Fundamental plane distances: providing observational data for cosmological tests

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The Correlated Universe
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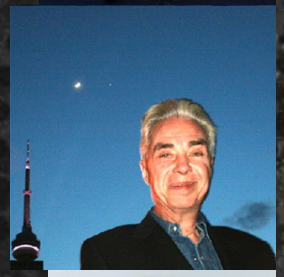
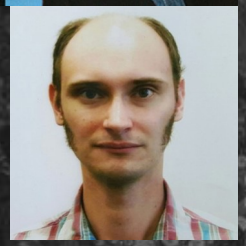
Collaborators

Christoph Saulder (KIAS)



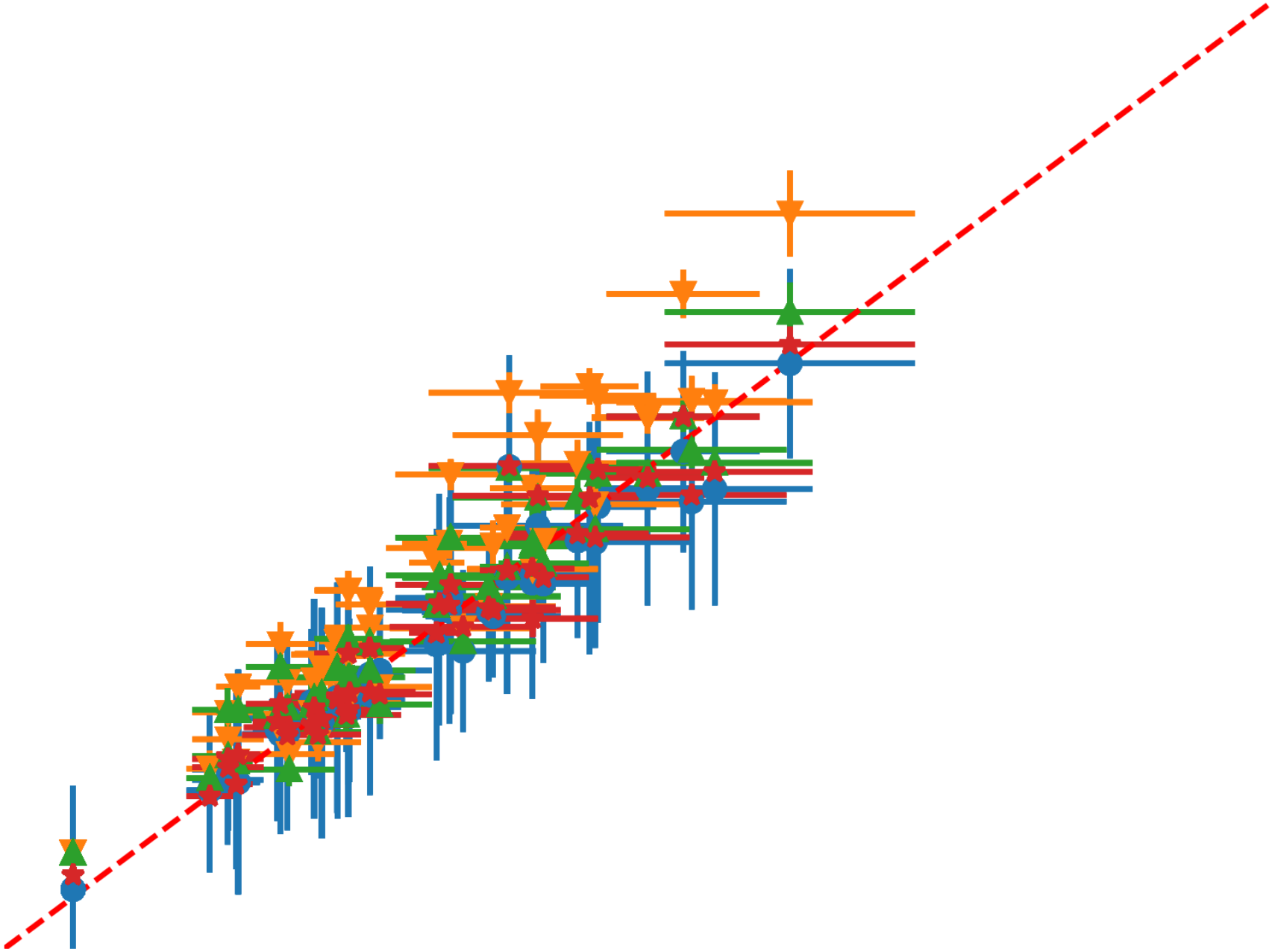
Ian Steer (NED)



Owain Snaith (Paris Observatory)

Changbom Park (KIAS)

Cullan Howlett (ICRAR/UWA)
(soon: University of Queensland)

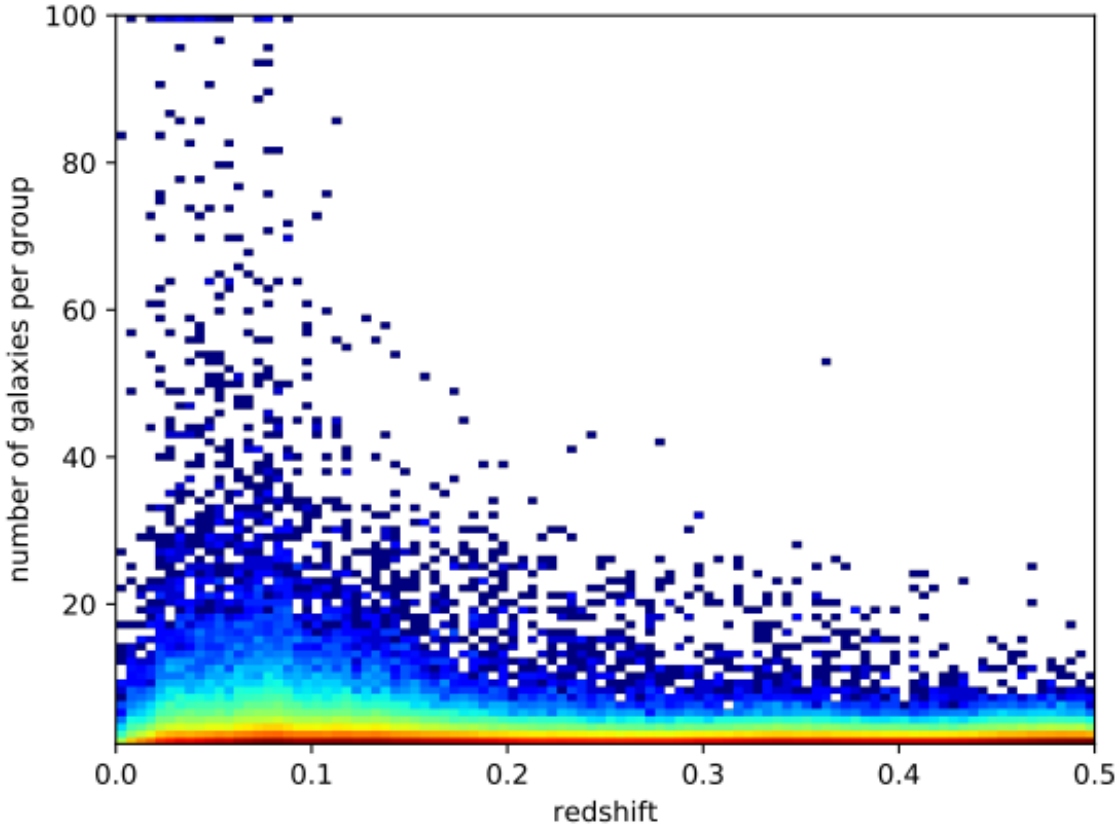


Group catalogue

- 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)

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)

$$\log_{10}(R_e) = a \cdot \log_{10}(\sigma_0) + b \cdot \mu_e + c$$

- Standard rod for early-type galaxies → comparing observed sizes with predicted sizes → angular diameter distances
- 317 285 suitable ETGs in SDSS DR15
  largest dataset every used for the FP

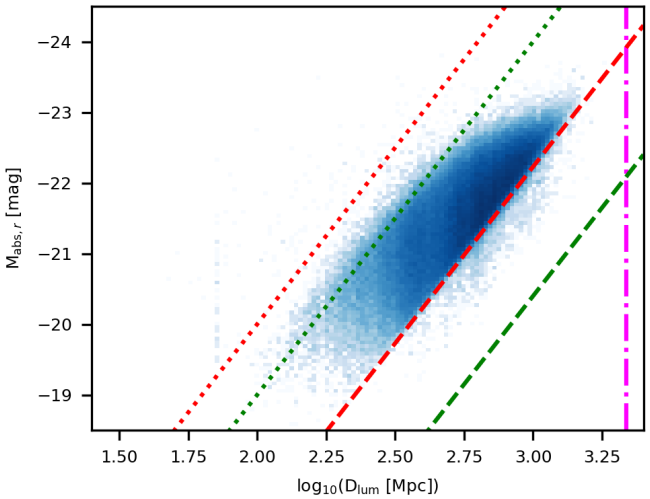
Fitting the traditional fundamental plane

- Applying basic calibrations and corrections to the data retrieved from SDSS
- Direct fit (minimizing the scatter in radii (Sheth&Bernardi 2013)) using least squares

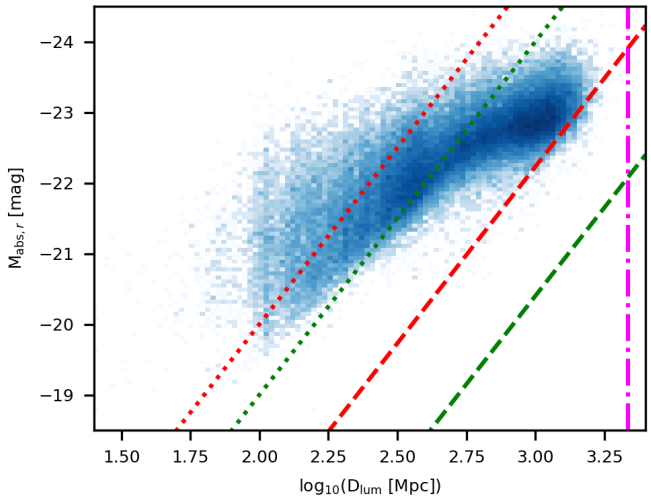
  → fundamental plane coefficients
- We INTENTIONALLY did NOT correct for the Malmquist bias (typical done using volume weightening)
- Because of the complex composition of our sample

