Using the fundamental plane to map peculiar motions in large-scale surveys

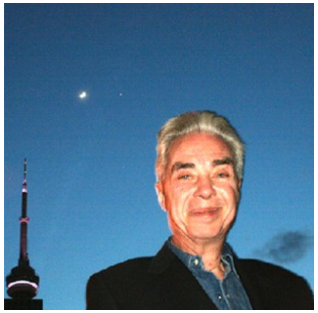
ESO lunch talk

by **Christoph Saulder**
(Korea Institute for Advanced Study)

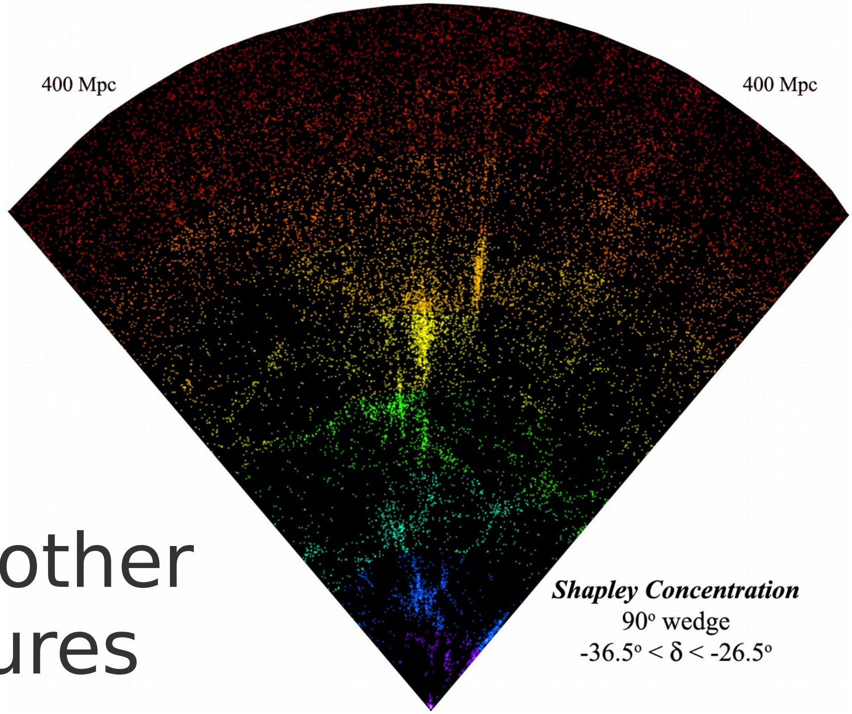
Tuesday, 4th of September 2018

Collaborators

- Christoph Saulder (KIAS)
- Ian Steer (NED)
- Owain Snaith (KIAS)
- Changbom Park (KIAS)

Peculiar motions

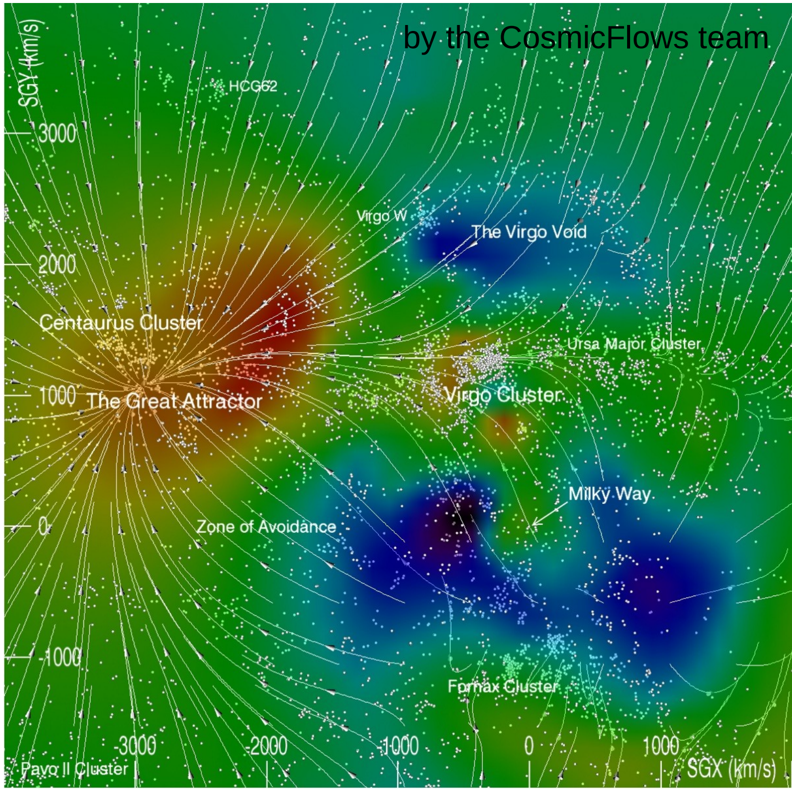


by Thomas Jarrett (IPAC/Caltech)

- Galaxies are not sitting still
- Motion induced by gravity of other galaxies/clusters/superstructures
- Visible as redshift space distortions:
  - Finger of God effect (random motion inside clusters)
  - Kaiser effect (coherent infall into clusters)
  - Bulk flows (motion of clusters and galaxies towards superstructures)

Peculiar motion studies

- At the moment:
- CosmicFlows-3 (Tully+ 2016)
  - Uses primarily Tully-Fisher relation data
  - Collects data from various sources (and methods)
  - All sky



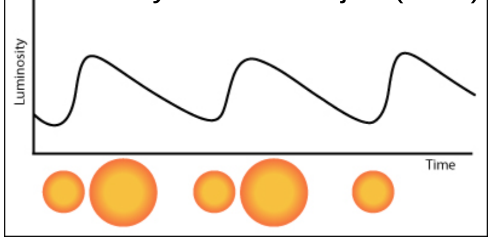
- 6dFGSv (Springob+ 2014)
  - Uses the fundamental plane
  - Only Southern hemisphere (6dFGS follow-up)

Measuring peculiar motions

- Observed redshift = cosmological redshift + redshift caused by peculiar motions + gravitational redshift (usually negligible)
- Cosmological redshift predicted by the expansion of the universe (Hubble flow)
- Compare observed redshift at a certain distance to the predicted one
- Requires a (mostly) redshift-independent distance indicator
- Lots of systematic biases need to be considered

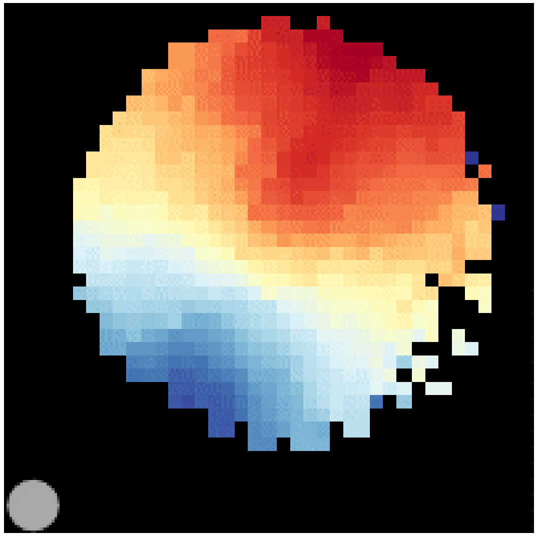
Distance indicators

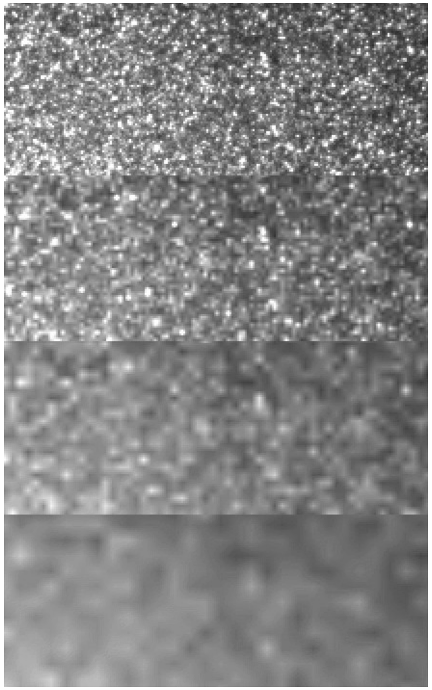
- *Redshifts*
- Cepheids
- Supernovae Type Ia
- Surface brightness fluctuation
- Tip of the red giant branch
- Tully-Fisher relation
- **Fundamental plane**
- Kinematic distances
- ...



