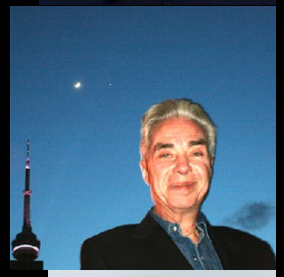
The fundamental plane as a probe for large-scale structure

Christoph Saulder
(Korea Institute for Advanced Study)

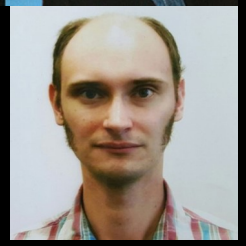
Cosmology on Safari 2019
March 3 2019, Hluhluwe, South Africa

Collaborators

Christoph Saulder (KIAS)



Ian Steer (NED)



Owain Snaith (KIAS)

Changbom Park (KIAS)

Cullen Howlett (ICRAR/UWA)

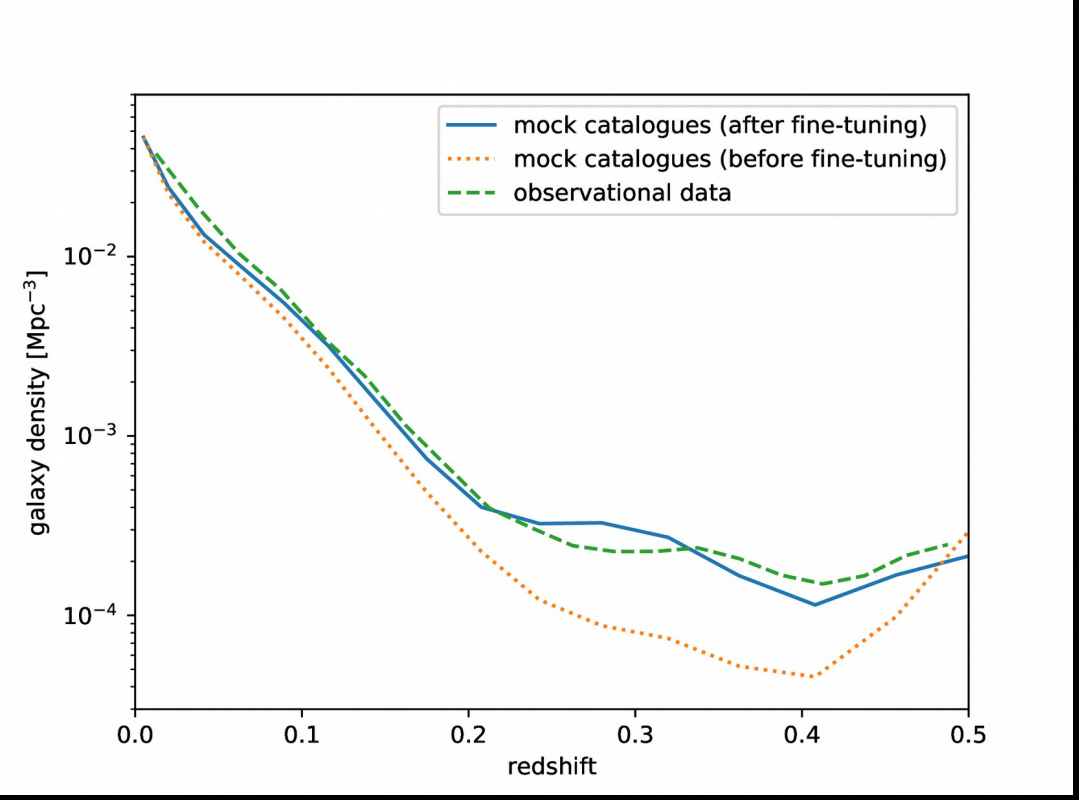
KIAS KOREA INSTITUTE FOR ADVANCED STUDY

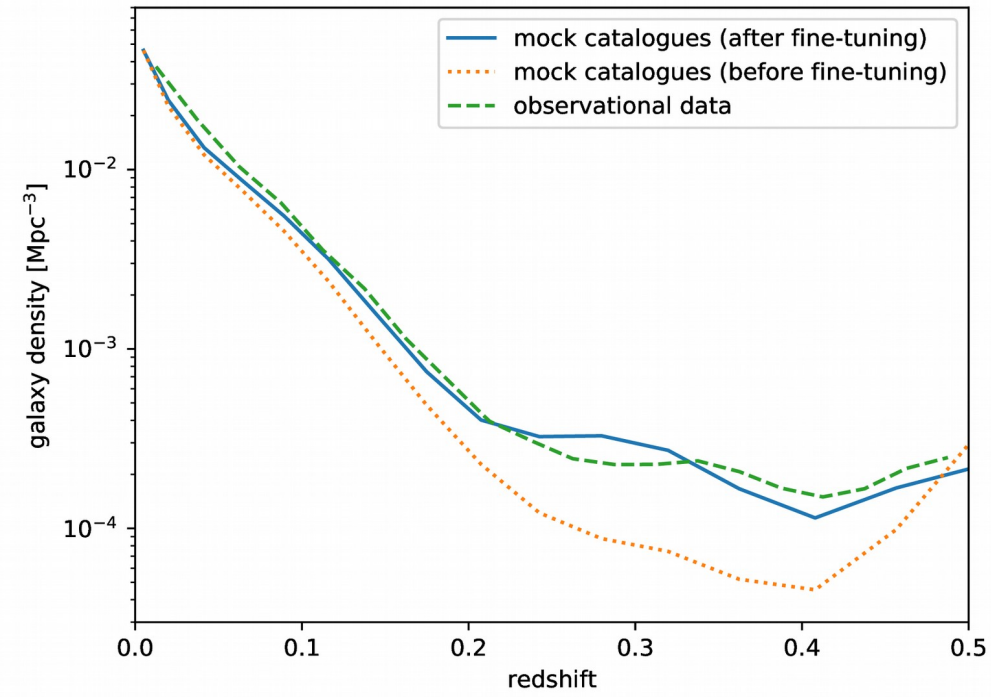
NED

ICRAR

Group catalogue

- Improving our special purpose group catalogue from Saulder+2016 and expanding it beyond z=0.1
- SDSS DR15
  - SDSS spectroscopic footprint (9 376 square degree)
  - Redshift up to z=0.5
- 2MRS (2MASS Redshift Survey)
  - Within the SDSS coverage
  - Compensate for the saturation bias of SDSS
- Linking length optimized using mock catalogues derived from the Millennium simlation (WMAP7 rerun by Guo+2011)


mock catalogues (after fine-tuning)
mock catalogues (before fine-tuning)
observational data
galaxy density [Mpc^{-3}]
10^{-2}
10^{-3}
10^{-4}
0.0
0.1
0.2
0.3
0.4
0.5
redshift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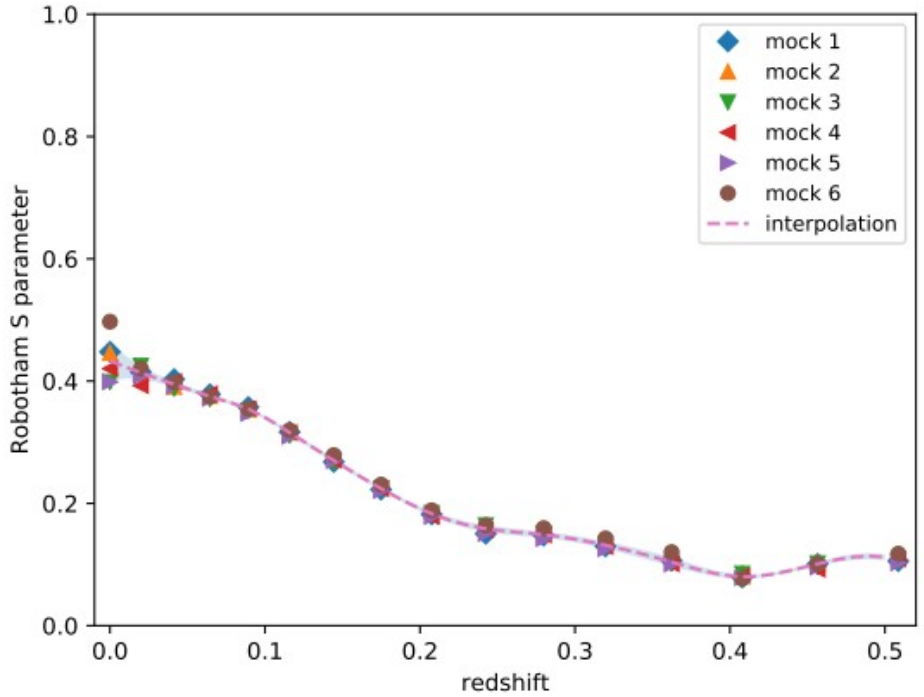
redshift


mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation
Robotham S parameter
1.0
0.8
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0.4
0.2
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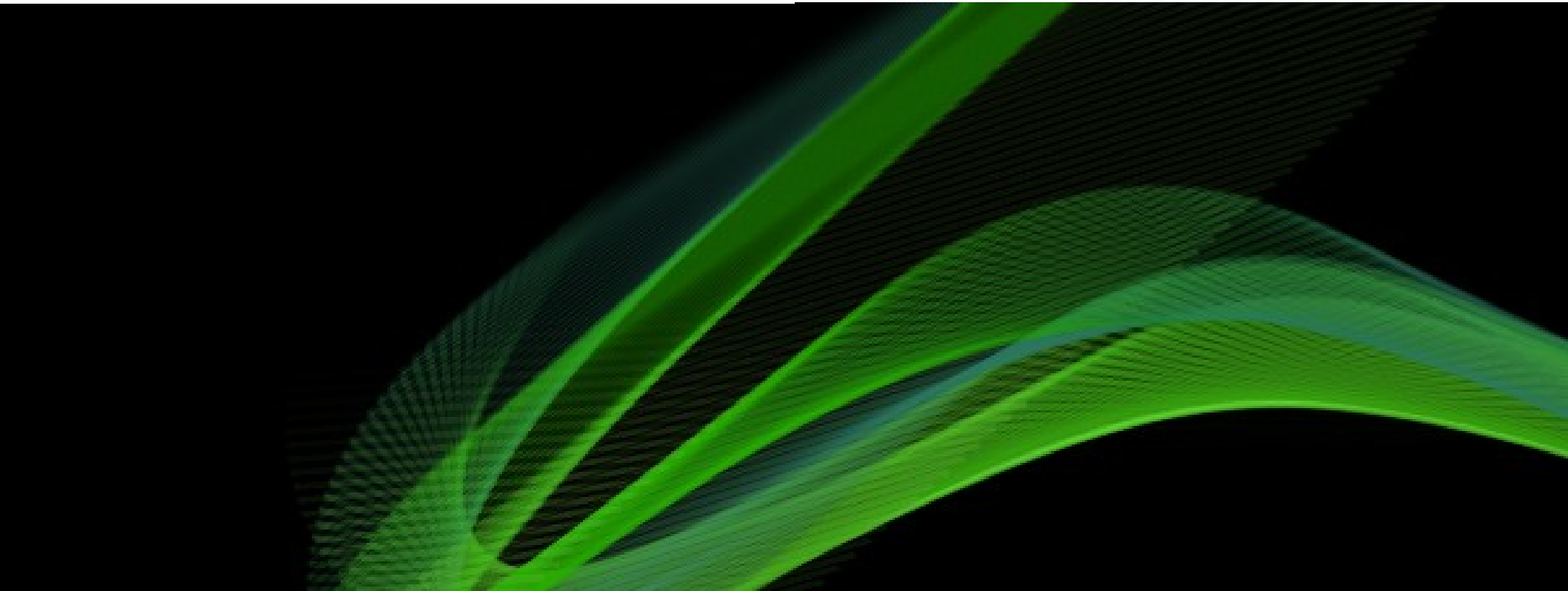
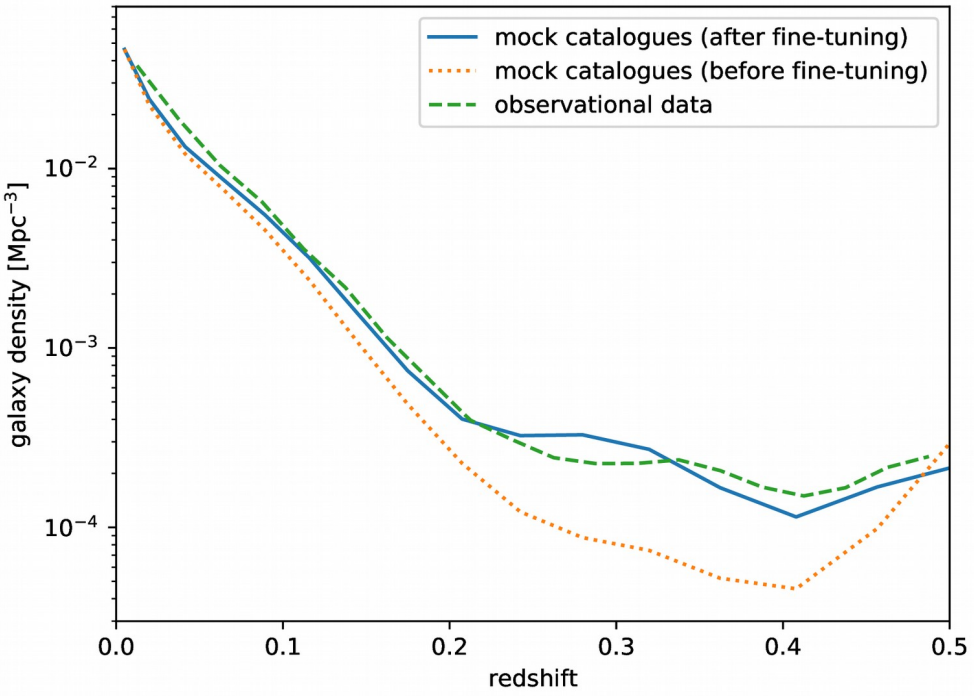
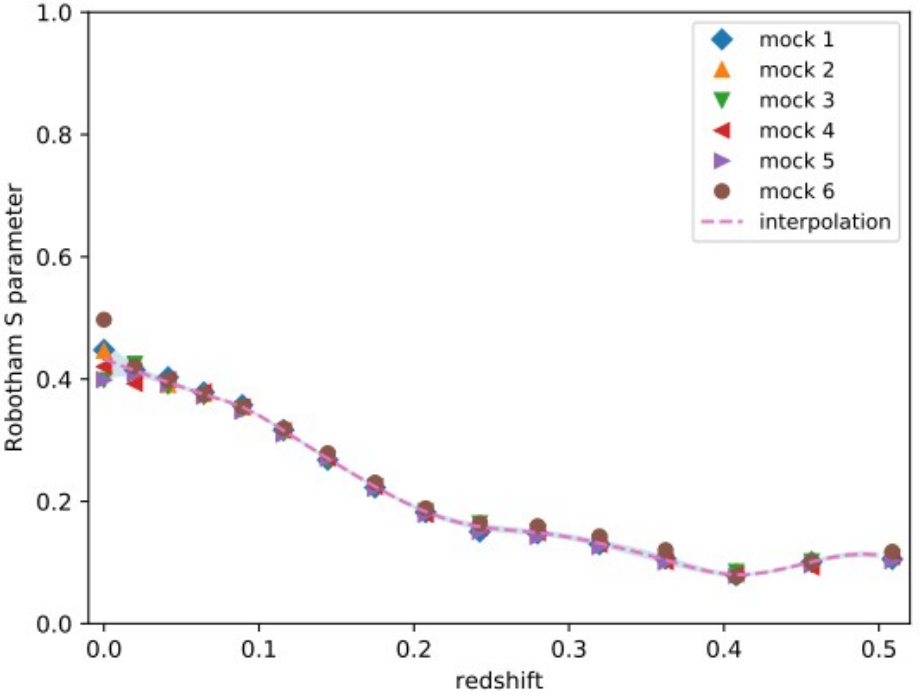
0.0
0.1
0.2
0.3
0.4
0.5
redshift