Subsets of our ETG sample

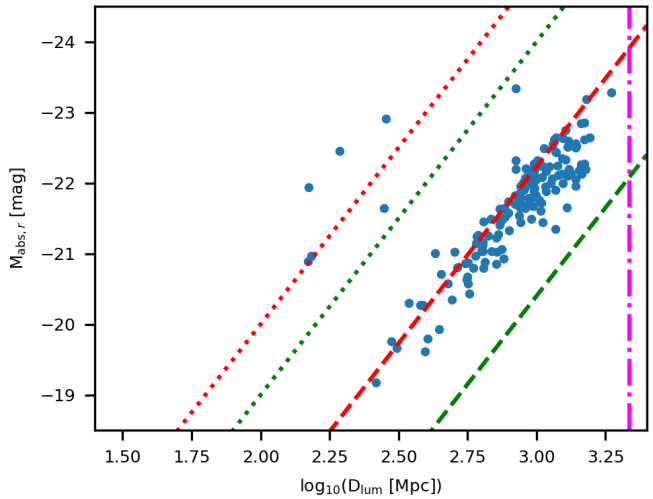
SDSS main galaxy sample

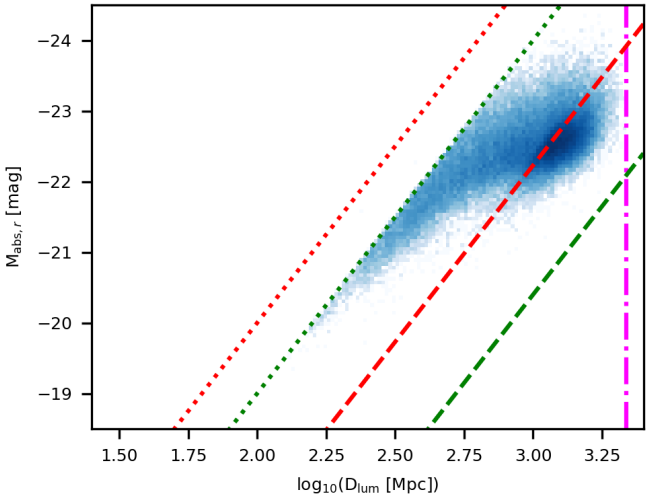


SDSS LRG sample

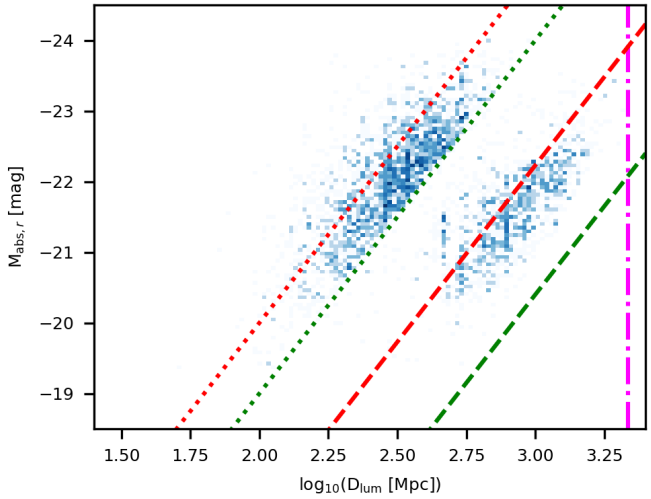


Other SDSS samples

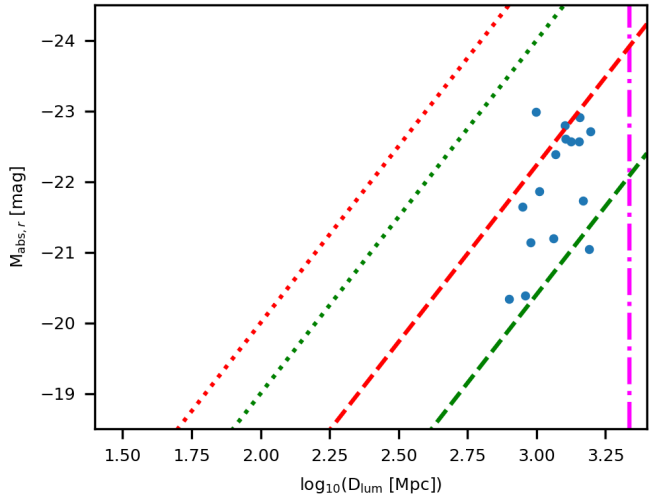




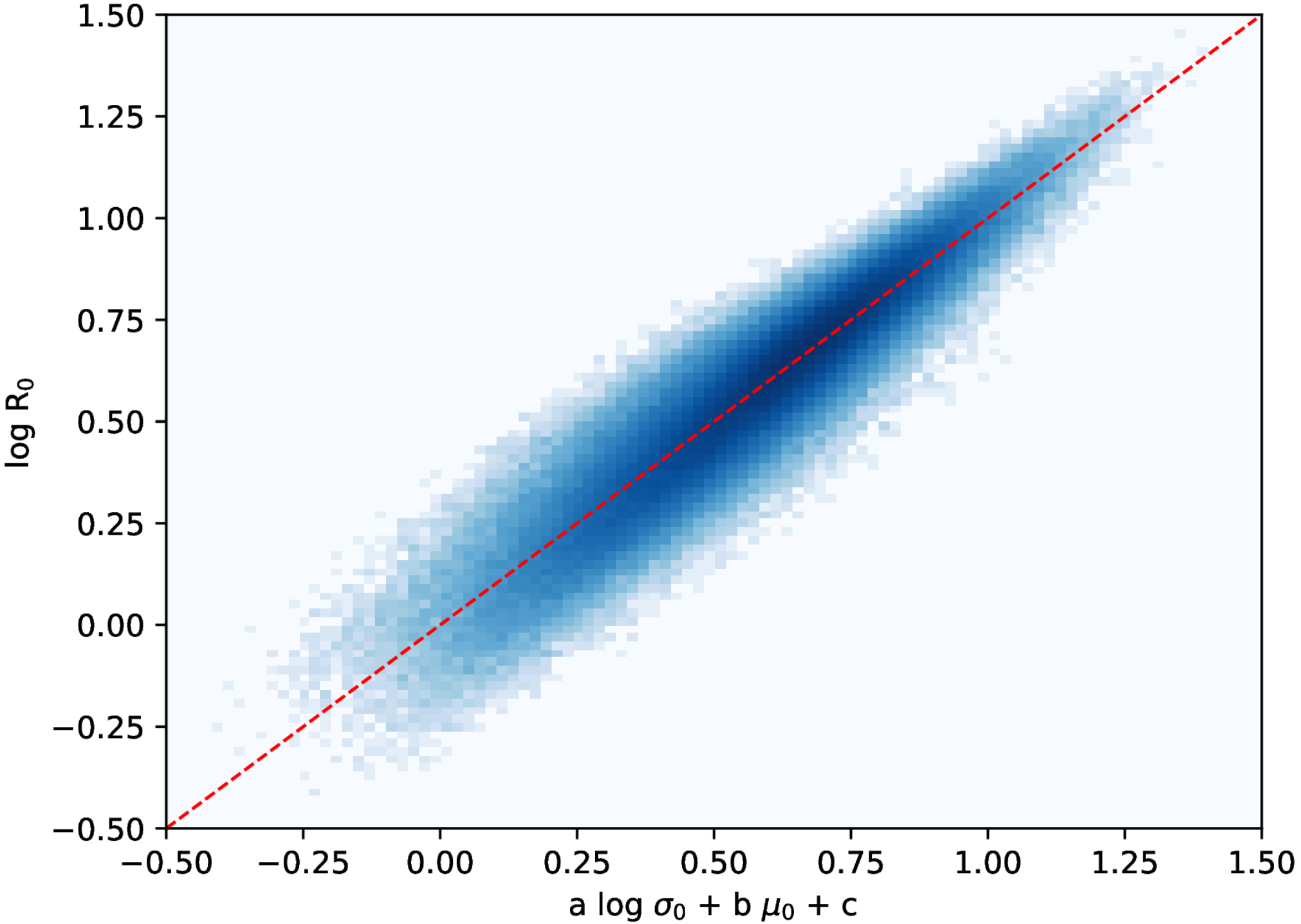
BOSS low-z sample



Other BOSS samples



CMASS samples


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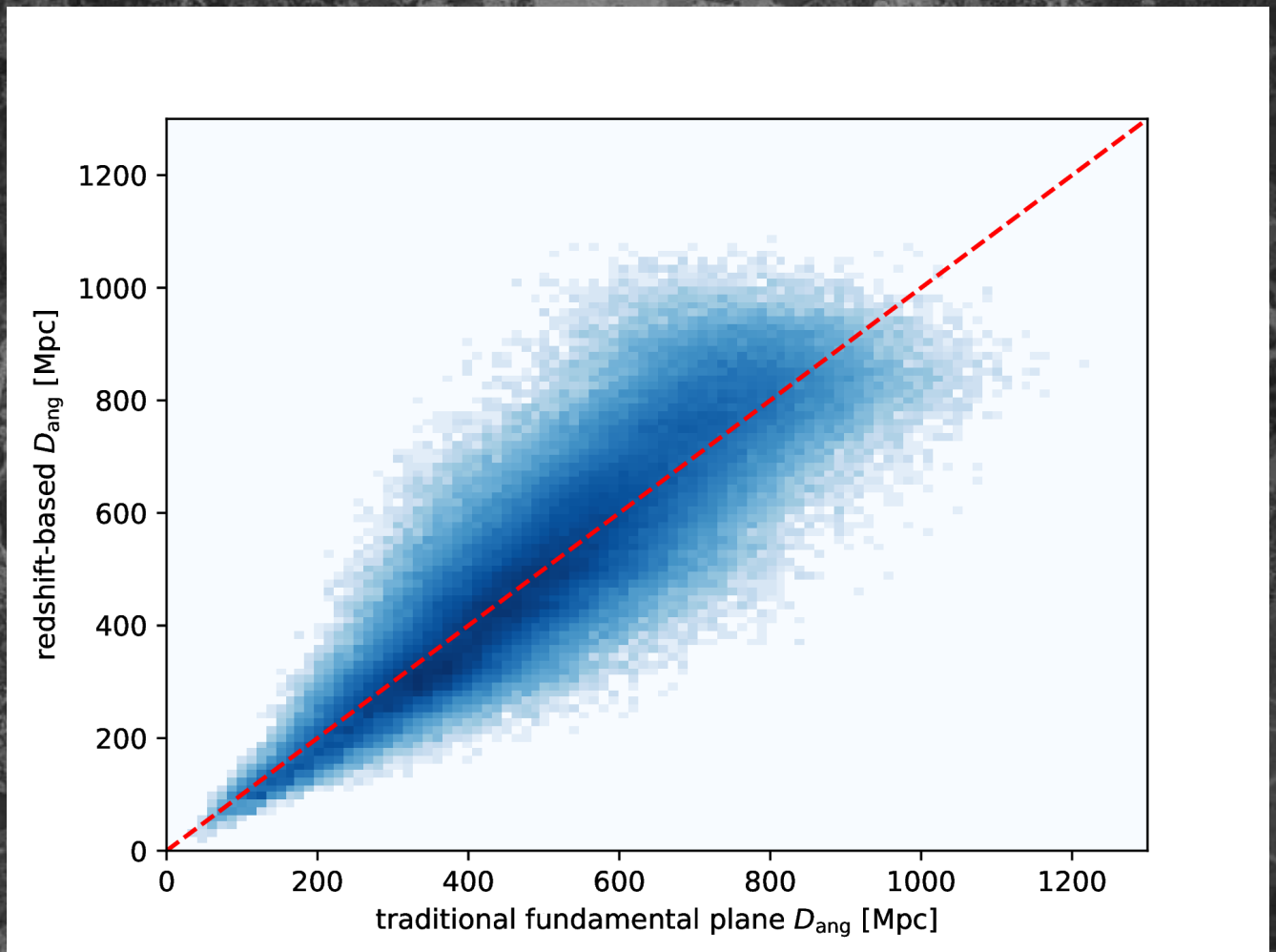
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
log R_0
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
a log σ_0 + b μ_0 + c

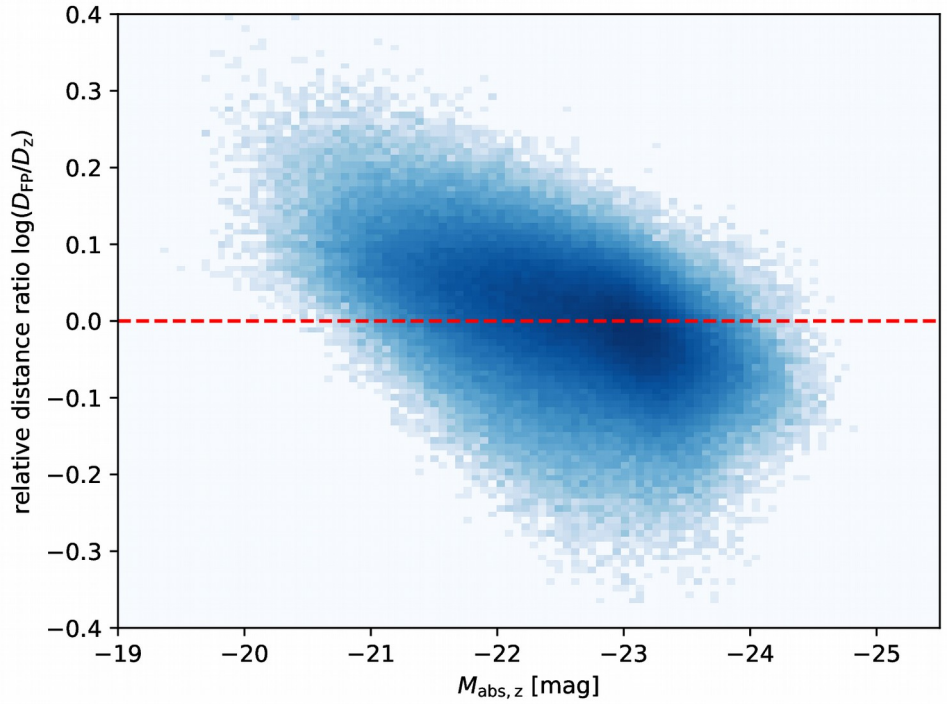
Fundamental plane distances

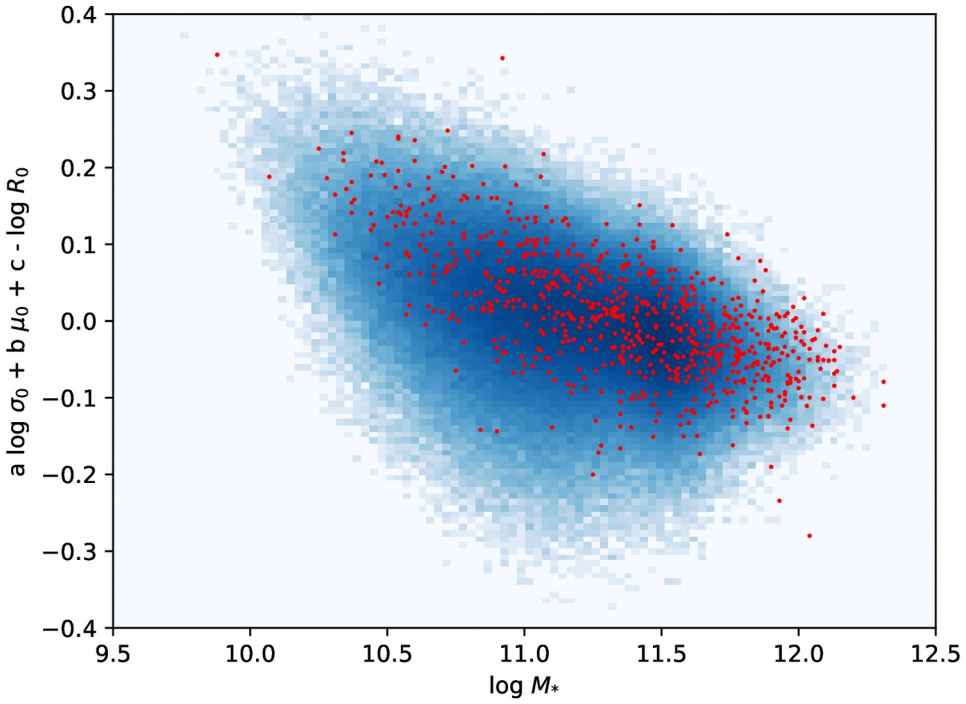
- Scatter of 20.2% without the group catalogue
- Scatter of 18.4% with the group catalogue



Luminosity / stellar mass biases

- Intrinsically fainter/brighter galaxies are systematically offset from the fundamental plane
- Stellar masses based on the Wisconsin method (Chen+ 2012) show the same effect, tighter relation with MaNGA data