by Helmut Jerjen (ANU)


by NASA

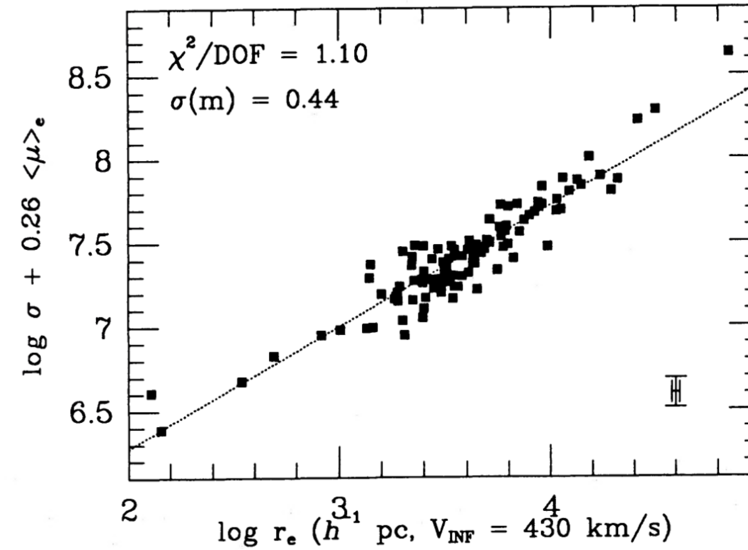

by SAMI


by Anon found at cosmoquest.org

The traditional fundamental plane

- Found as a generalization/unification of the Faber-Jackson relation and the Kormendy relation

$$\log(R_0) = a \log(\sigma_0) + b\, \mu_0 + c$$



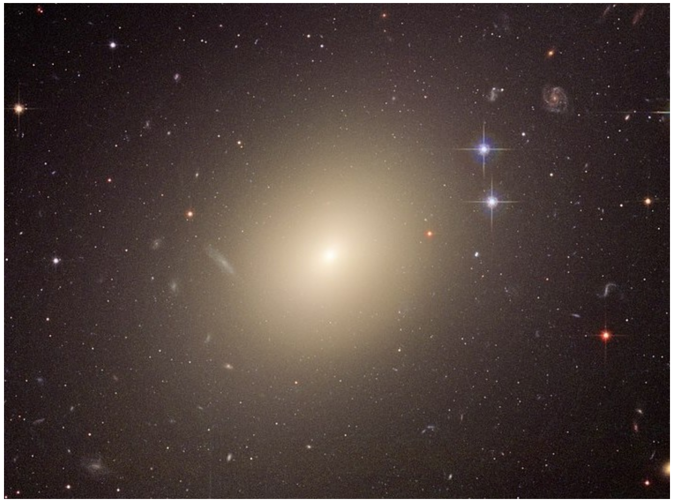
by Djorgovski&Davis 1987

- physical radius R_0 is distance dependent
- central velocity dispersion σ_0 and surface brightness μ_0 are distance independent
- Distance accuracy of about 20%

Selecting early-type galaxies

- Previously, we used GalaxyZoo, which limited us the galaxies within the sample of SDSS DR7

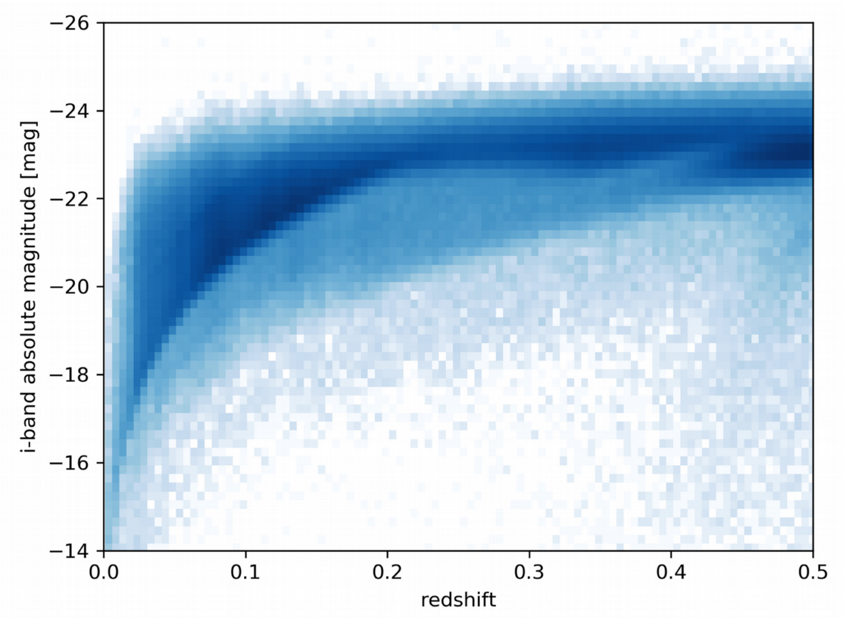
- Selection only by galaxy parameters
  - 60km/s < σ_0 < 420 km/s
  - decent quality data
  - Ellipticity small than 0.7
  - Likelihoods of the light profile (de Vaucouleurs profile is best fit)
  - Colour cuts (red sequence galaxies only)

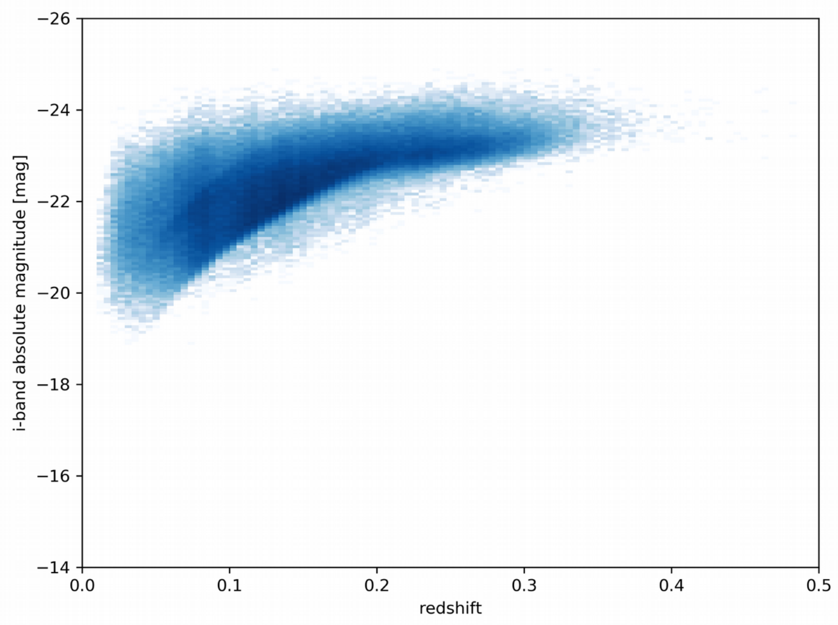


by NASA, ESA, and
The Hubble Heritage Team

The largest sample for fundamental plane calibrations ever used

- **~290 000 early-type galaxies**





Previous large samples: ~120 000 (Saulder+ 2015), ~90 000 (Saulder+ 2013), ~50 000 (Hyde+ 2009), ~10 000 (Campbell+2014), ~9 000 (Bernardi+ 2003)

Obtaining σ_0

- Usually measured using fibre spectroscopy with fixed fibre diameters (e.g. SDSS: 3 arcseconds)
- At different distances, different fractions of the galaxies are covered
- Fibre correction by Jorgensen+ 1995 and Wegner+ 1999

$$\sigma_0 = \sigma_{obs} \left(\frac{r_{fibre}}{r_\circ / 8} \right)^{0.04}$$

- Data on central velocity dispersions is rare:
  - 6dFGS follow-up (6dFGSv)
  - SDSS/BOSS
  - Taipan galaxy survey (upcoming)

Obtaining R_0

- observed angular radii r_{obs}
- circularized angular radii r_{circ} $$r_{\circ} = r_{obs} q_{b/a}$$
- secondary distance indicator required for calibrations: redshifts
- angular diameter distances D_A
- simple trigonometry → R_0
- For distance measurements: we go compare the observed R_0 with the predicted R_0

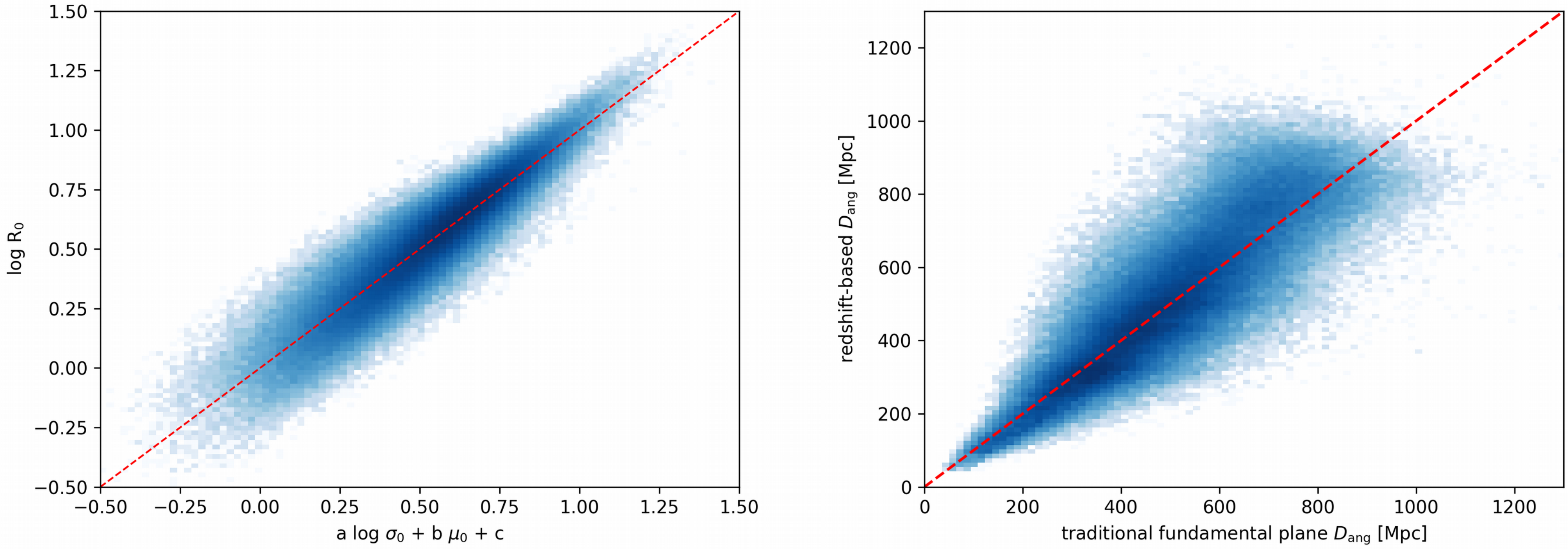
Obtaining μ_0

- Observed magnitudes m_{obs} and circularized angular radii r_{circ}
- Extinction corrections and K-corrections (redshift-dependent, but physically understood)
- Evolution correction: $Q \cdot z$ (model and redshift dependent correction)
- → apparent magnitude: m_{app}
- Surface brightness:

