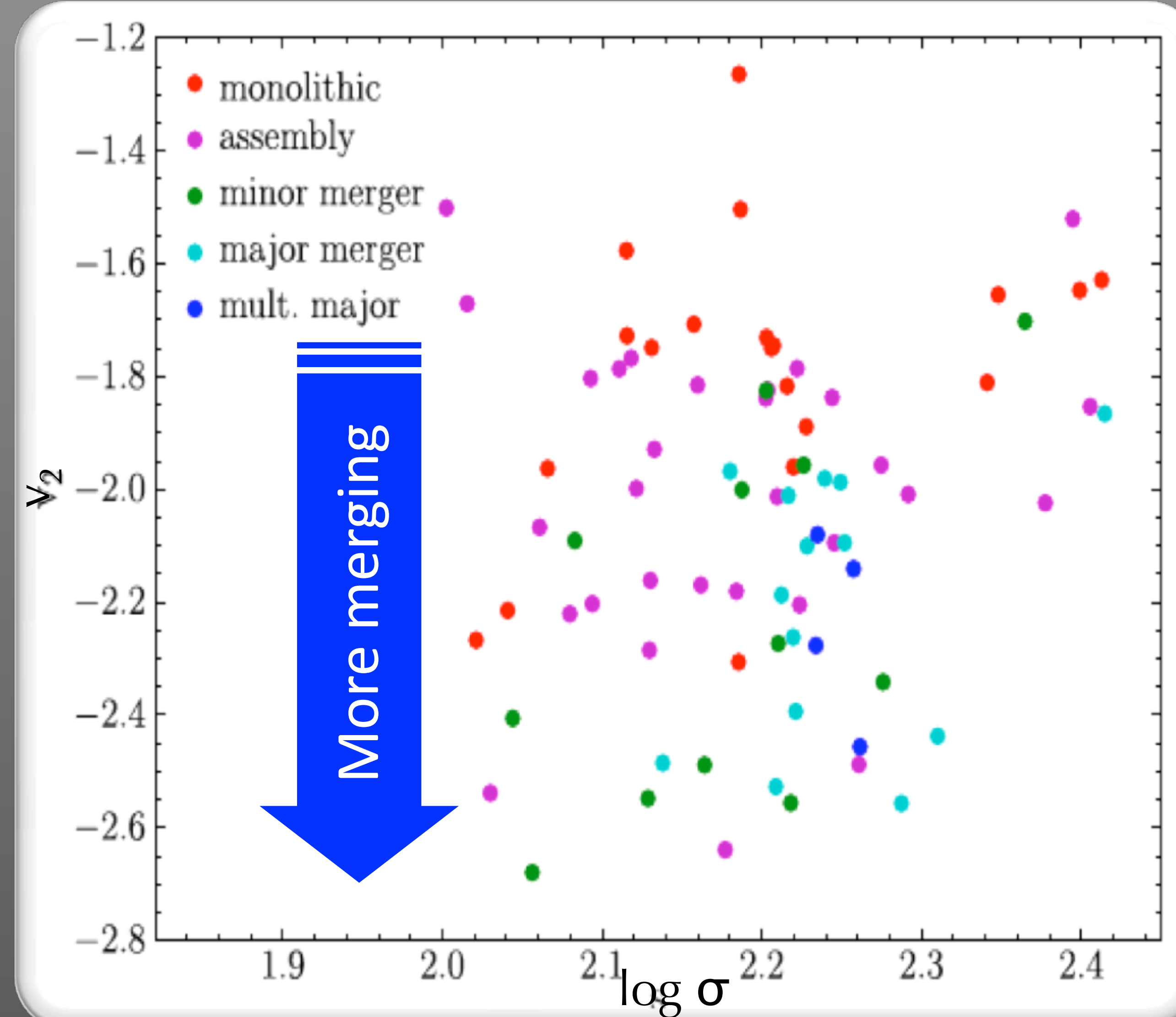
No stellar population parameter has *any* significant trend with v_2, the long axis of the FP – i.e. *no variation in stellar population with luminosity density*.