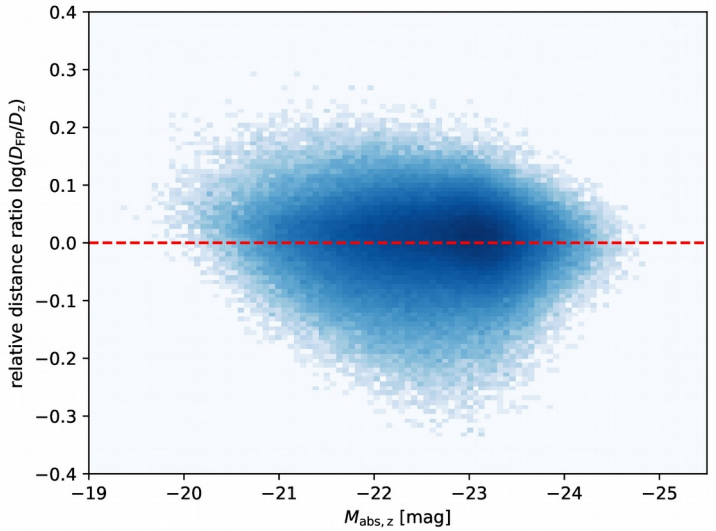


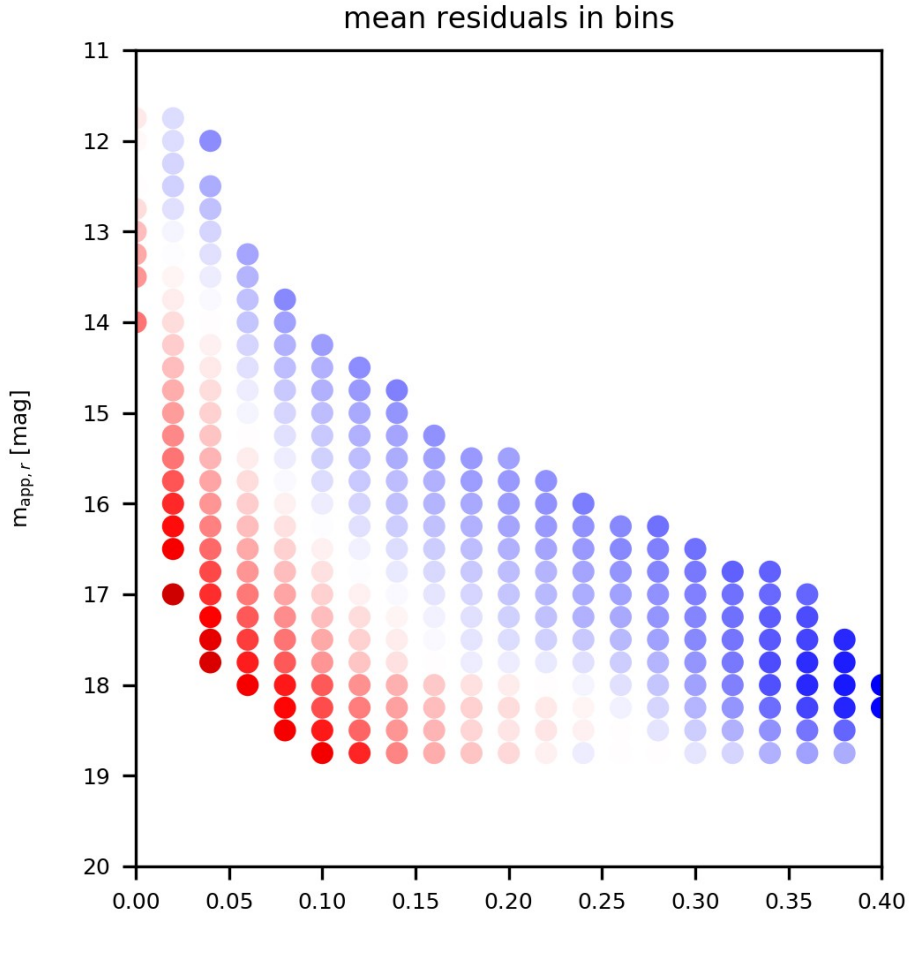


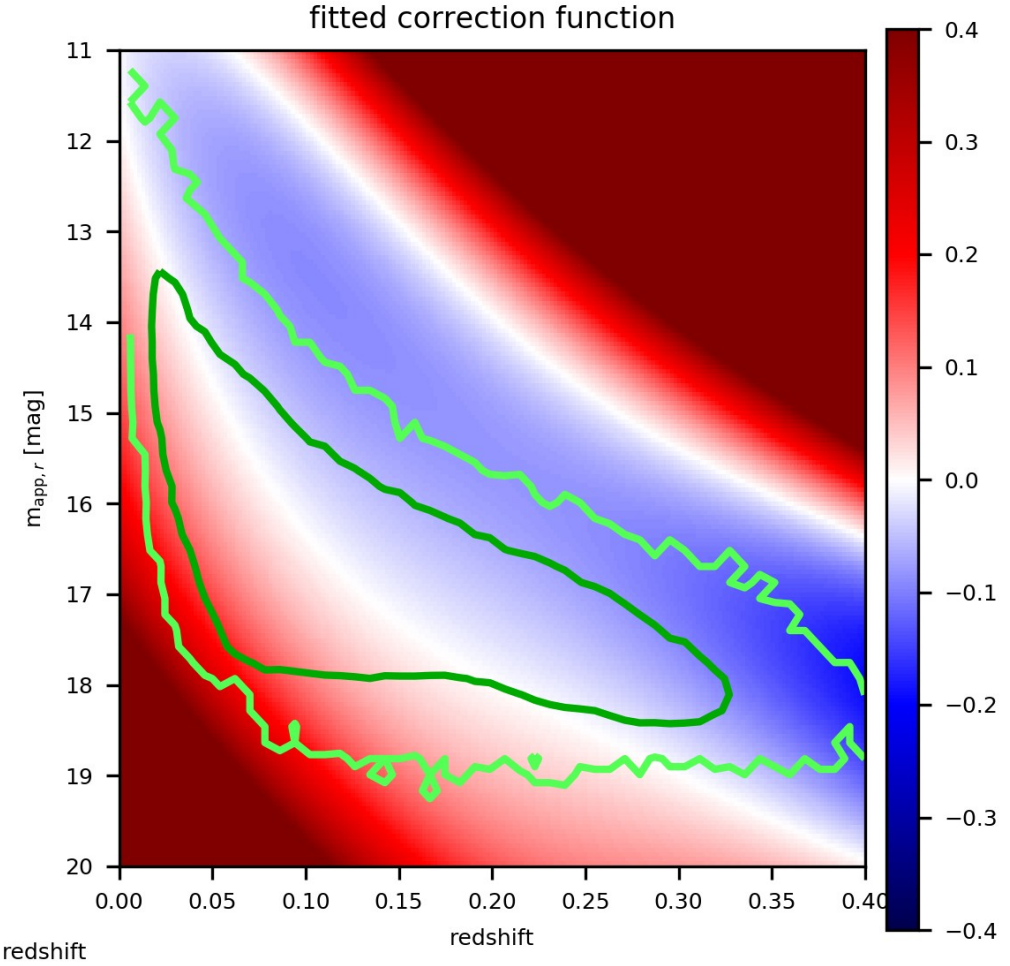
Corrected fundamental plane

- Studying the mean FP residuals in the in the (apparent) magnitude-redshift plane
- Clear trends, but complex functions
- Fitted with a 2D-polynonimal f_{cor}
- $\log_{10}(R_{e,cor}) = a \cdot \log_{10}(\sigma_0) + b \cdot \mu_e + c + f_{cor}(m,z)$

- Reduced scatter to 14.5%
- Luminosity bias removed





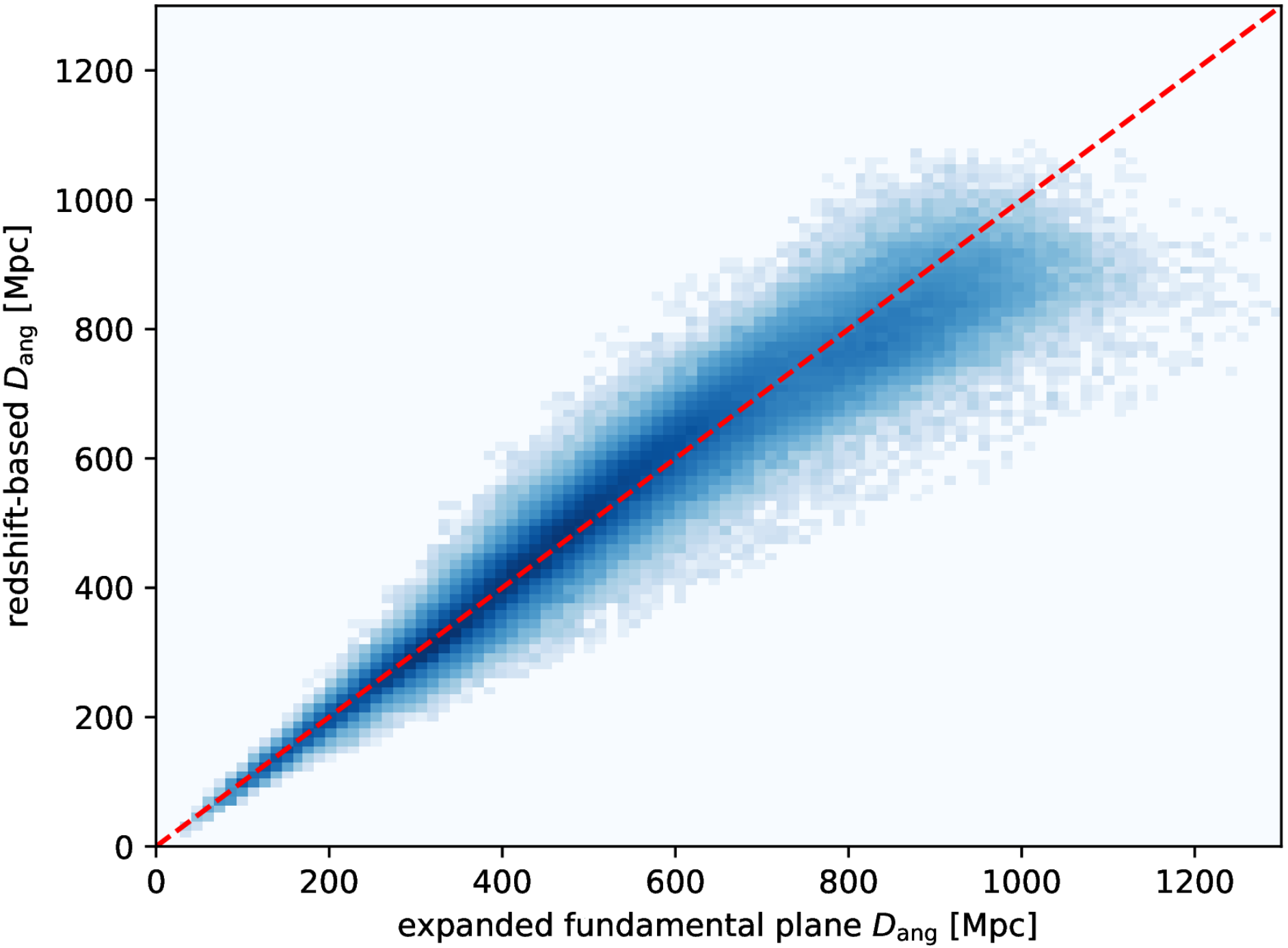


Expanded funamental plane

- Alternative way to adjust for the biases
- Expanding the FP by the stellar mass

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

- Photo-spectroscopical measured stellar mass using the method of Chen+2012 (from SDSS)
- Significant reduction in scatter → 9%
- Removes systematic offsets at low redshifts as well


redshift-based D_{ang} [Mpc]
expanded fundamental plane D_{ang} [Mpc]
0
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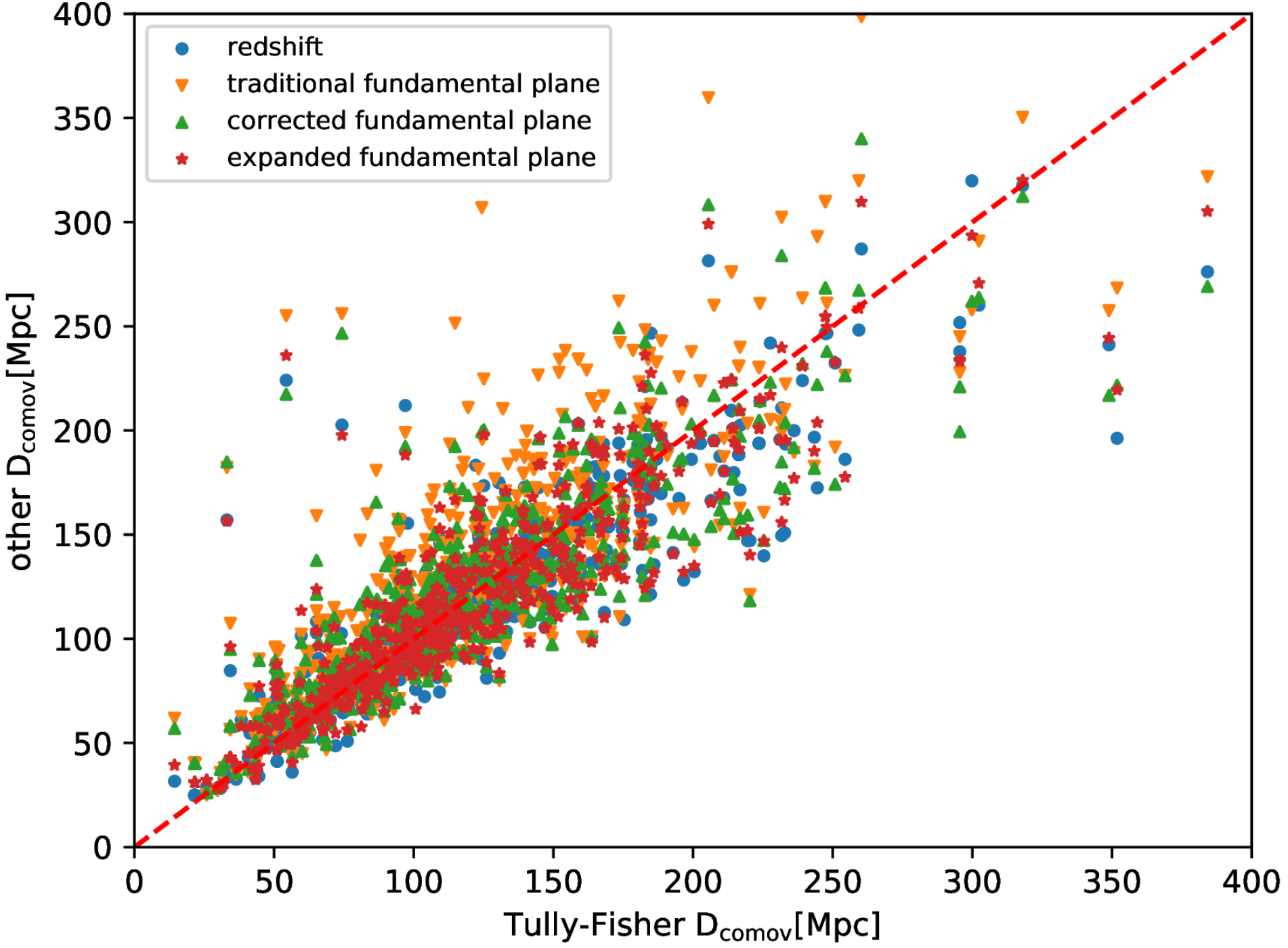
Paying the price