  $\mu_0 = m_{app} + 2.5 \cdot \log(2\pi \cdot r_{circ}) - 10 \cdot \log(1+z)$
- Tolman correction (physically understood)

Fitting the fundamental plane

- Direct fit minimizes errors in R_0 (Sheth+ 2012)
- For SDSS bands: the redder the better
- Scatter of 20.2% in z band



Improving the fundamental plane

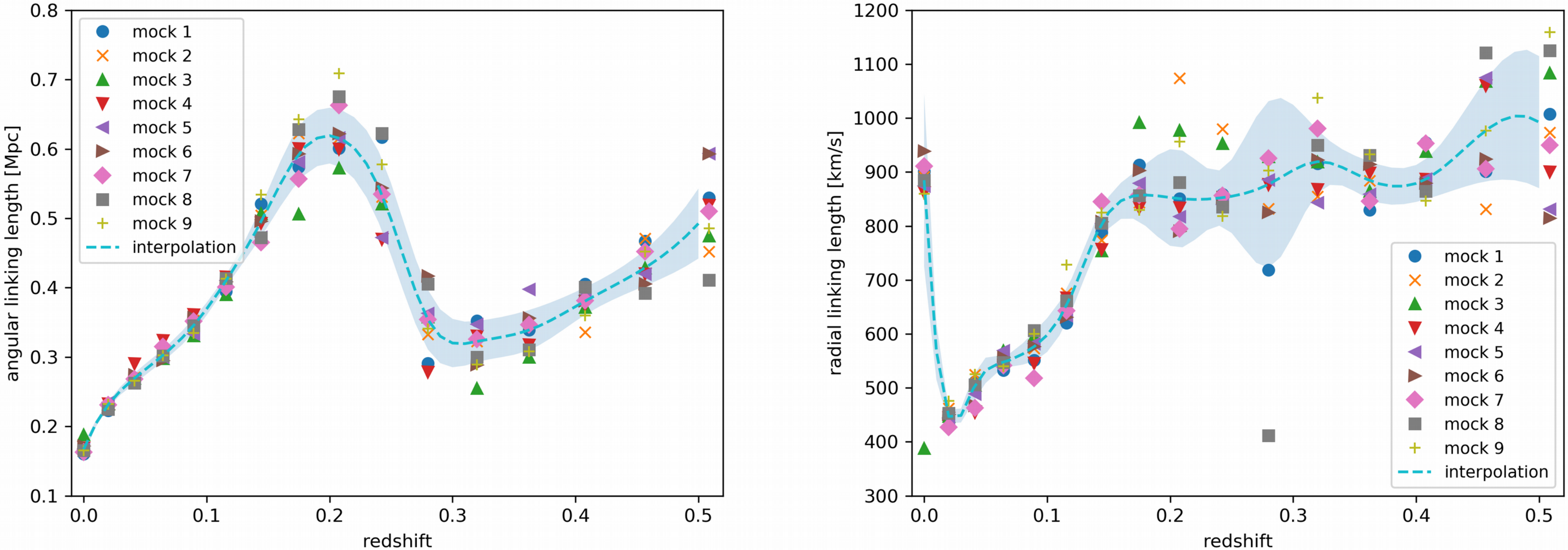
- Re-estimating the evolution correction

- Group finder
  - Use median group redshift instead of individual redshifts for distance calibration
    (collapses finger-of-god effect)
  - Calculate the median FP-distance for every group hosting more than one ETG
    (better distances for rich groups/clusters)

- Find additional correlations, study residuals to better understand the biases

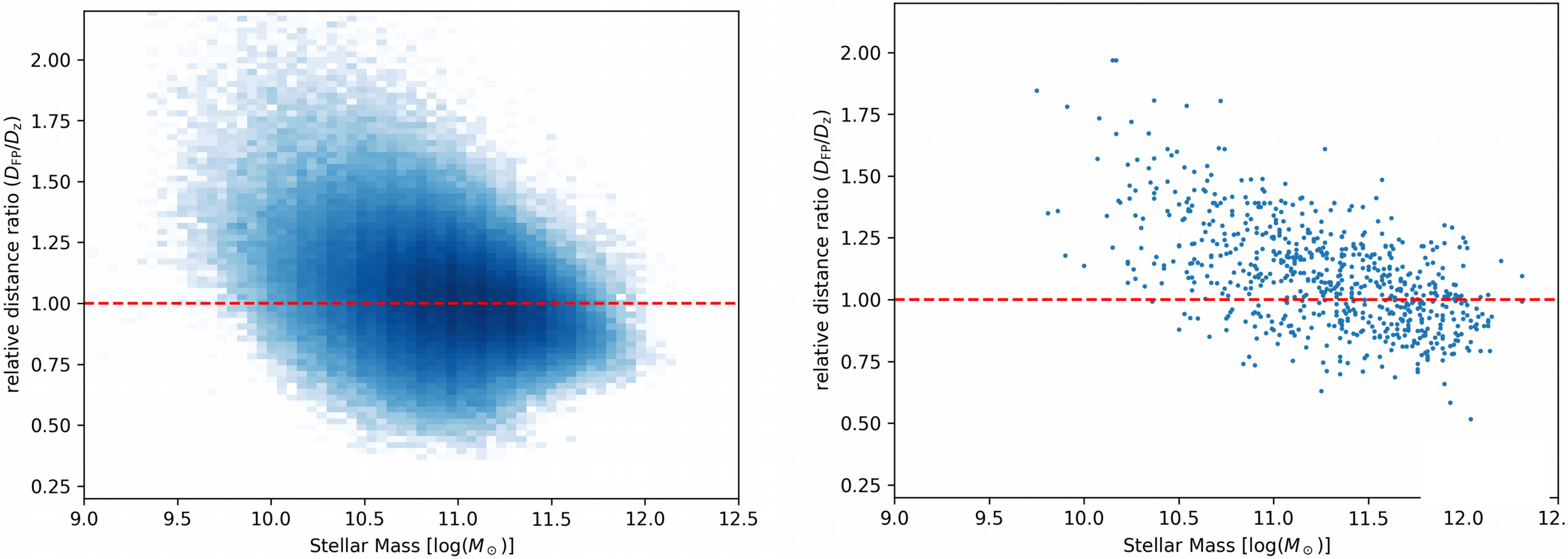
Group finder

- FoF-group finder (Snaith+ in prep., based on Duarte&Mamon 2014 and Robotham+ 2011)
- Linking lengths calibrated for SDSS/BOSS using mock-catalogues derived from the WMAP7 rerun of the Millennium simulation (Guo+ 2013)



Fundamental plane residuals

- Environmental effects: only secondary as a consequence of the morphology-density relation (the brightest ETGs are typically in clusters)
- Strong dependence on (red) absolute magnitudes
- Most striking dependence is on the stellar mass



The stellar mass fundamental hyperplane

- Stellar mass fundamental plane (just replacing μ_0 by $\log(M^*)$) does not reduce the overall scatter

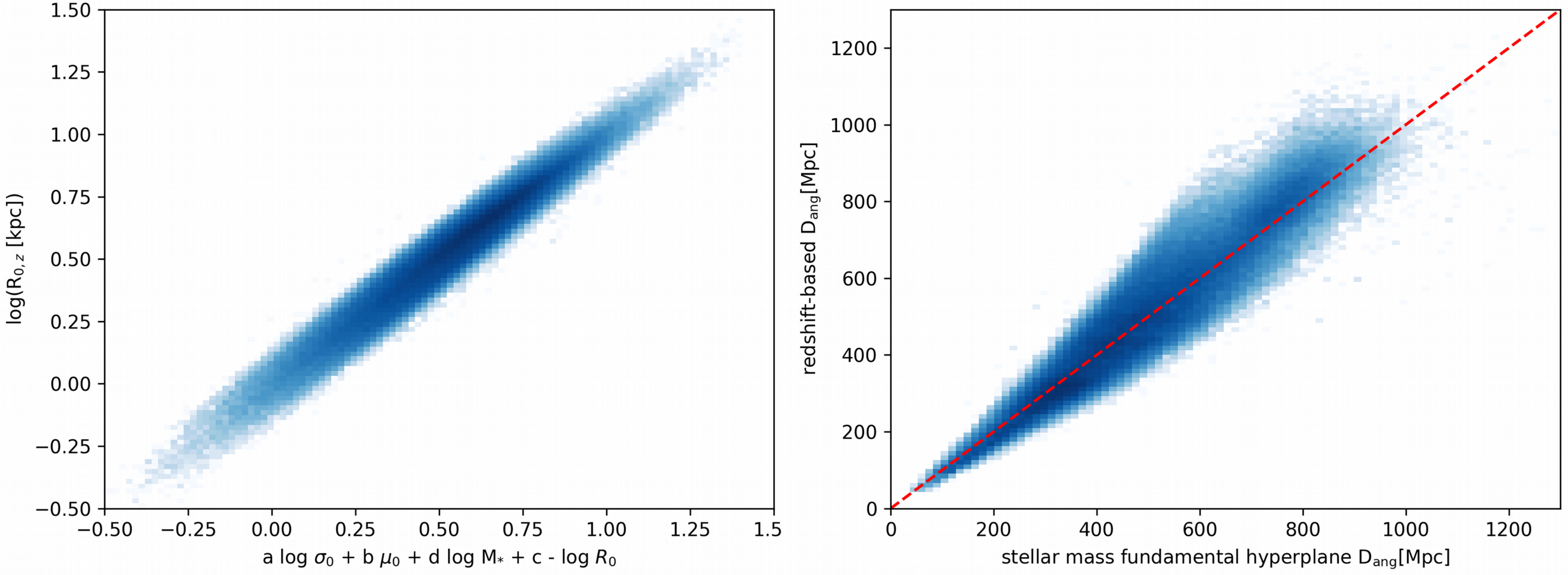
- Adding a new term proportional to the stellar mass

  $\log(R_0) = a \log(\sigma_0) + b\,\mu_0 + \mathbf{d\,log(M_*)} + c$

- The new term mainly "steals" contributions from the $a \log(\sigma_0)$ term.

