The Challenges of Measuring Reliable FP Distances for an All-Sky Sample of Early-Type Galaxies

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The key aspects:

- (a) Sample selection (and Completeness)
- (b) FP photometric parameter measurement, i.e. r_H and SB_H, random and systematic errors
- (c) Velocity dispersion measurement, random and systematic errors

Conclusion: Future FP surveys need to work very hard at reducing the systematic errors in the velocity dispersion measurements.

101 Peculiar Velocities

Measured directly via $V_{pec} = cz - H_0 d$

cz is easy and accurate.
$H_0 d$ is always a challenge to measure well,
has sizeable errors (10 – 20%) and scales with redshift.

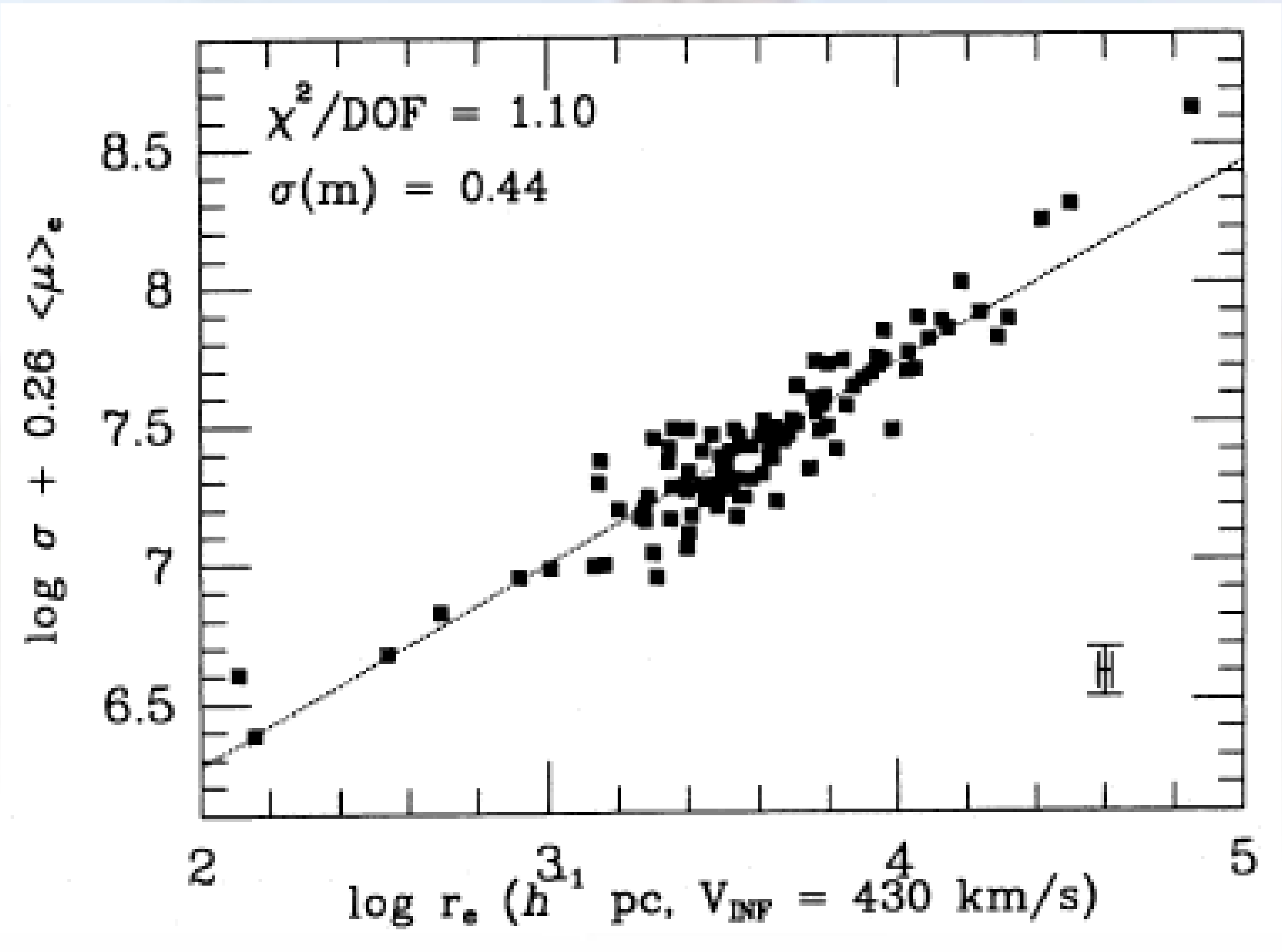
Four distance indicators primarily used:
- Fundamental Plane (FP),
- Tully-Fisher (TF),
- Surface Brightness Fluctuations,
- Type Ia supernovae.

Each method has advantages and limitations, e.g.
- numbers of objects,
- intrinsic precision,
- sensitivity to systematic uncertainties.

First Fundamental Plane Studies

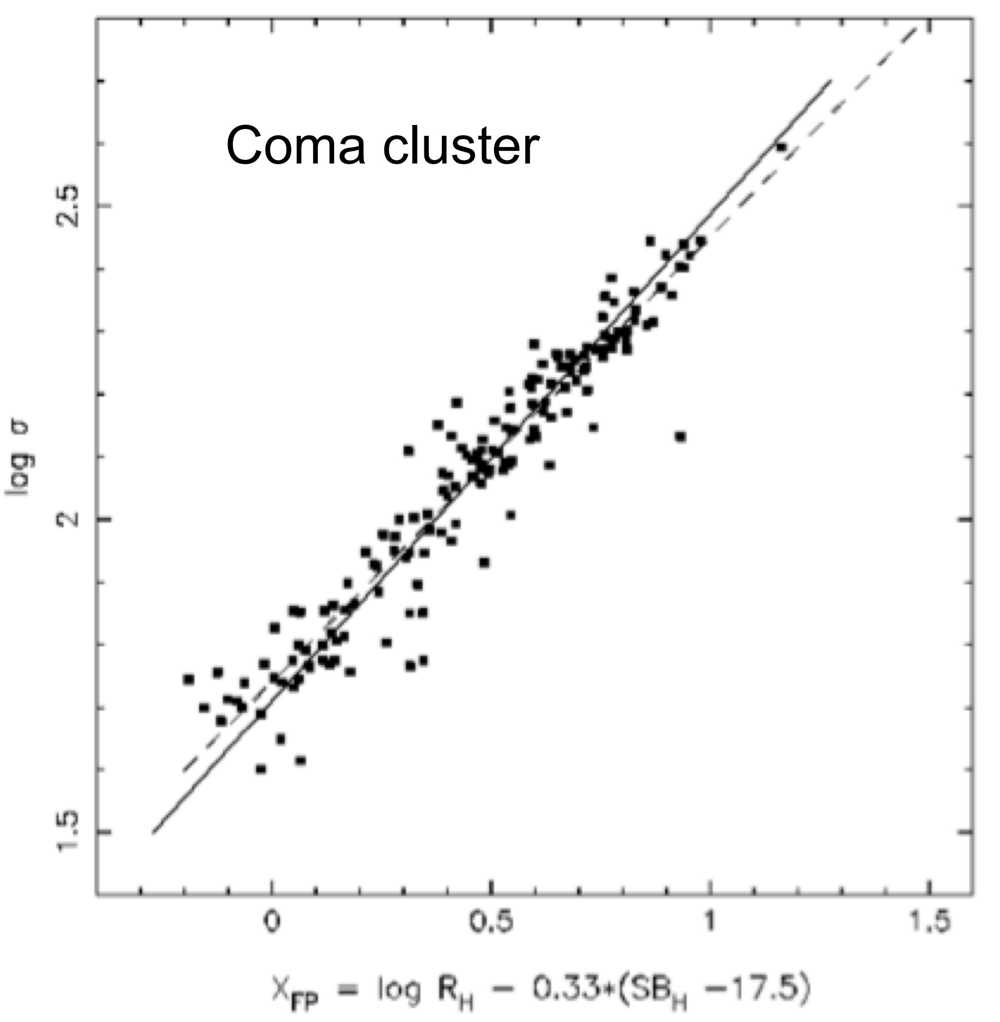
Dressler et al 1987 (7S) Six clusters (Dn-sigma)

Djorgorvski & Davis 1987 “Fundamental Plane”



101 Fundamental Plane

The empirical relation between the central velocity dispersion, the effective (half-light) radius and effective surface brightness. (Dressler et al 1987 (7S, Dn-sigma), Djorgorvski & Davis 1987 "Fundamental Plane").



Sample of early-type galaxies

Total magnitude → r_H and SB_H

Central velocity dispersion (sigma)

X_{FP} is effectively an edge-on view.

Clearly for large surveys the "gain" is only realised if the systematic errors are controlled.

For example, for clusters the distance uncertainties reduced by √n but only if the systematic errors are small enough.

30 years of FP studies

7-Samurai 1987-1989	All sky sample of ~400 early-types
Lucey & Carter 1988	Five southern clusters (Dn-sigma) first fibre sigma measurements
Jorgensen et al 1995	Ten clusters
Pahre et al 1995	K-band FP for five clusters
Hudson et al 1999	SMAC
Colless et al 1999	EFAR (Cor-Bor, Per-Pis-Cetus)
Bernardi et al 2002	ENEAR
Blakeslee et al 2002	FP vs SBF
Bernardi et al 2003	SDSS FP
Smith et al 2004	NFPS
D'Onofrio et al 2008	WINGS+SDSS+NFPS
La Barbera et al 2010	SDSS + NIR, Enviro trends
Magoulas et al 2012	6dFGSv
Saulder et al 2013	SDSS FP
Kopylova & Kopylov 2017	SDSS FP clusters

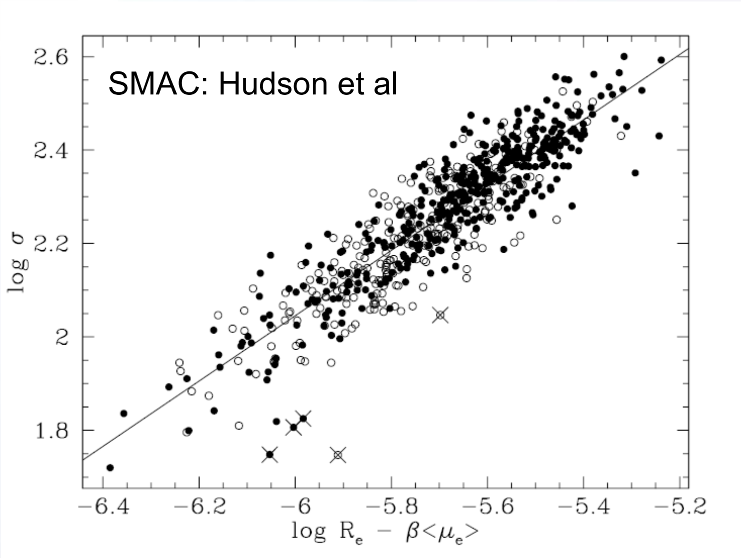
Heron Island Workshop on
Peculiar Velocities in the Universe
17-21 July 1995