mock catalogues (after fine-tuning)
mock catalogues (before fine-tuning)
observational data
galaxy density [Mpc^{-3}]
10^{-2}
10^{-3}
10^{-4}
0.0
0.1
0.2
0.3
0.4
0.5
redshift


mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation
Robotham S parameter
1.0
0.8
0.6
0.4
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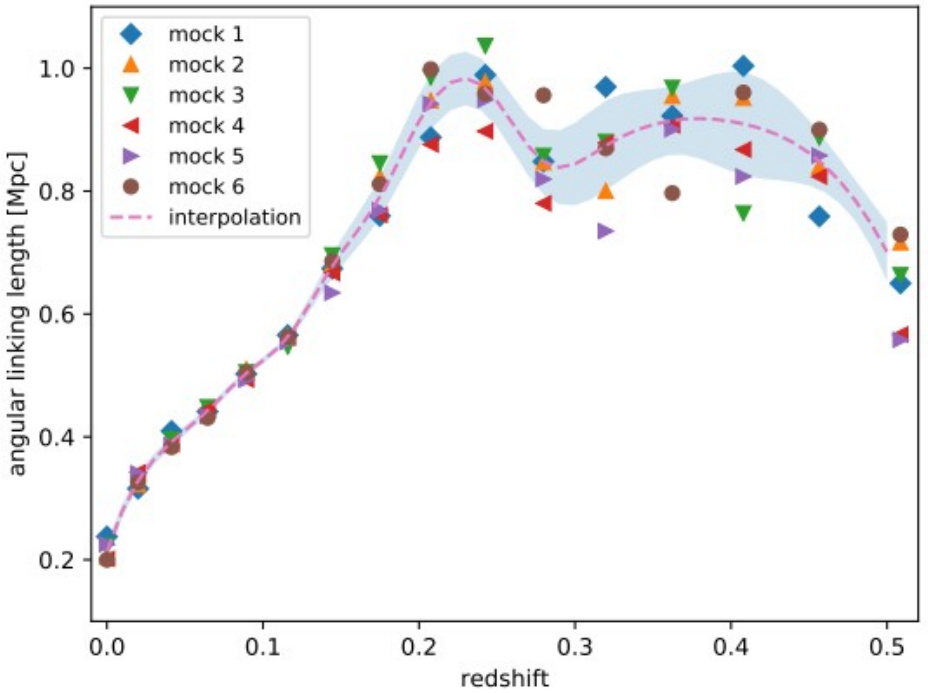
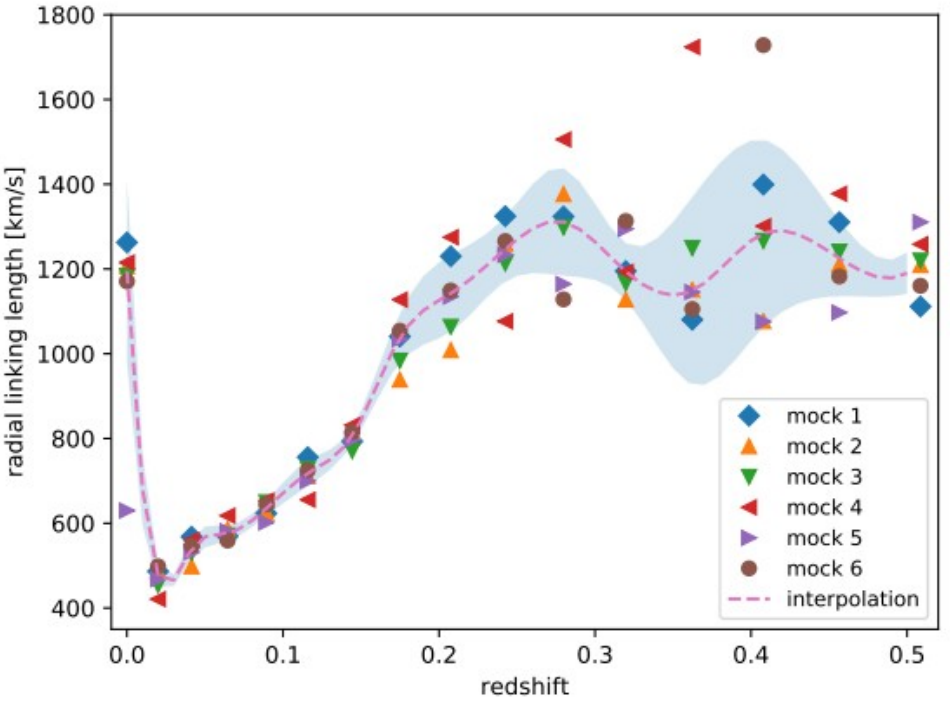
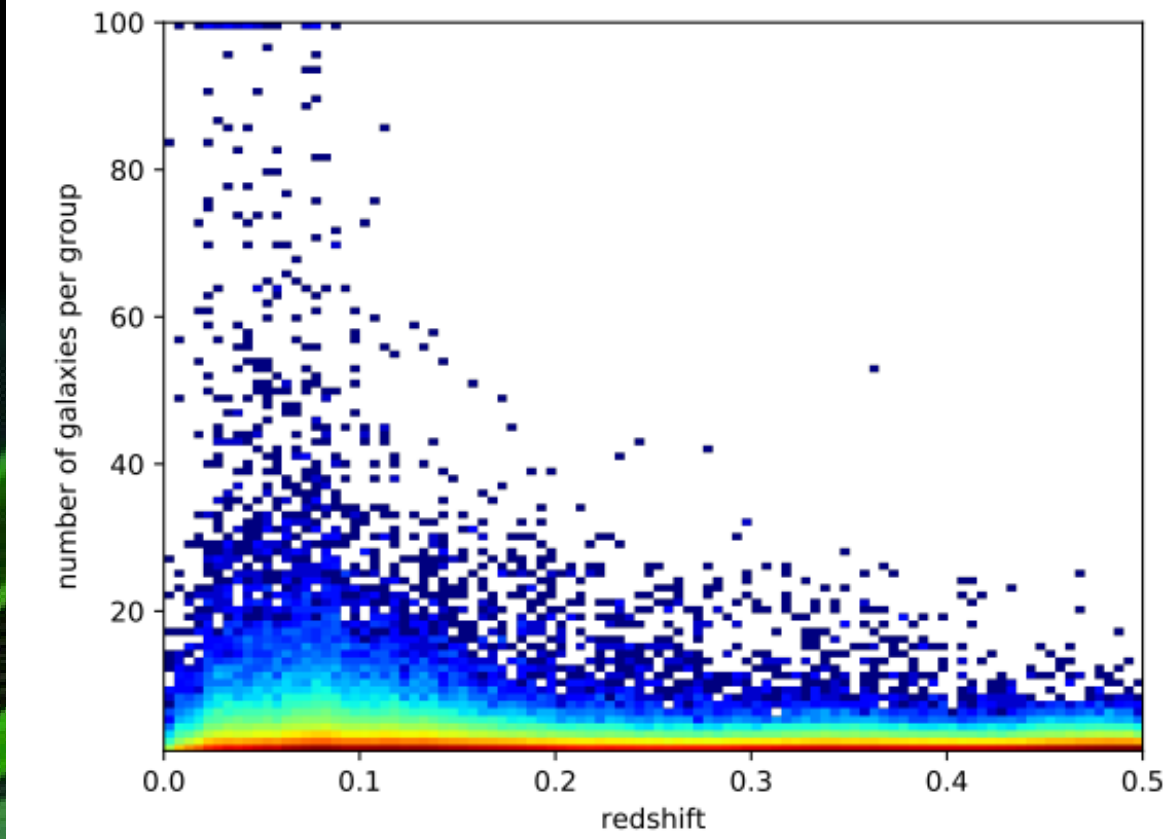
0.0
0.0
0.1
0.2
0.3
0.4
0.5
redshift


mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation
angular linking length [Mpc]
1.0
0.8
0.6
0.4
0.2
0.0
0.1
0.2
0.3
0.4
0.5
redshift


mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation
radial linking length [km/s]
1800
1600
1400
1200
1000
800
600
400
0.0
0.1
0.2
0.3
0.4
0.5
redshift

Statistics

- 1 480 600 galaxies in our group catalogue
- 997 161 individual galaxies (or groups with only one detectable member)
- 165 132 groups
- 3 467 clusters with N≥10
- 25 clusters with with N≥100



Traditional fundamental plane

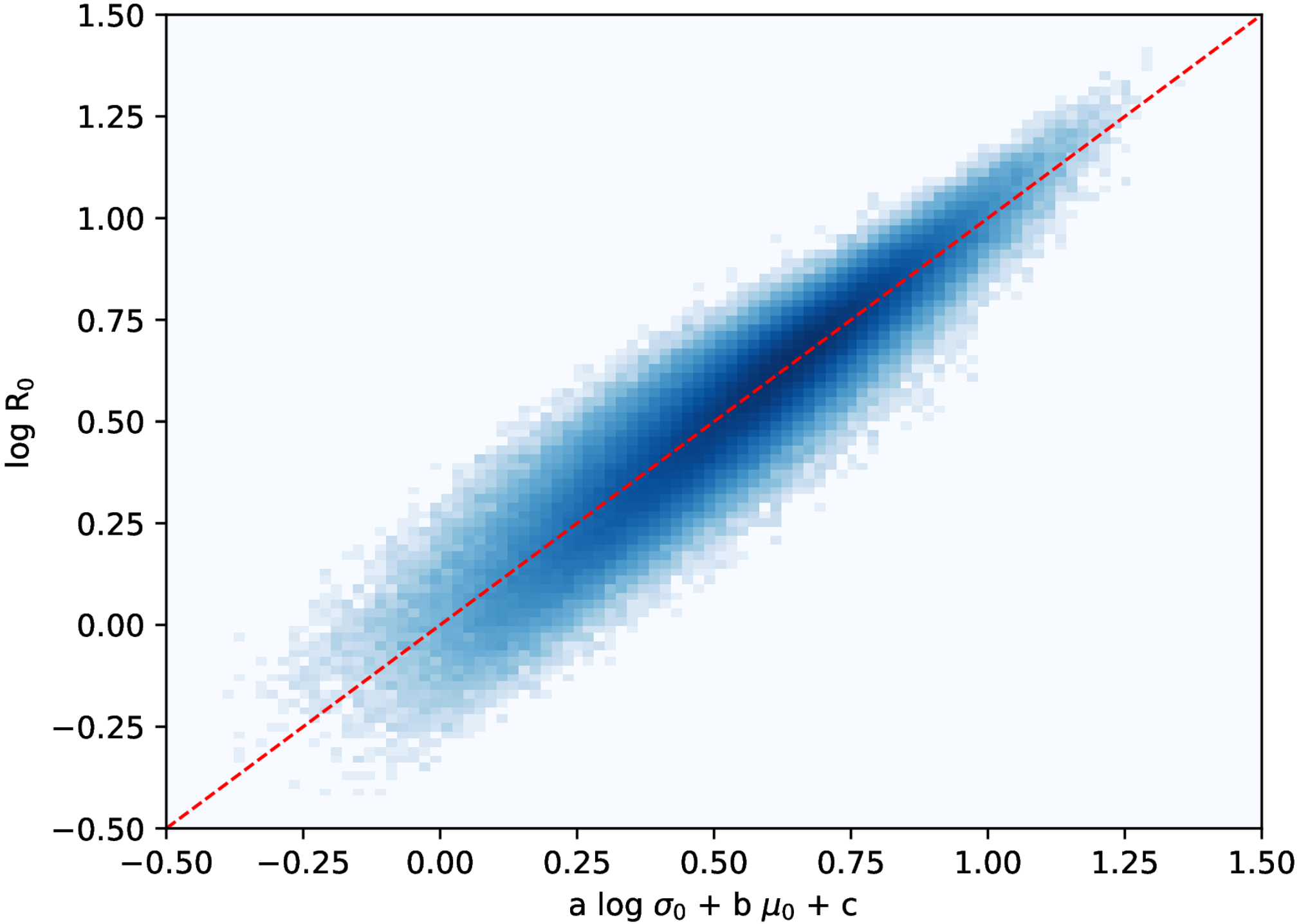
- Empirical relation between two redshift-independent observables and one distance dependent quantity (Dressler+ 1987, Djorgovski&Davis 1987)

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

- Standard rod for early-type galaxies
  → comparing observed sizes with predicted sizes
  → angular diameter distances
- 318 149 suitable ETGs in SDSS DR15
  largest dataset every used for the FP