- Reduces the statistical error to only 12.3%

- The stellar mass is not a measurable quantity
- Systematic bias because of hidden redshift dependence (adds ~2% systematic error)
- Model dependent (we use Maraston+ 2009)



The dynamical fundamental plane

- The traditional fundamental plane is biased
- The scatter of the traditional FP is large (20%)
- There are hidden redshift dependences in the traditional FP (evolution correction, selection, ...)
- Stellar masses are model dependent (which model is the best?) and cannot be observed directly

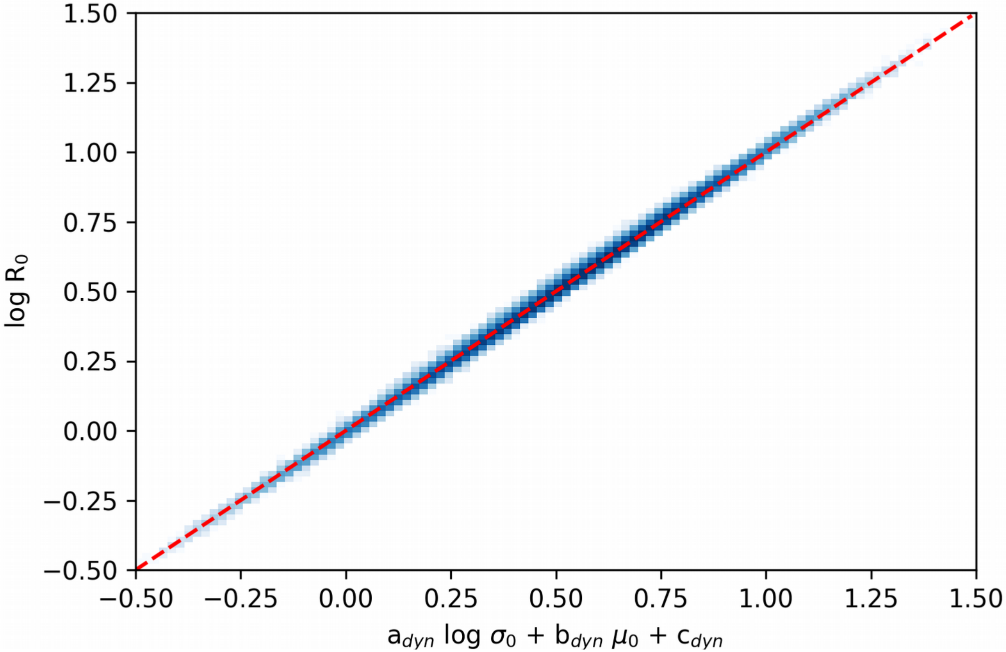
Let’s go nuts!

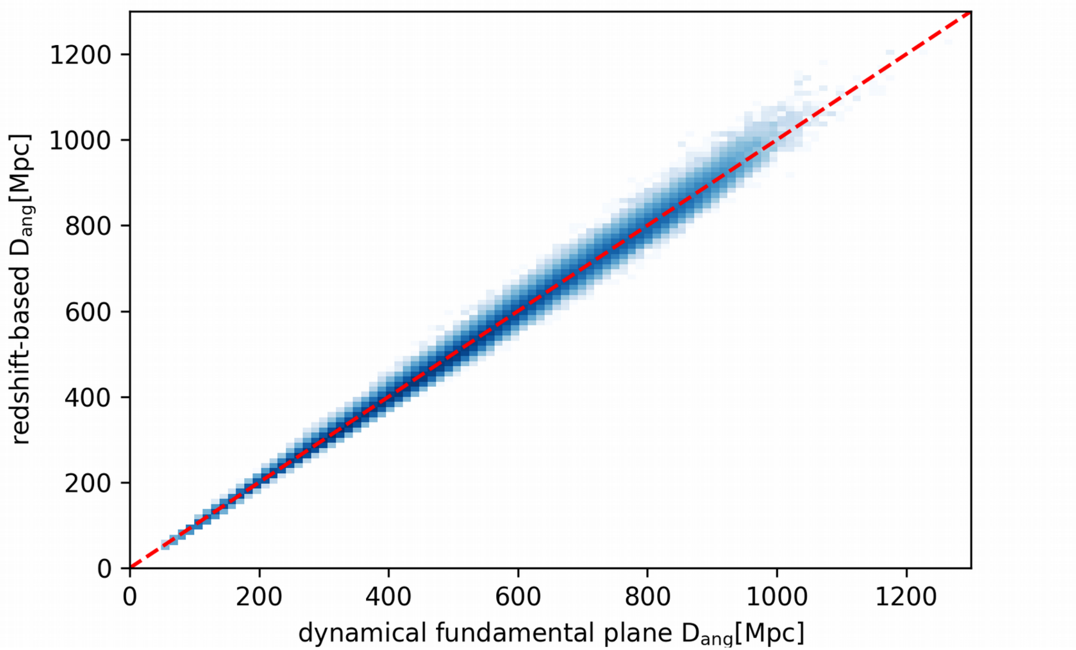
and make the redshift dependence explicit

FP coefficients now depend on apparent magnitudes and redshifts (observational quantities)

$$\log(R_0) = a_{dyn}(m,z)\,\log(\sigma_0) + b_{dyn}(m,z)\,\mu_0 + c_{dyn}(m,z)$$

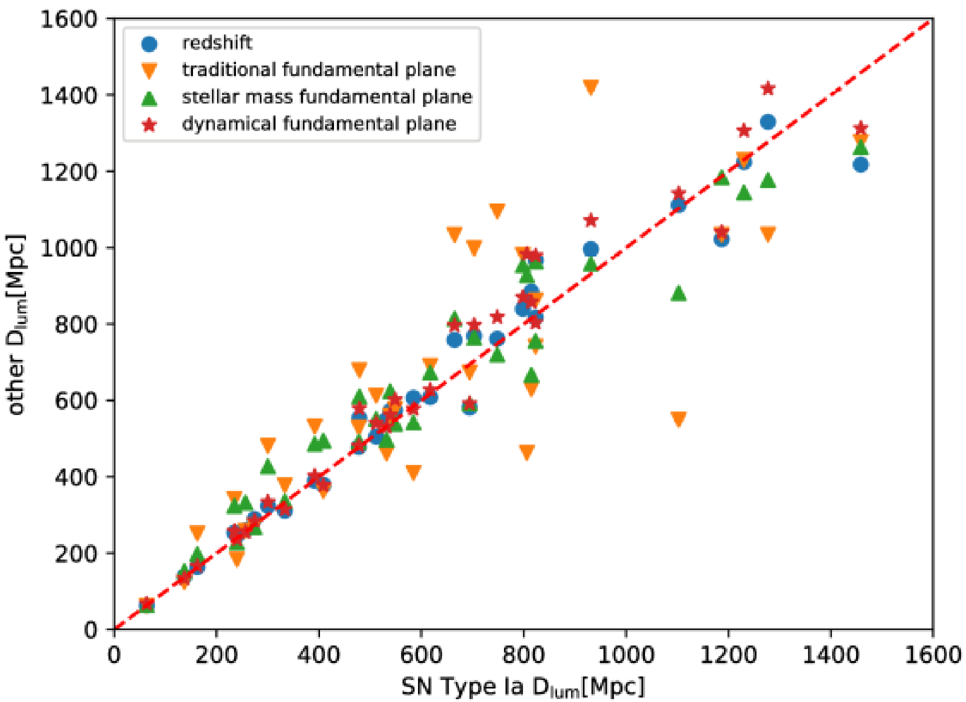
- Functions for the coefficients obtained by binning
- Statistical error down to 3.5% (when comparing to redshift distances), but notable systematics
- Combined redshift-FP distance indicator … does it carry information of peculiar motions?