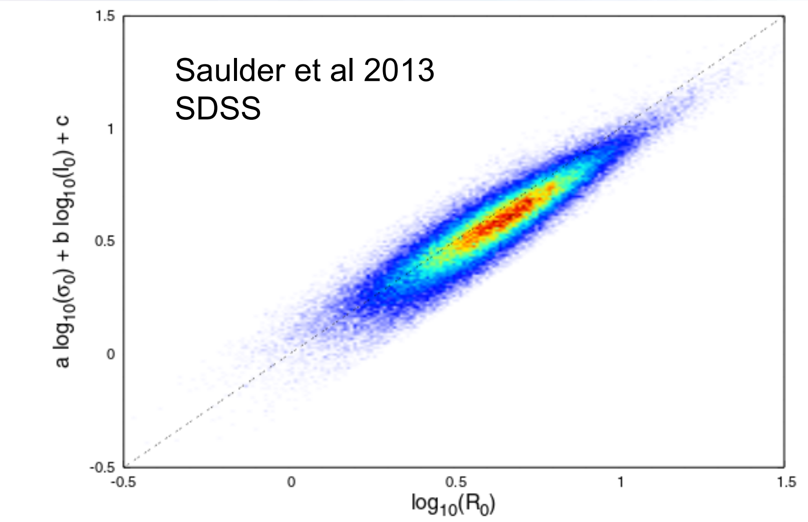
First Golden Age of
Peculiar Velocity Studies
~1984 to ~1999

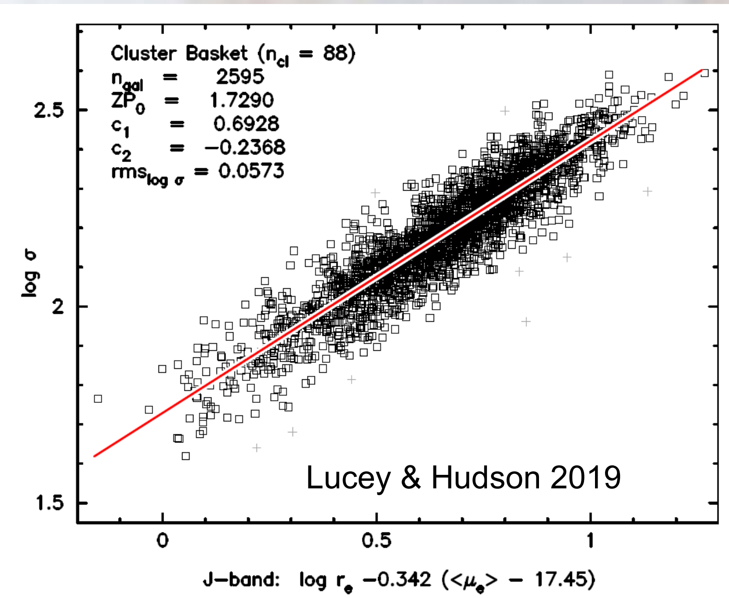
Concluding remark by Paul Schechter
“Don’t do better statistics … do better experiments”
Ernest Rutherford

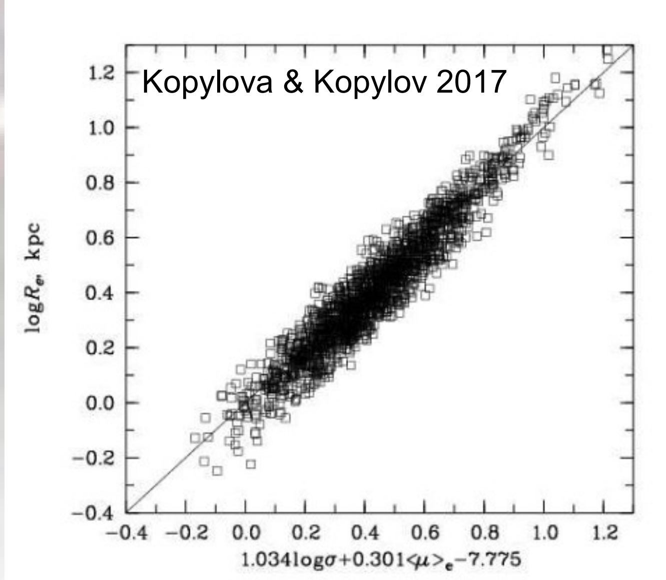
Various Fundamental Planes:

Good quality data has a distance error per galaxy of 15% to 20%.









Sample Selection and Completeness

Historically done by eye-ball searching on photographic plates.

Now extensive, high quality, large area, multi-band photometry is available, e.g.
grizy PS1 (north of Dec = -30 deg),
re-calibrated ugriz SDSS onto PS1,
YJHK VHS and UHS (to Dec = +60 deg) + the 2MASS legacy,
grizY DES plus DECaLS,
uvgriz Skymapper,
etc.

Linking these surveys together will enable the construction of an all-sky uniform set of FP early-type galaxy targets, via colours (e.g. multi-colour red-sequence), structural parameters (e.g. Sersic index/concentration, asymmetry/bumpiness). However eye-ball inspection will still be needed to remove the oddballs.

Should yield in total ~200,000 FP targets to z ~ 0.1

The assessment of the completeness will be the challenge as existing image surveys are not uniform but the overlap is large.

Systematic Errors in the Photometric Zero-points

101 Case

cz = 15000 km/s

FP scatter = 20% per galaxy

average over 25 galaxies (cluster or patch of sky)

i.e. 4% = PV random error of 600 km/s

A systematic photometric zero-point error of 0.02 mag leads to systematic PV error of 230 km/s.

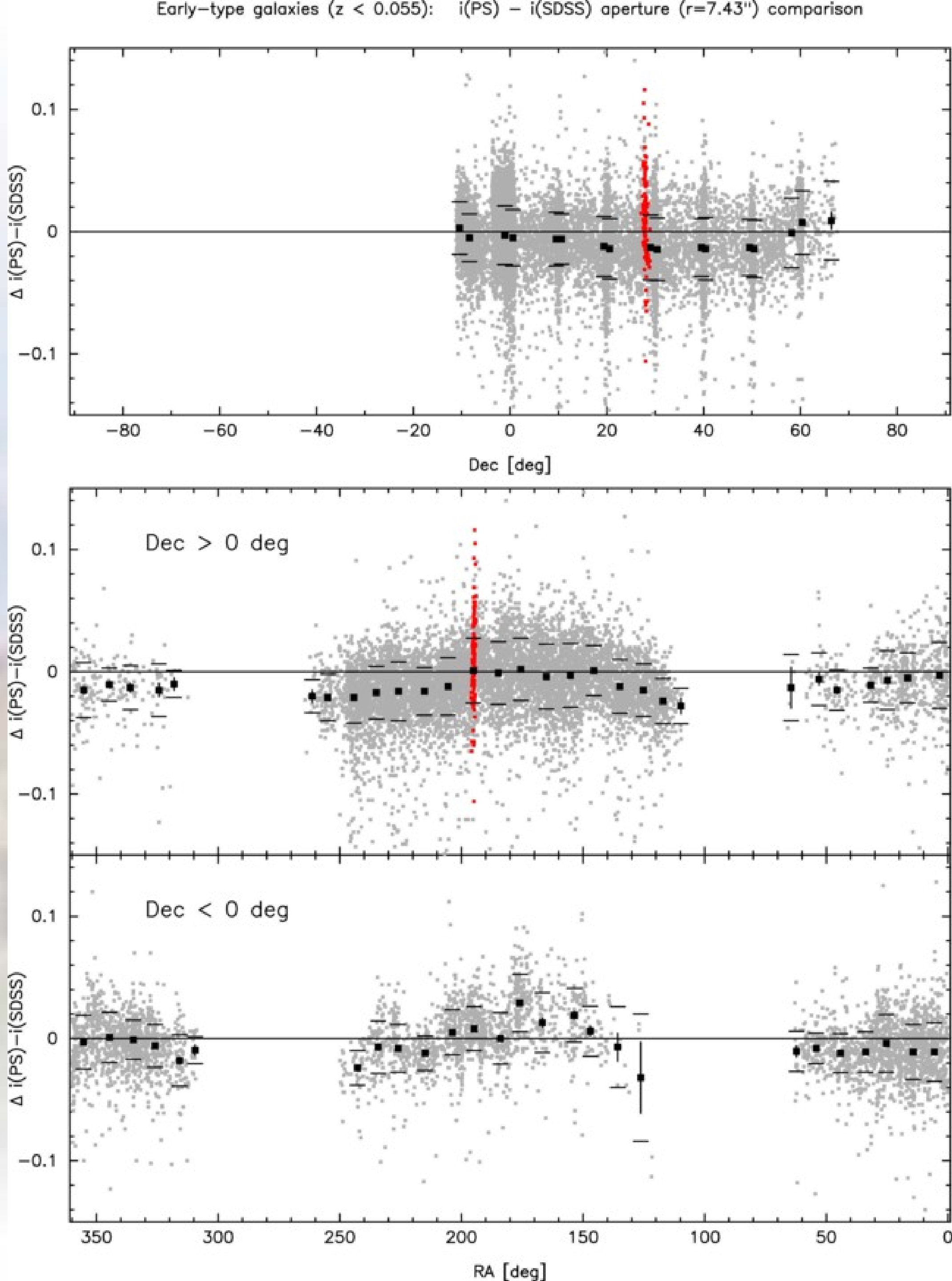
Can we realistically achieve 0.02 mag homogeneity?

Test of Photometric ZPs: i-band PS1 vs SDSS

Aperture (r = 7.43 arcsec) for early-type galaxies z < 0.055

First cut implies PS1 and SDSS agree at the 0.02 mag level.