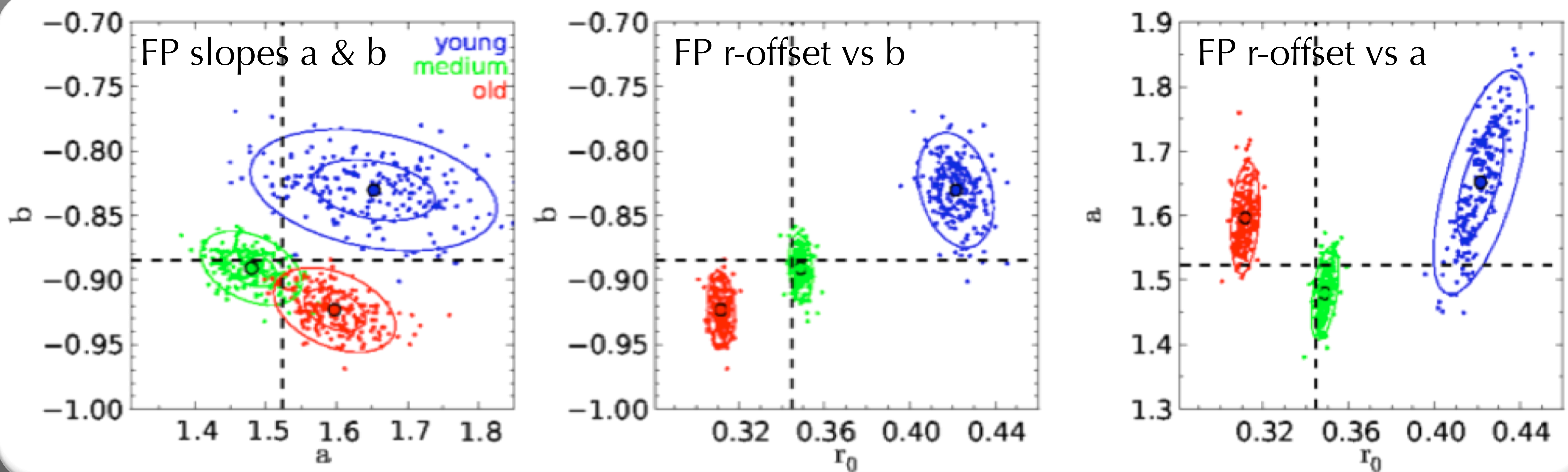
FP relation for galaxies in Kobayashi (2004) simulation of galaxy merger histories

There is a trend in merger history *along* the FP, but no trend between merger history & scatter *off* the FP.

v_2 *vs* log σ for elliptical galaxies in Kobayashi (2004) simulation

There is a clear trend of merger history with v_2 (luminosity density), but there is no readily apparent trend with σ.

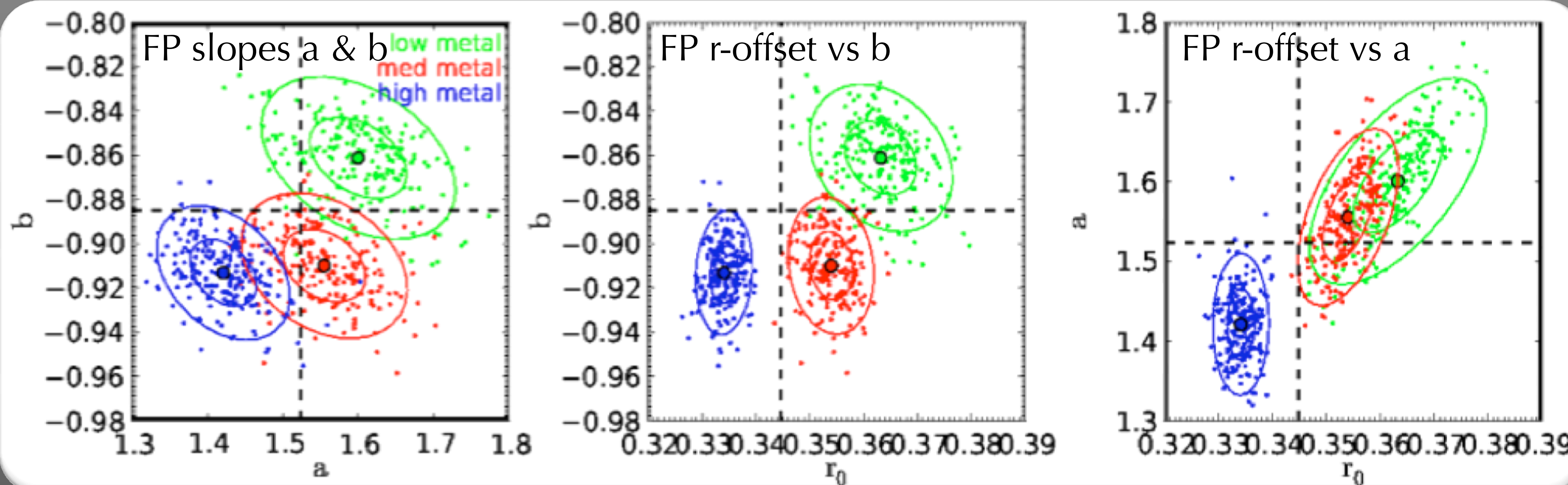
Fundamental Plane differences with age of stellar population



There is a clear trend in the r-offset of the FP with age; additionally, galaxies with ages <3Gyr have larger rms scatter in distance than older galaxies. So, in principle, we can reduce the scatter in the overall FP either by *selection* on age or by *compensating* for the variation with age of the FP.

