Improving fundamental plane distance measurements

- an intersection of observations, simulations, and data science

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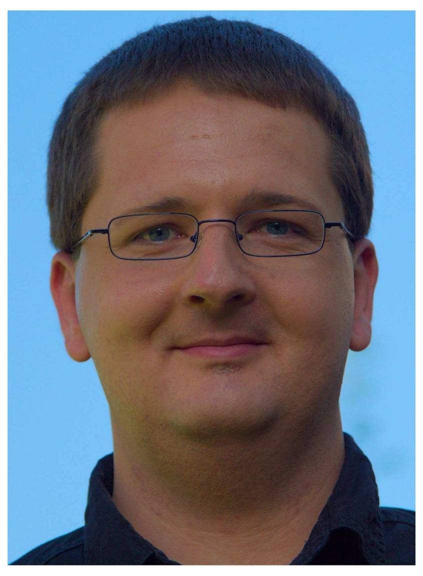

Abstract

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 can be used for to further improve established tools, such as the fundamental plane of early-type galaxies. Using SDSS DR14 data, we identify about 280 000 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 calibrate the classical fundamental plane with these data sets. By carefully studying the residuals and the survey parameters, we managed to develop a new dynamical fundamental plane that considers evolution, biases and intrinsic differences between early-type galaxies. Thereby, we managed to obtain significantly improved distance measurements. We also compare these new distances to other distance indicators such as supernovae Type Ia, Tully-Fisher relation, and BCG. In the future we will use this data to derive peculiar motions for a large area of the observable universe and compare the thereby obtained momentum power spectrum to mock catalogues based on the Horizon Run 4 simulation.

Observational data

We use SDSS DR14 as the primary source of data for our project. For our applications, we select all galaxies with spectroscopic data below a redshift of $z < 0.5$. Hence, our data set is composed of:

- SDSS main galaxy sample
- SDSS LRG (low- and high-z) sample
- BOSS low-z sample
- BOSS CMASS sample

We use colour-cuts and the shape of the luminosity profiles to identify early-type galaxies within the basic data set. For additional calibrations, we also use the kinematic data by Graham+2018 based on MaNGA as well as the SDSS-based value add catalogues by Simard+2011 and Mendel+2013.

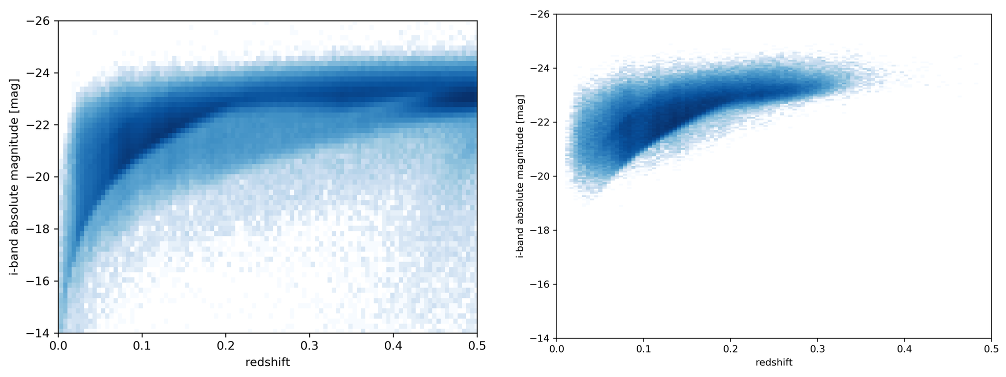

Figure 1: The redshift distribution of the 1 260 000 galaxies of our basic data set (left panel) and of the about 280 000 early-type galaxies (right panel) within it.

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. Since our data set was obtained by a multitude of programmes with different selection criteria (limiting magnitudes, colour cuts, ...), we created a set of mock-catalogues from the re-run of the Millennium simulation with WMAP7 parameters that reflect these constraints. With the help of these mock-catalogues that cover the entire redshift range of our observational data set, we optimized the linking lengths using the methods presented in Robotham+2011.