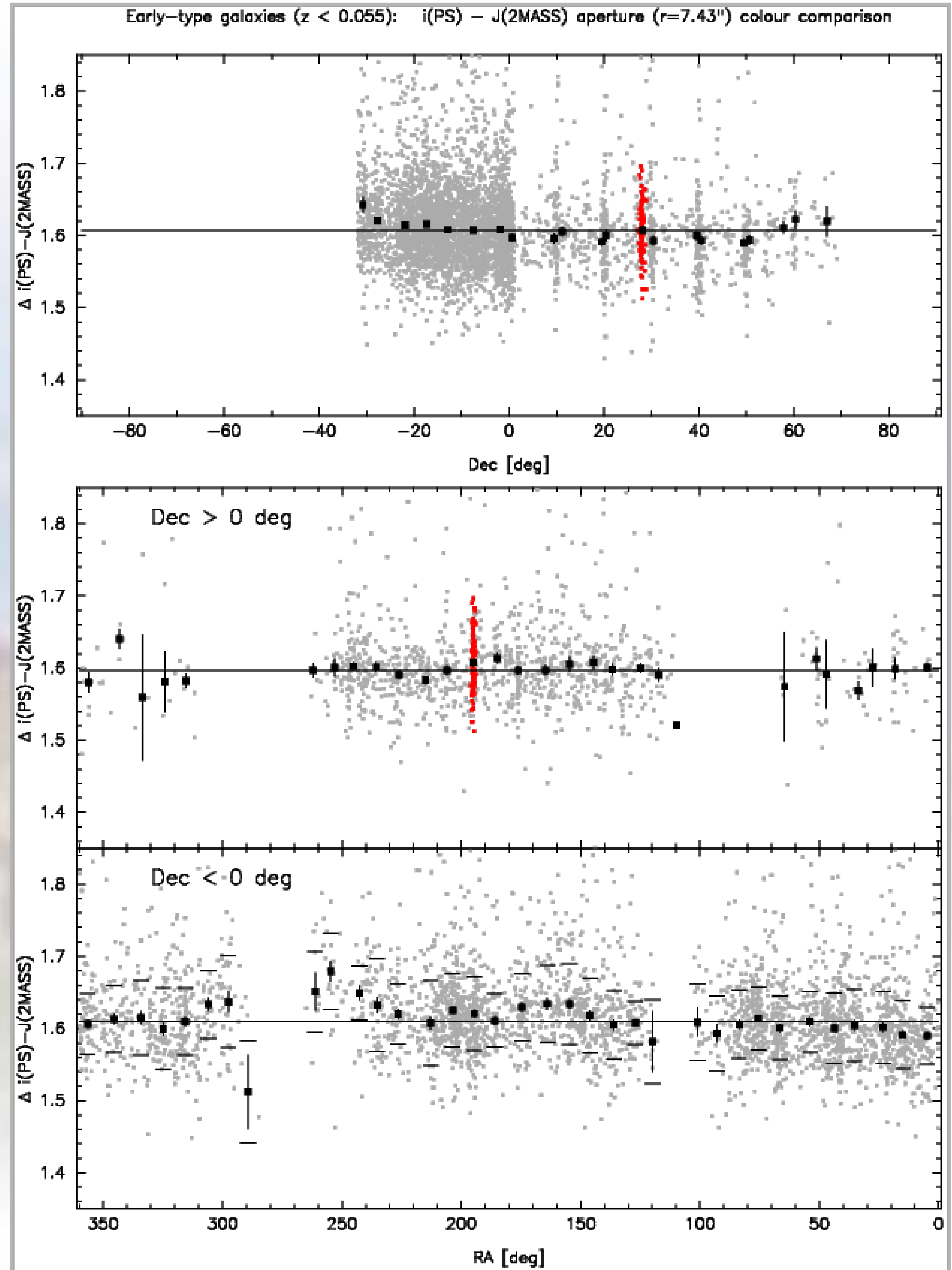
Probably can get to 0.01 mag.



Test of Photometric ZPs: i-band PS1 vs J-band 2MASS

Aperture (r = 7.43 arcsec) for early-type galaxies with z < 0.055; after various corrections.

First cut implies PS1 and 2MASS agree at the 0.02 mag level.



FP Photometric Parameters (r_H and SB_H) from 2MASS

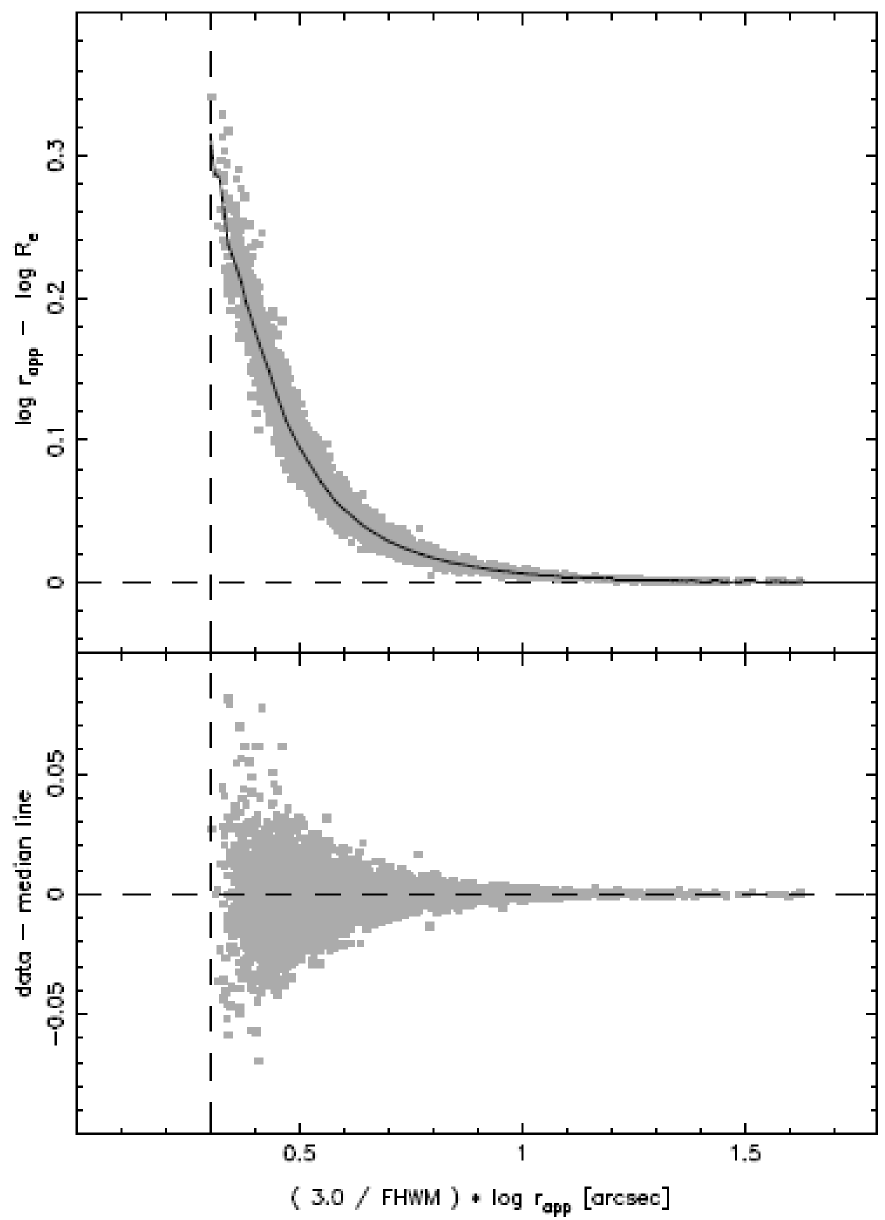
Despite the very shallow depth and PSF ~3”, 2MASS is really excellent for FP studies out to z ~ 0.07 but misses galaxies with r_H > 2”.

The 6dFGSv procedure to correct r_H for the 2MASS PSF.

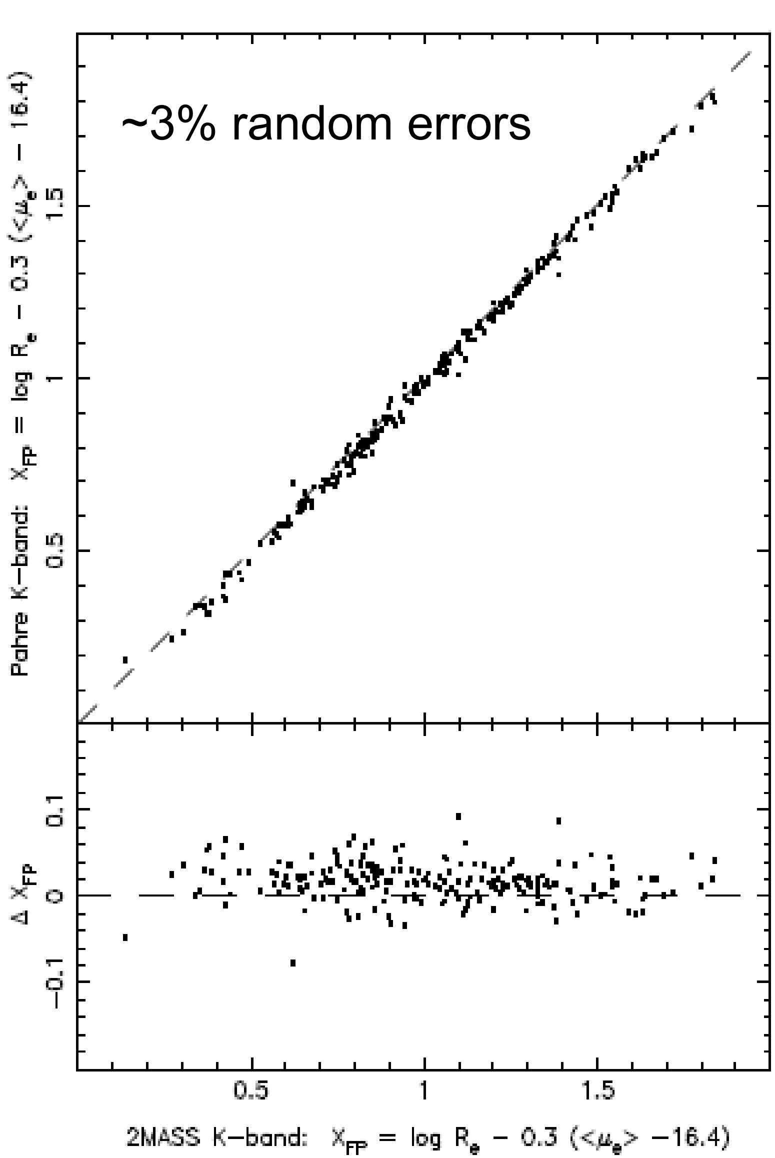
Adopt the listed 2MASS **J_ext** and use Sersic model with GALFIT to find the required PSF correction.

Very well-behaved (expected).