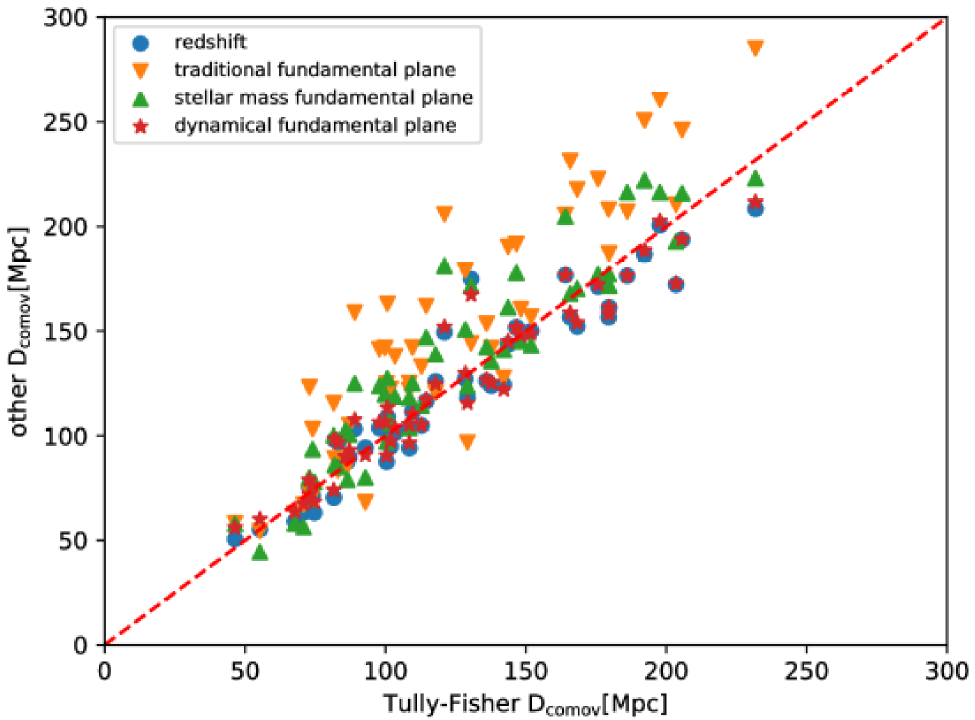




Comparison to other distance indicators

- Supernovae Type Ia distance (Betoule+ 2014)
- Tully-Fisher relation distances (NED-D)
- Systematic bias at low distances due to the SDSS saturation bias



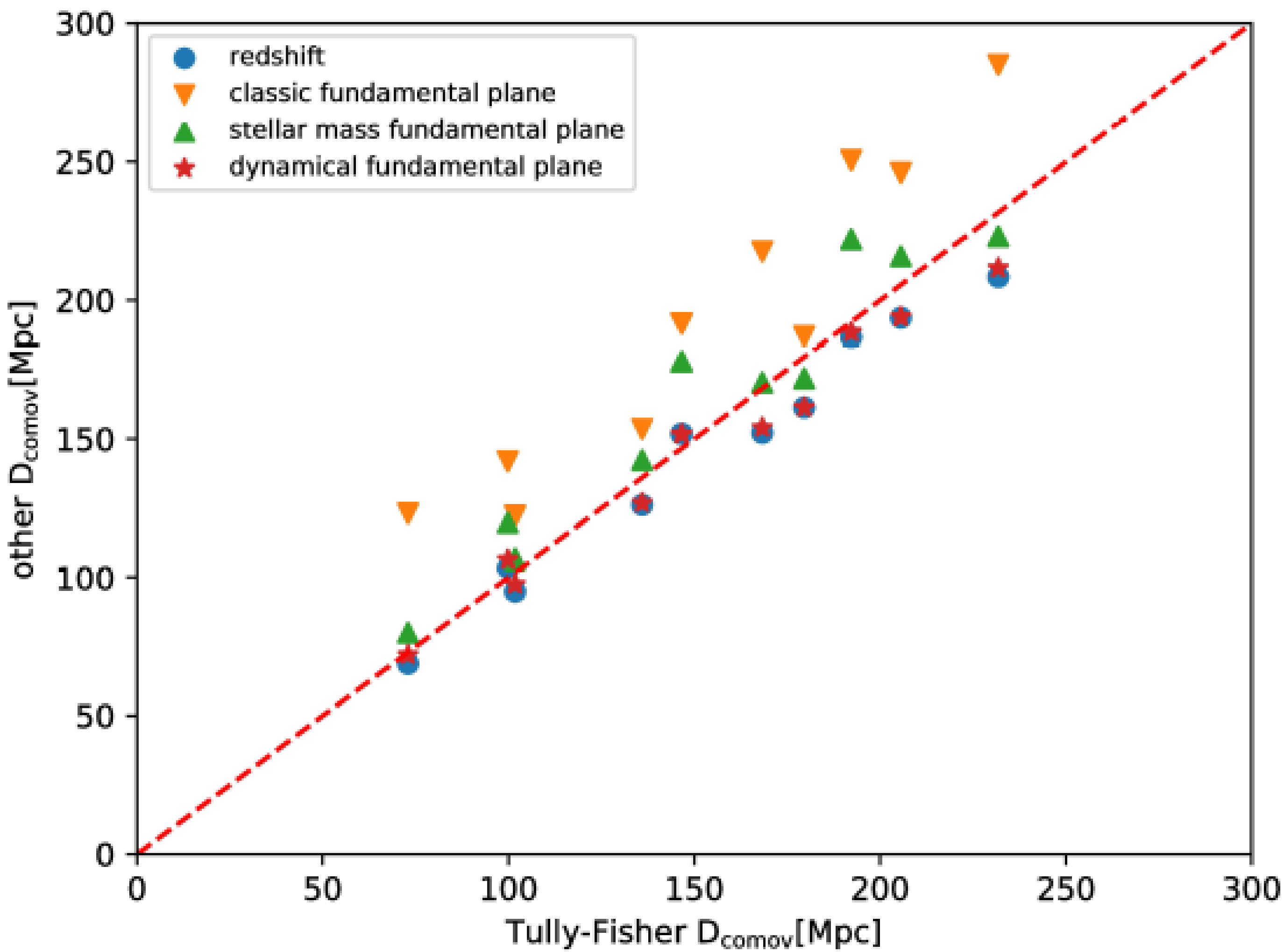


Trading gains and biases

- All fundamental planes are biased in different ways
- How much systematic error is one willing to accept for a reduced statistical error?
- Systematics will bias the peculiar velocity field, but with too much statistical uncertainty we do not have sufficiently good data.
- A balancing act that might not be necessary any more in the future (→ kinematic distances)

- Surprise correlation for between the dynamical fundamental plane and the Tully-Fisher relation for rich* clusters

*Clusters with at least two galaxies with fundamental plane data and at least two galaxies with Tully-Fisher data



Dynamical fundamental plane distances agree better with Tully-Fisher distances than redshift-based distances agree with Tully-Fisher distances

TF-dFP error: ~6%
TF-redshift error: ~7%

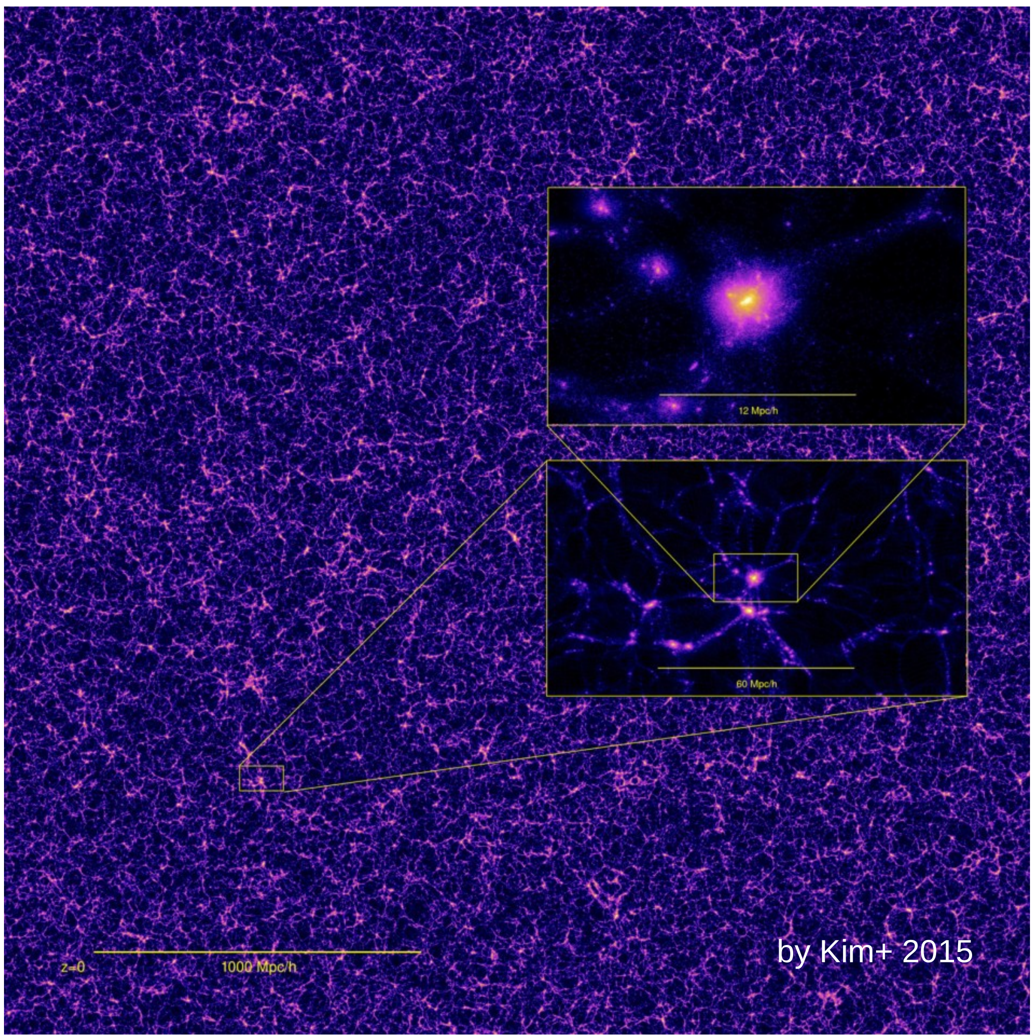
A correlation between two mutually exclusive distance indicators (no shared galaxies)