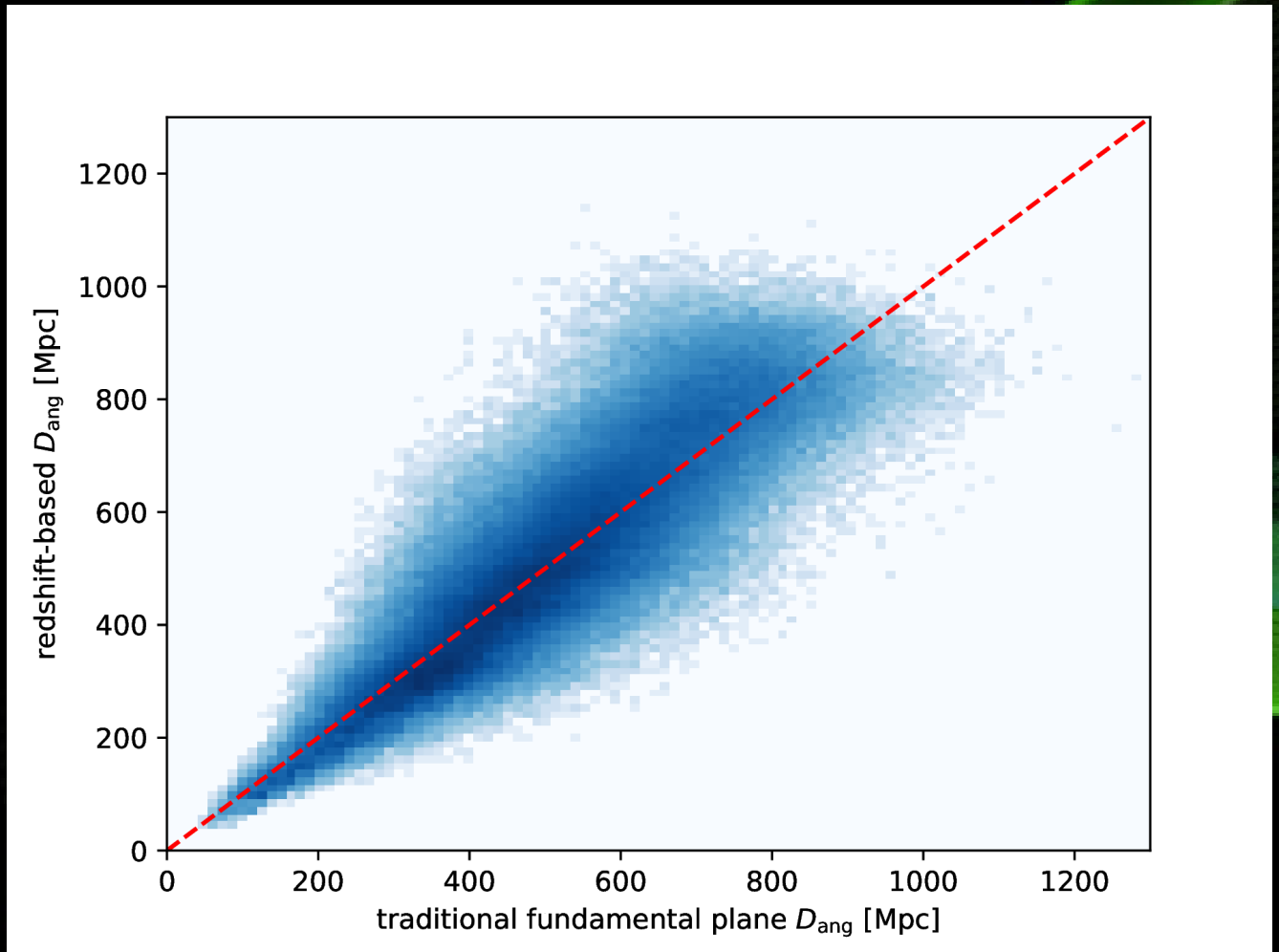
Fitting the traditional fundamental plane

- Applying basic calibrations and corrections to the data retrieved from SDSS
- Direct fit (minimizing the scatter in radii (Sheth&Bernardi 2013)) using least squares → fundamental plane coefficients
- We INTENTIONALLY did NOT correct for the Malmquist bias (typical done using volume weightening)
- → coefficients will **only work for our sample**
- Currently testing another calibration method (based on Howlett+, submitted)


1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
log R_0
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
a log σ_0 + b μ_0 + c

Fundamental plane distances

- Scatter of 20.4% without the group catalogue
- Scatter of 18.6% with the group catalogue

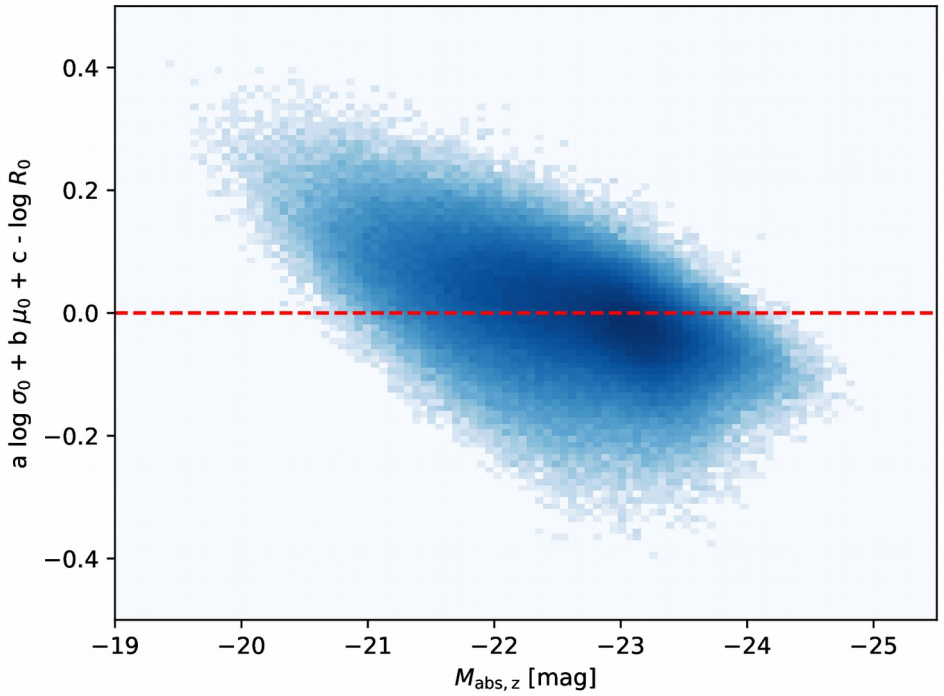


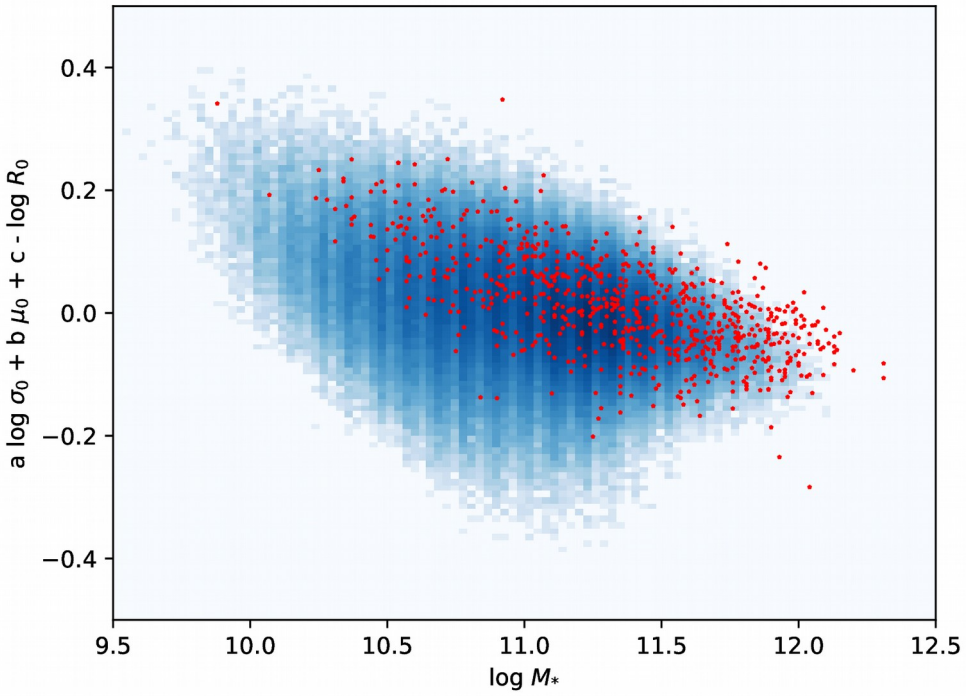
Biases of the traditional fundamental plane

- Hidden redshift dependences
  - Tolman effect correction $\sim(1+z)^4$
  - Evolution correction $\sim Q \cdot z$
- Contributing a systematic error of about ~0.3% on the distance estimates
- Luminosity / stellar mass biases
- Systematic offset for richer groups … environment (Joachimi+2015) or selection effects
- Malmquist bias correction would also be redshift dependent

Luminosity / stellar mass biases

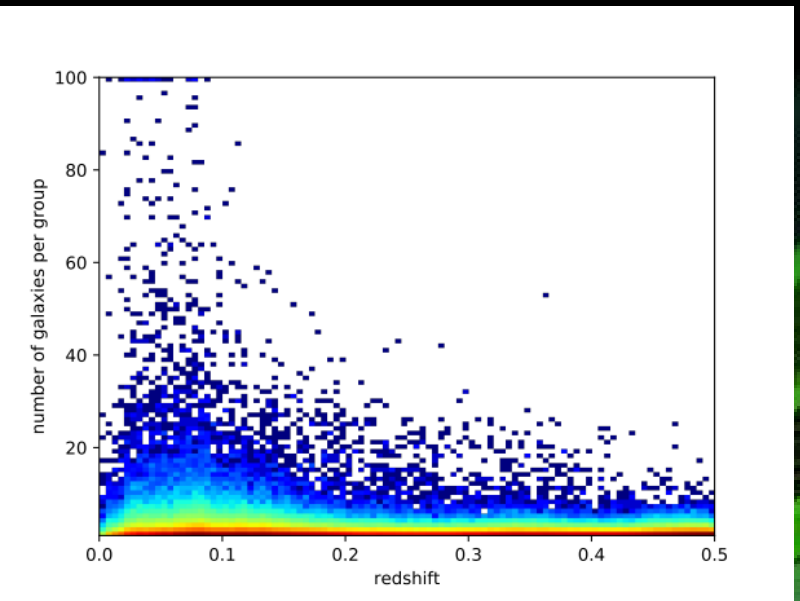
- Intrinsically fainter/brighter galaxies are systematically offset from the fundamental plane
- Stellar masses based on Maraston+ 2009 show the same effect, tighter relation with MaNGA data

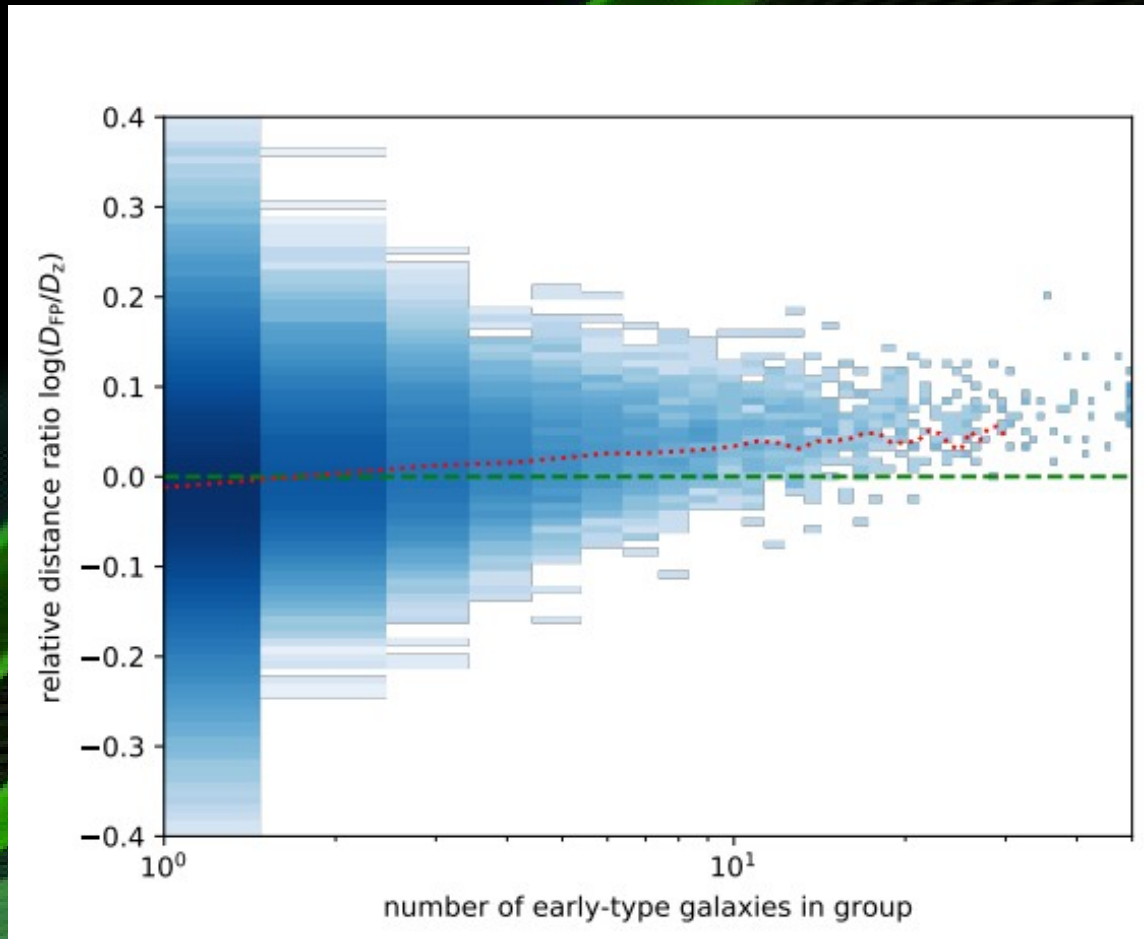




Group bias

- Systematic offset correlates with the number of detected ETGs in SDSS
- Saturation bias removes brightest nearby galaxies