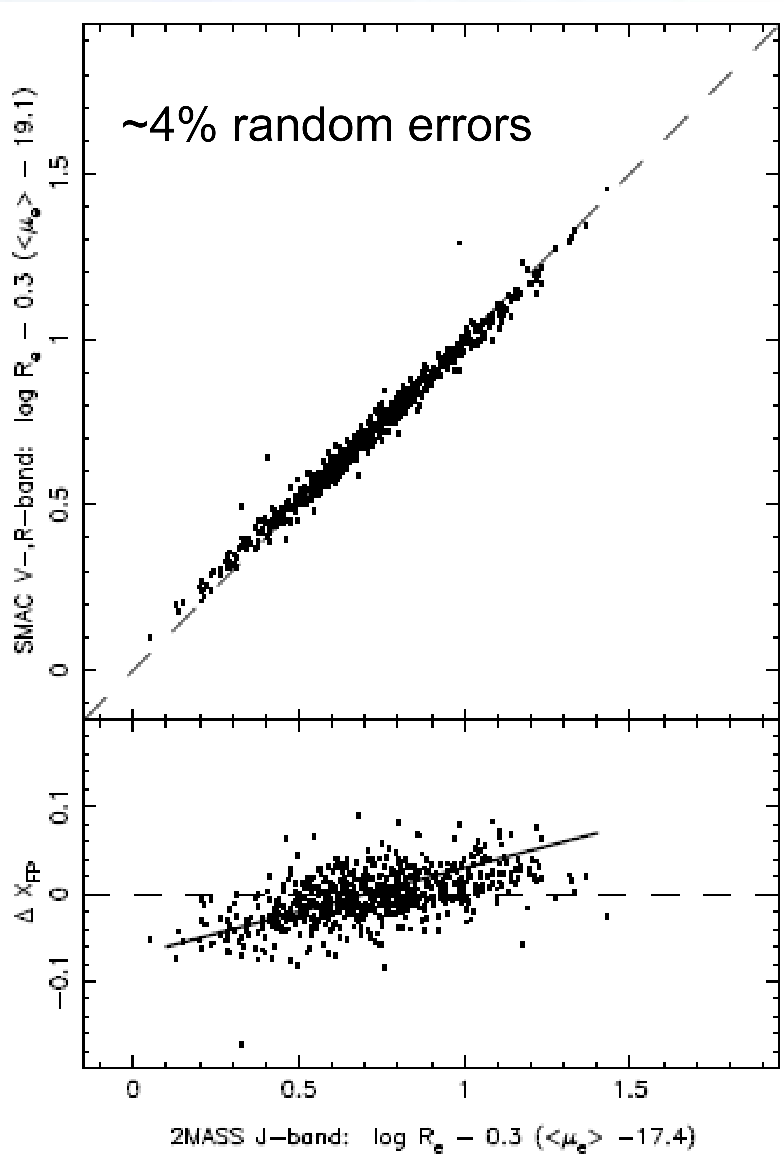
Usual corrections applied for
(i) galactic extinction (SF11)
(ii) (1+z)^4 SB dimming
(iii) k-correction
(iv) evolution-correction