Peculiar motions from our dataset

- Work in progress ...
- Quality selection of our 290 000 fundamental plane distances
- Only the richest and most massive cluster hosting many ETG (with FP distances)
- Almost 3500 clusters with 10 or more ETG
- Trouble with the SDSS saturation bias (especially for the traditional fundamental plane)
- Our goal: largest peculiar velocity dataset produced by using the same (self-consistent) method

HorizonRun 4

- Huge cosmological simulation (DM-only)
- Cube: 3150 Mpc/h side length



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Momentum Power Spectrum

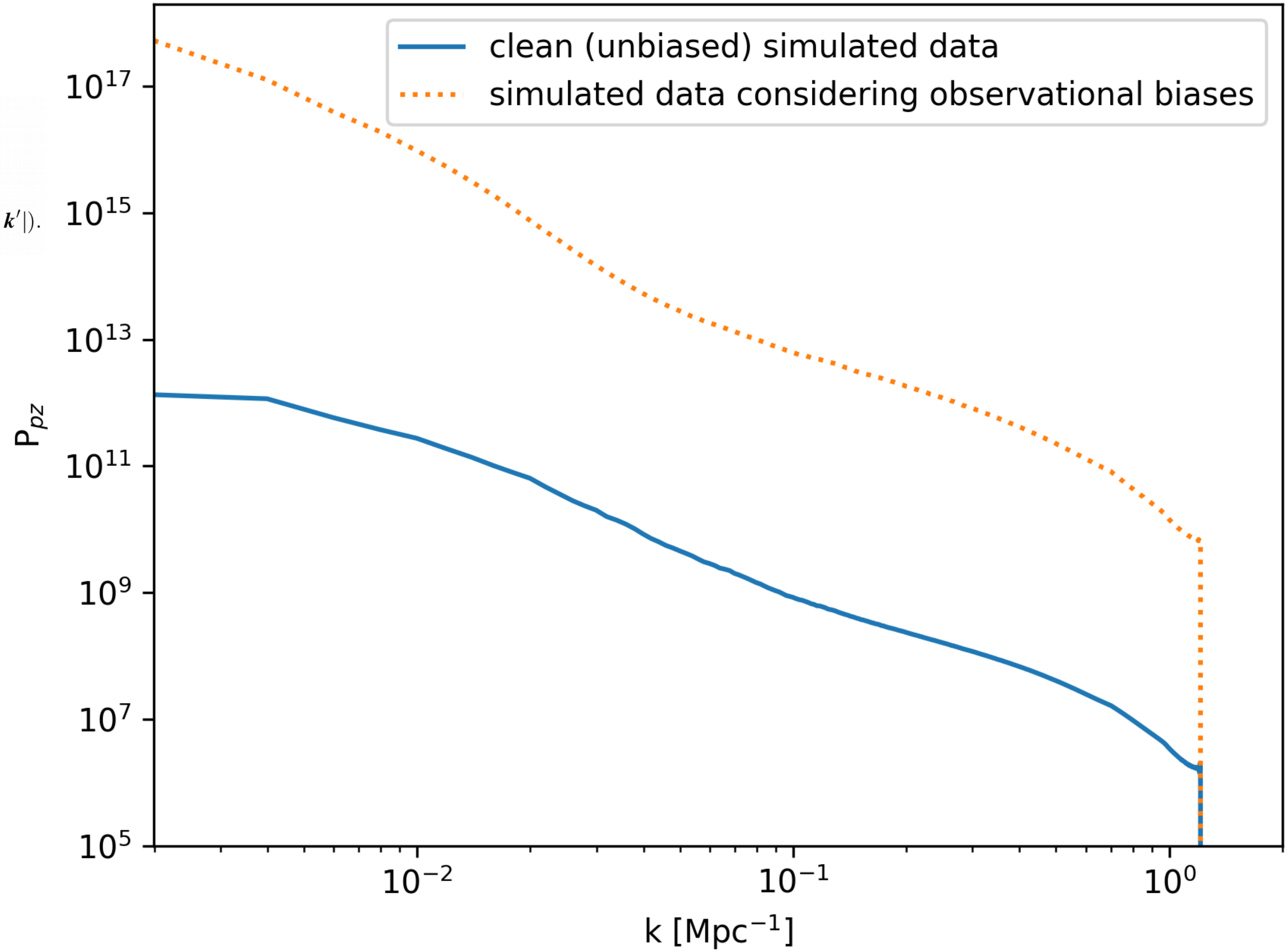
- Following Park+ 1994,2000,2006

$$P_p(k) \approx P_v(k) + P_{\delta v}(k)$$
$$= (DHf)^2 \frac{P_\delta(k)}{k^2}$$
$$+ \frac{1}{2}\left(D^2 Hf\right)^2 \int \frac{d^3k'}{(2\pi)^3} \frac{k^2}{k'^2 |\boldsymbol{k} - \boldsymbol{k}'|^2} P_\delta(k') P_\delta(|\boldsymbol{k} - \boldsymbol{k}'|).$$

$$P_v(k) = (H_0 \beta)^2 \frac{P_{\delta_g}(k)}{k^2},$$

$$\beta_S(k) = \frac{P_p^{\text{obs}}(k)}{P_p^{\text{der}}(k)}.$$

$$\beta_S = \Omega_m^{0.6} / b_S$$

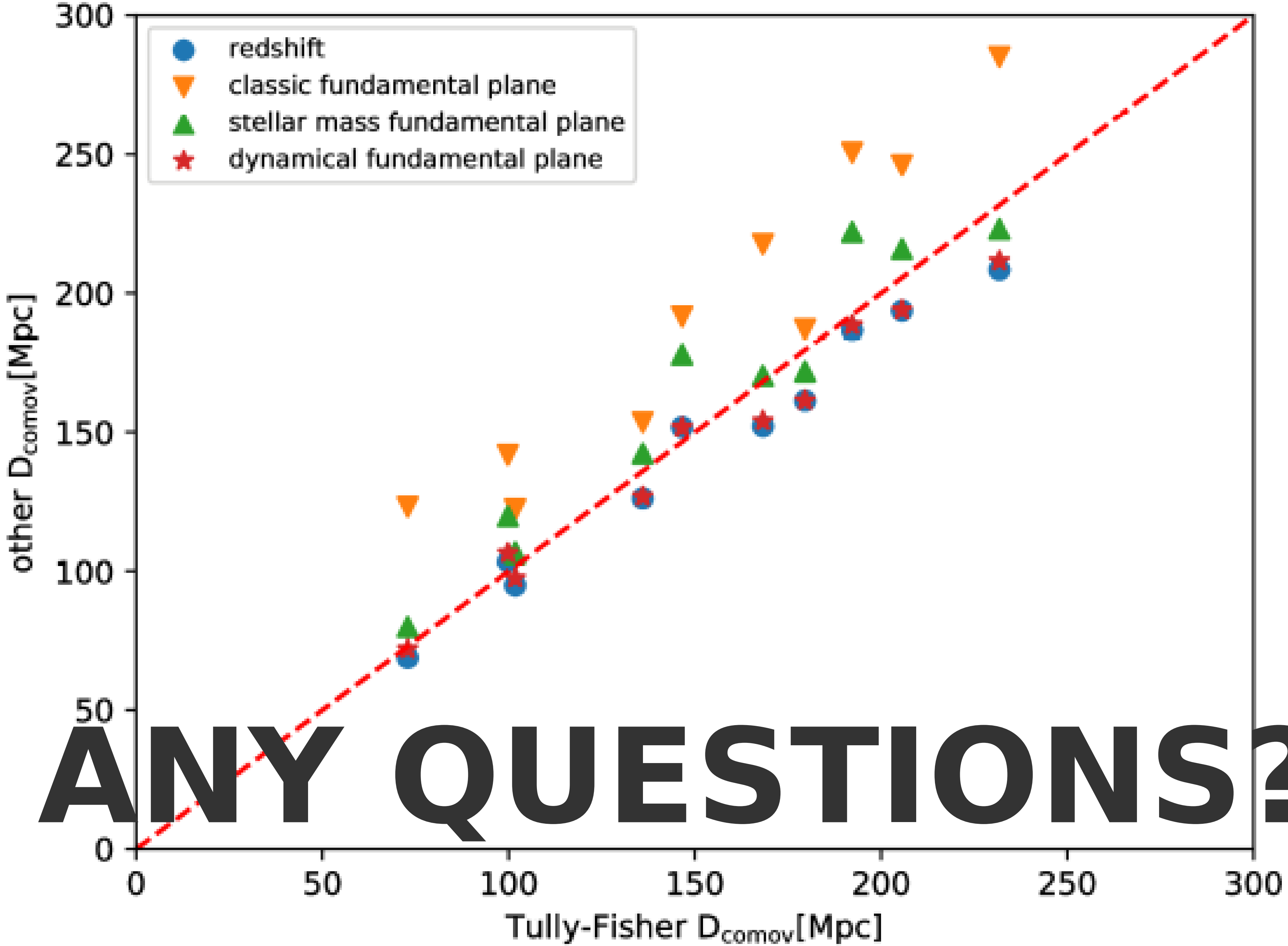


- Biennial conference
- Seoul, Republic of Korea
- Korea Institute for Advanced Study
- November 4 – 9
- always fancy posters

Summary and Conclusions

- Peculiar motions are a hot topic again, currently profiting from the era of large-scale surveys
- The fundamental plane and the Tully-Fisher relation are the main tools for large data sets
- With the rise of IFU-surveys and recent advances in understanding the dynamics of galaxies → new (more precise) distance indicators
- The fundamental plane is biased
- Strong dependence on the stellar mass
- Corrections cause systematic biases
- Systematic biases vs. statistical errors

- Traditional fundamental plane: ~20% scatter
- Stellar mass fundamental hyper-plane: ~12% scatter and ~2% systematic bias
- Dynamical fundamental plane: ~3.5% scatter, but strong systematic bias
- Is the dynamical fundamental plane a combined redshift-fundamental plane distance indicator?
- Surprisingly tight correlation with Tully-Fisher relation distances … causation?
- 290 000 fundamental plane distances: largest sample of FP distances yet (Saulder+ in prep.)
- Peculiar motion study and comparison with HorizonRun 4 will follow next year.