Subsample	N_{gals}	a	b	c	$\bar{r}$	$\bar{s}$	$\bar{i}$	r_0	σ_1	σ_2	σ_3	σ_r
Full Sample	8901	1.524±0.026	-0.885±0.008	-0.329±0.054	0.183±0.004	2.188±0.004	3.188±0.004	0.345±0.002	0.0519±0.0009	0.3177±0.0038	0.1699±0.0030	0.127 (29.7%)
S Unknown	2222	1.529±0.050	-0.840±0.016	-0.495±0.110	0.213±0.008	2.194±0.006	3.154±0.008	0.338±0.004	0.0534±0.0017	0.3161±0.0073	0.1638±0.0051	0.134 (31.5%)
Age $\leqslant$ 3 Gyr	1419	1.651±0.087	-0.828±0.022	-0.729±0.185	0.189±0.012	2.145±0.010	3.171±0.010	0.421±0.008	0.0558±0.0022	0.3223±0.0101	0.1648±0.0074	0.135 (31.5%)
3 < Age $\leqslant$ 8 Gyr	3181	1.472±0.036	-0.889±0.013	-0.195±0.074	0.183±0.008	2.186±0.006	3.195±0.007	0.348±0.003	0.0485±0.0014	0.3085±0.0065	0.1735±0.0050	0.116 (27.1%)
Age > 8 Gyr	2079	1.599±0.043	-0.927±0.015	-0.401±0.089	0.151±0.008	2.213±0.006	3.223±0.008	0.311±0.003	0.0434±0.0018	0.3233±0.0076	0.1684±0.0054	0.117 (27.2%)

Fundamental Plane differences with metallicity of stellar population



There is a weaker trend in FP r-offset with metallicity; so in principle could further reduce overall FP scatter by compensating for the effects of [Z/H].