- Overall scatter of 9% … **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 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
corrected fundamental plane
expanded fundamental plane
other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
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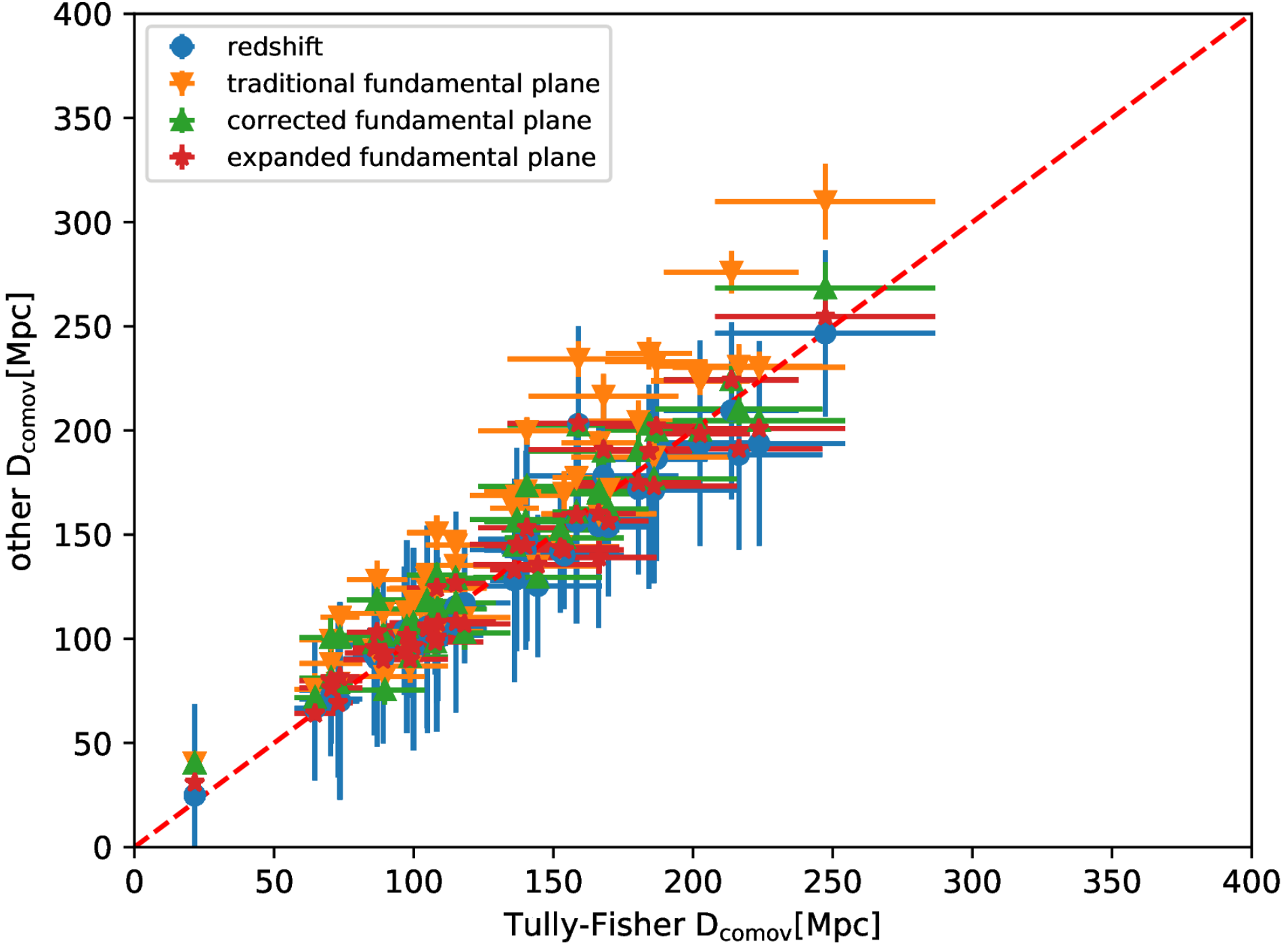
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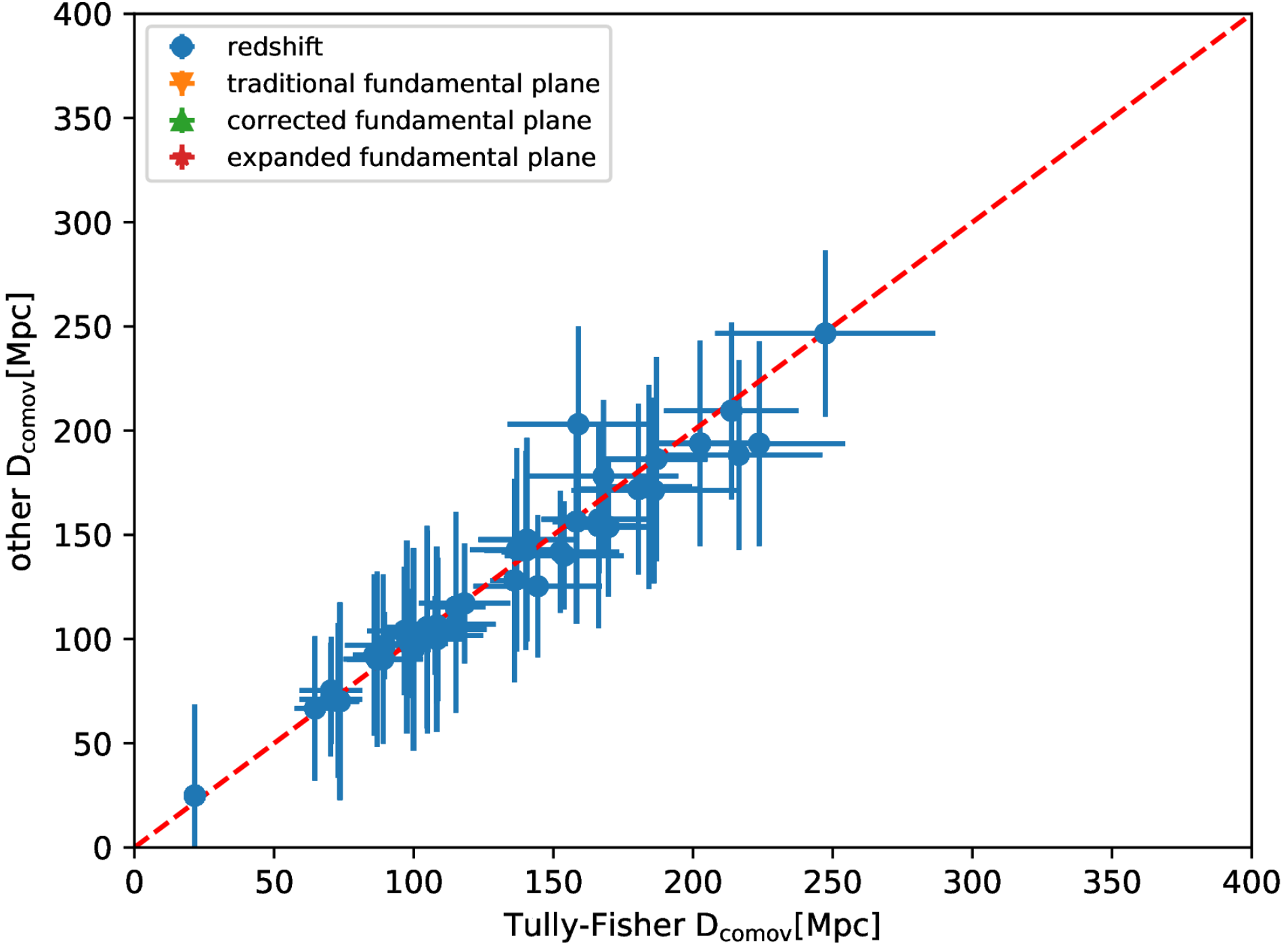
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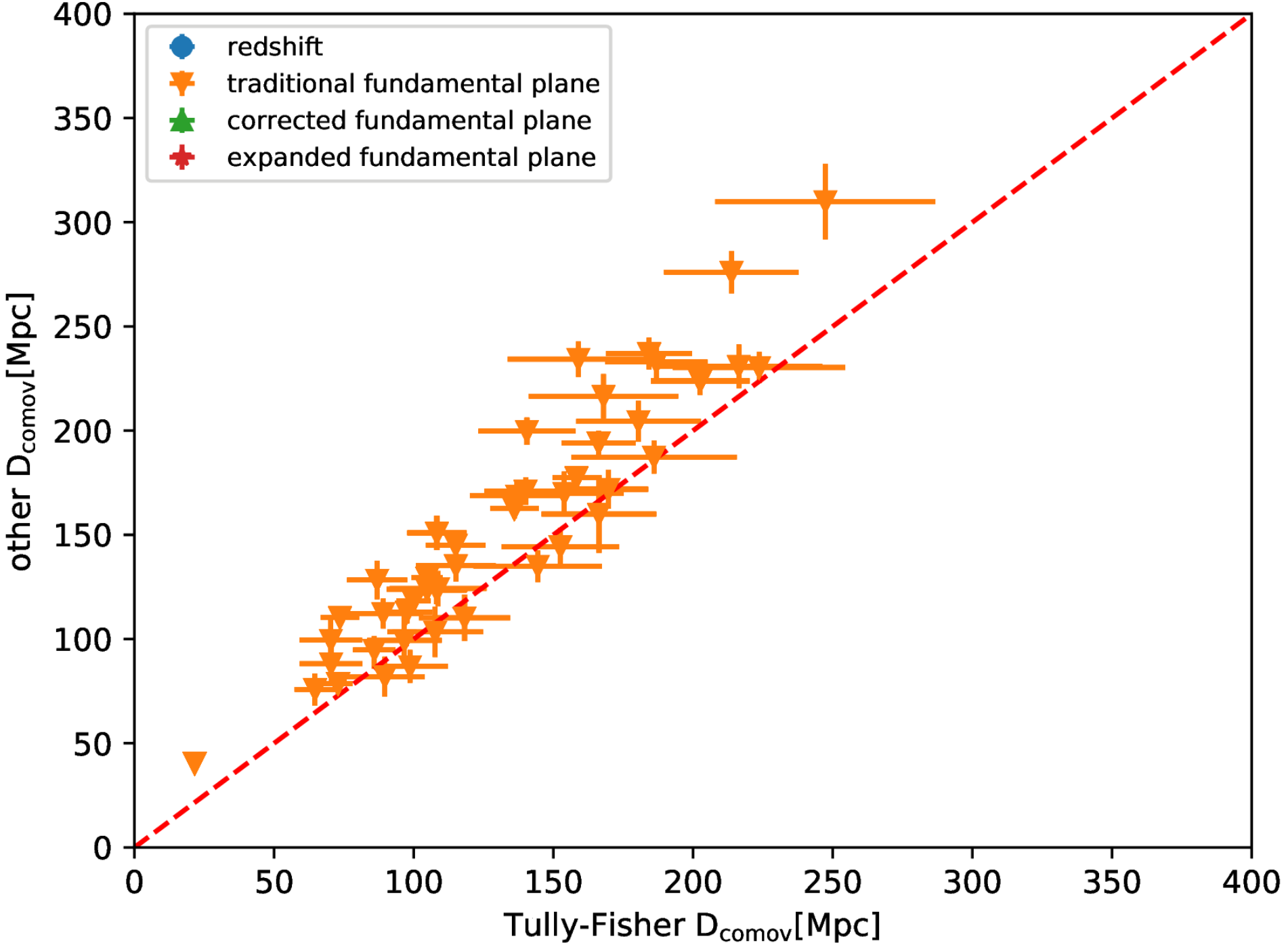