2MASS FP Parameters and External Comparisons

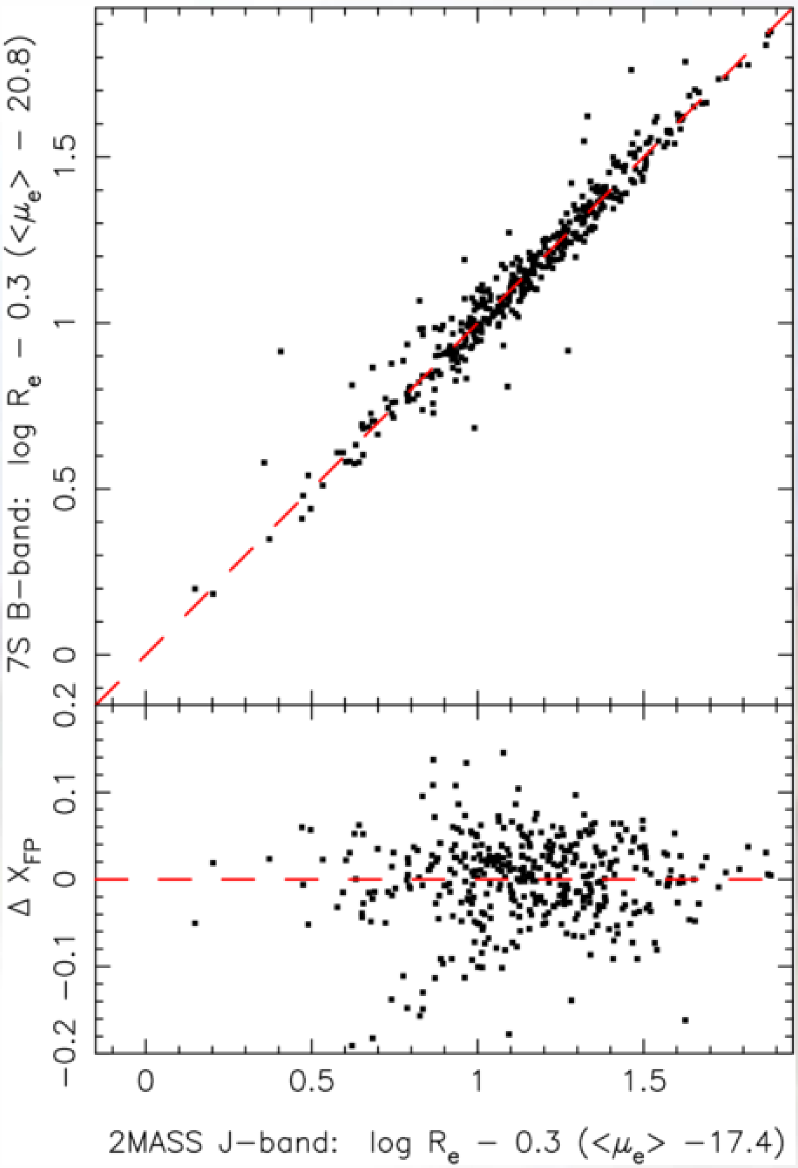


Pahre (1998) K-band values

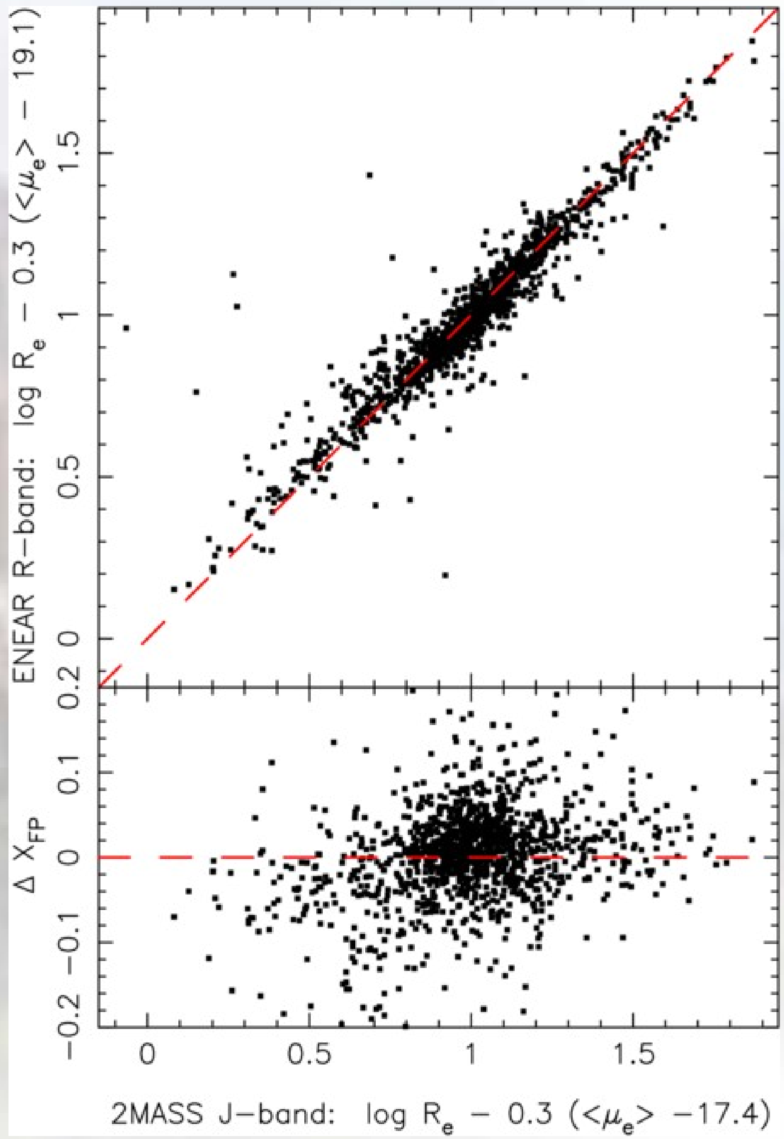


SMAC V/R-band

2MASS FP Parameters comparison with older datasets

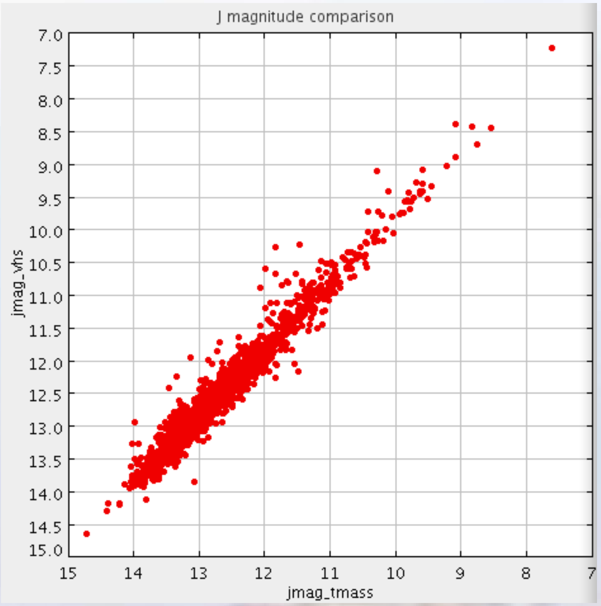


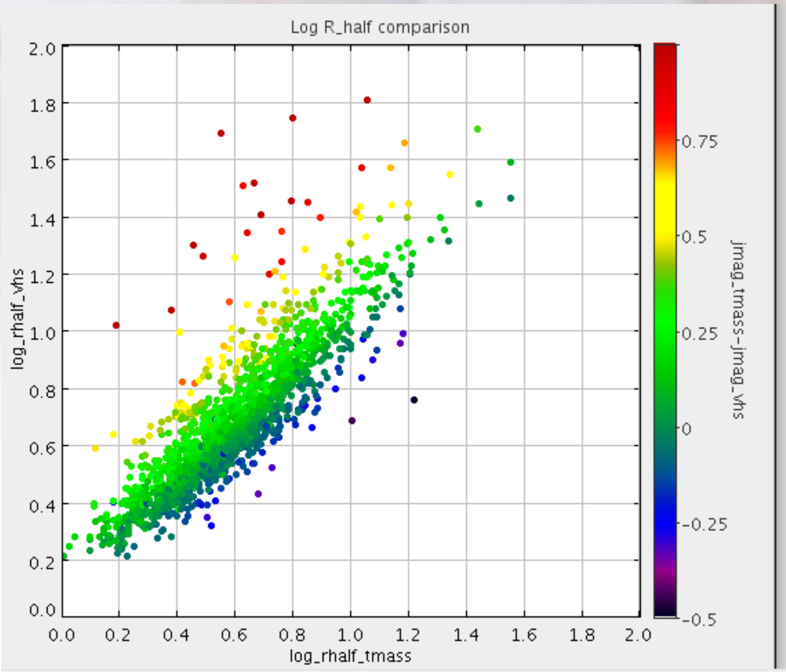
7S B-band

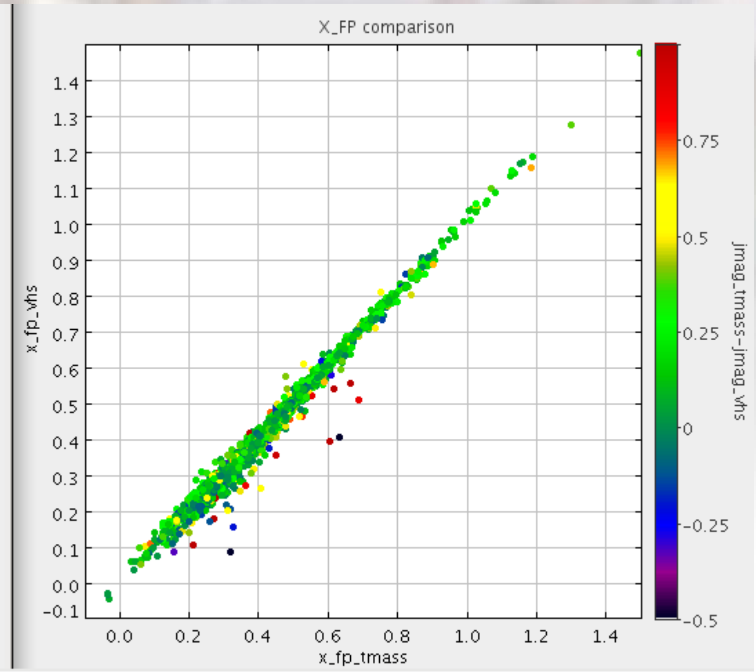


ENEAR R-band

J-band FP Parameters: 2MASS vs VHS



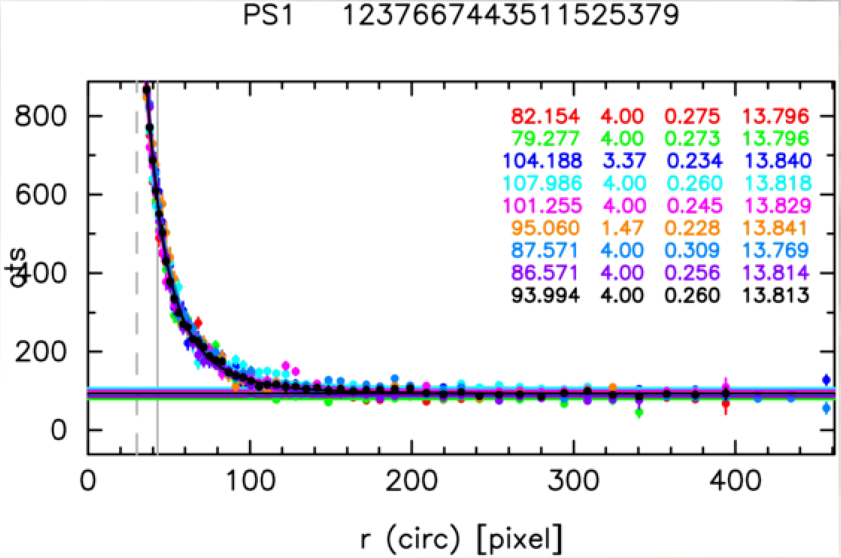


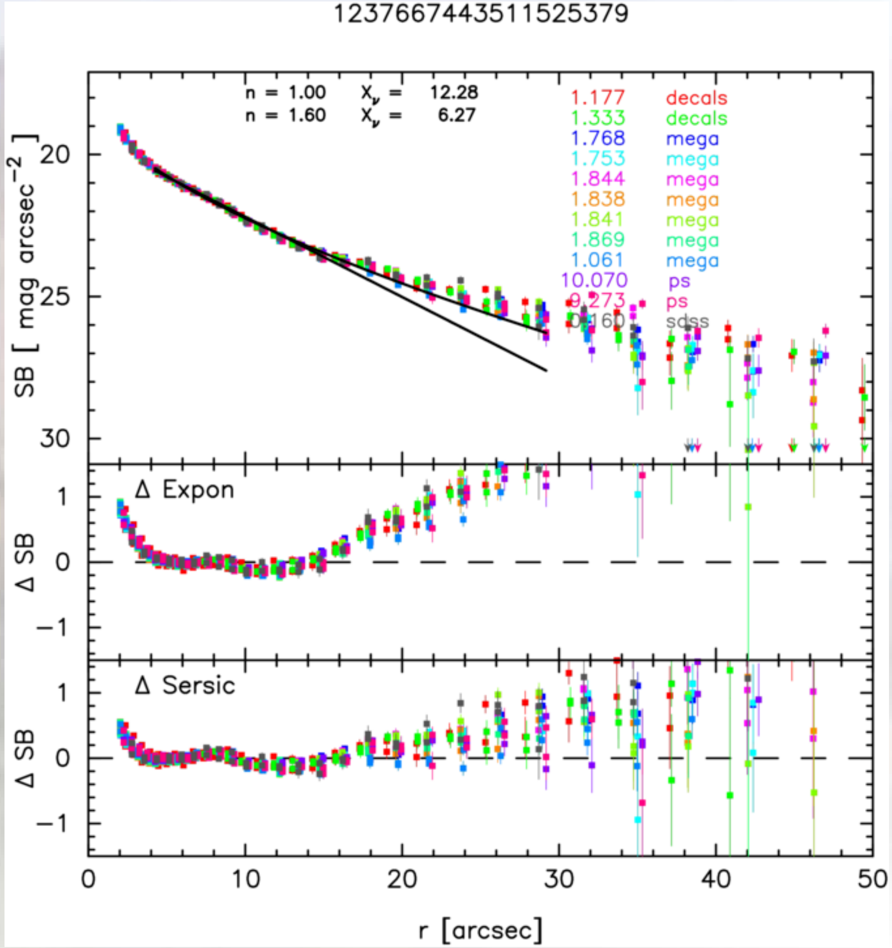


Systematic Errors in FP Photometric Parameters
r_SB, SB_H

Measure uniformly with the same definition of total magnitude.

Run the same code on the pixel data from the different surveys to measure a non-parametric total magnitude/flux.





Relatively easy to process and put on a homogeneous system.

Systematic Errors in the Velocity Dispersions

101 Case
cz = 15000 km/s
FP scatter = 20% per galaxy
average over 25 galaxies (cluster or patch of sky)
i.e. 4% = PV random error of 600 km/s

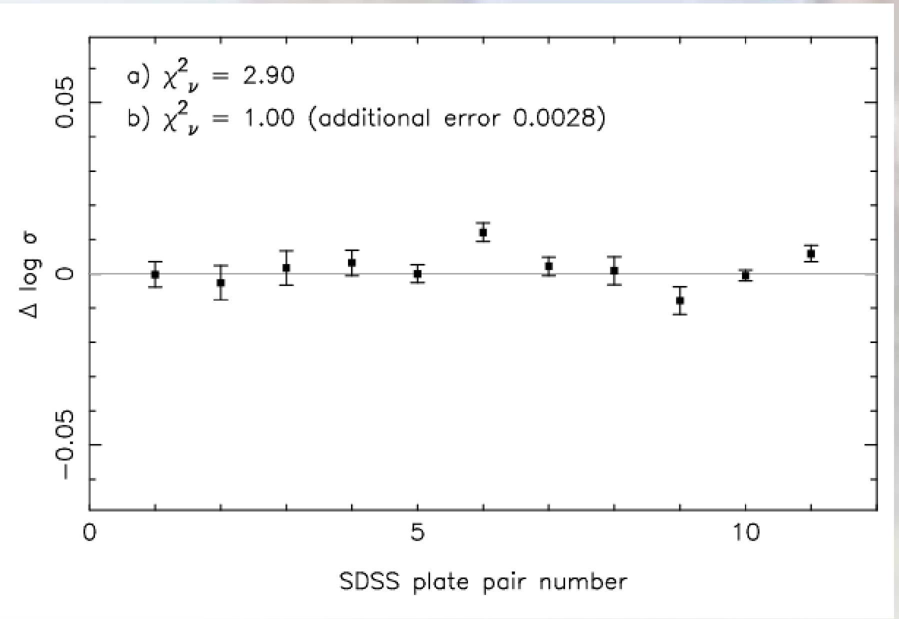
A systematic sigma error of 0.01 dex leads to
a systematic PV error of 500 km/s

Can we realistically achieve 0.01 dex homogeneity?

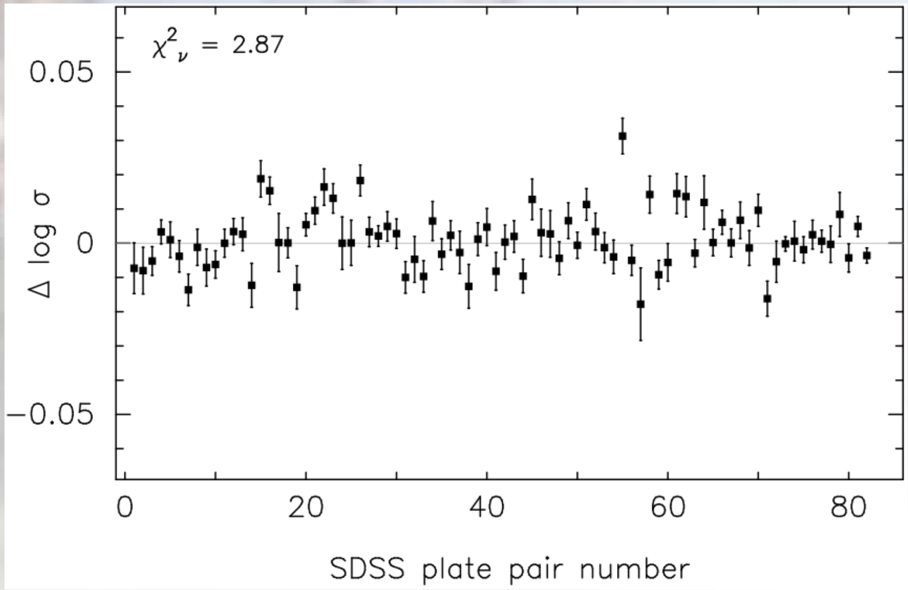
Systematics in the Velocity Dispersion Measurements

Sigma measurements are affected by (a) spectrograph issues, (b) low S/N biases, (c) poor (>1 arcsec) target positions, (d) PSF variations, (e) wavelength range covered.

Issues exist in all existing work and we currently only have a limited information for the large surveys (6dFGSv, SDSS), e.g. very few repeat measurements in SDSS with “good” plate-Quality.