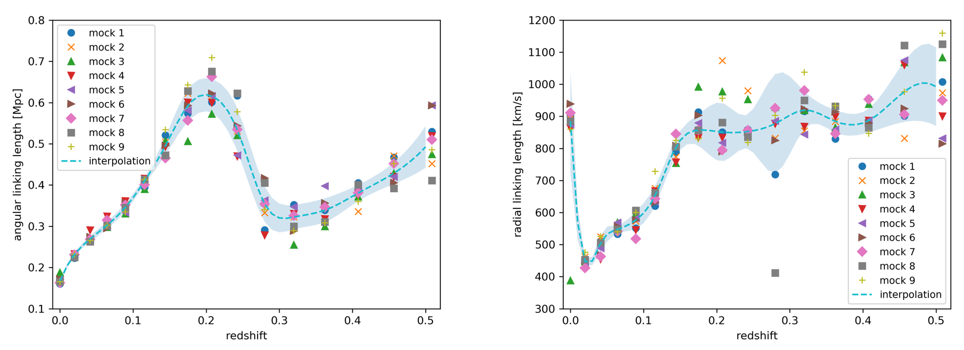

Figure 2: Projected (left panel) and angular (right panel) linking length as a function of redshift.

Applying our calibrated group finder algorithm on the observational data, we find about 1 090 000 groups (of which about 89 000 have more than one visible member). Aside from reducing the scatter introduced by peculiar motions in clusters, we could use our group catalogue to improve the distance estimates to all groups hosting more than one early-type galaxy by averaging their distance estimates. Furthermore, it also allows us to compare fundamental plane distances to Tully-Fisher relation distances for groups hosting both early-type and late-type galaxies.

Classical fundamental plane

The fundamental plane is an empirical relation between the physical radius R_0, the central velocity dispersion σ_0, and the surface brightness $\mu_0 = -2.5 \cdot \log_{10}(I_0)$ that can be used a redshift independent distance indicator.

$$\log_{10}(R_0) = a \cdot \log_{10}(\sigma_0) + b \cdot \log_{10}(I_0) + c. \quad (1)$$

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.

Dynamical fundamental plane

When studying the residuals of the classical fundamental plane using our huge sample of 280 000 early-type galaxies, we found that the absolute magnitude of the galaxies and their redshift (evolutionary state and selection bias) are the dominate factors contribution to the scatter of the fundamental plane. To keep our approach empirical and as model-independent as possible, we only use directly observable quantities such as redshift and the apparent magnitude as a prior for our improved calibrations:

- Bin sample galaxies in the log(z)-apparent magnitude plane
- Calculate the fundamental plane coefficients for each bin
- Remove bins with fewer than 100 galaxies
- Fit 2D-functions to the FP coefficients in the bins
- Use these fits instead of the static coefficients to derive the dynamical fundamental plane:

$$\log_{10}(R_0) = \overline{a_{fp}}(\log_{10}(z), m) \cdot \log_{10}(\sigma_0) + \overline{b_{fp}}(\log_{10}(z), m) \cdot \log_{10}(I_0) + \overline{c_{fp}}(\log_{10}(z), m). \quad (2)$$