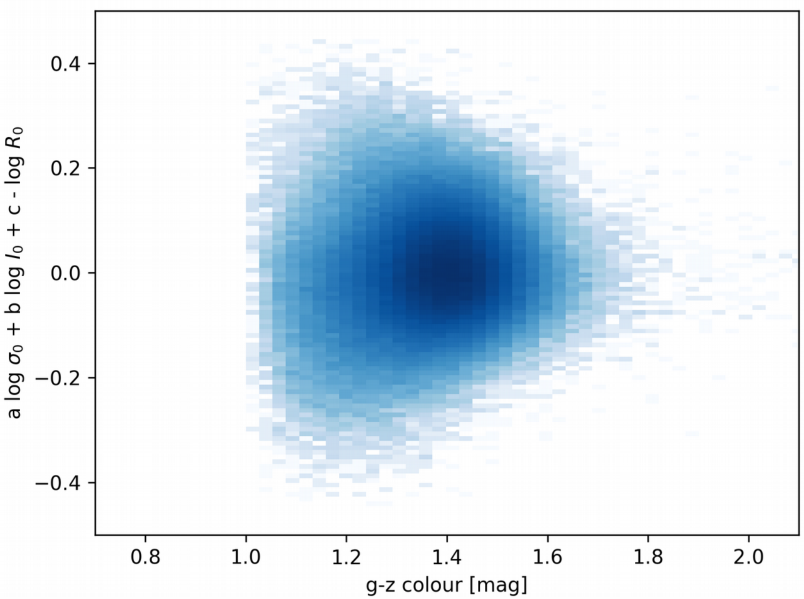


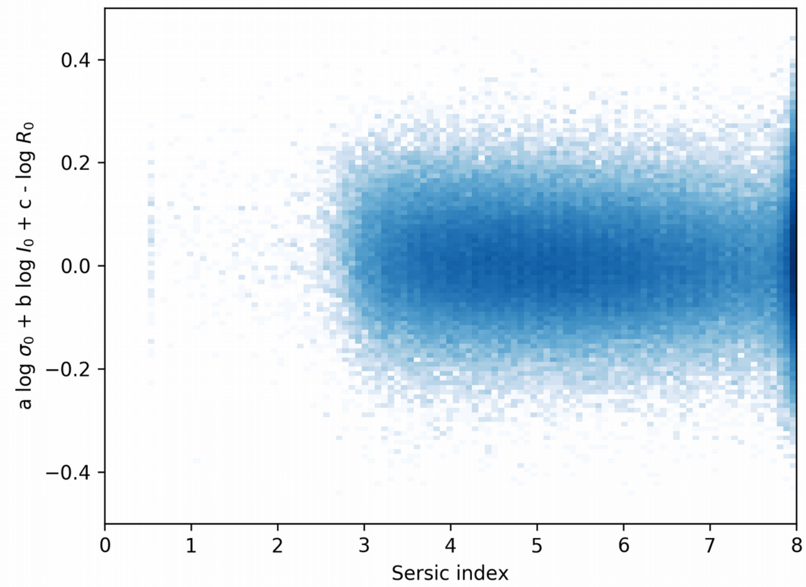
ANY QUESTIONS?

