# Moving beyond the traditional fundamental plane

## - a delicate balancing act between systematic biases and gains

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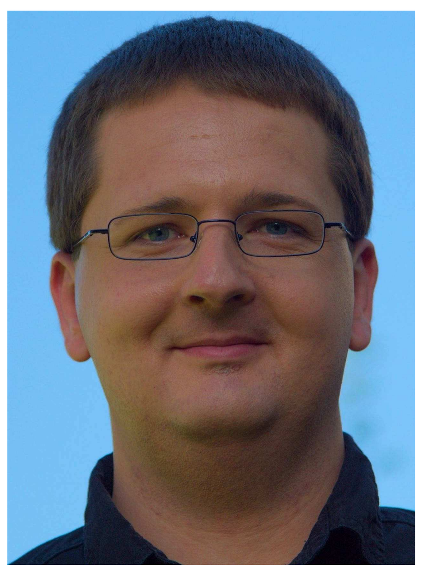

### Abstract

With the rise of large-scale spectroscopy surveys, the amount of self-consistent data has reach unprecedented magnitudes. This data can be used to derive a multitude of parameters for the targeted galaxies, which may help to further improve established tools, such as the fundamental plane of early-type galaxies. Using SDSS DR14 data, we identified about 290 000 early-type galaxies within a sample of more than 1 260 000 galaxies below a redshift of 0.5. Applying a group finder and the standard calibrations, we calibrated the traditional fundamental plane with these data sets. By carefully studying the residuals and the survey parameters, we managed to develop two improved versions of the traditional fundamental plane: the stellar mass fundamental (hyper-)plane and the dynamical fundamental plane. Each fundamental plane suffers from different systematic biases and corresponding statistical uncertainties. The main question is how much (hidden) redshift-dependence/bias, one is willing to tolerate for a substantial improvement in distance measurement. As a constancy test, we compared these new distances to other distance indicators such as supernovae Type Ia and the Tully-Fisher relation.

### Observational data

We used SDSS DR14 as the primary source of data for our project. For our applications, we selected all galaxies with spectroscopic data below a redshift of $z < 0.5$. Hence, our data set is composed of the SDSS main galaxy sample, the SDSS LRG (low- and high-z) sample, the BOSS low-z sample, and the BOSS CMASS sample. We used colour-cuts and the shape of the luminosity profiles to identify early-type galaxies within the basic data set. For additional calibrations, we took advantage of the kinematic data by Graham+2018 based on MaNGA as well as the SDSS-based value add catalogues by Maraston+2009.

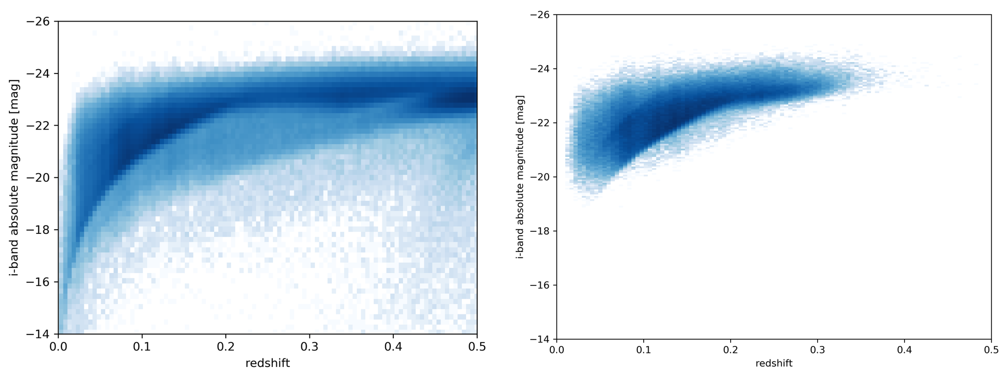

Figure 1: The redshift distribution of the 1 260 000 galaxies of our basic data set (left panel) and of the about 290 000 early-type galaxies (right panel) within it.

### Group finder

In order to collapse the redshift-space distortion caused by peculiar motions inside galaxy cluster, we applied a friends-of-friends group finder algorithm to our basic data set. We used the Millennium simulation re-run with WMAP7 parameters to create our mock-catalogues based on the SDSS/BOSS selection functions and calibrated the algorithm following the methods of Robotham+2011.