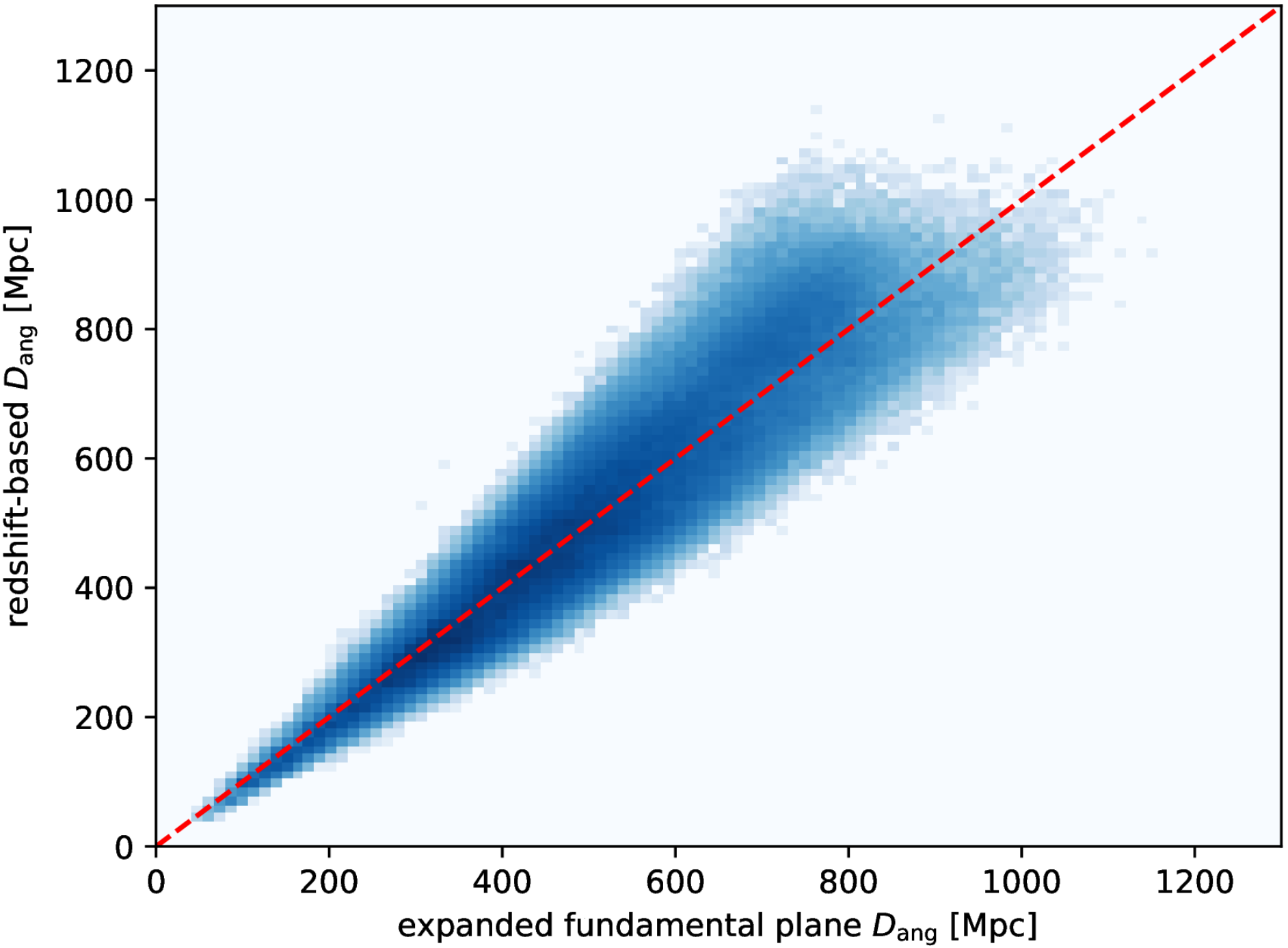


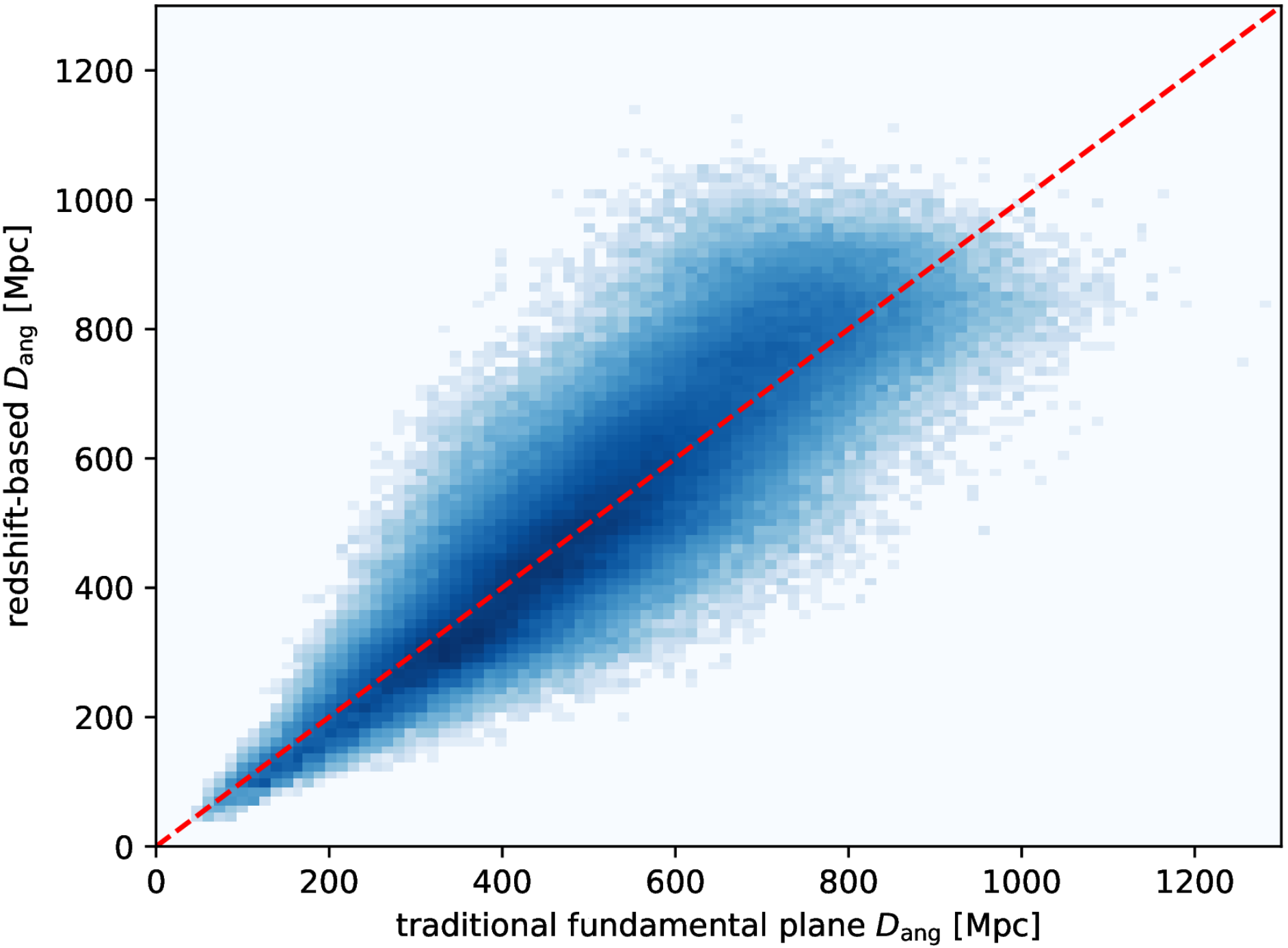
Expanded funamental plane

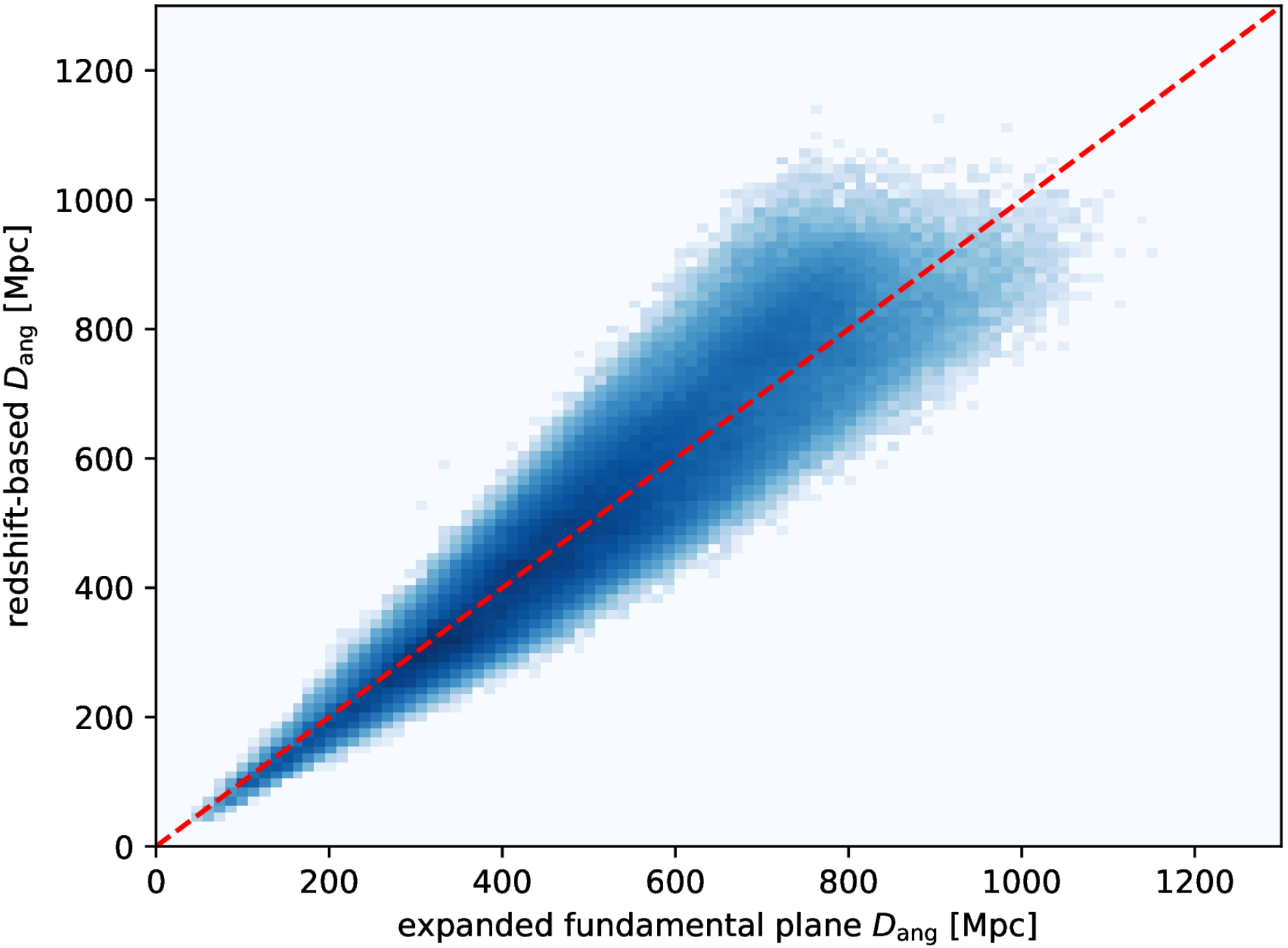
- Including known biases as corrections to the traditional fundamental plane

$$\log_{10}(R_0) = a_{exp} \cdot \log_{10}(\sigma_0) + b_{exp} \cdot \mu_0 + c_{exp} \cdot \log_{10}(M_*) + d_{exp} \cdot \log_{10}(N_{ETG}) + e_{exp}$$

- Expanding the fundamental plane by additional terms
- Significant reduction in scatter and removal of two notable systematic biases


redshift-based D_{ang} [Mpc]
expanded fundamental plane D_{ang} [Mpc]
0
200
400
600
800
1000
1200


redshift-based D_{ang} [Mpc]
traditional fundamental plane D_{ang} [Mpc]
0
200
400
600
800
1000
1200