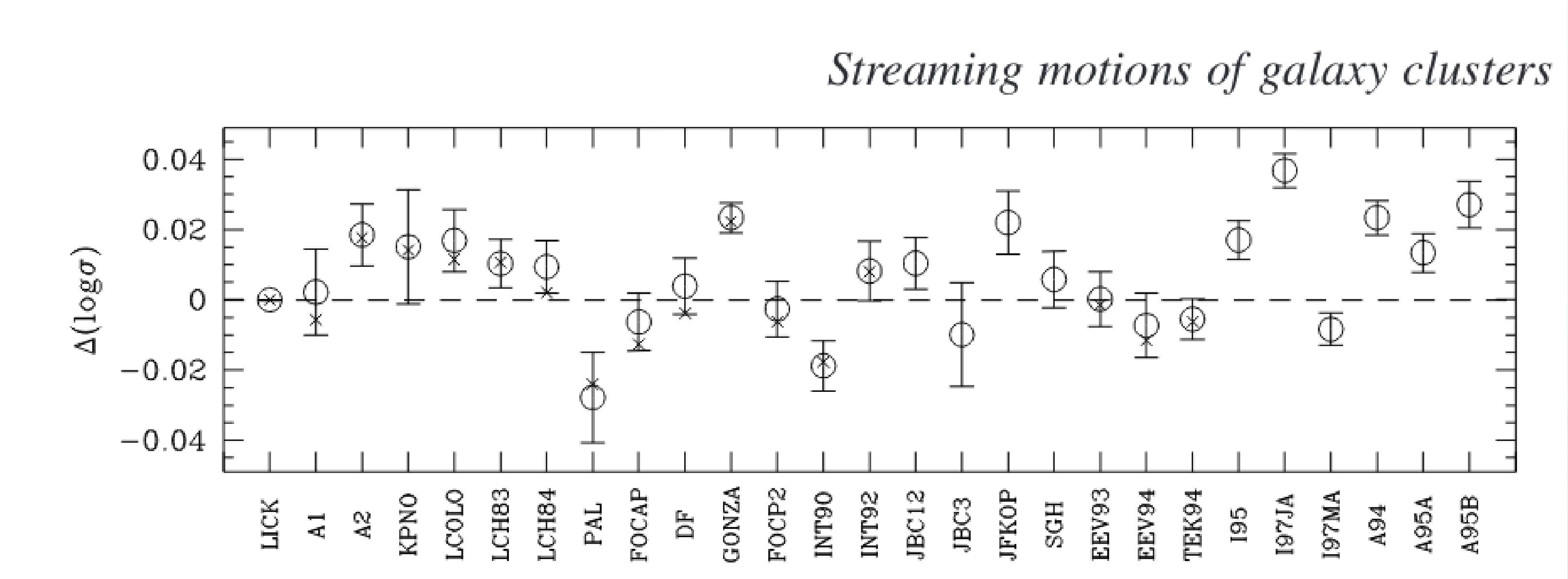
SDSS “good” plate-Quality repeats



all SDSS repeat fields

Velocity Dispersion Measurements

Traditional approach is to cross-match objects in common between different surveys and/or observing runs and find a set of offsets, e.g. SMAC (Hudson et al 2001)



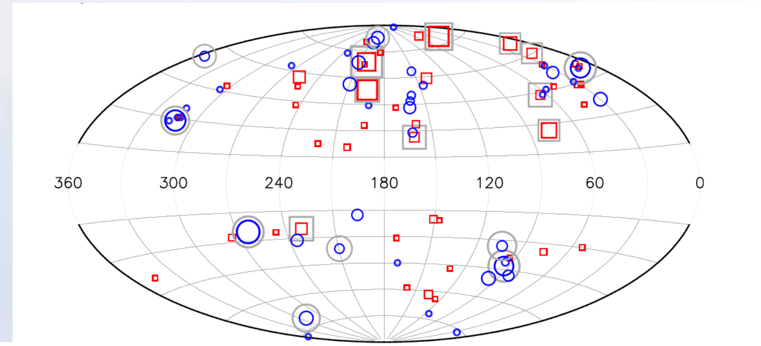
Typically ~60 galaxies in common between systems.
Offsets are ~0.015 dex
“Nominal” uncertainty in matching is 0.005 dex

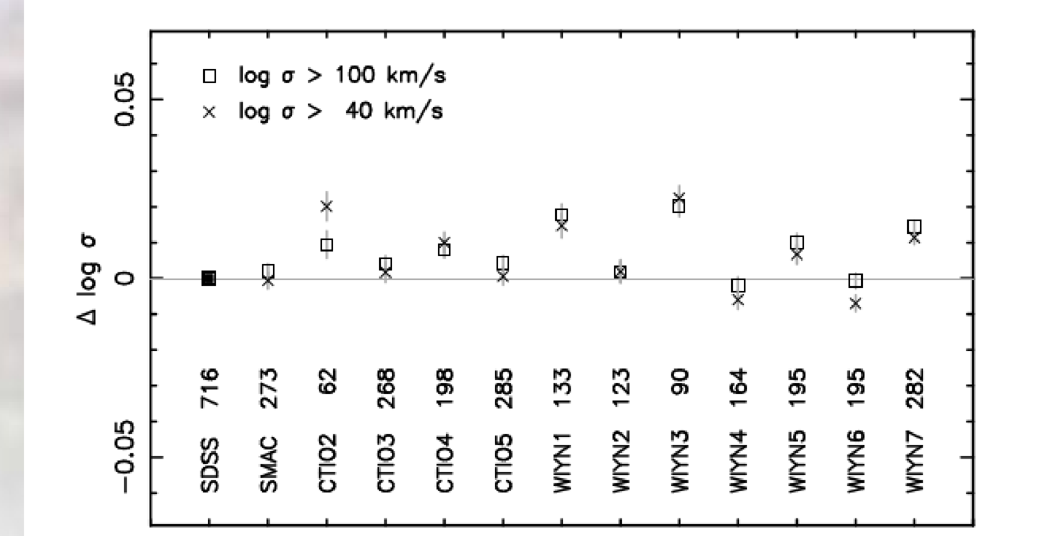
Does this approach really capture the “true” systematic offsets?
Only if each dataset is homogeneous.

NIR Fundamental Plane Cluster Distances

An Illustration of what can be done with currently available data

All-sky sample of 88 clusters in 0.020 < z < 0.055 with a homogenized set of sigmas from merging SDSS, NFPS, SMAC measurements and 2MASS J-band FP photometric parameters.