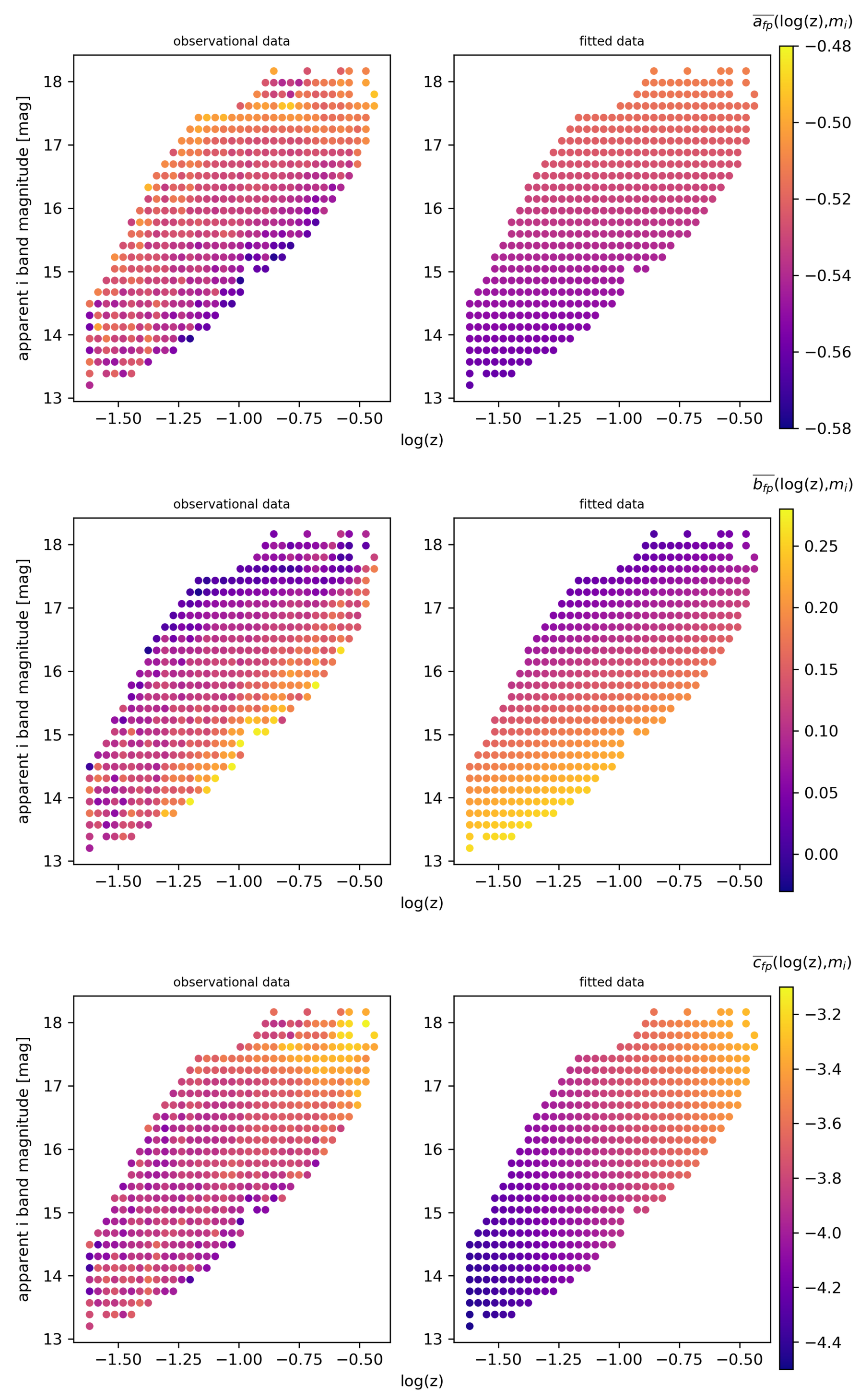

Figure 3: The coefficients of the dynamical fundamental plane. Left column: observational data plotted for the centre of each bin. Right column: values of the fitted planes for each coefficient in each bin.

There are still some systematic deviations for very nearby galaxies and very distance galaxies. At the moment, we only fit a plane for each coefficient, because higher order fits are too sensitive to individual outliers at the edges of the binned area. Since we use a redshifts as a prior, we get additional systematics for the distance measurements. We estimated them (based on the typical peculiar velocity) to cause a additional systematic error of $\sim 1\%$ on top of the statistical error of our improved distance estimator of $\sim 4\%$.