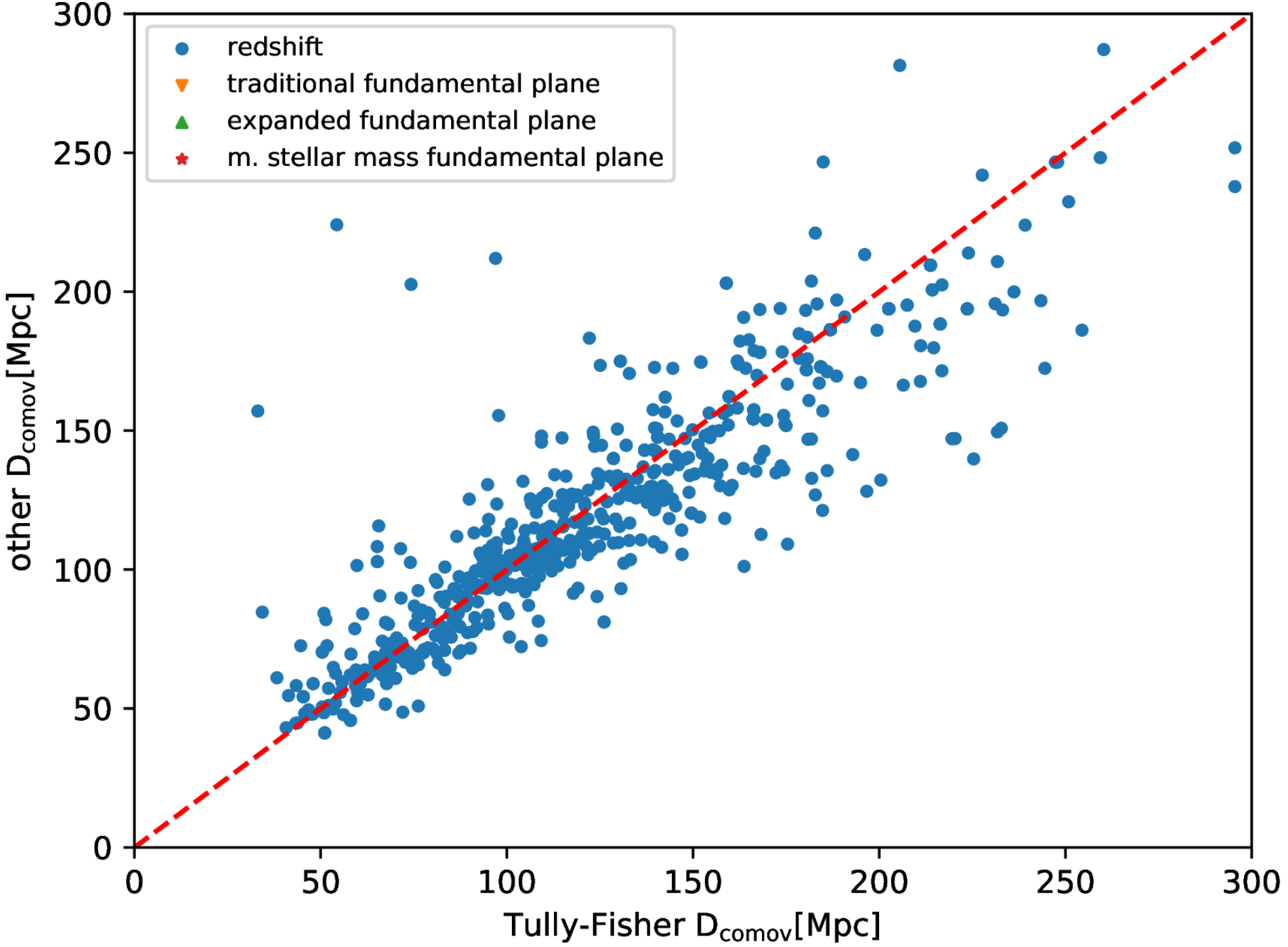

redshift-based D_{ang} [Mpc]
expanded fundamental plane D_{ang} [Mpc]
0
200
400
600
800
1000
1200

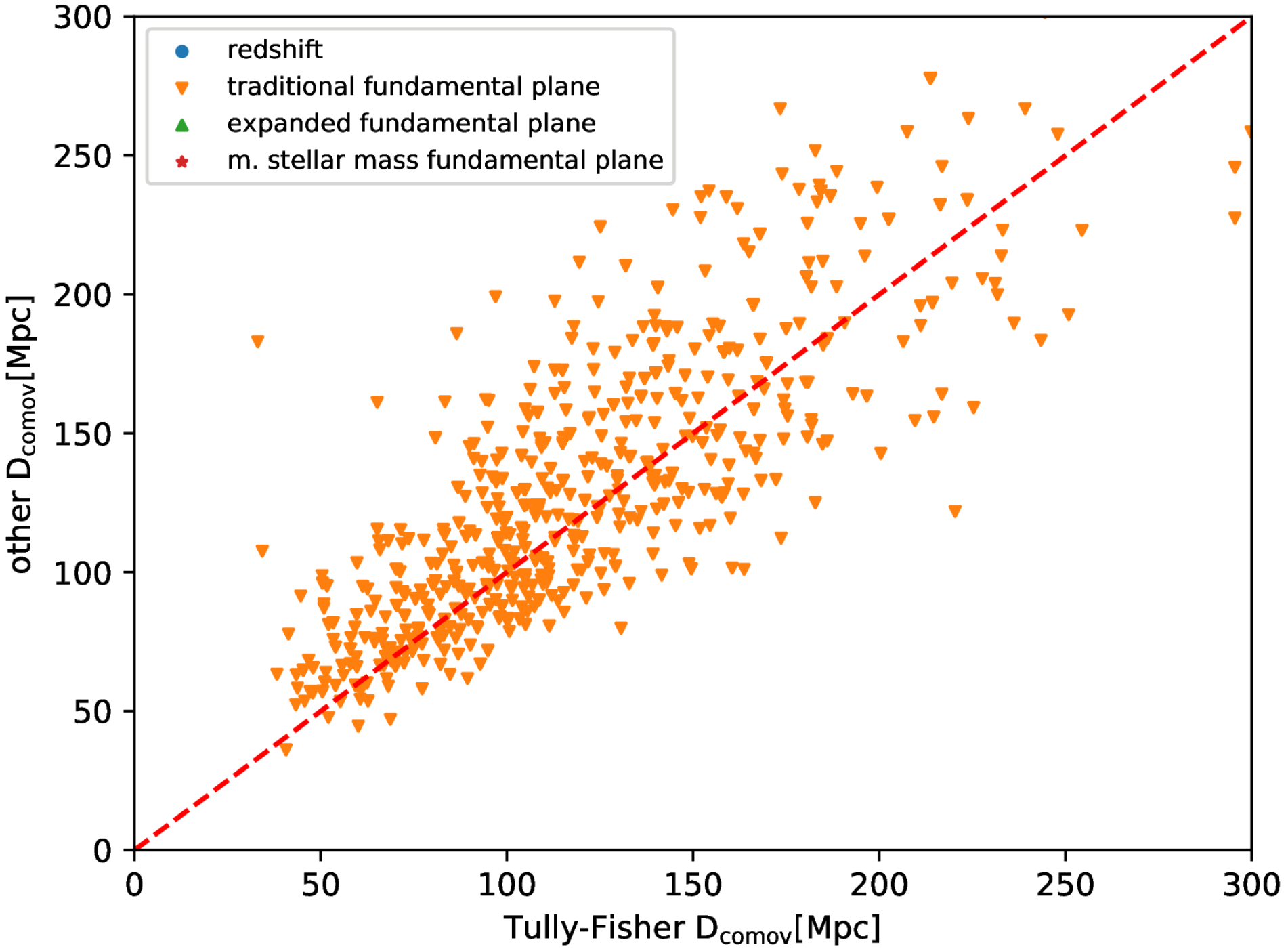
Paying the price

- Overall scatter of 12.8% … **but**
- Redshift-dependent systematic biases are getting worse
- Up to 2% for nearby galaxies
- But very low at higher redshifts (z>0.2), bias is less than 0.1%
- Could cause minor problems for peculiar motion studies in the future

Comparison to the Tully-Fisher relation

- NASA/IPAC Extragalactic Database (NED)
- 20 900 Tully-Fisher relation based distance measurements to 4 481 unique galaxies
- Error weighted average for galaxies that have more than one measurment
- Using our group catalogue to compare them


redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
0
50
100
150
200
250
300


redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
0
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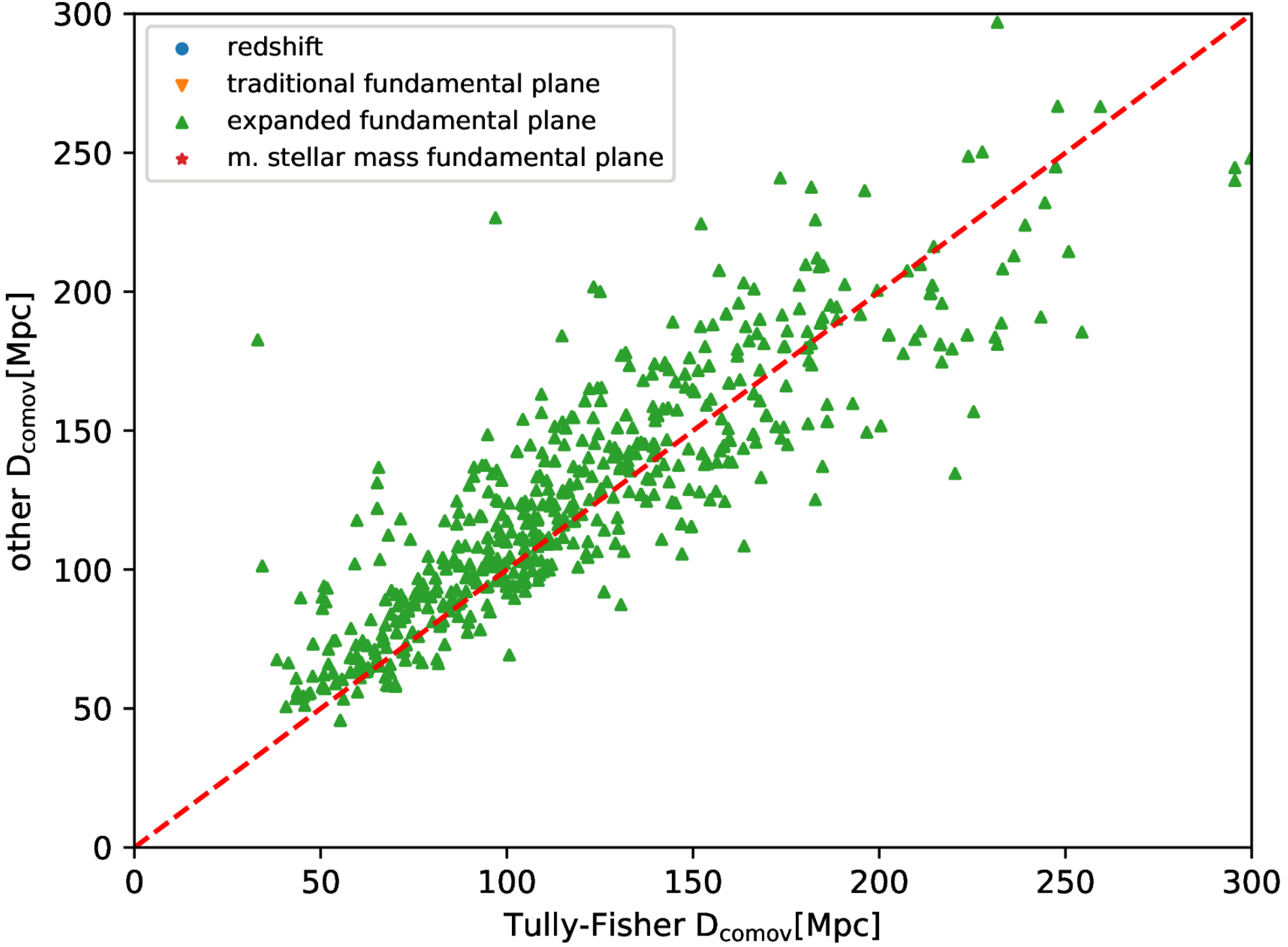
250
300


redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
0
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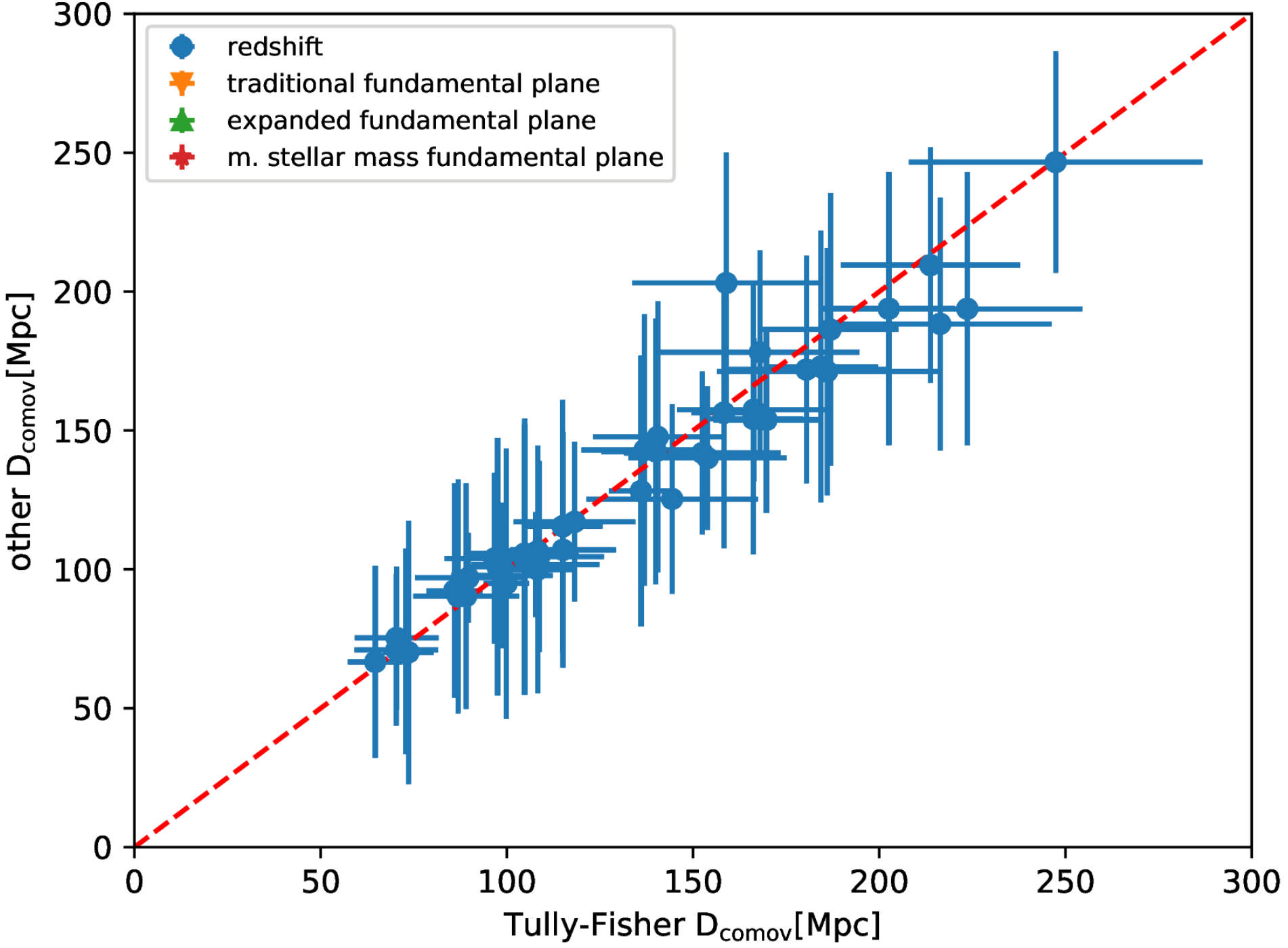
100
150
200
250
300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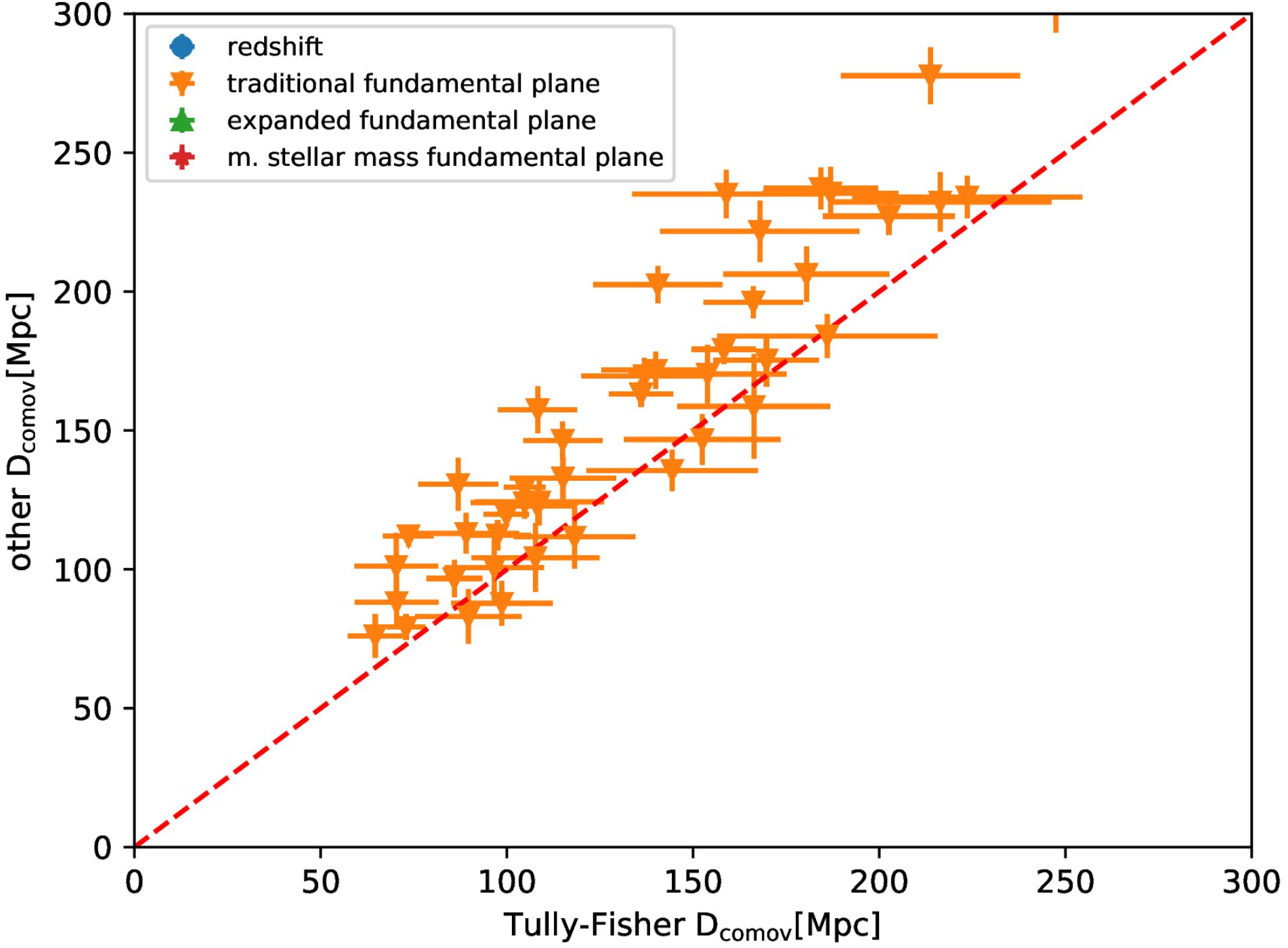
redshift
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expanded fundamental plane
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Tully-Fisher D_{comov}[Mpc]
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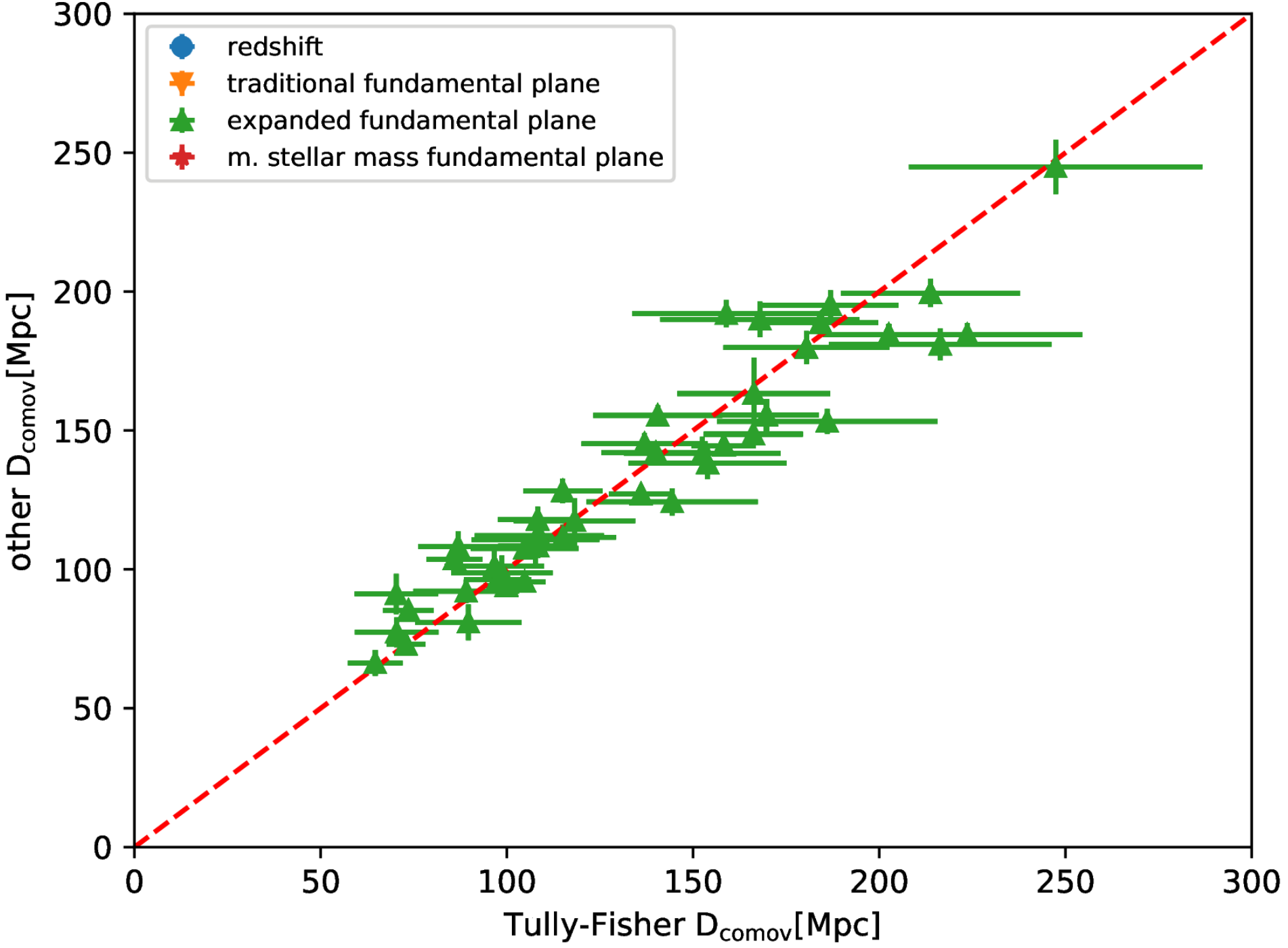
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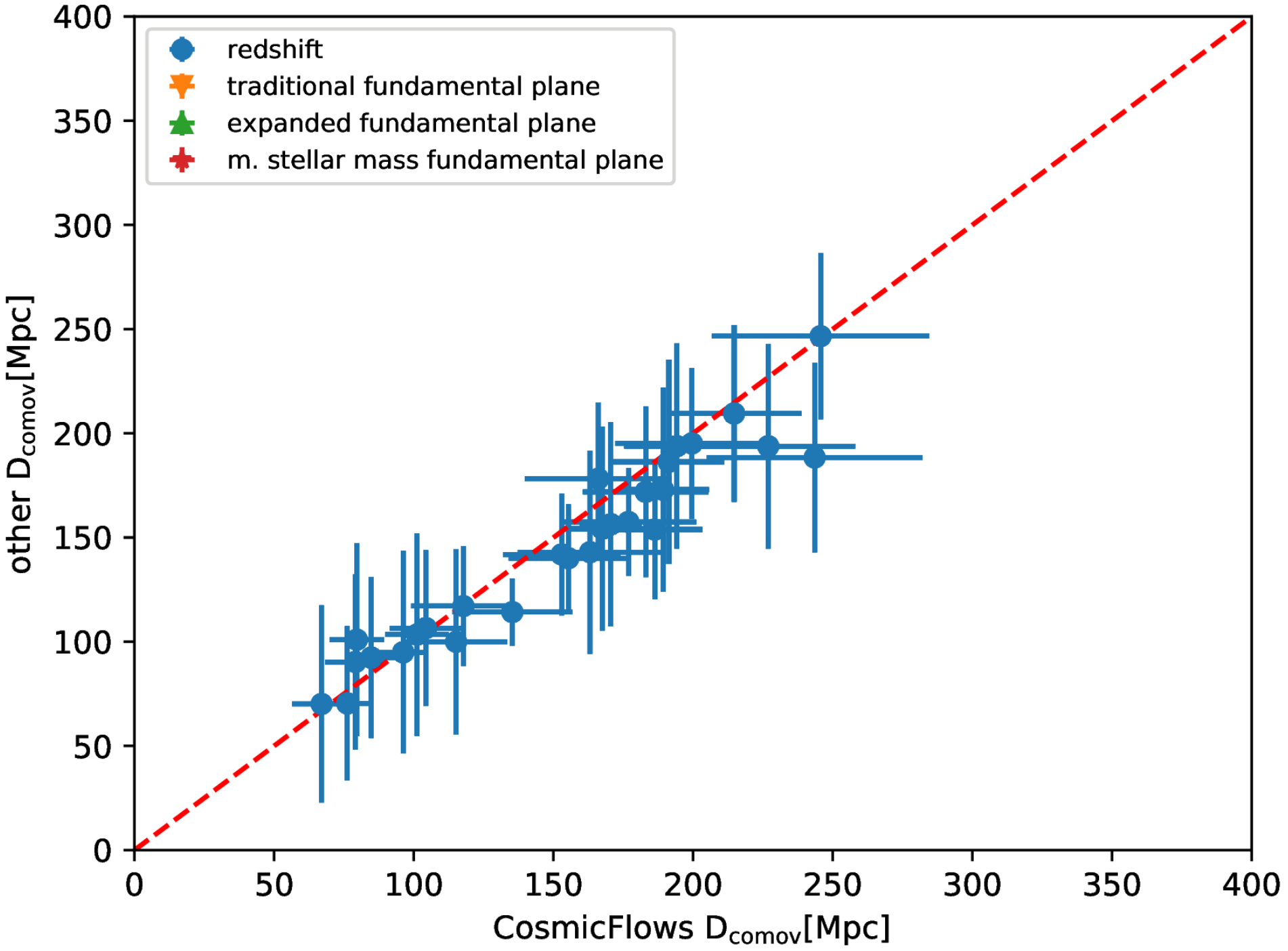
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
0
50
100
150
200
250
300

Comparison to the CosmicFlows-3 sample

- A well-calibrated sample of distances in the local universe (Tully+2016)
- Uses a large range of different distance indicators: Tully-Fisher relation, surface brightness fluctuations, fundamental plane, tip of the red giant branch, ...
- We exclude their fundamental plane data
- Using our group catalogue to compare the samples


redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{comov}[Mpc]
CosmicFlows D_{comov}[Mpc]
0
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150
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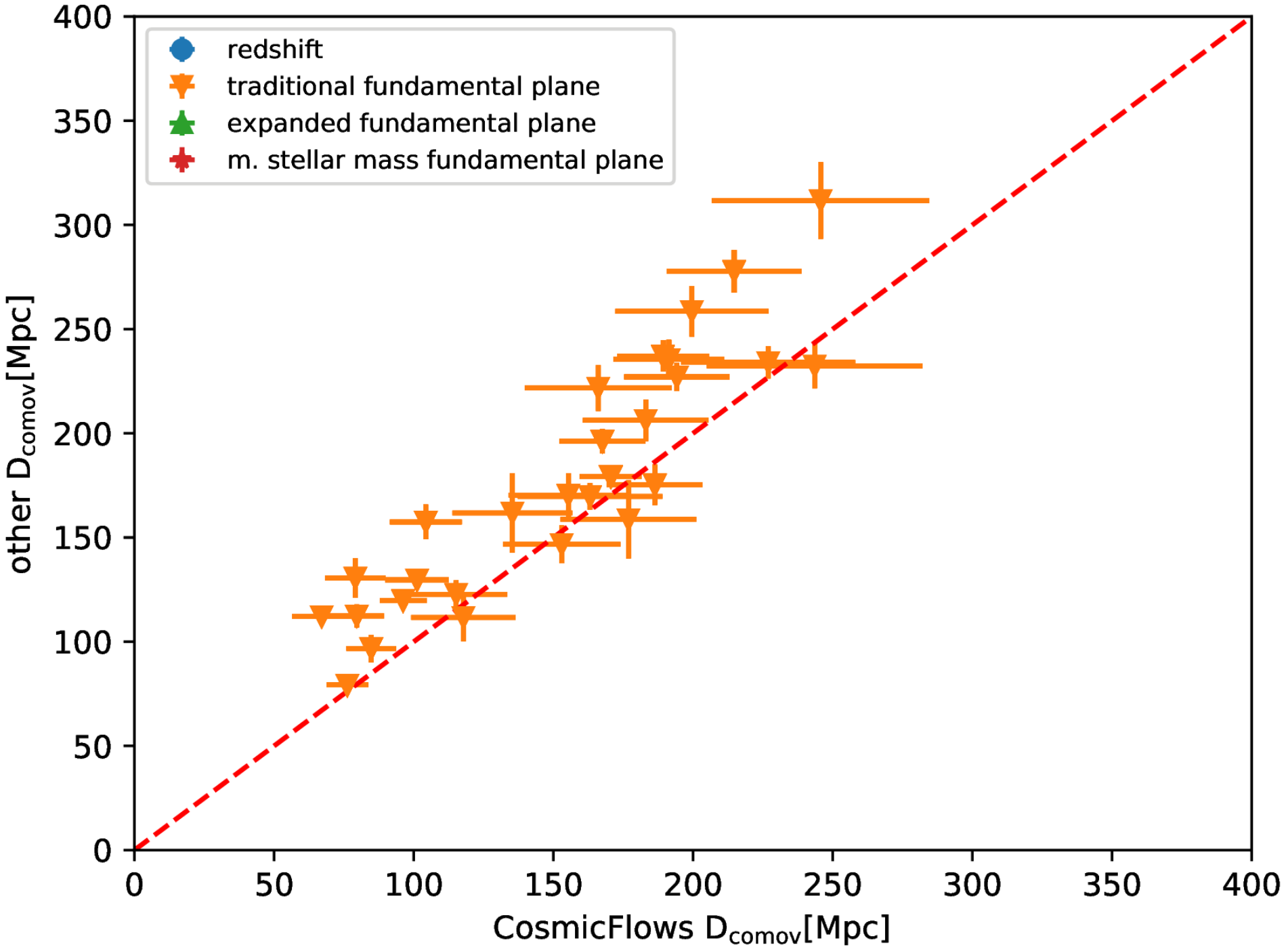
350
400


redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
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CosmicFlows D_{comov}[Mpc]
0
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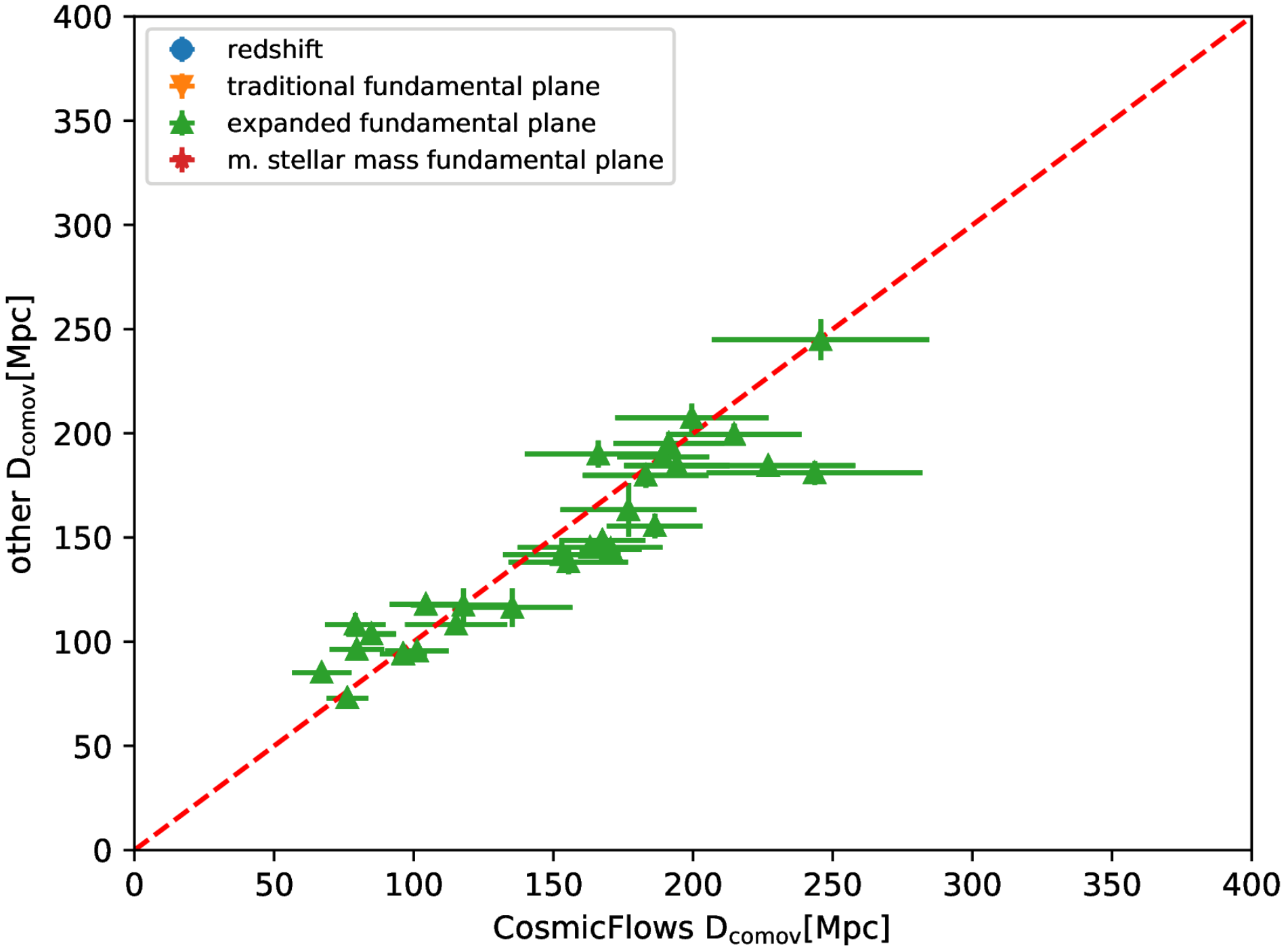
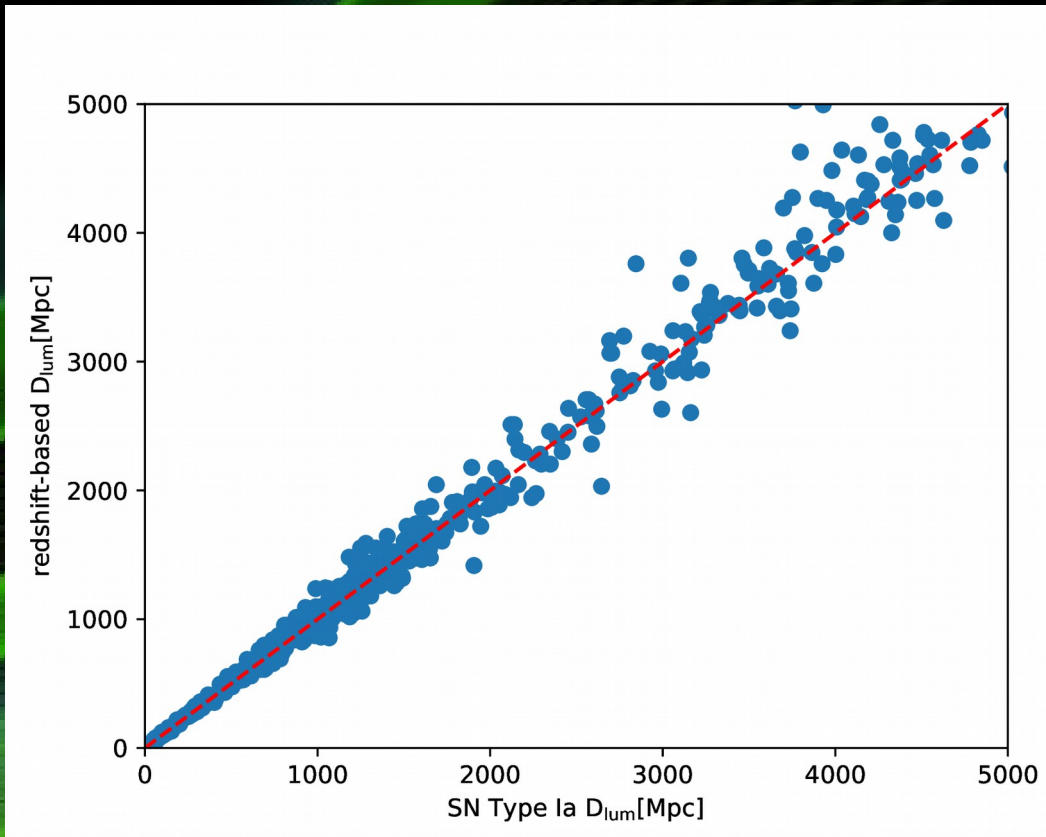
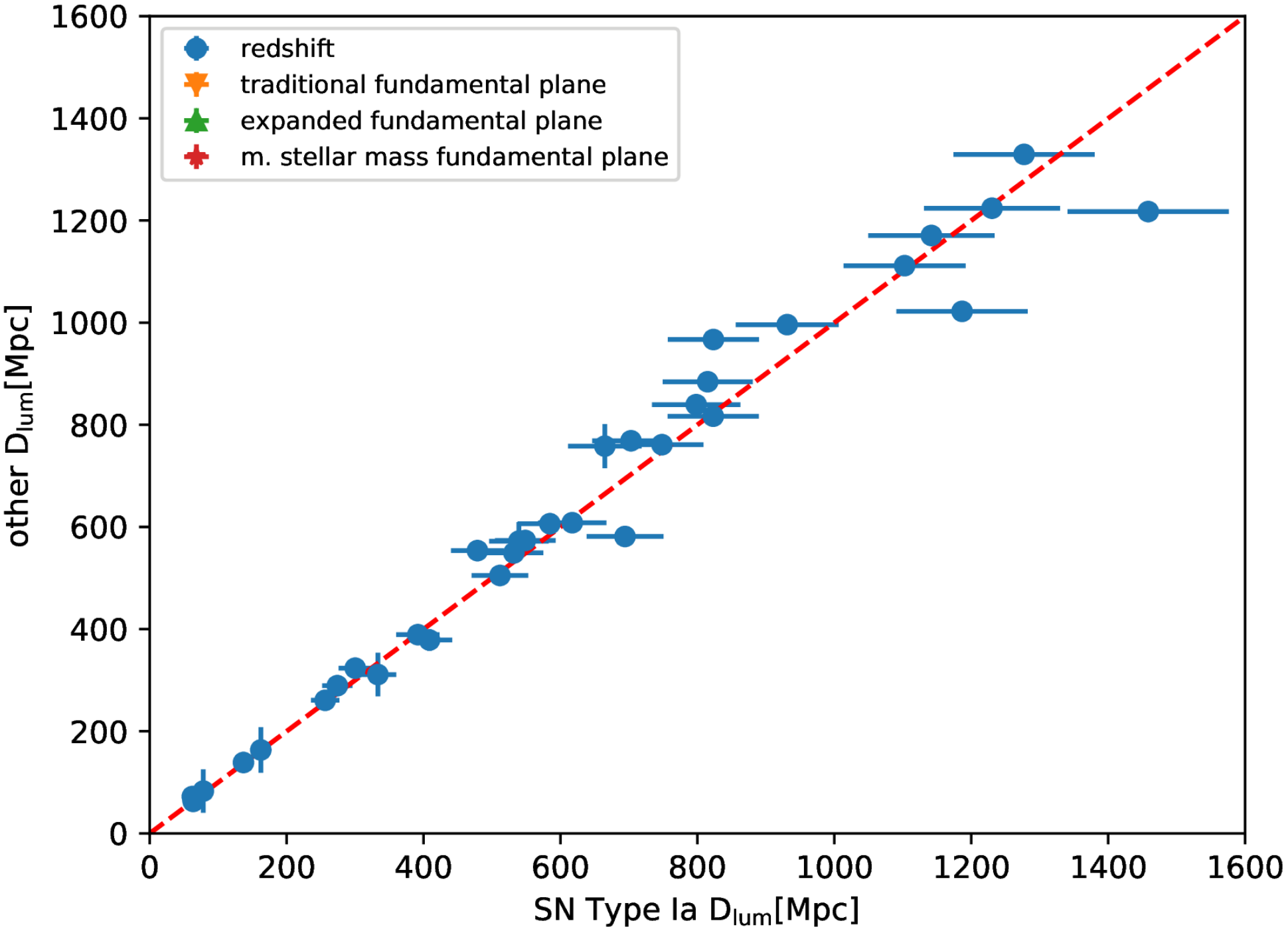
400