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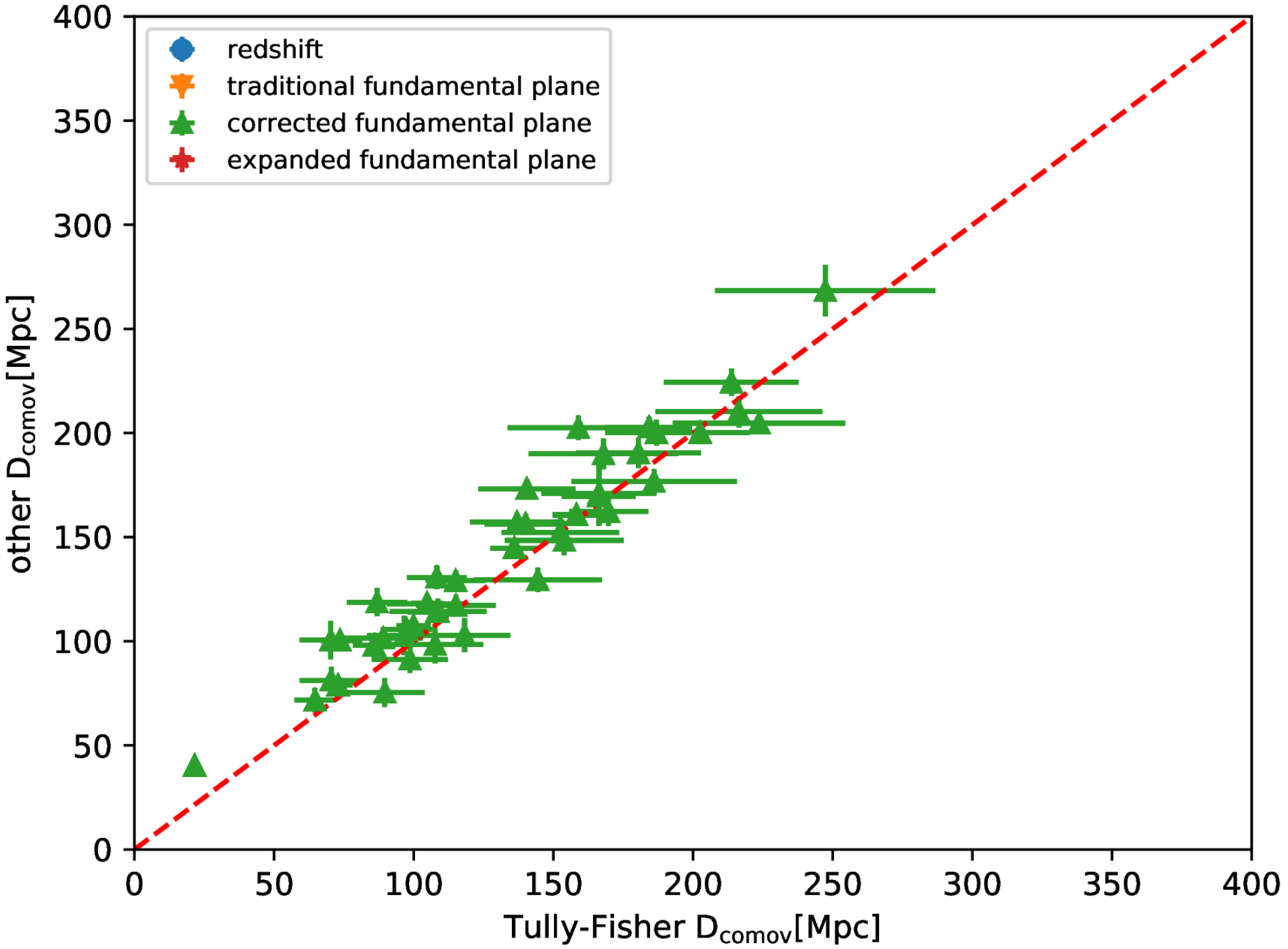
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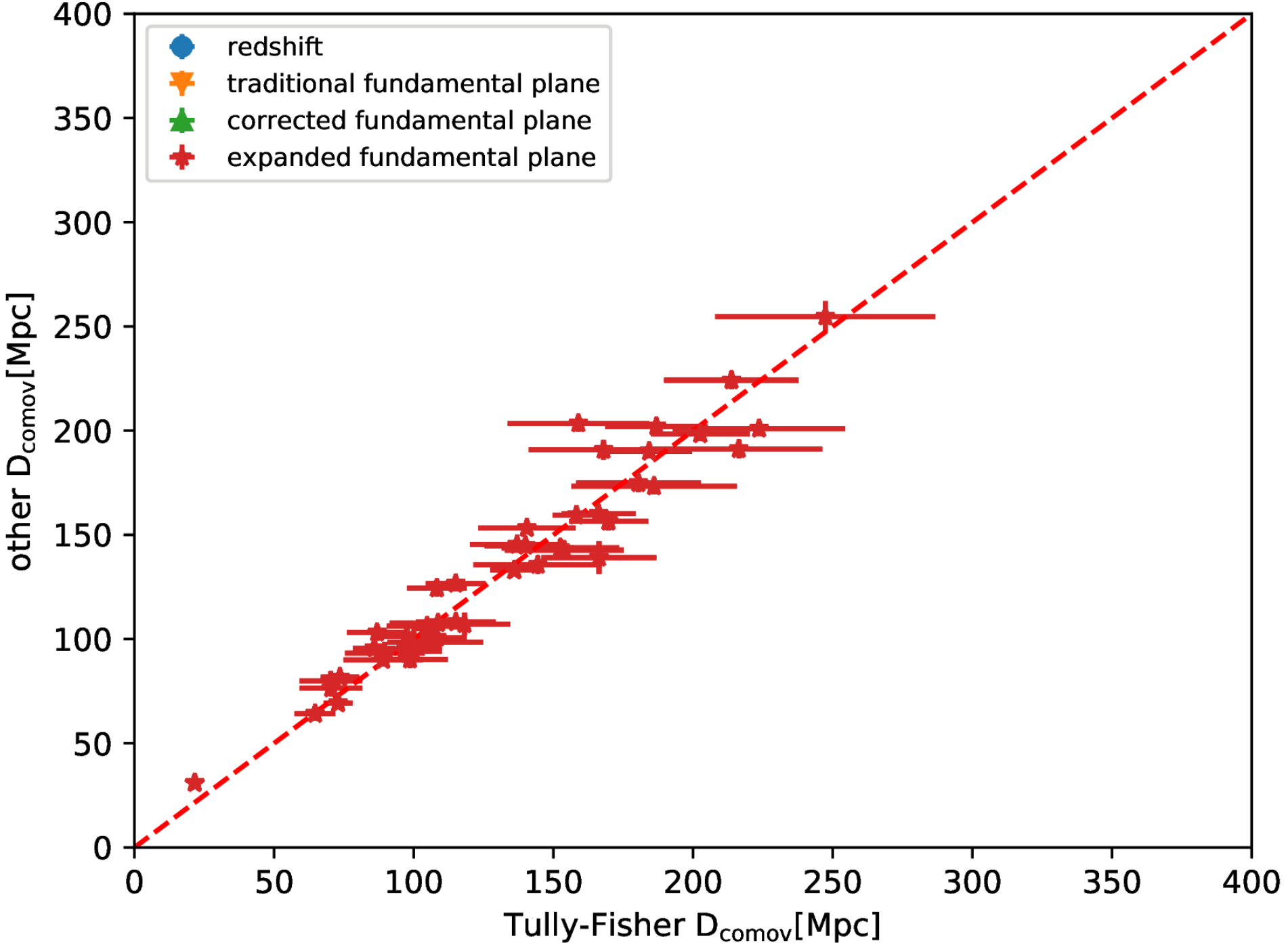
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expanded fundamental plane
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Tully-Fisher D_{comov}[Mpc]
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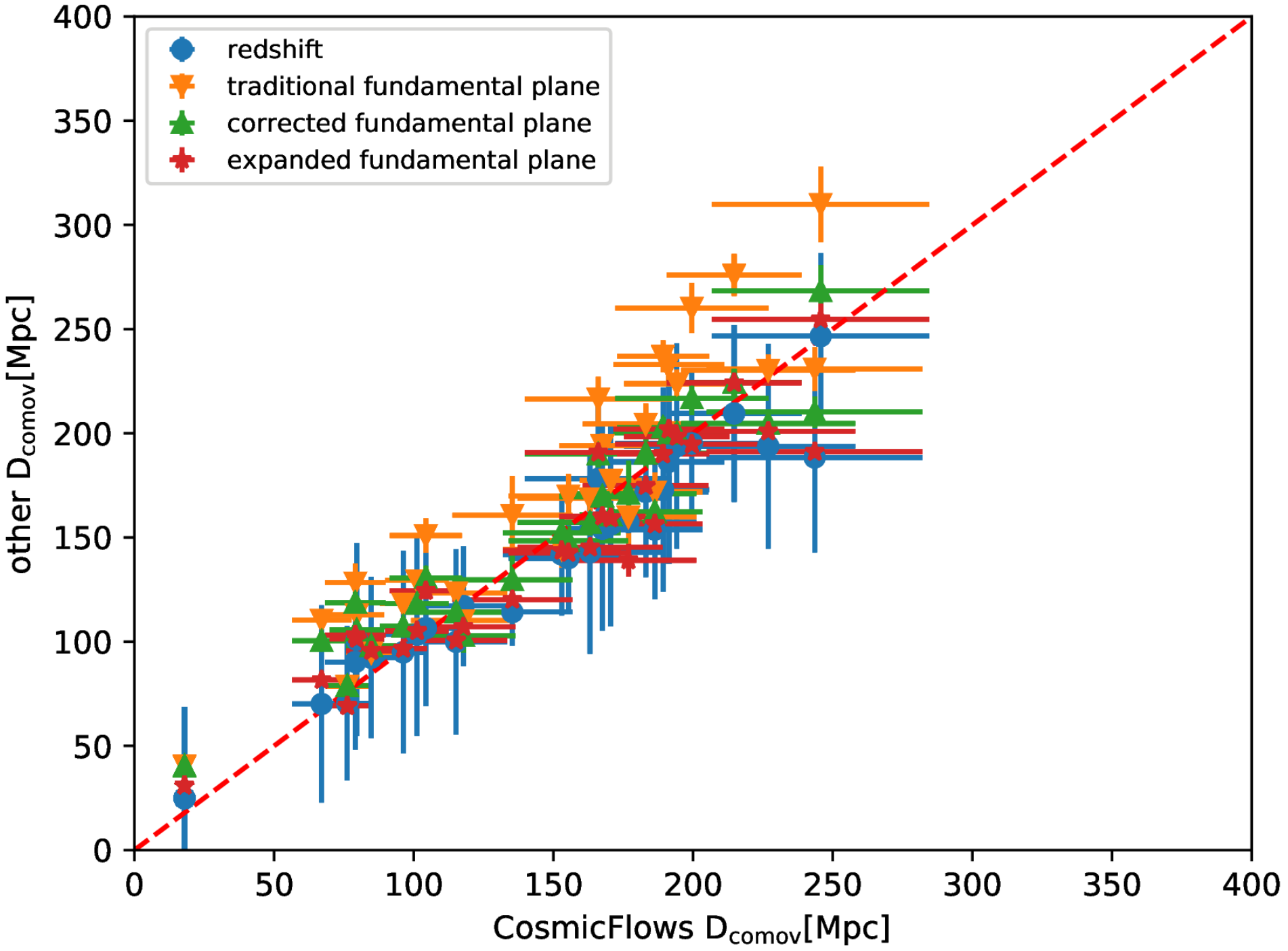
Comparison to the CosmicFlows-3 sample