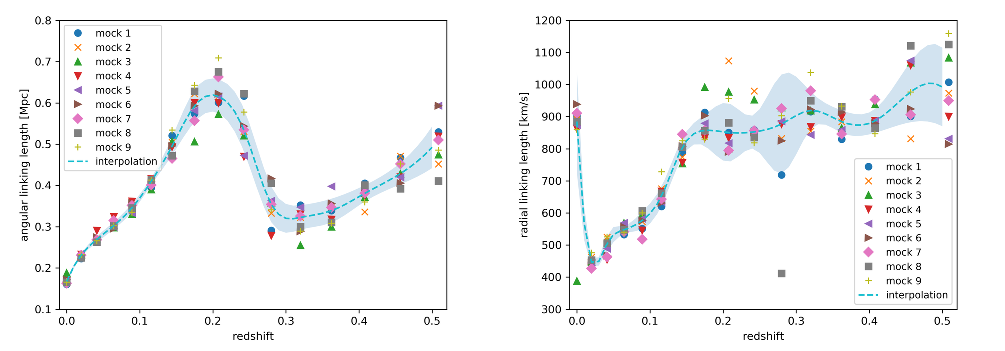

Figure 2: Projected (left panel) and angular (right panel) linking length as a function of redshift.

The thereby obtained catalogue of more than 1 000 000 groups (almost 100 000 with more than one detectable member) allows us to compare fundamental plane distances to Tully-Fisher relation distances for groups hosting both early-type and late-type galaxies.

### Traditional fundamental plane

The fundamental plane is an empirical relation between the physical radius $R_0$, the central velocity dispersion $\sigma_0$, and the surface brightness $\mu_0$ that can be used a redshift independent distance indicator.

$$\log_{10}(R_0) = a \cdot \log_{10}(\sigma_0) + b \cdot \mu_0 + c. \qquad (1)$$

It requires several calibrations that are actually redshift-dependent: Tolman-effect (purely physical), K-correction (physical and model-dependent), size-correction (physical and model-dependent), evolution (mostly model-dependent), and Malmquist-bias corrections.

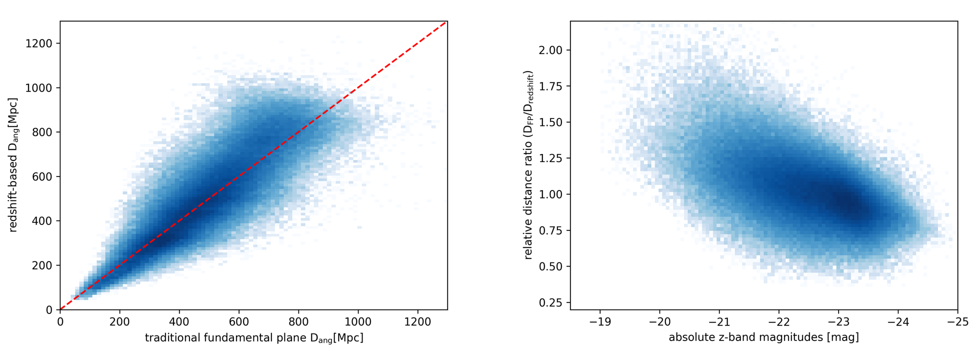

Figure 3: Left panel: The traditional fundamental plane has a scatter of $\sim 20\%$ in its distance estimate. Right panel: It systematically overestimates distances for intrinsically faint galaxies, while underestimating distances to bright galaxies.

### Stellar mass fundamental (hyper-)plane

The most dominant factor causing the scatter of the traditional fundamental plane are the stellar masses of the galaxies (Hyde & Bernardi. 2009).