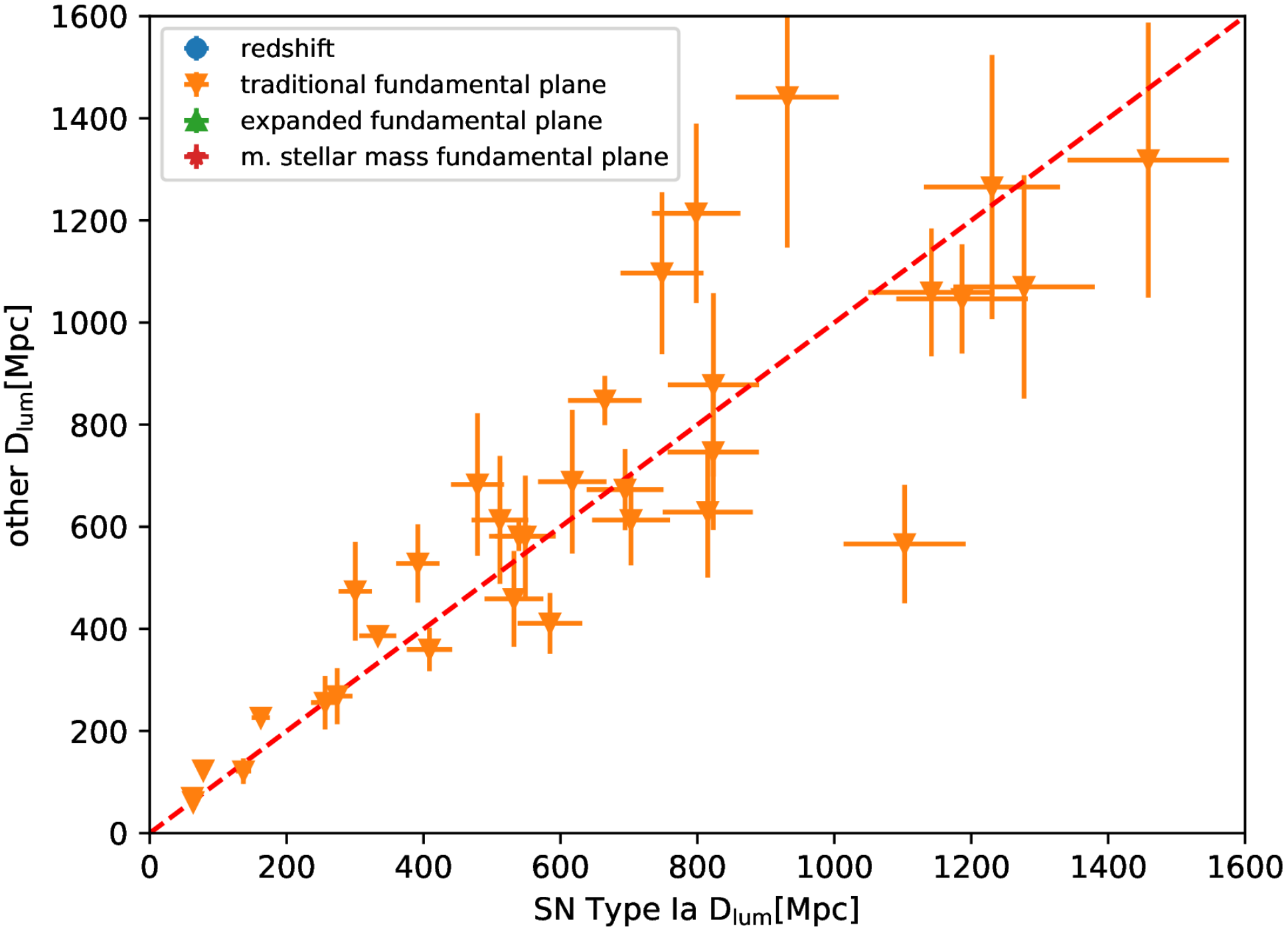

redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{comov}[Mpc]
CosmicFlows D_{comov}[Mpc]
0
50
100
150
200
250
300
350
400

Comparison to supernovae Type Ia

- Sample of Betoule+ 2014 containing 740 SN Type Ia (consistently calibrated)
- 33 of these supernova in our ETGs
- Scatter of supernova distances about ~8%




redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{lum}[Mpc]
SN Type Ia D_{lum}[Mpc]
0
200
400
600
800
1000
1200
1400
1600


redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{lum}[Mpc]
SN Type Ia D_{lum}[Mpc]
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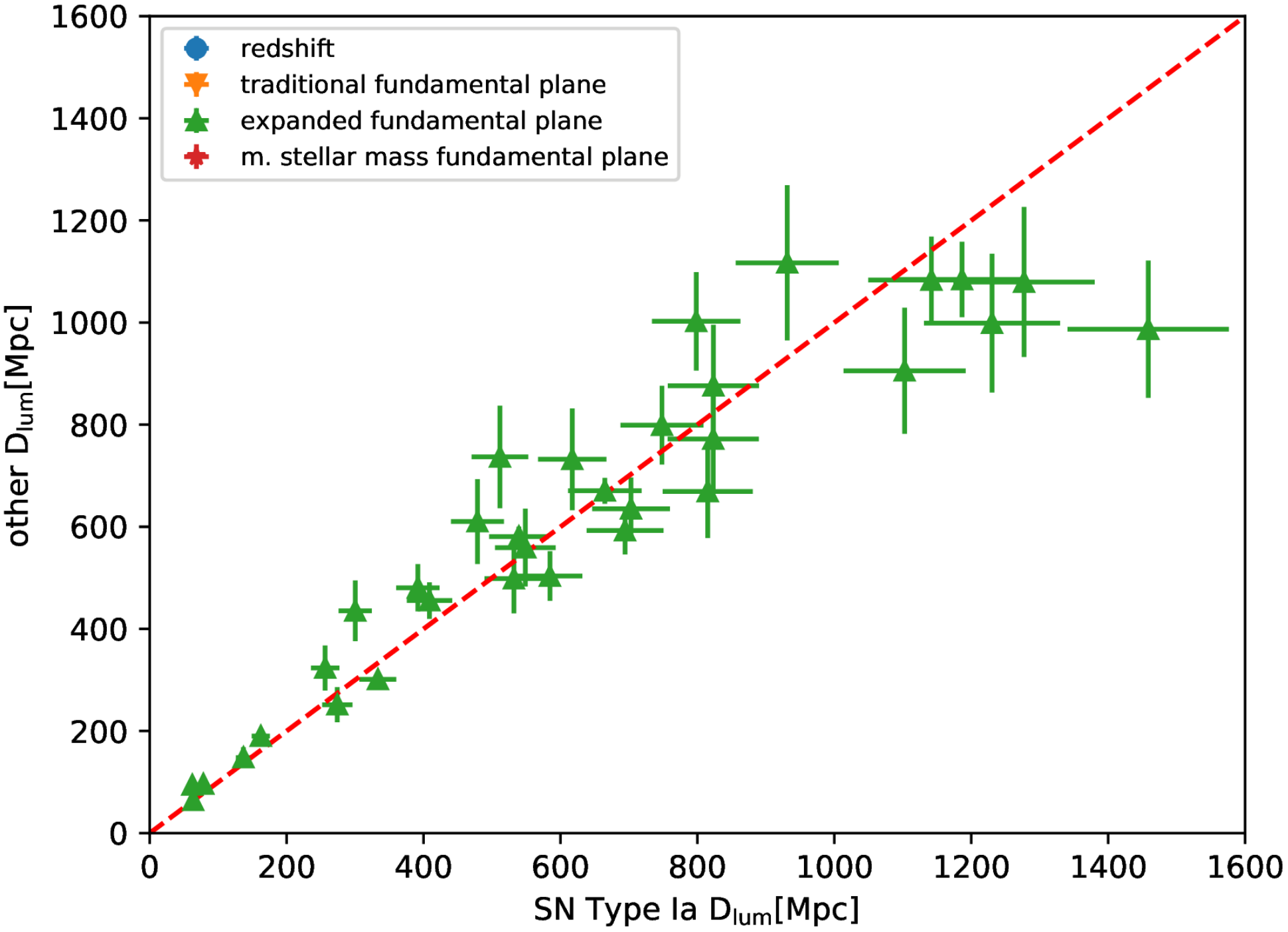
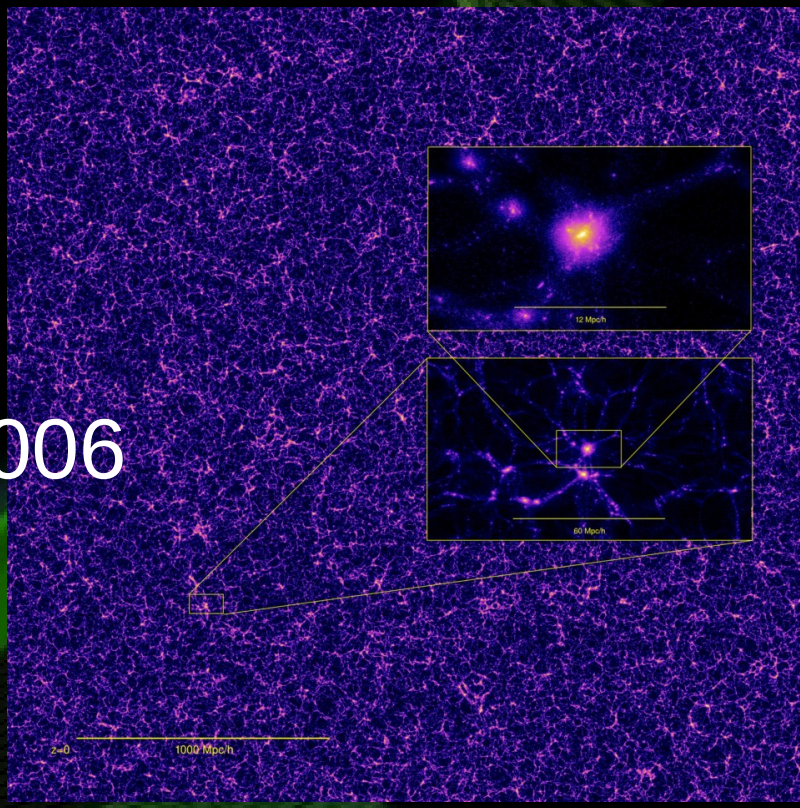
1200
1400
1600


redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{lum}[Mpc]
SN Type Ia D_{lum}[Mpc]
0
200
400
600
800
1000
1200
1400
1600

Peculiar motions

- Focus on rich groups/clusters in the nearby universe (error bars are lower and easier comparison to simulations)
- Comparing redshift-independent distances with redshifts → peculiar velocities
- Handeling systematics … very difficult
- Comparision to CosmicFlows-3
- We will derive mass estimates for the largest structures in the universe
- Studying inflows into clusters (along the filaments)

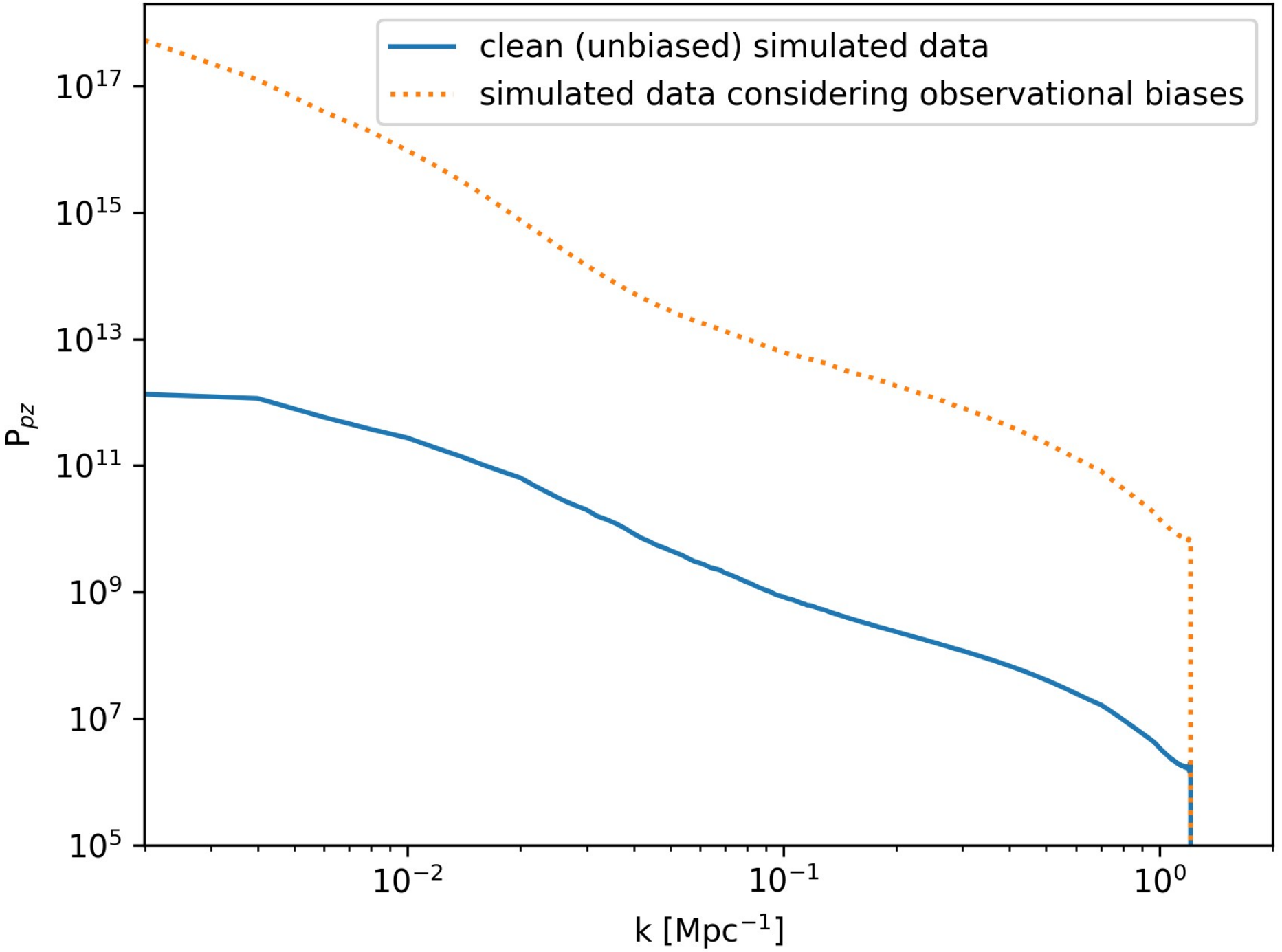
Momentum power spectrum



- HorizonRun 4
  - Huge DM-only simulation: 3150 Mpc/h side-length cube
- method of Park+ 1994, 2000, 2006

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

- Measuring β_s: $\beta_S(k) = \frac{P_p^{\rm obs}(k)}{P_p^{\rm der}(k)}$. $\beta_S = \Omega_m^{0.6}/b_S$
- Prediction from the simulation assuming the uncertainties of the fundamental plane


clean (unbiased) simulated data
simulated data considering observational biases
10^{17}
10^{15}
10^{13}
10^{11}
10^{9}
10^{7}
10^{5}
P_{pz}
10^{-2}
10^{-1}
10^{0}
k [Mpc^{-1}]

Summary

- Group catalogue covering ~1 500 000 galaxies
- ~320 000 fundamental plane distances
- Largest self-consistent set of redshift-indepenent distances ever produced
- Fundamental plane calibrations suffer from biases → looking for the best solution
- Comparison to Tully-Fisher relation, CosmicFlows-3, and Supernova Type Ia distances
- Presented in **Saulder+, submitted** … additional improvements will be included in the final paper

Outlook

- Working on peculiar motions and momentum power spectrum (comparision to HorizonRun 4)
- Expanding to full-sky … we need the Southern Hemisphere
- Our new collaborator is doing the same with 6dFGSv and will also be involved in Taipan.
- Still new to expanding our group catalogue
- Combining data from the Northern and Southern hemisphere
- How deep can we go? (to reasonably use the fundamental plane to study peculiar motions)

ANY QUESTIONS?