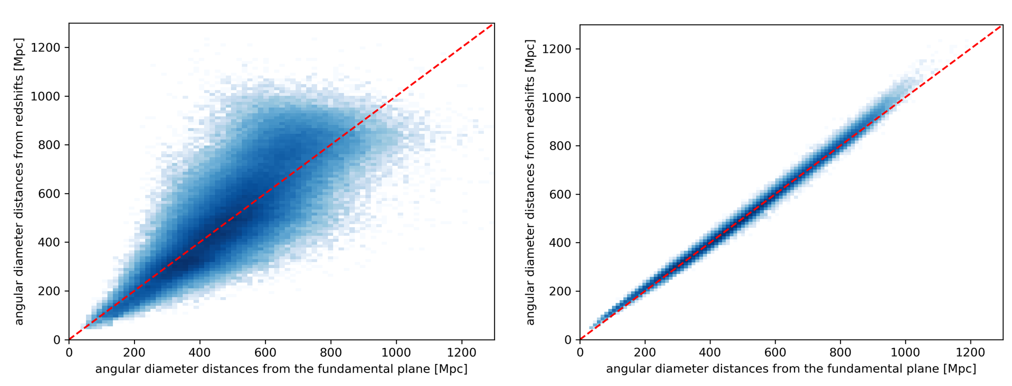

Figure 4: Comparing classical fundamental plane distances (left panel) to redshift distances yields a distance accuracy of about 18%, while the dynamical fundamental plane (right panel) is able to reduce the uncertainties down to about 5%.

Comparison to other distance indicators

To test our method, which was calibrated using redshift distances, we compare the distances derived from the dynamical fundamental plane to distance measurements obtained from supernovae Type Ia and in the case of clusters also from the Tully-Fisher relation. In the future, we will use the newly calibrated brightest cluster galaxies distances for additional comparisons.

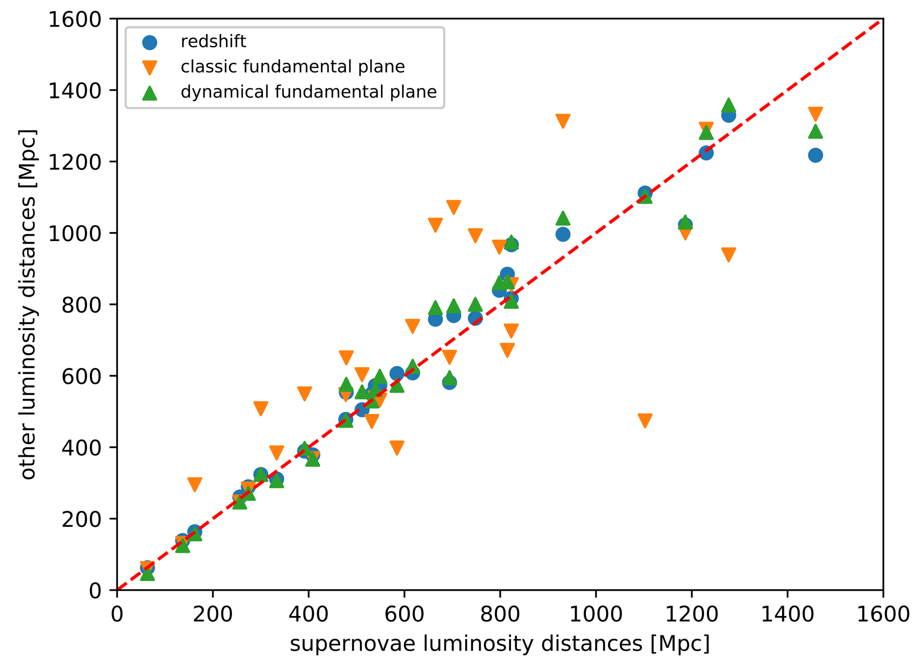

Figure 5: Comparing the distances measured for early-type galaxies in our sample that also happened to host a known Supernovae Type Ia (Betoule+ 2014) using different distance indicators.