- 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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other D_{comov}[Mpc]
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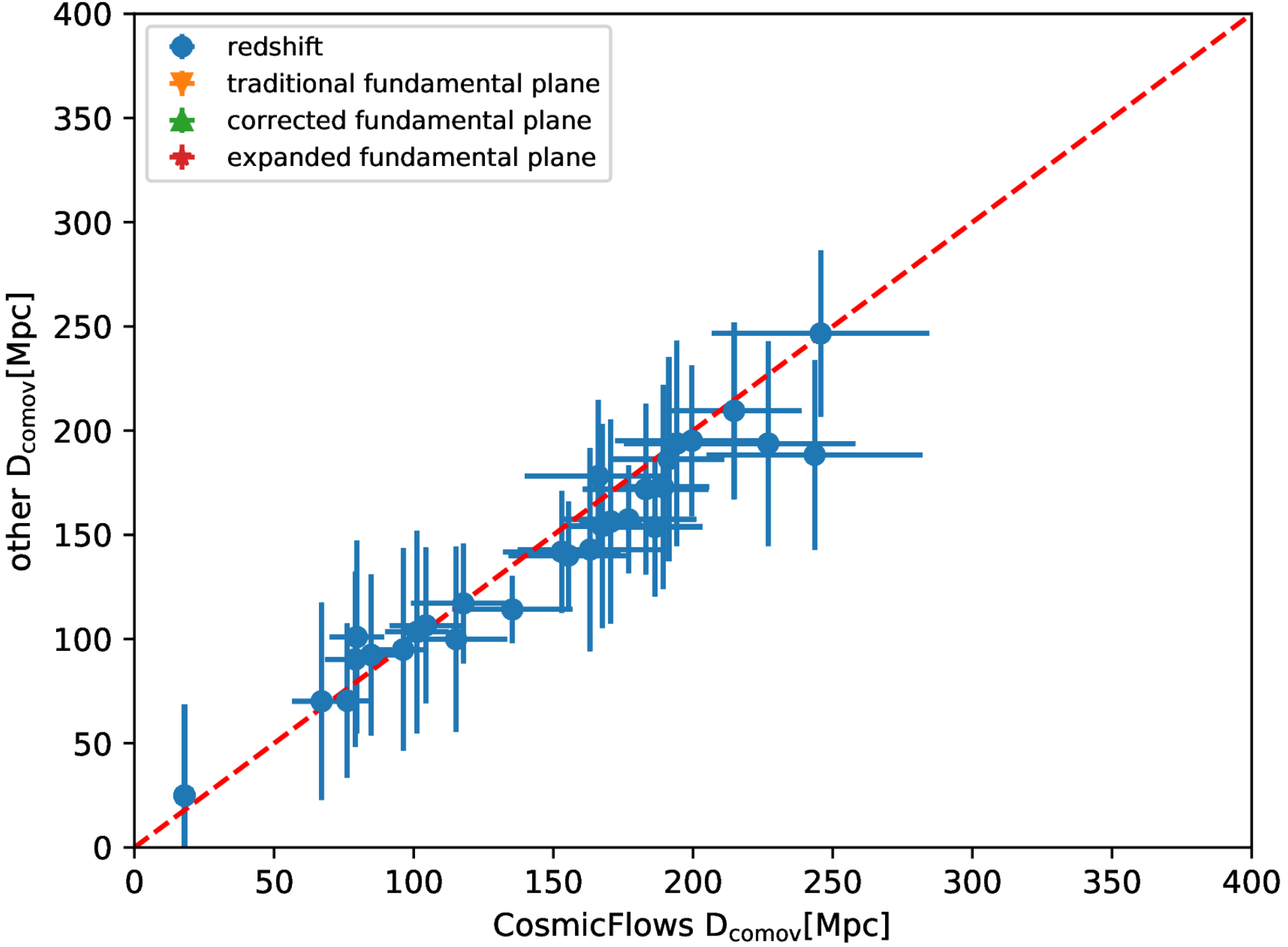
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CosmicFlows D_{comov}[Mpc]
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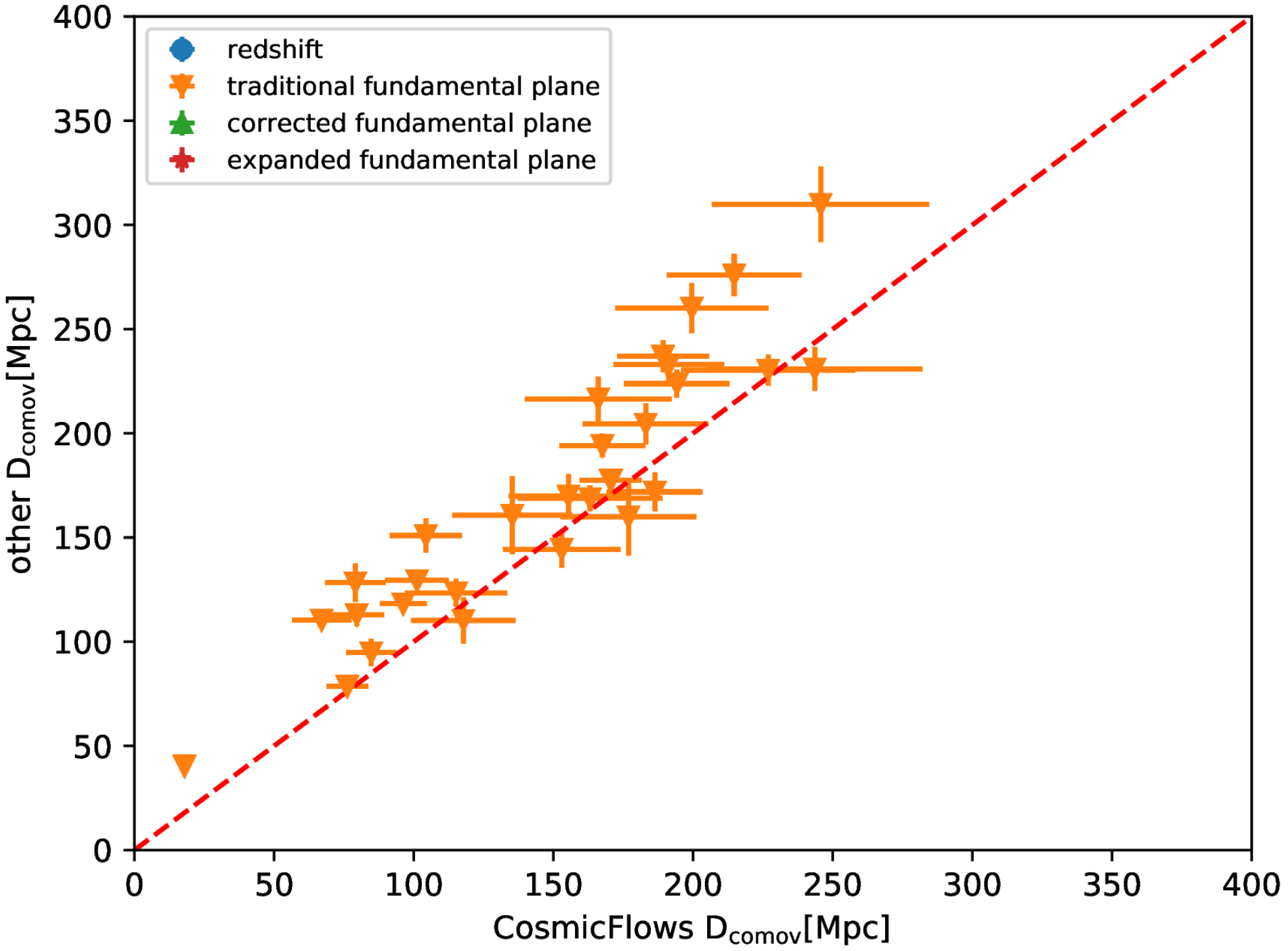
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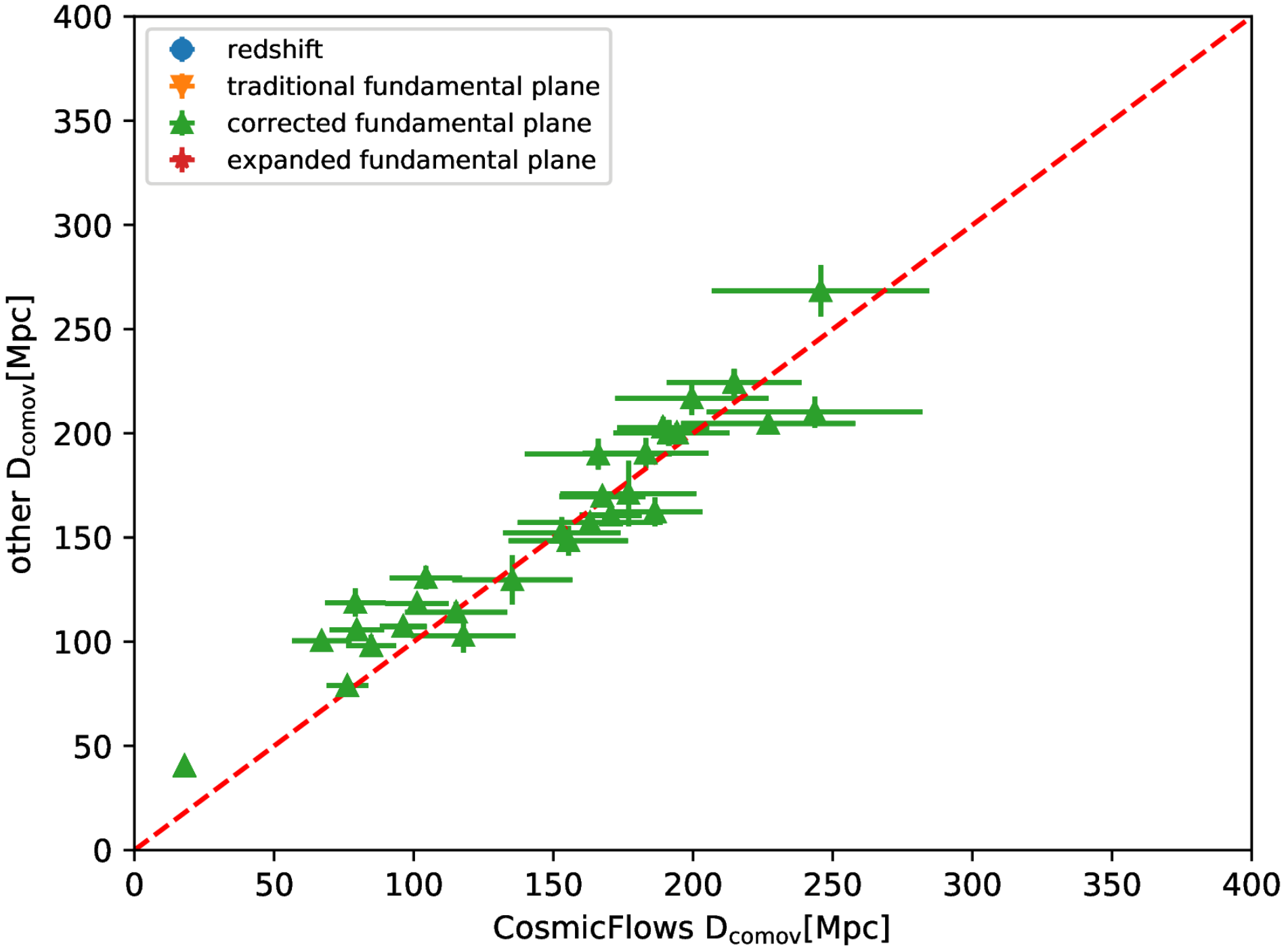
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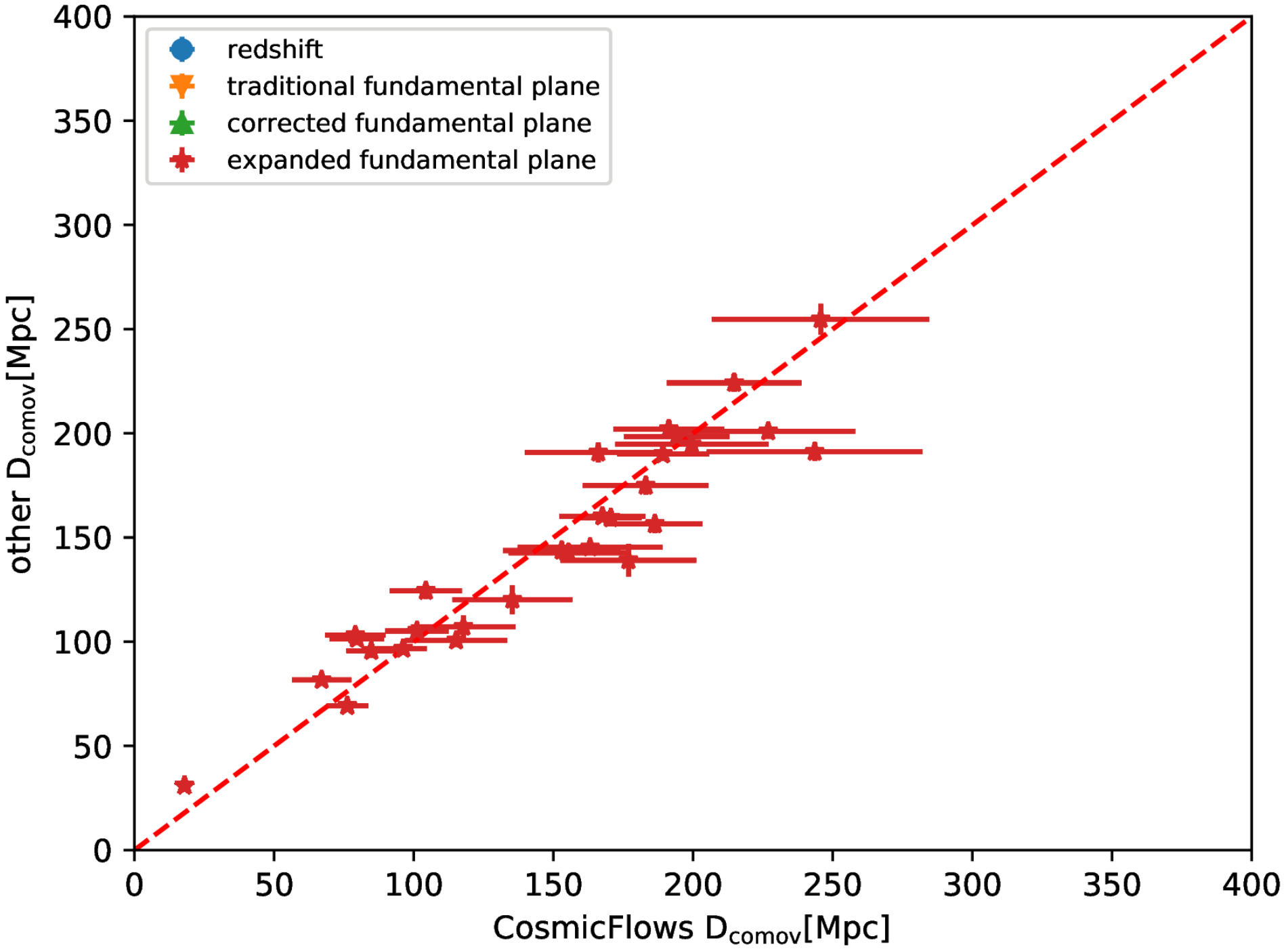
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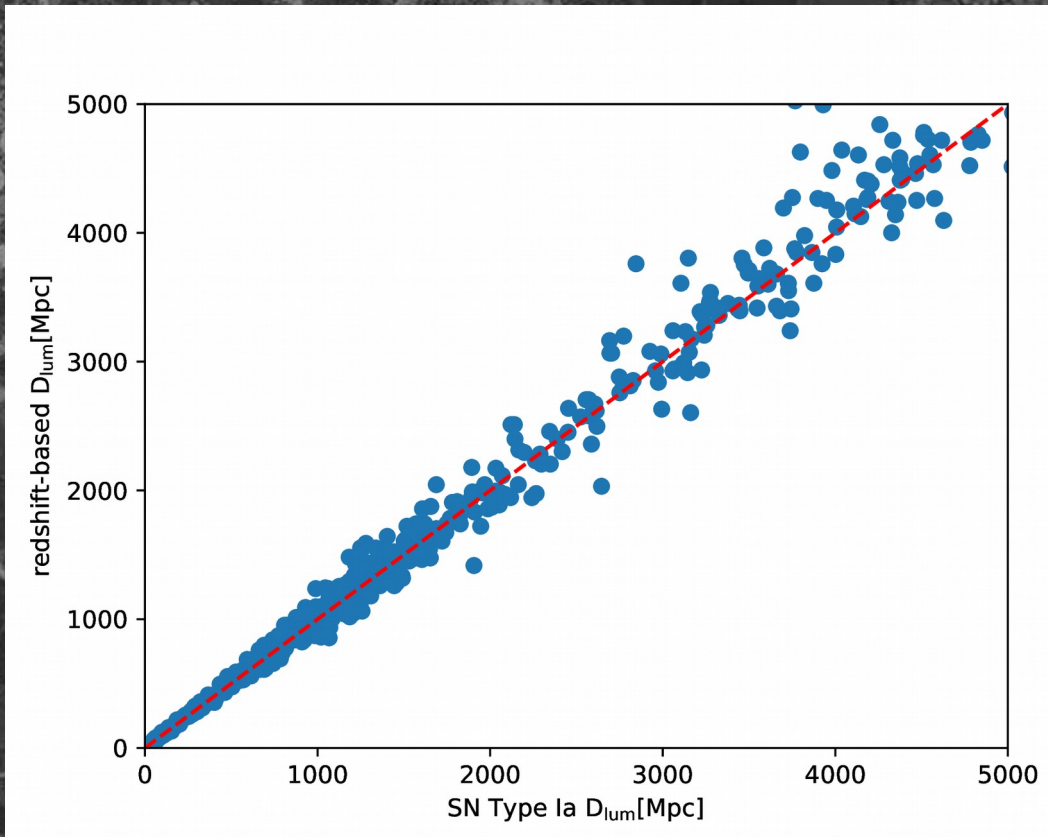
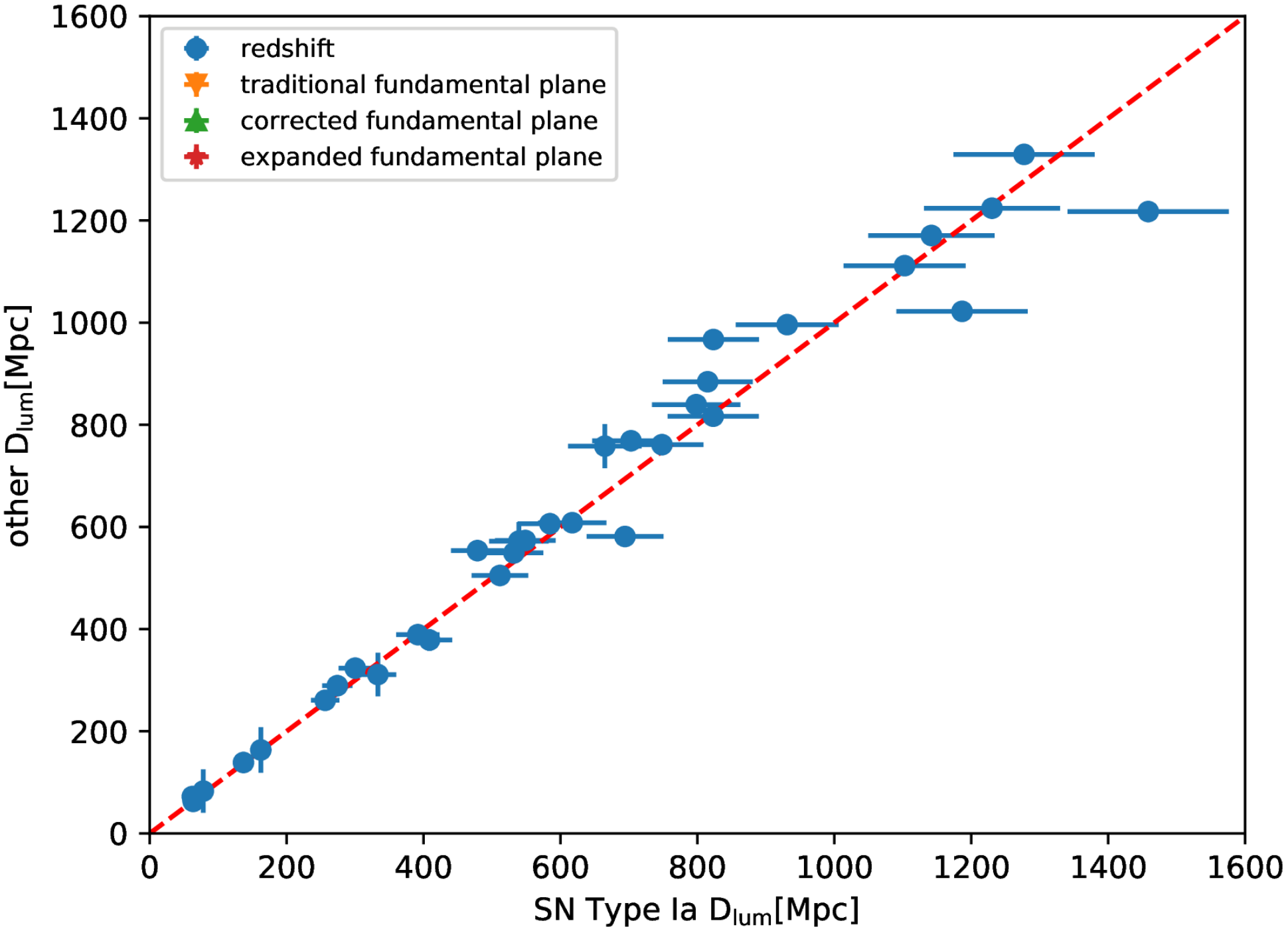
Comparison to supernovae Type Ia