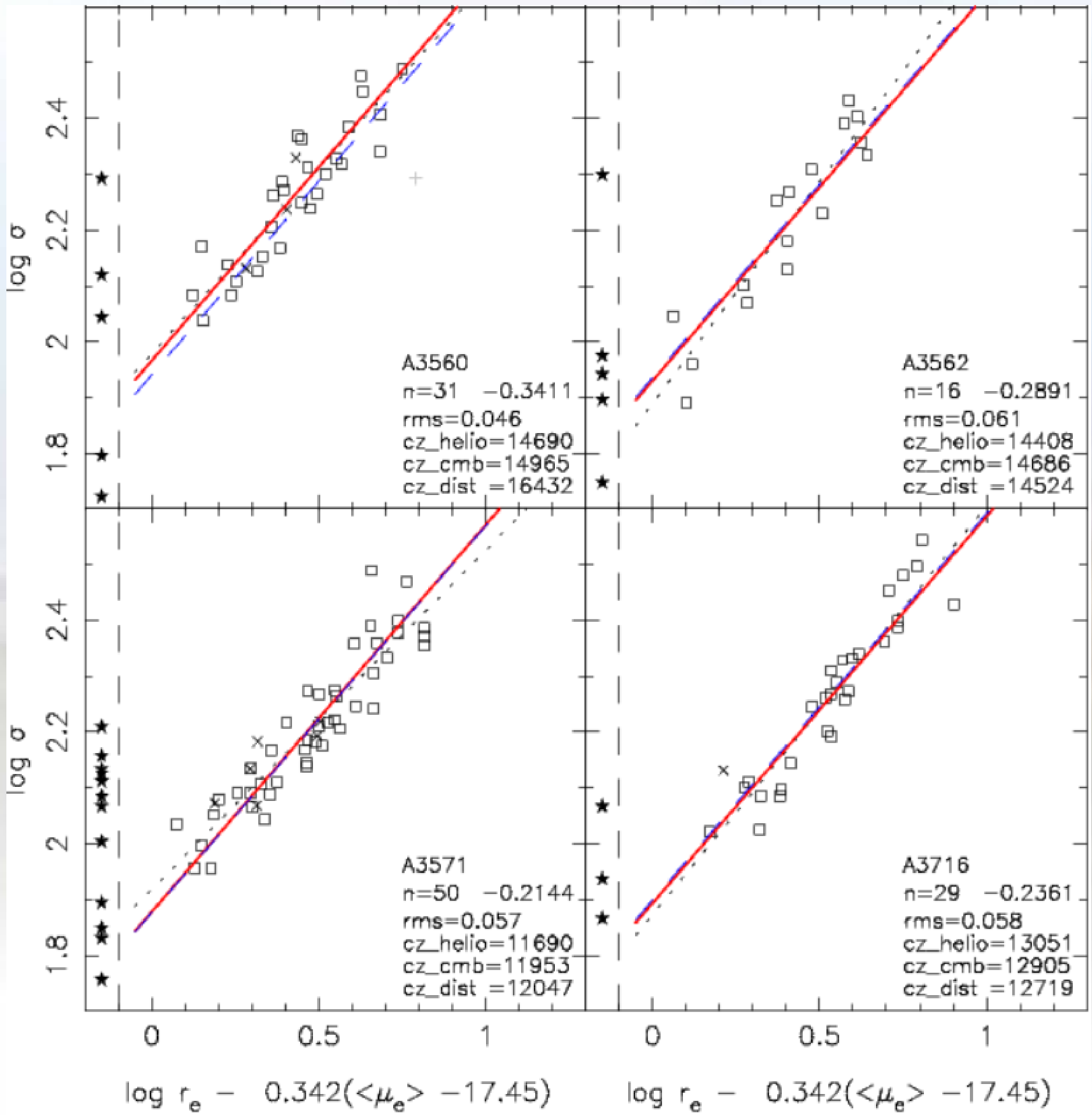




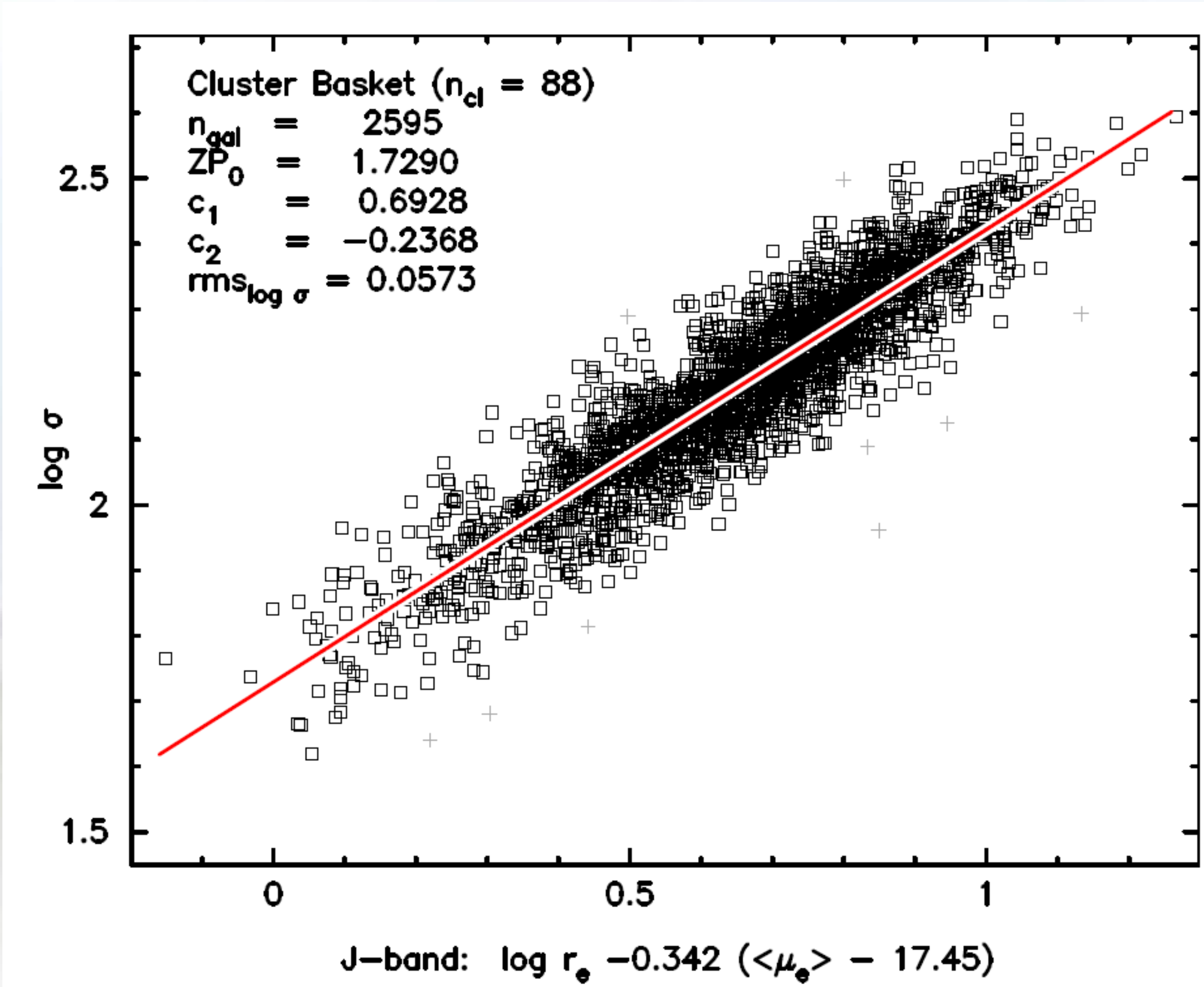
Typically ~200 galaxies in common between systems.
Offsets are ~0.010 dex
"Nominal" uncertainty in matching is 0.003 dex

Again does this approach really capture the "true" systematic offsets ?

NIR Fundamental Plane Cluster Distances



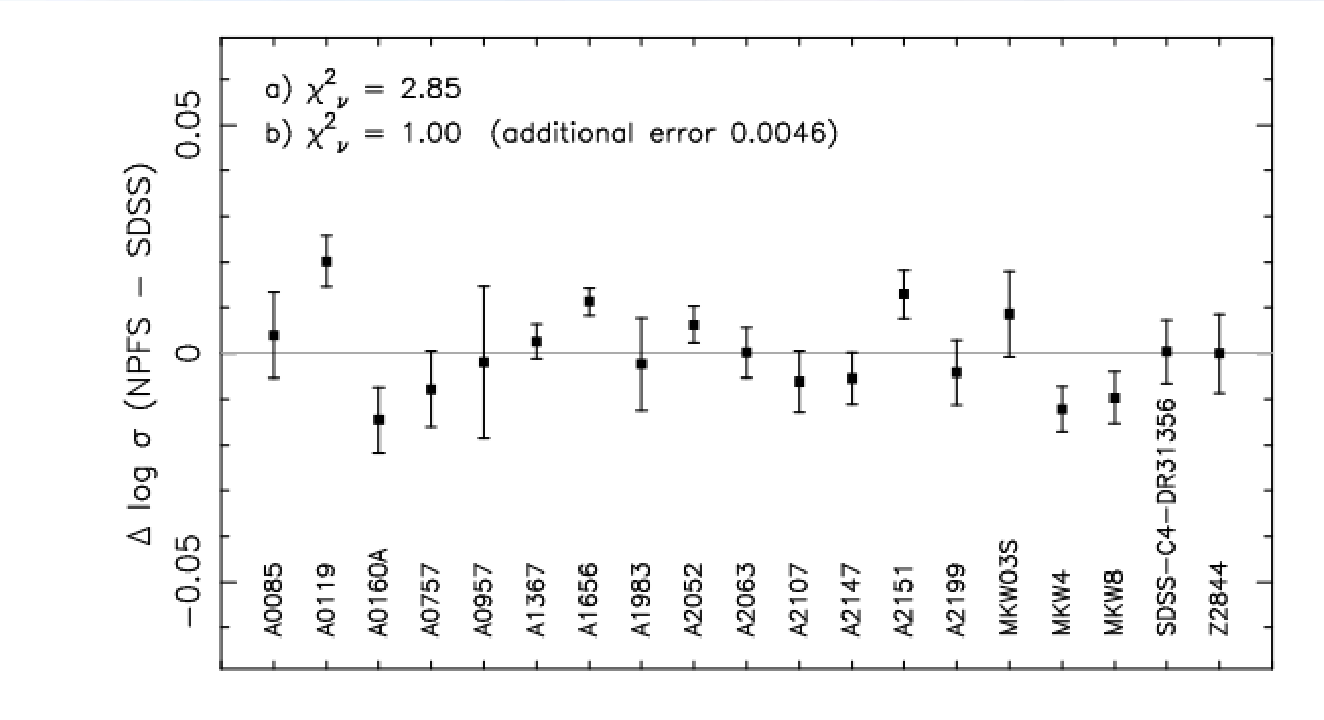
Base FP Relation from 2595 Galaxies in the 88 Clusters



Distance error per galaxy of ~19%.
Mean cluster distance error is 4%.

Systematics in the Velocity Dispersion Measurements

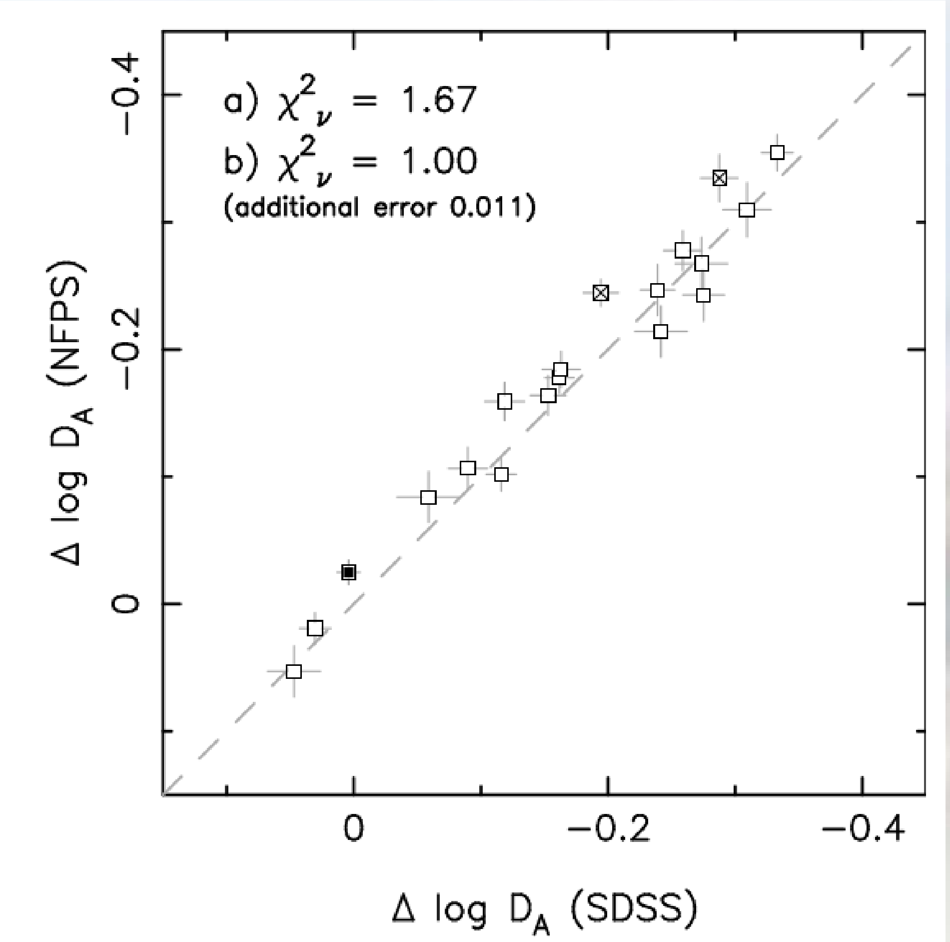
SDSS and NFPS have 19 clusters in common



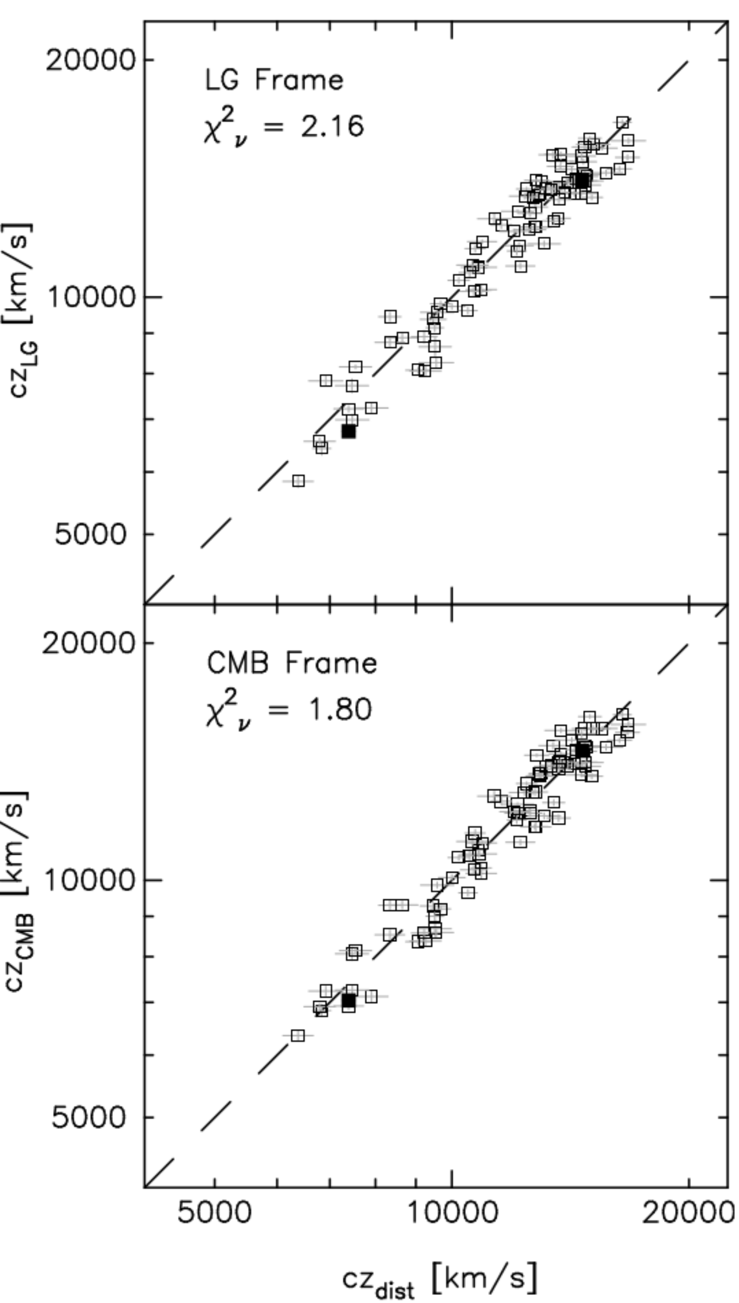
Extra noise in the peculiar velocity measurements.