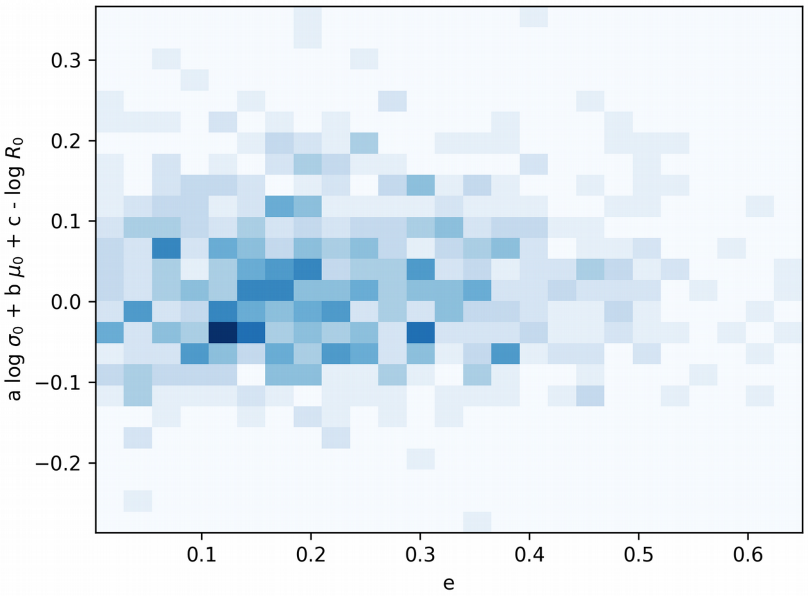
ADDITIONAL SLIDES

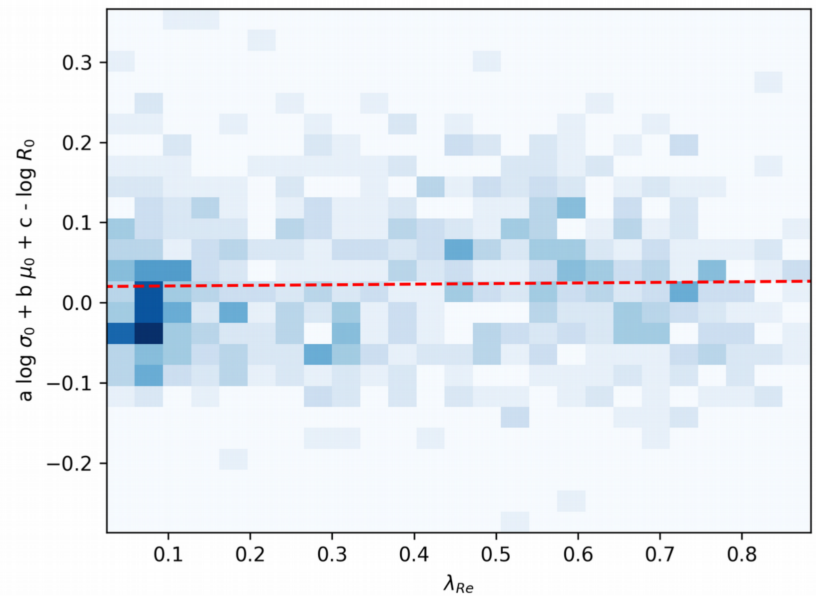
for possible questions

Other residuals of the traditional fundamental plane

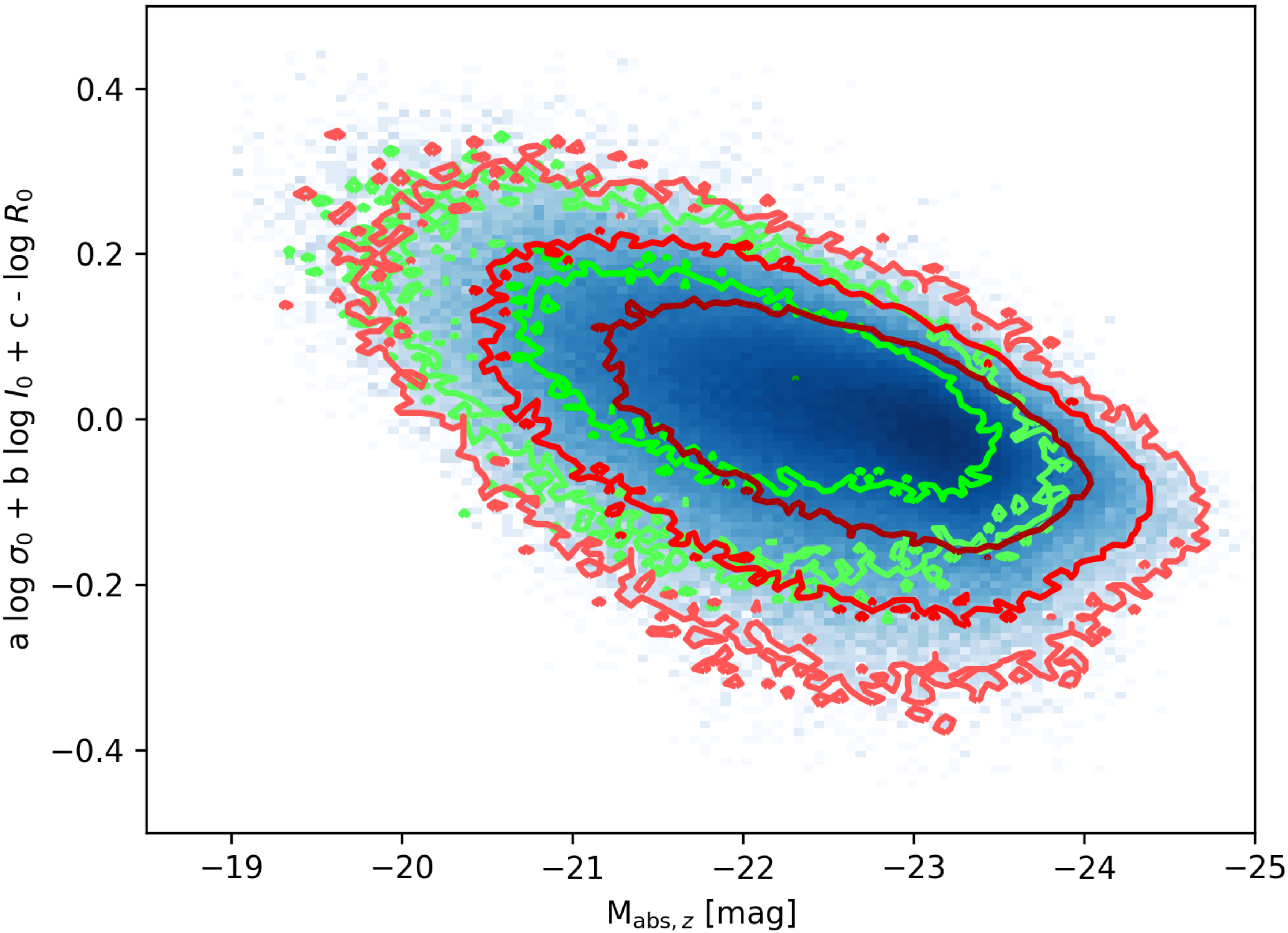








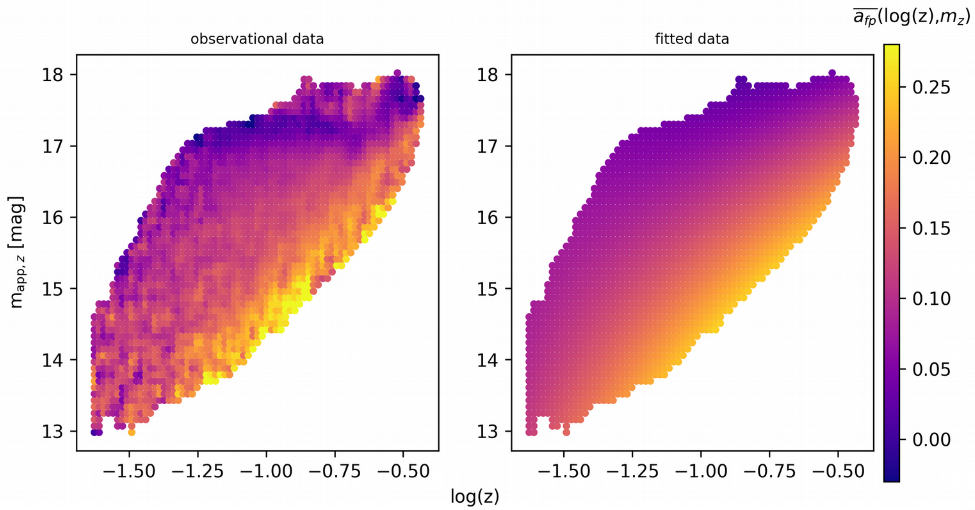
Environmental effects

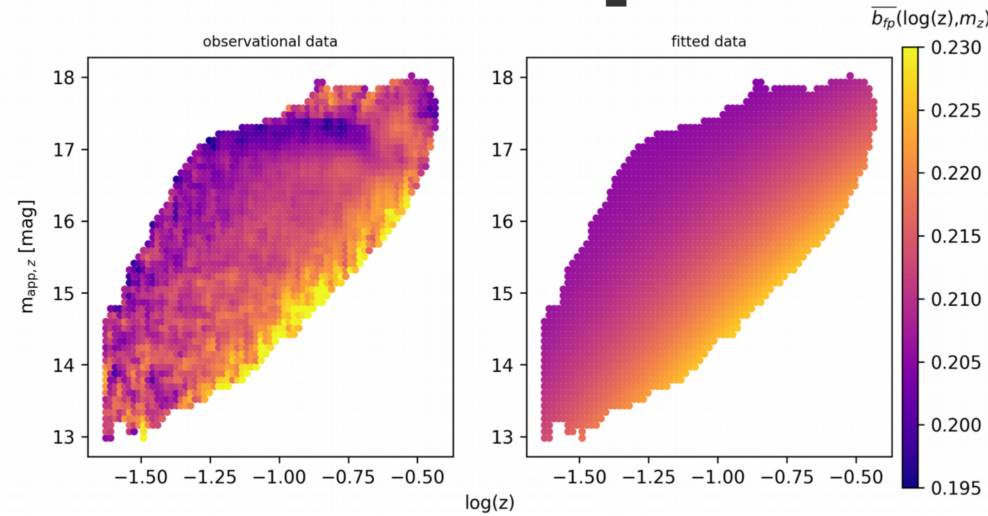


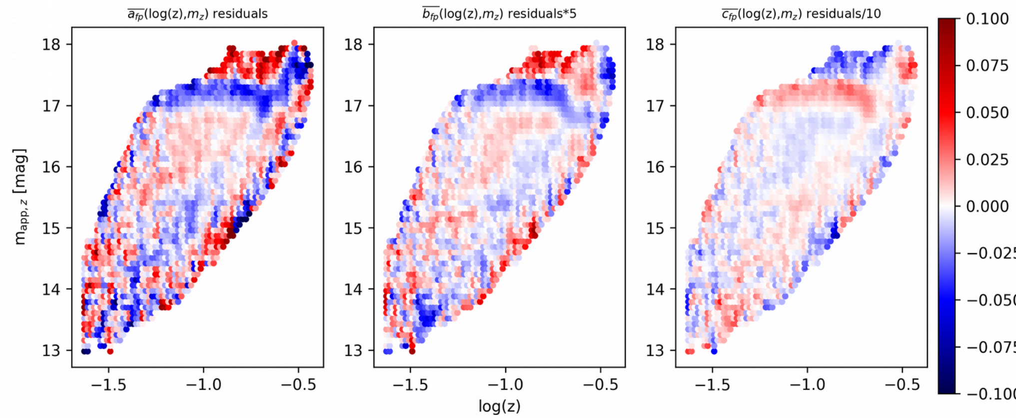
Kinematic distances

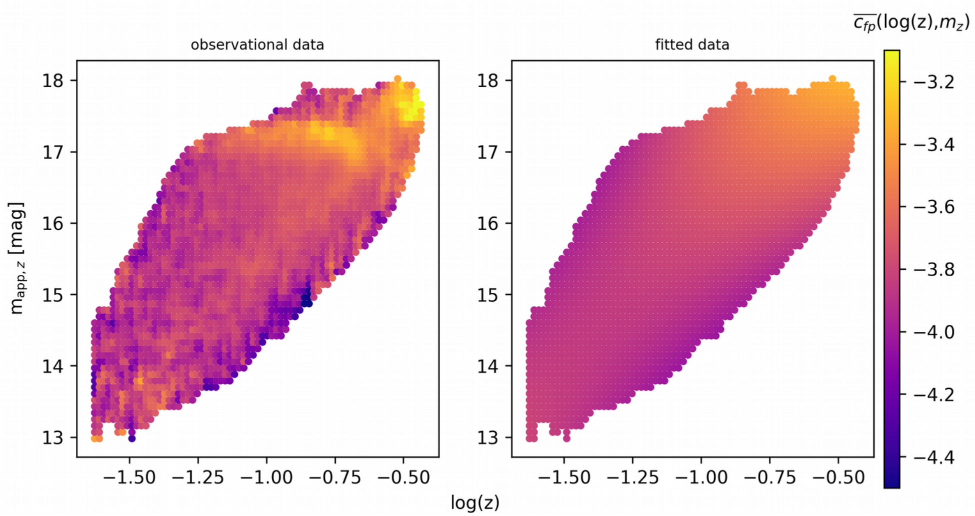
- Generalised mass plane – unification of the fundamental plane and Tully-Fisher relation
- Two approaches:
  - σ_e (Cappellari+2013, Serra+16) within R_e $$\sigma_e \approx \sqrt{\langle V^2 + \sigma^2 \rangle}$$
  - $S_{0.5}$ (Kassin+ 2007) $$S_{0.5} = \sqrt{0.5\, V_{rot}^2 + \sigma^2}$$ for all baryonic matter (stars and gas)
- Lots of progress thanks to MaNGA, Califa, & SAMI
- Scatter about 12% (better than Tully-Fisher relation and the fundamental plane)

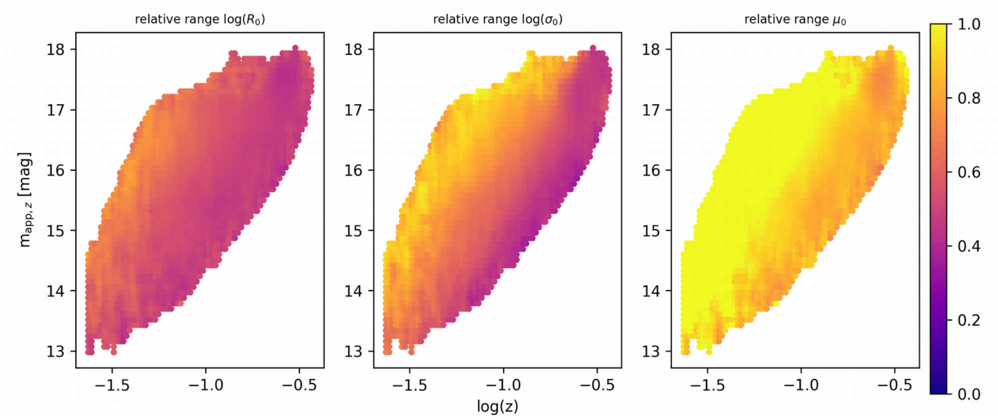
Dynamical fundamental plane parameters











Bin sizes for the dynamical fundamental plane