Subsample	N_{gals}	a	b	c	$\bar{r}$	$\bar{s}$	$\bar{i}$	r_0	σ_1	σ_2	σ_3	σ_r
Full Sample	8901	1.524±0.026	-0.885±0.008	-0.329±0.054	0.183±0.004	2.188±0.004	3.188±0.004	0.345±0.002	0.0519±0.0009	0.3177±0.0038	0.1699±0.0030	0.127 (29.7%)
S Unknown	2222	1.529±0.050	-0.840±0.016	-0.495±0.110	0.213±0.008	2.194±0.006	3.154±0.008	0.338±0.004	0.0534±0.0017	0.3161±0.0073	0.1638±0.0051	0.134 (31.5%)
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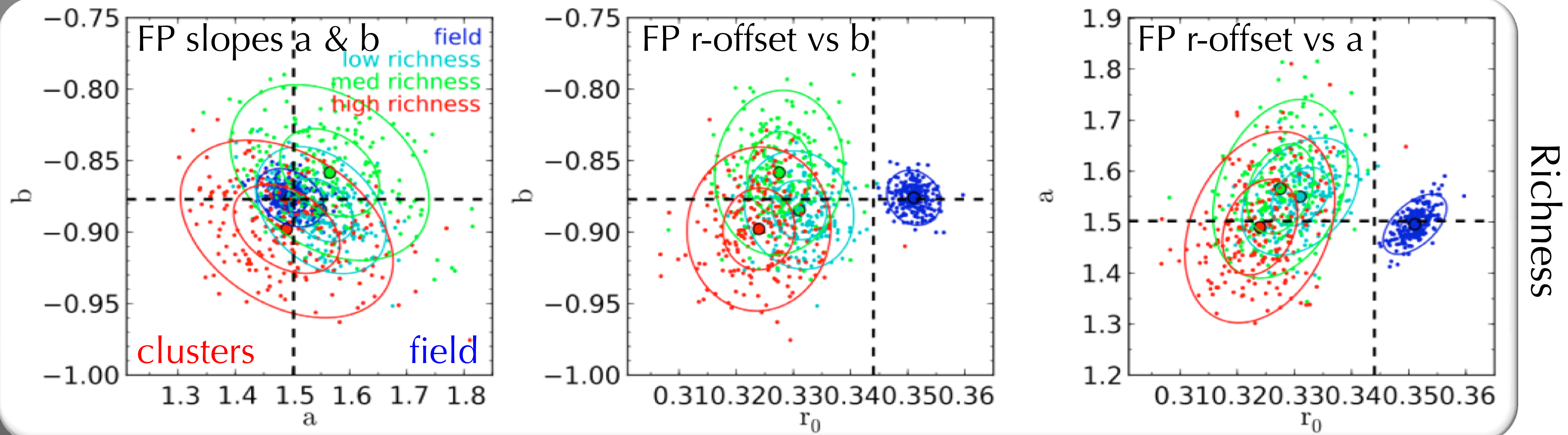
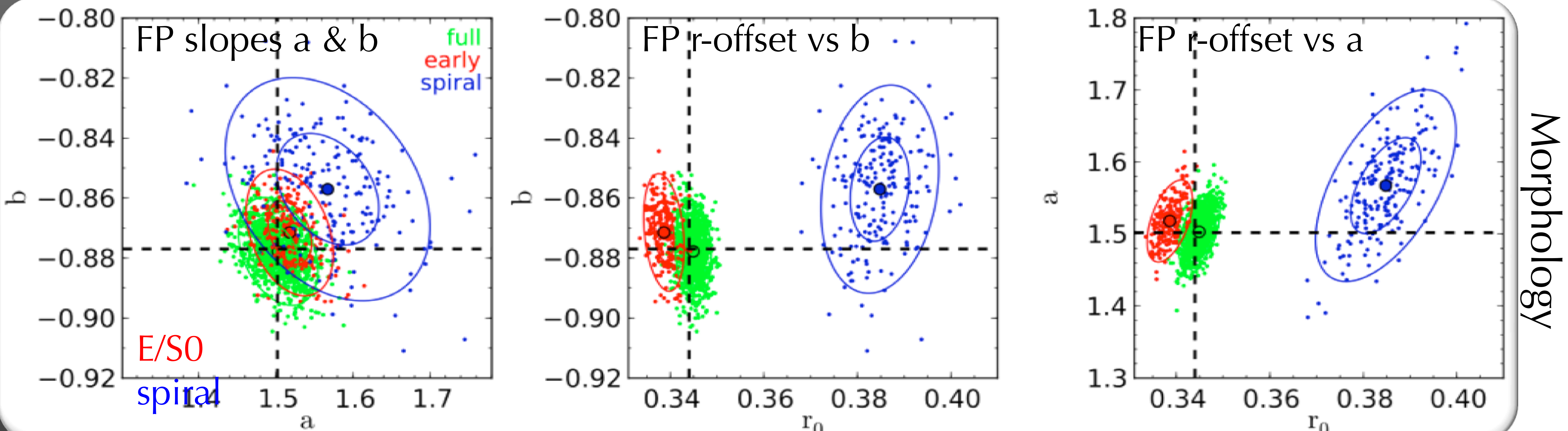
Age > 8 Gyr	2079	1.599±0.043	-0.927±0.015	-0.401±0.089	0.151±0.008	2.213±0.006	3.223±0.008	0.311±0.003	0.0434±0.0018	0.3233±0.0076	0.1684±0.0054	0.117 (27.2%)
$[Z/H] \leqslant 0.05$	2231	1.632±0.065	-0.872±0.017	-0.599±0.130	0.100±0.010	2.130±0.008	3.189±0.009	0.368±0.006	0.0546±0.0021	0.3147±0.0071	0.1646±0.0058	0.134 (31.4%)
$0.05 < [Z/H] \leqslant 0.2$	2144	1.548±0.056	-0.908±0.015	-0.303±0.118	0.195±0.009	2.205±0.005	3.212±0.008	0.354±0.004	0.0514±0.0018	0.3176±0.0071	0.1472±0.0049	0.125 (29.3%)
$[Z/H] > 0.2$	2304	1.403±0.044	-0.907±0.014	0.009±0.094	0.268±0.007	2.261±0.004	3.210±0.006	0.333±0.003	0.0447±0.0013	0.3111±0.0064	0.1443±0.0037	0.111 (25.8%)

Variation of FP parameters with group richness & morphology





Simulations show that these significant FP r-offsets are *not* explained by the stellar population differences between clusters & field (or E/S0's & early-type spiral bulges).

Summary and conclusions

[1] Successfully fit distribution of ~10^4 6dFGS galaxies in Fundamental Plane space as a 3D Gaussian distribution using maximum likelihood

[2] For ~7000 of these galaxies, stellar population parameters (age, metallicity, [α/Fe]) are measured from Lick absorption line indices

[3] The 3D directional derivatives of the stellar population parameters in Fundamental Plane space show variations with *all* of σ, R_e, I_e and δ_{FP}

[4] We recover the pair-wise 2D relations between stellar population & FP variables from these 3D trends, with some unexpected dependencies

[5] Stellar population parameters vary with v_1 (*through* FP) and v_3 (*across* FP), but <u>not</u> v_2 (*along* FP ~ luminosity density); suggests that the extent of the FP in v_2 is driven by merger histories not stellar populations

[6] These SP trends can in principle be used to reduce the scatter in the FP