NIR Fundamental Plane Cluster Distances

19 clusters in common



Hubble Diagrams

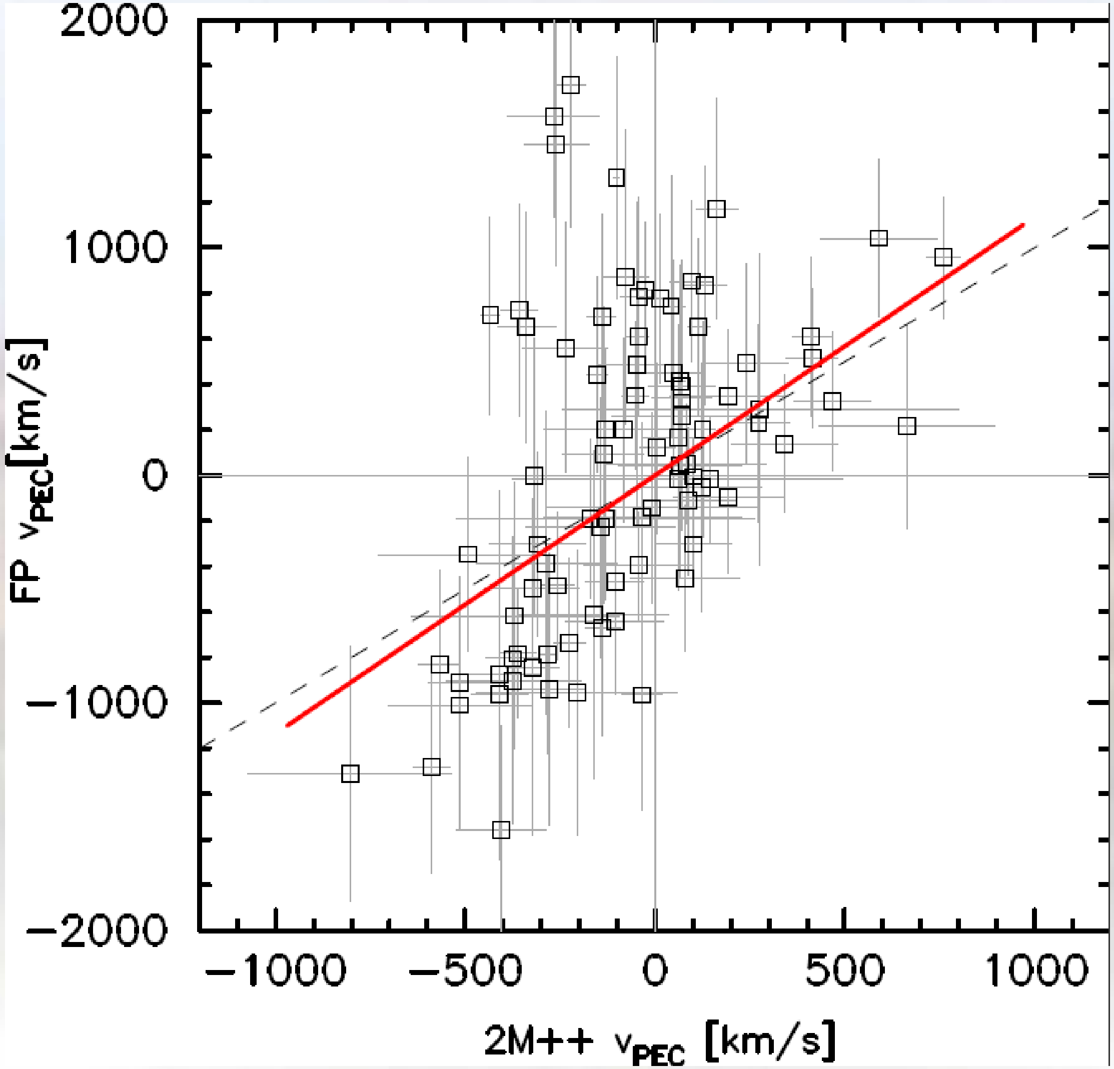


Lower chi-squared in CMB frame than the LG frame, i.e. 1.80 vs 2.16.

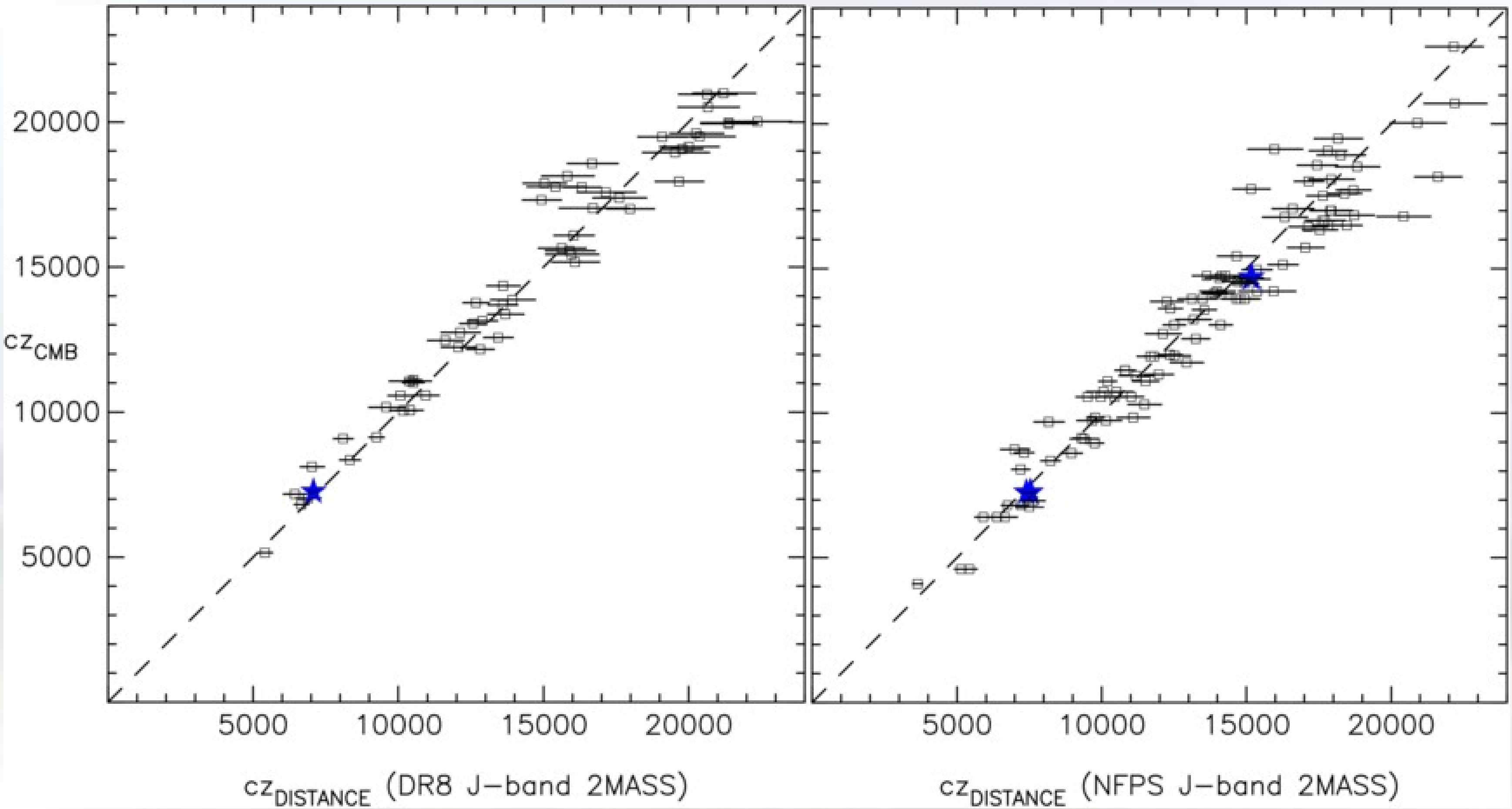
$$\chi^2_\nu = \frac{1}{n_{\rm cluster}} \sum_i^{\rm cluster} \frac{(v_{{\rm pec},i} - \mathbf{V} \cdot \hat{\mathbf{r}}_i)^2}{\epsilon_i^2}$$

Relative to our sample of 88 clusters we find a LG motion of 589 +/- 151 km/s towards (l,b) = (285+/-13, 15+/-10), i.e. we detect the expected reflex motion of the LG.

Comparison with the 2M++ Predictions



Beyond z = 0.055 is clearly a challenge



How to Get Good Sigma Measurements?

Get a very stable spectrograph; minimal focus changes.

Get sufficient S/N and take many repeat measurements, e.g. a set of standard fields (clusters?), under different observing conditions, etc, so that systematics can be adequately investigated to the 0.01 dex level.

Real time sigma measurements and quality control, i.e. continuous demonstration that the sigma measurements are reliable.

Ensure that the effective PSF is measured for each field observed; must take out any Dec dependence!

Future Fundamental Plane Prospects

Extensive, high quality, large area, multi-band photometry will enable an excellent all-sky set of Fundamental Plane photometric parameters to be measured.

New measurement of velocity dispersions from

Taipan
plus better linking to existing surveys, i.e.
SDSS, 6dFGSv, NFPS, SMAC, etc
will enable a high quality ‘all-sky’ sigma catalogue to be constructed.

The level of success that will be achieved is ultimately tied to how well we can control the systematics particularly in the velocity dispersion measurements.
This limitation has been known for > 25 years!

SF11 Galactic Extinction Works!