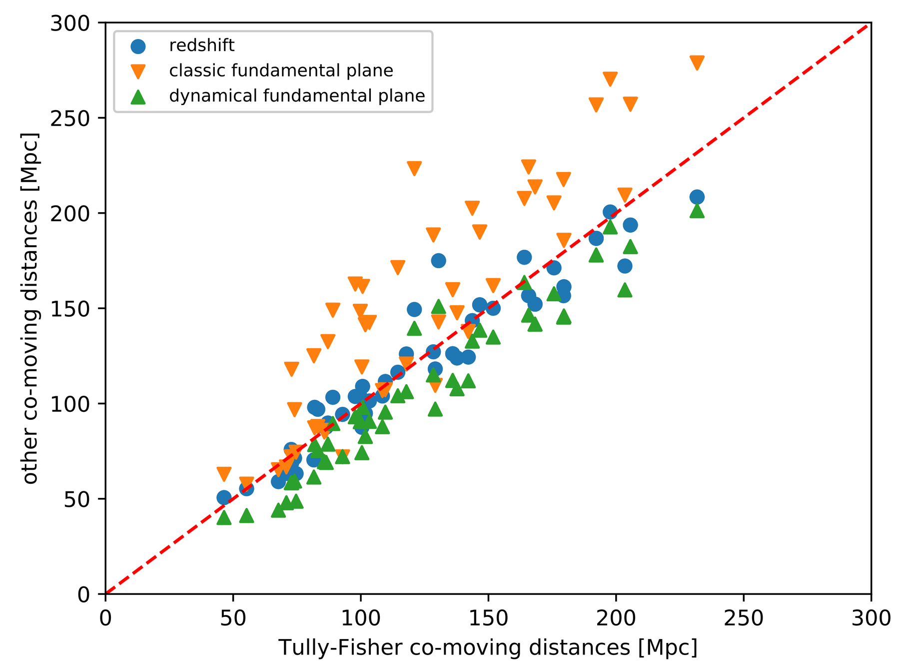

Figure 6: Comparing the distances measured for galaxy groups in our sample that host more than one galaxy for which we have fundamental plane distances and also more than one galaxy for which Tully-Fisher relation distances are available in the NASA/IPAC Extragalactic Database.

Momentum power spectrum

In the future, we will use the peculiar motions derived with the help of our improved fundamental plane calibrations to study the power spectrum of the cosmic momentum field (Park2000) and measure the $\beta = \Omega_m / b$ parameter.

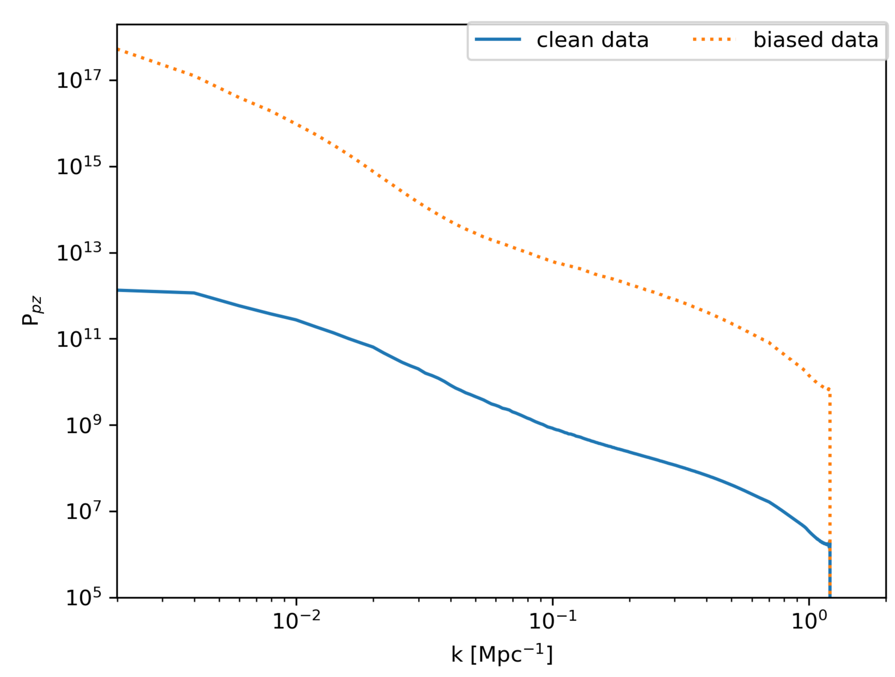

Figure 7: The momementum power spectrum derived from Horizon Run 4 considering various observational biases (orange dotted line) such as the scatter of the dynamical fundamental plane.