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

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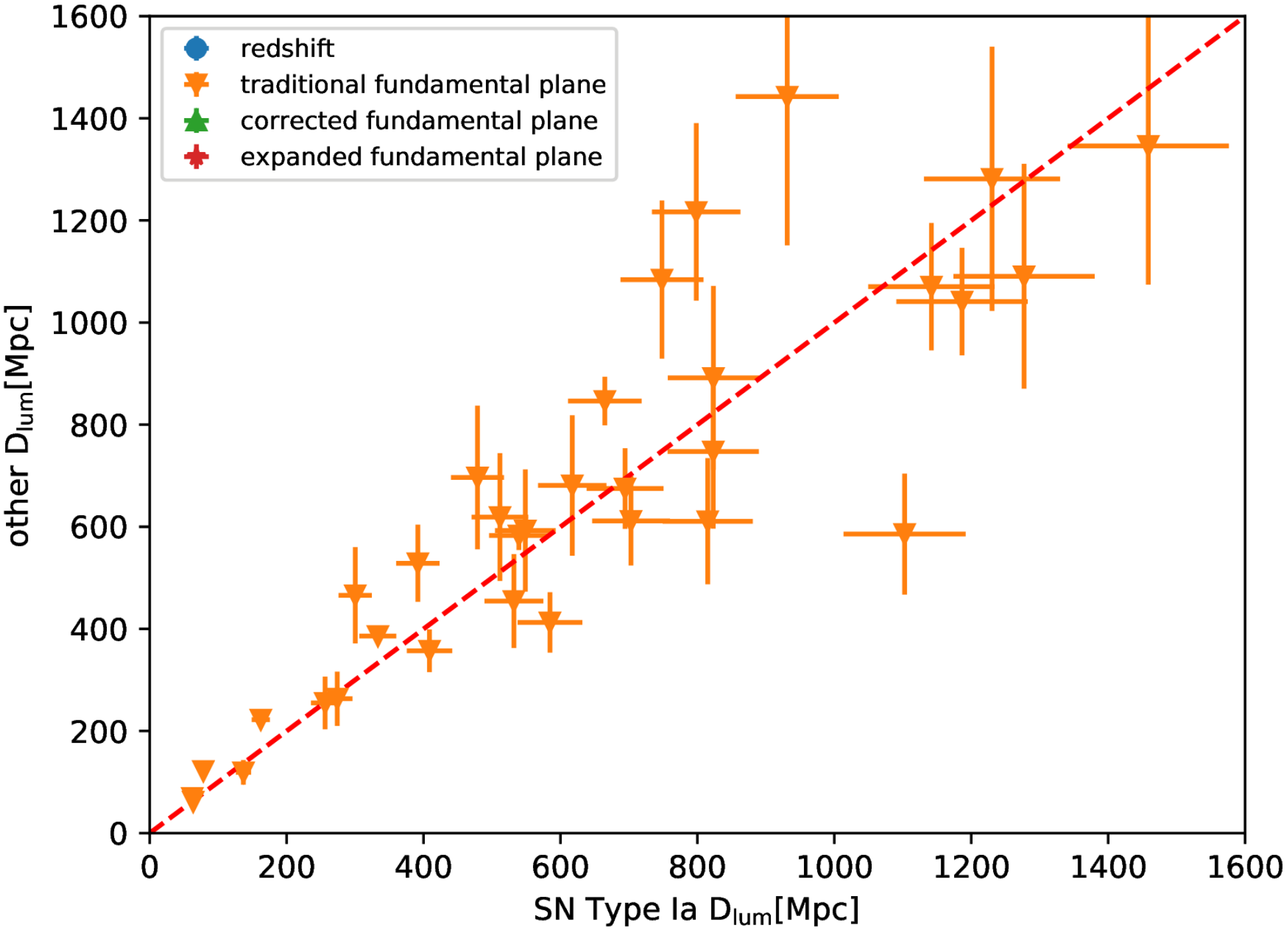
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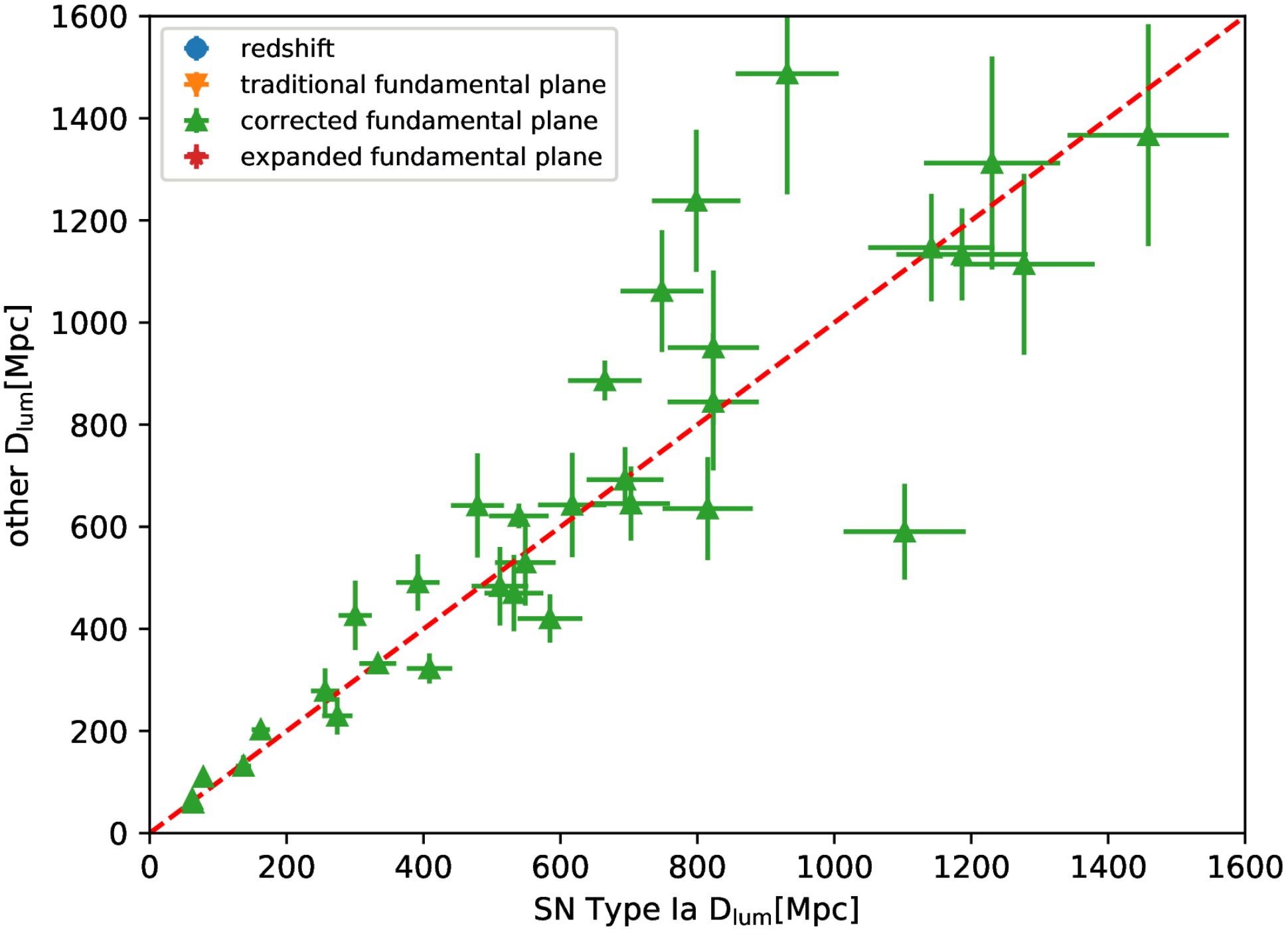
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SN Type Ia D_{lum}[Mpc]
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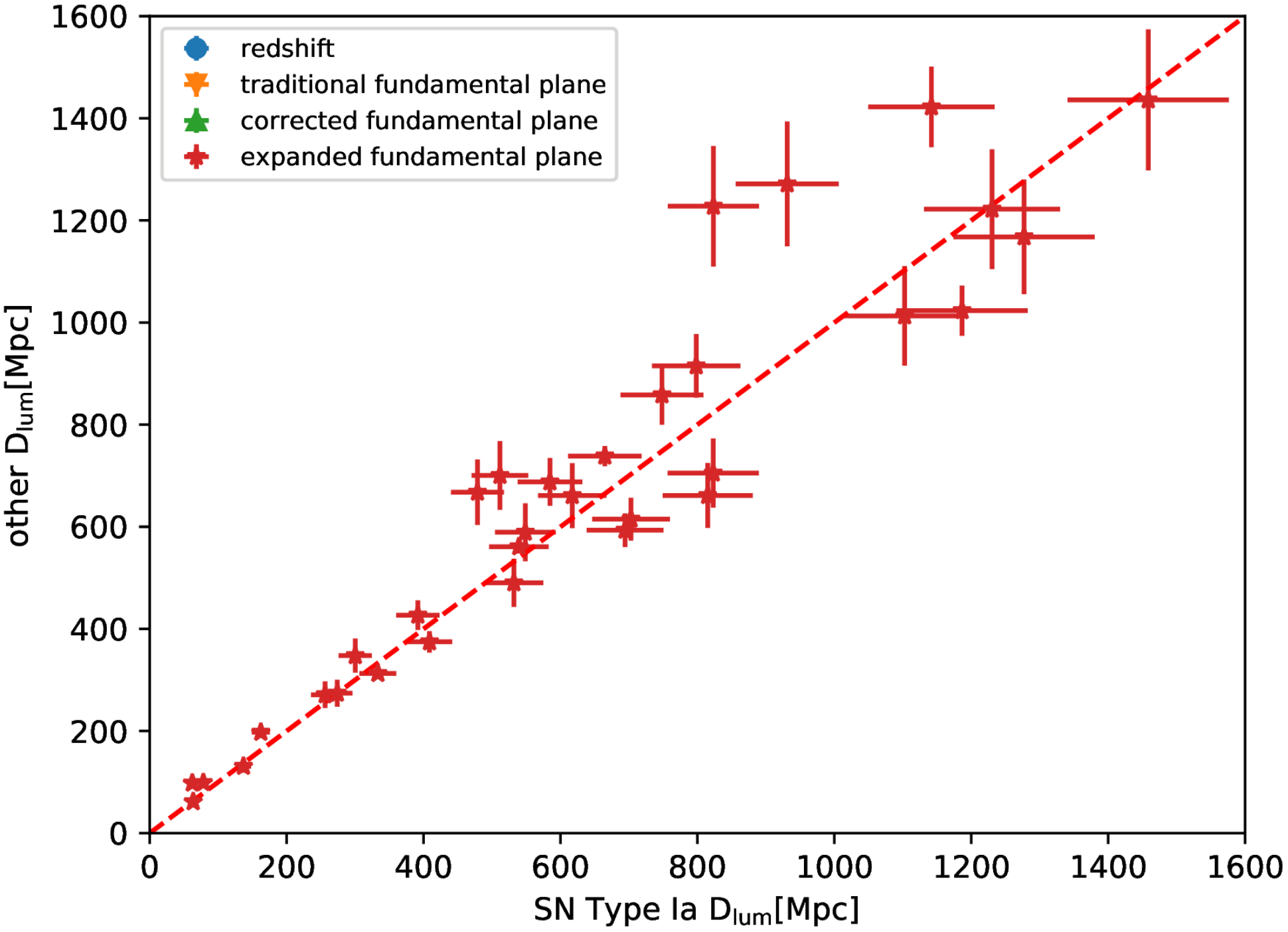
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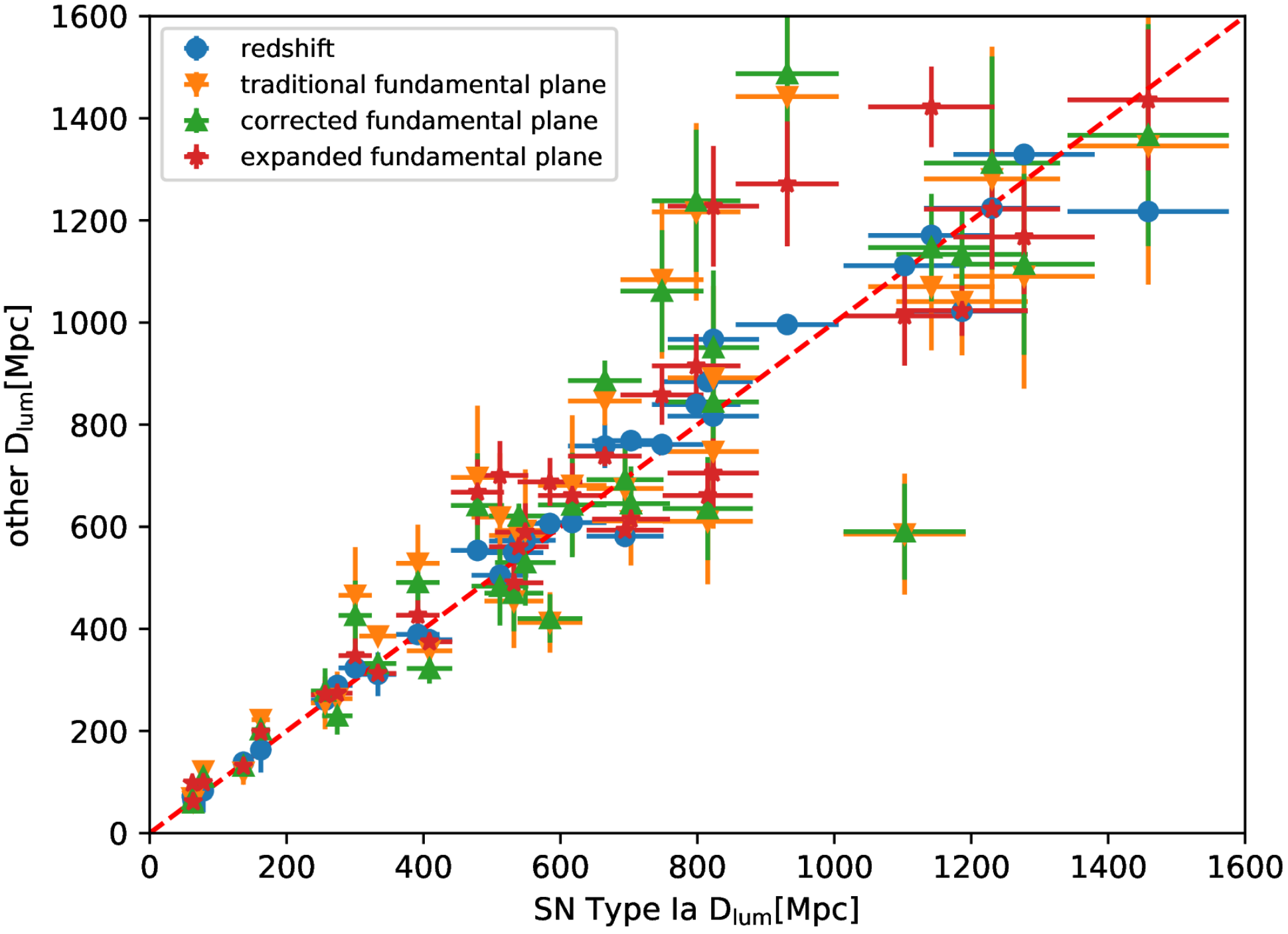
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other D_{lum}[Mpc]
SN Type Ia D_{lum}[Mpc]
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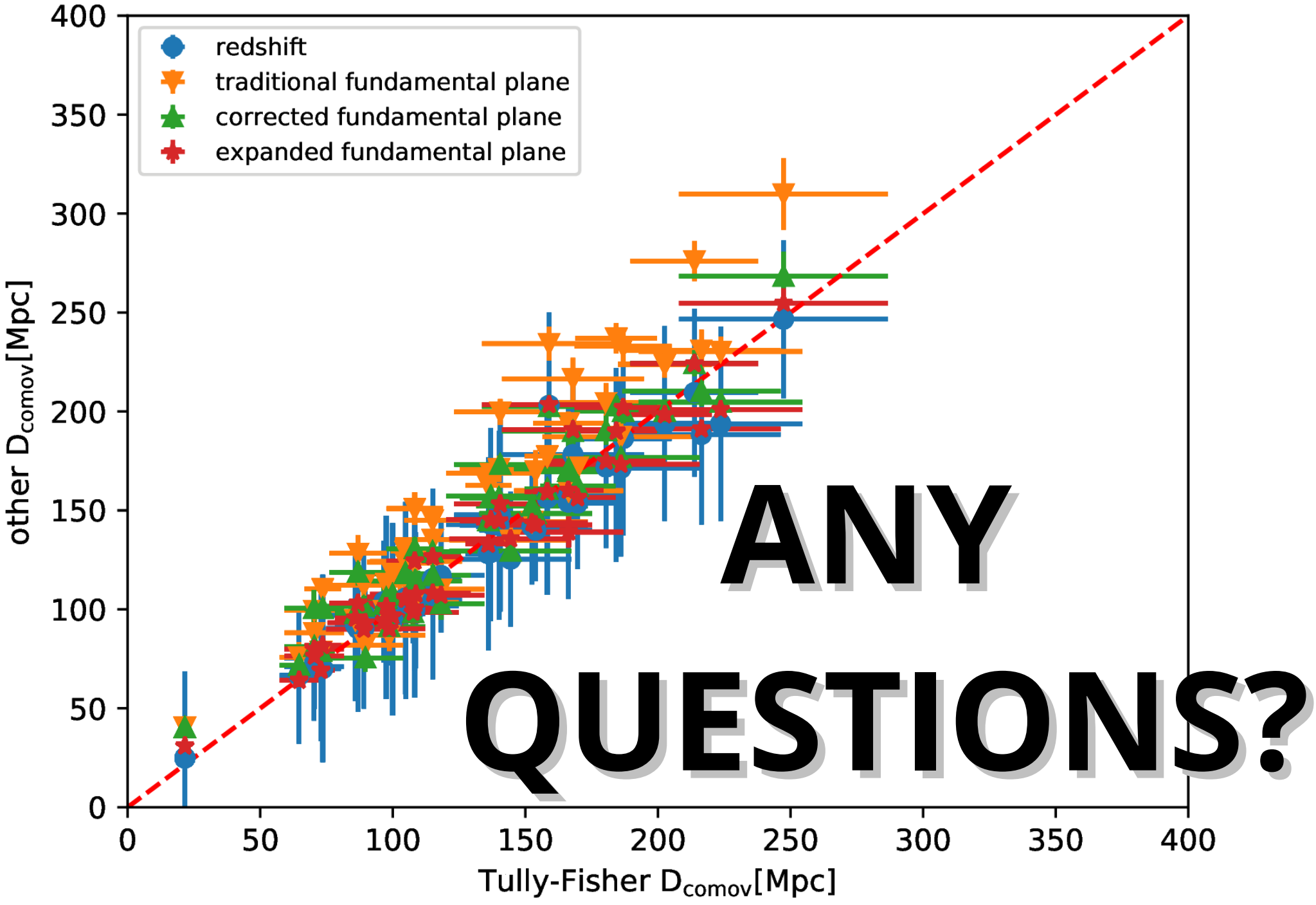
Summary

- Group catalogue covering ~1 500 000 galaxies
- ~317 000 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**

Outlook

- Improved subsamples using Bayesian statistics (methods from Howlett+,submitted)

- **Applications:**
  - Momentum Power Spectrum (with Park C.)
  - Correlations with clusters from LOFAR data (with Schwarz D.)
  - **Your ideas ... I am open to suggestions!**


redshift
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other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
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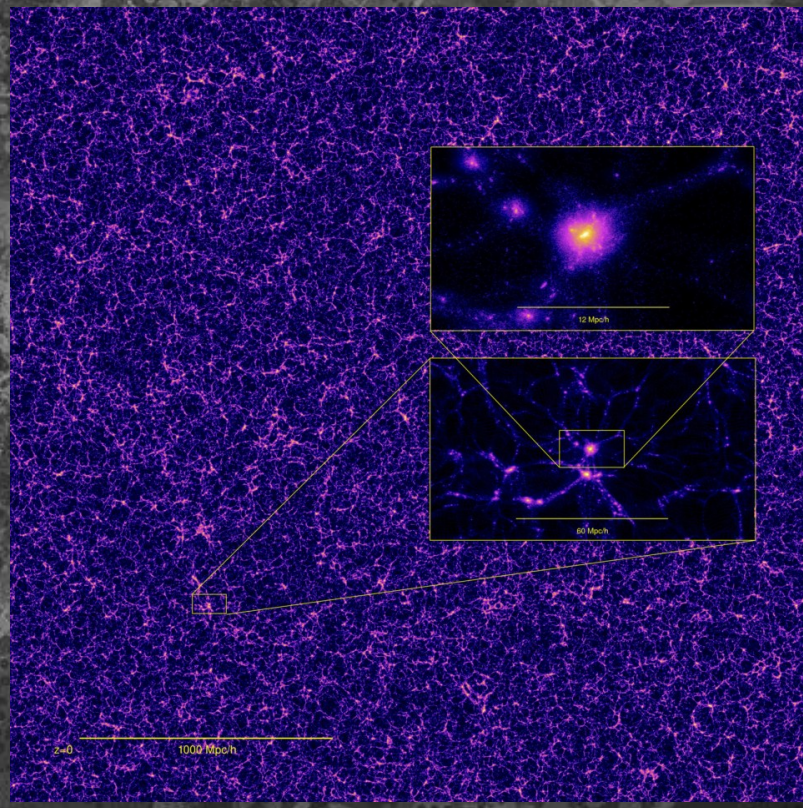
ANY
QUESTIONS?