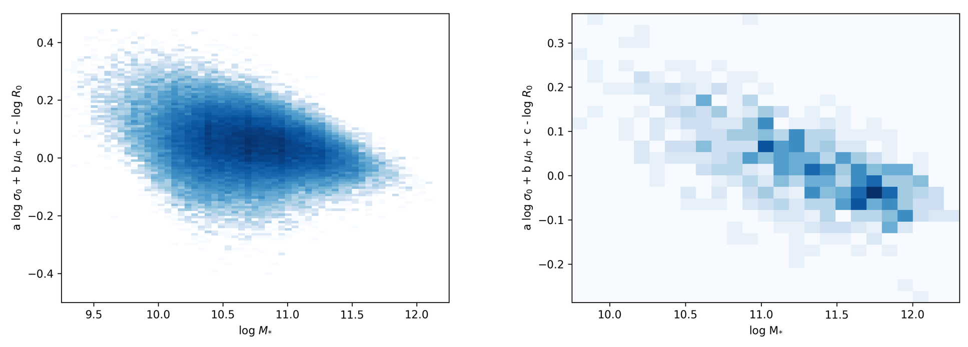

Figure 4: Left panel: The residuals of the traditional fundamental plane depending on the stellar masses by Maraston+2009. Right panel: The stellar mass dependence for MaNGA galaxies based on data by Graham+2018.

$$\log_{10}(R_0) = a \cdot \log_{10}(\sigma_0) + b \cdot \mu_0 + c + d \cdot \log_{10}(M_*). \qquad (2)$$

By adding an additional term depending on the stellar mass $M_*$ to the traditional fundamental, we were able to correct for that bias. However, all stellar mass models contain hidden information on the redshift (via absolute magnitudes) causing another systematic bias.

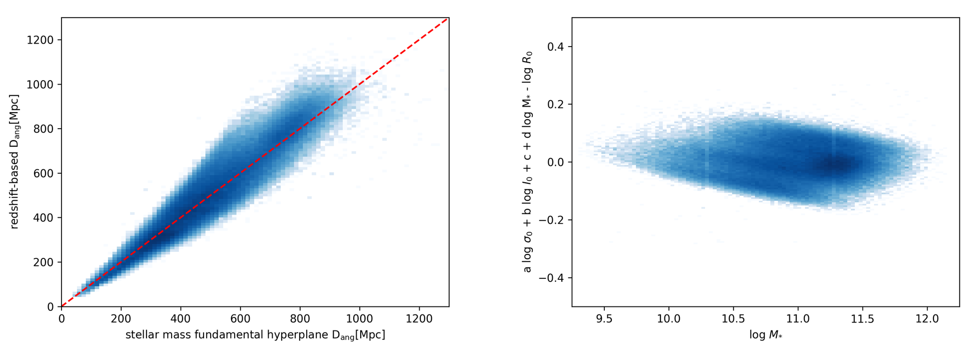

Figure 5: Left panel: The stellar mass fundamental hyperplane has a scatter of $\sim 12\%$ in its distance estimate. Right panel: No systematic dependence on the stellar masses.

### Dynamical fundamental plane

To avoid relying on any specific stellar mass model as well as to consider various selection biases and evolutionary effects with a specific model, we split the huge sample of 290 000 early-type galaxies in a tight set of overlapping bins. To keep our approach empirical and as model-independent as possible, we only split the sample in bins of directly observable quantities such as redshift and the apparent magnitude. We calculated the fundamental plane coefficients in each bin and fitted a 2D-function to the coefficients.

$$\log_{10}(R_0) = \overline{a_{fp}}(\log_{10}(z), m) \cdot \log_{10}(\sigma_0) + \overline{b_{fp}}(\log_{10}(z), m) \cdot \mu_0 + \overline{c_{fp}}(\log_{10}(z), m). \qquad (3)$$

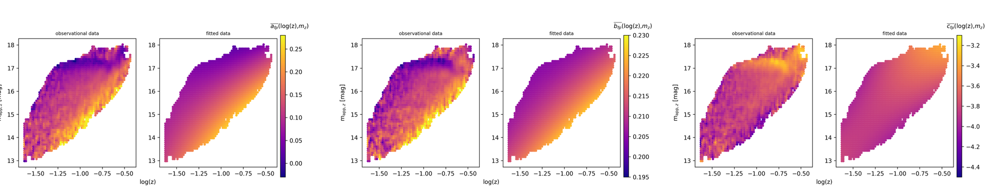

Figure 6: The coefficients of the dynamical fundamental plane from the observational data and th fitted 2D-function that were used for distance measurments.

Since we used a redshifts directly, we got additional systematics for the distance measurements. We estimated them (based on the typical peculiar velocity) to cause a additional systematic error of $\sim 2\%$ on top of the statistical error of our improved distance estimator of $\sim 3\%$. However, there might be additional systematics and biases hidden in our calibrations due to cross-correlations.

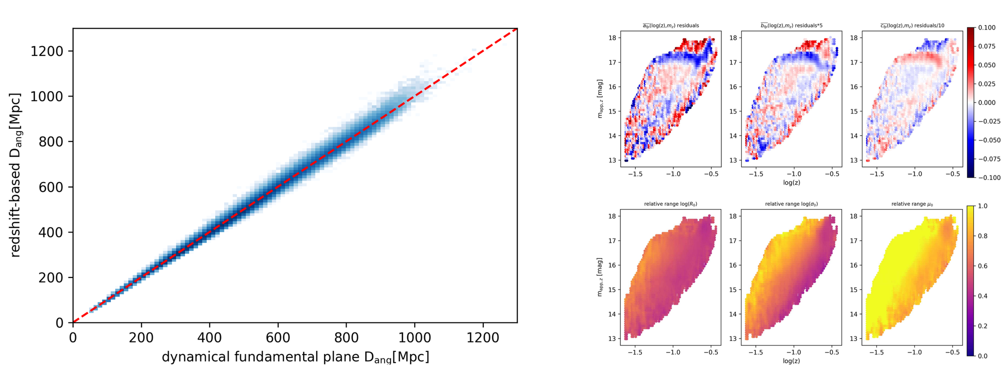

Figure 7: Left panel: The dynamical fundamental plane can reproduce redshift distance with only $\sim 3\%$ uncertainty. Upper right panel: The residuals of the dynamical fundamental plane parameters. Lower right panel: The bins do not limit the range of the fundamental plane parameters much.

### Comparison to other distance indicators

To test our methods, which were calibrated using redshift distances, we compared the distances derived from the traditional fundamental plane, the stellar mass fundamental plane, dynamical fundamental plane to distance measurements obtained from supernovae Type Ia and in the case of clusters also from the Tully-Fisher relation. Interestingly, the dynamical fundamental plane distance agree better with the Tully-Fisher relation distances (uncertainty $\sim 6\%$) than the redshift based distances do with the Tully-Fisher relation distances (uncertainty $\sim 7\%$).

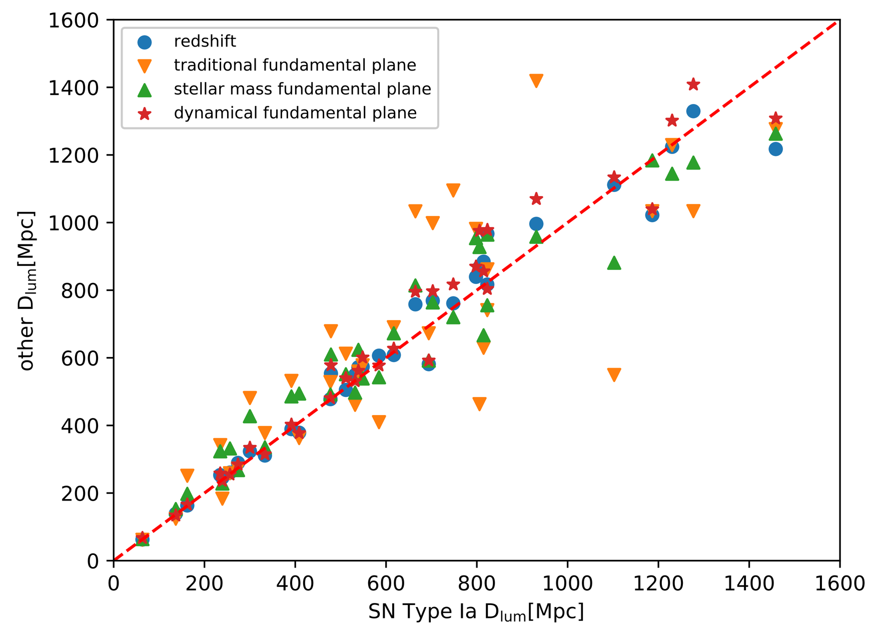


Figure 8: Comparing the distances measured for early-type galaxies in our sample that also happened to host a known Supernovae Type Ia (Betoule+ 2014) using different distance indicators.

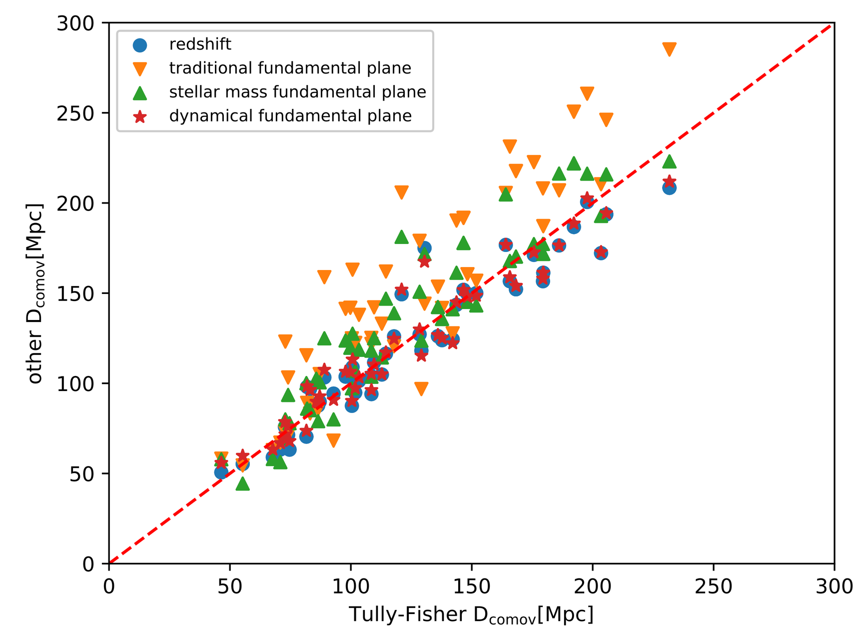


Figure 9: Comparing the distances measured for galaxy groups in our sample that host more than one galaxy for which we have fundamental plane distances and also more than one galaxy for which Tully-Fisher relation distances are available in the NASA/IPAC Extragalactic Database.

### Kinematic distances

With the rise of integral field spectroscopic surveys (MaNGA, Califa, SAMI), new opportunities to study well-known distance distance indicator such as the fundamental plane and the Tully-Fisher relation open up. In the last decade, we learned that early-type galaxies have significant rotational support, which is indicated by the $\lambda_{Re}$ parameter (Emsellem+2007). However, the naive approach does not provide an improvement, which means that a more sophisticated analysis is necessary to make use of the full potential of integral field spectroscopic data.

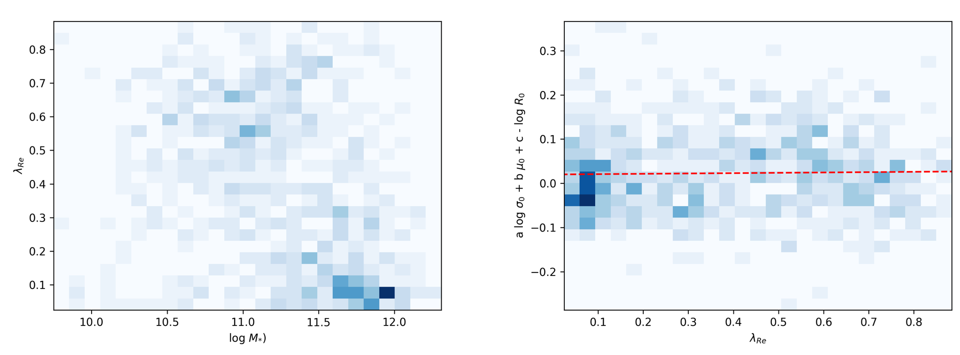

Figure 10: Left panel: There is a correlation between the stellar mass and the $\lambda_{Re}$ parameter in the MaNGA data. Right panel: No correlation between the $\lambda_{Re}$ parameter and the residuals of the traditional fundamental plane.