Additional slides for possible questions

Momentum power spectrum

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

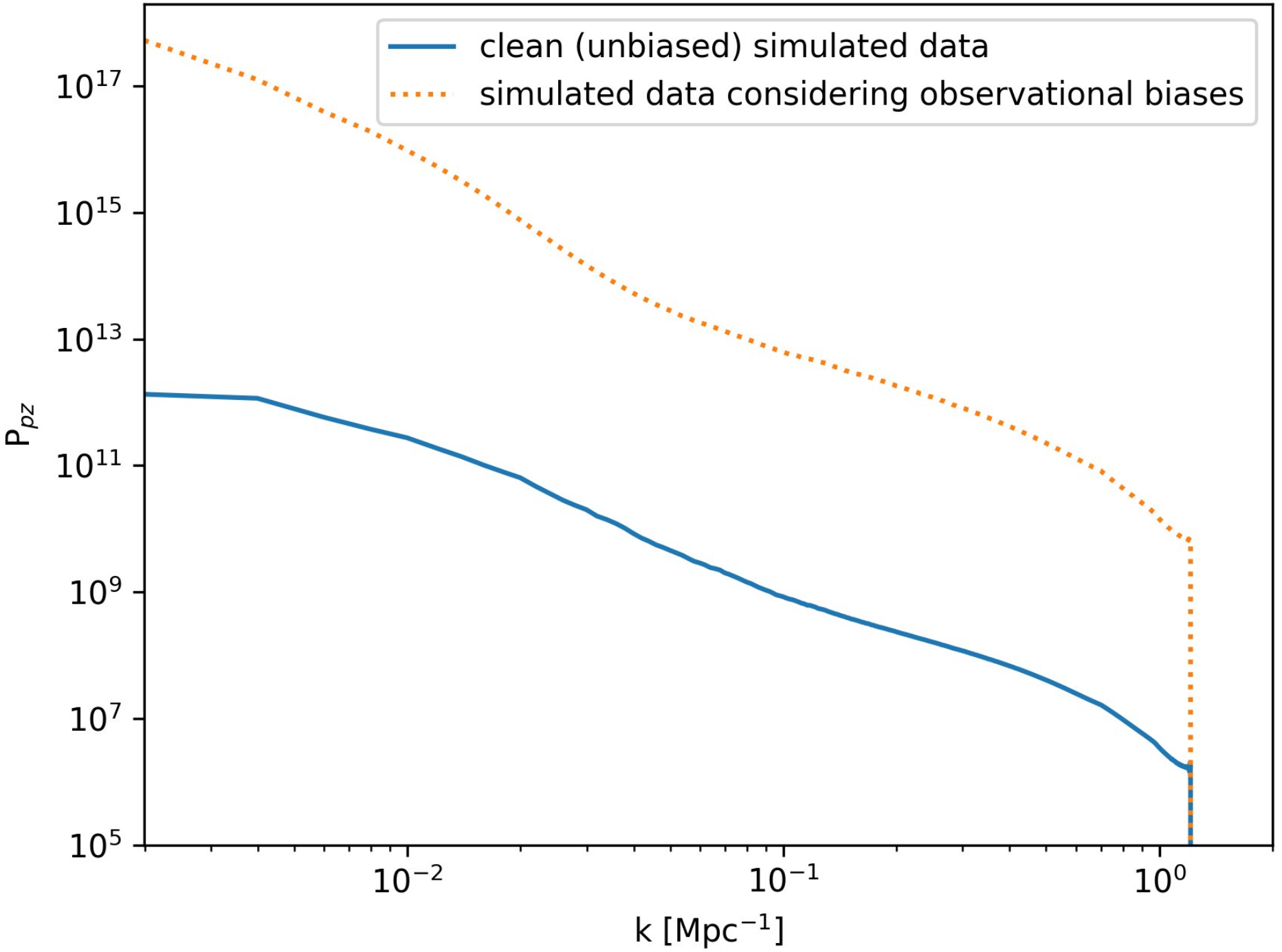
$$P_p(k) \approx P_v(k) + P_{\delta v}(k)$$
$$= (DHf)^2 \frac{P_\delta(k)}{k^2}$$
$$+ \frac{1}{2}(D^2 Hf)^2 \int \frac{d^3k'}{(2\pi)^3} \frac{k^2}{k'^2 |\boldsymbol{k} - \boldsymbol{k}'|^2} P_\delta(k') P_\delta(|\boldsymbol{k} - \boldsymbol{k}'|).$$

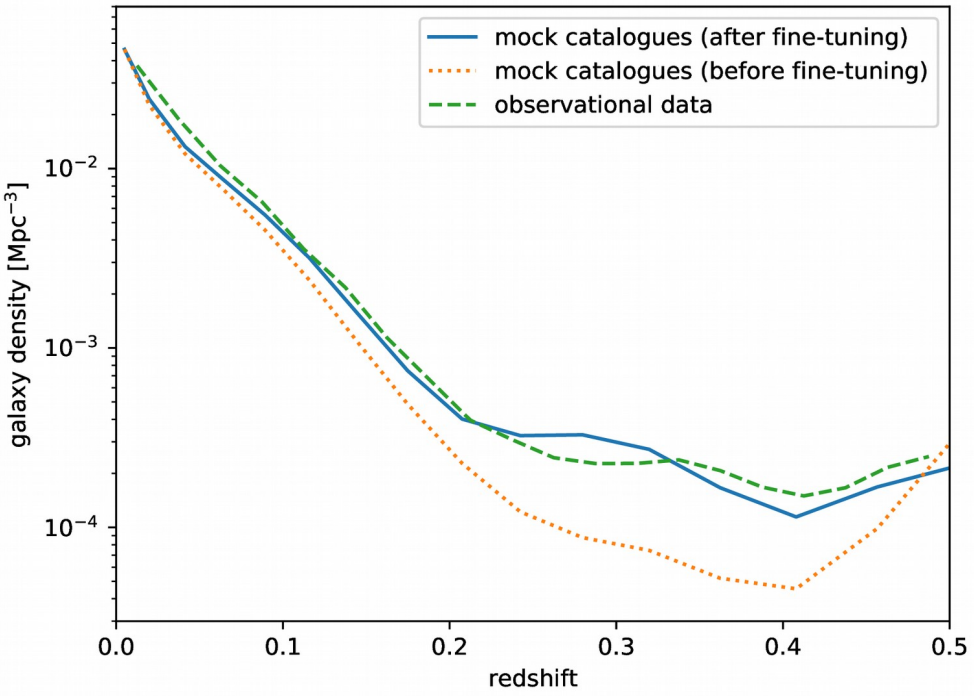


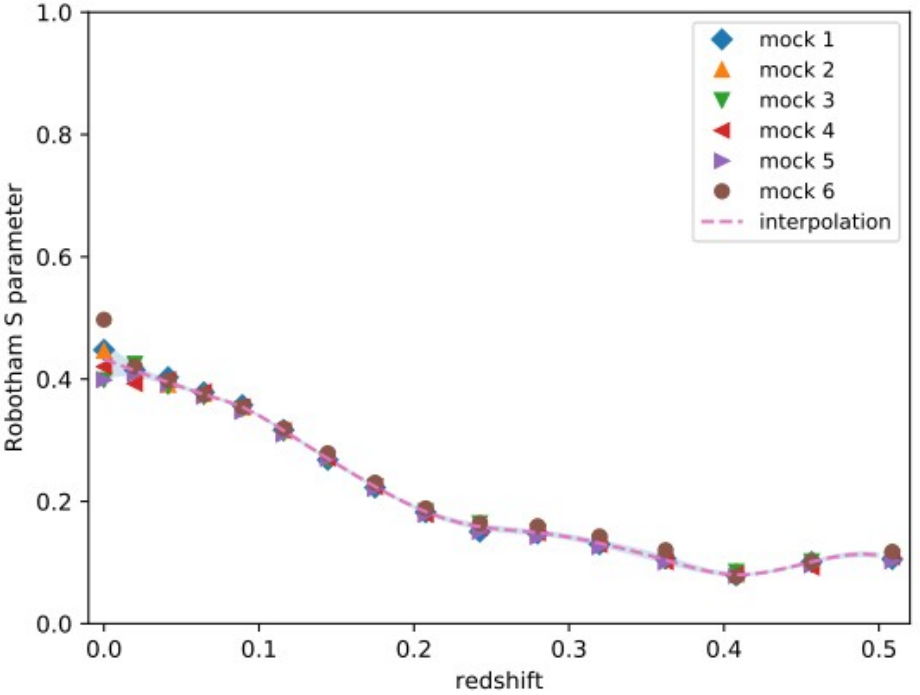
- Measuring β_s:

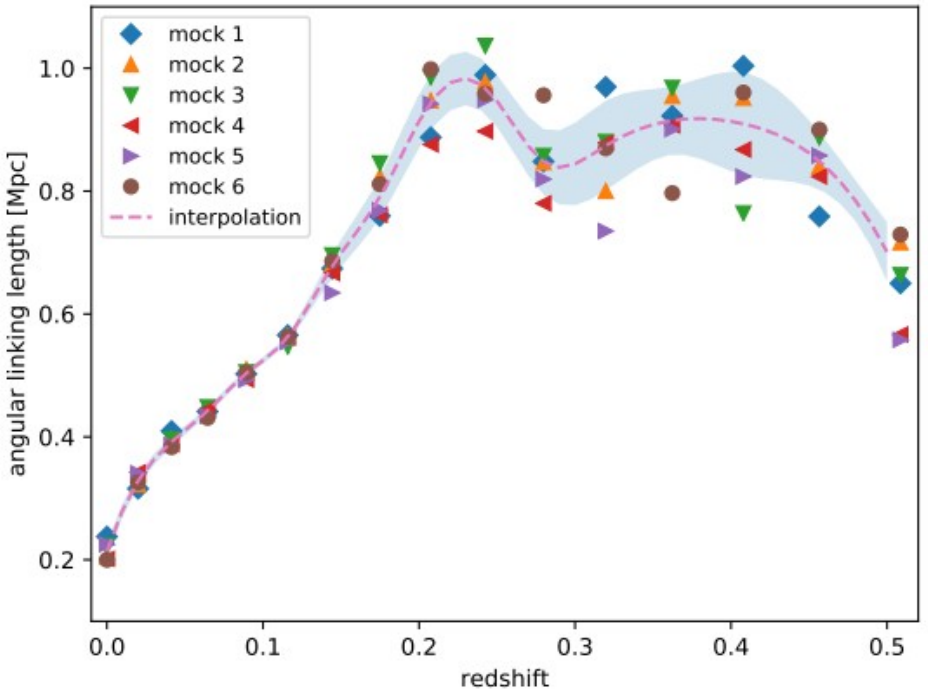
$$\beta_S(k) = \frac{P_p^{\rm obs}(k)}{P_p^{\rm der}(k)}. \qquad \beta_S = \Omega_m^{0.6}/b_S$$

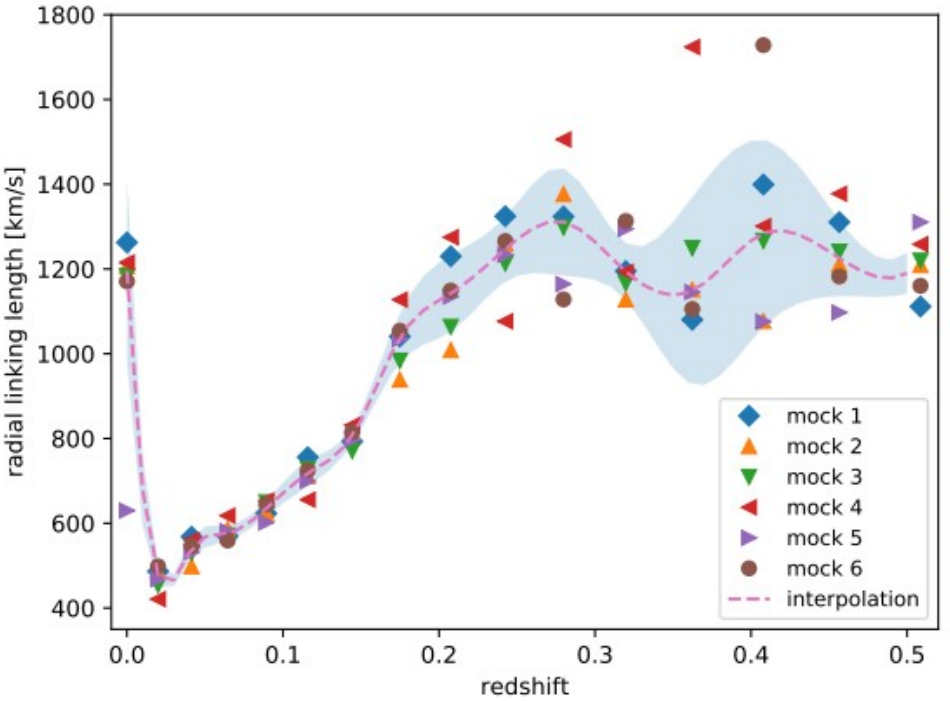
- Prediction from the simulation assuming the uncertainties of the fundamental plane

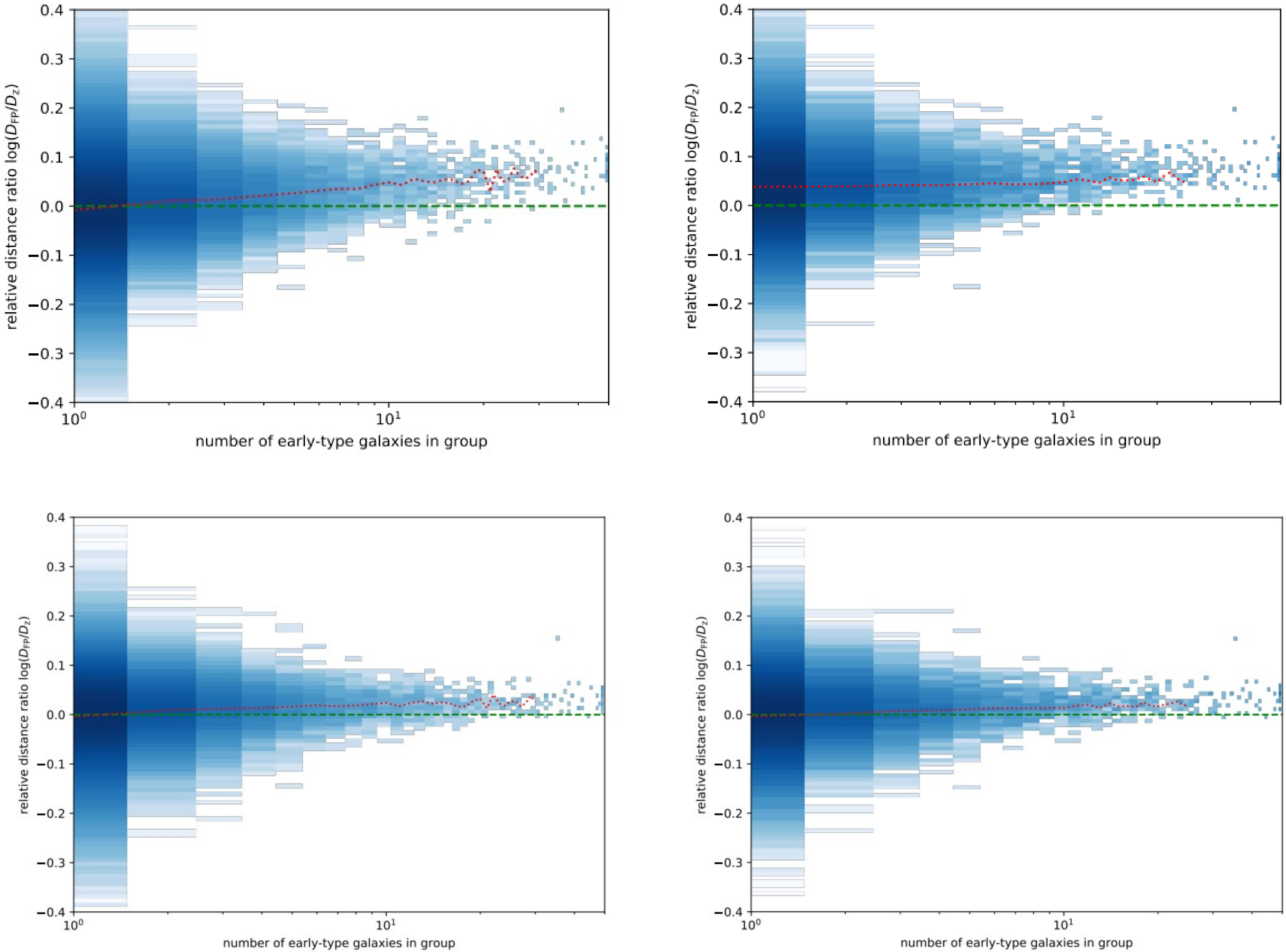

clean (unbiased) simulated data
simulated data considering observational biases
10^{17}
10^{15}
10^{13}
10^{11}
10^{9}
10^{7}
10^{5}
P_{pz}
10^{-2}
10^{-1}
10^{0}
k [Mpc^{-1}]

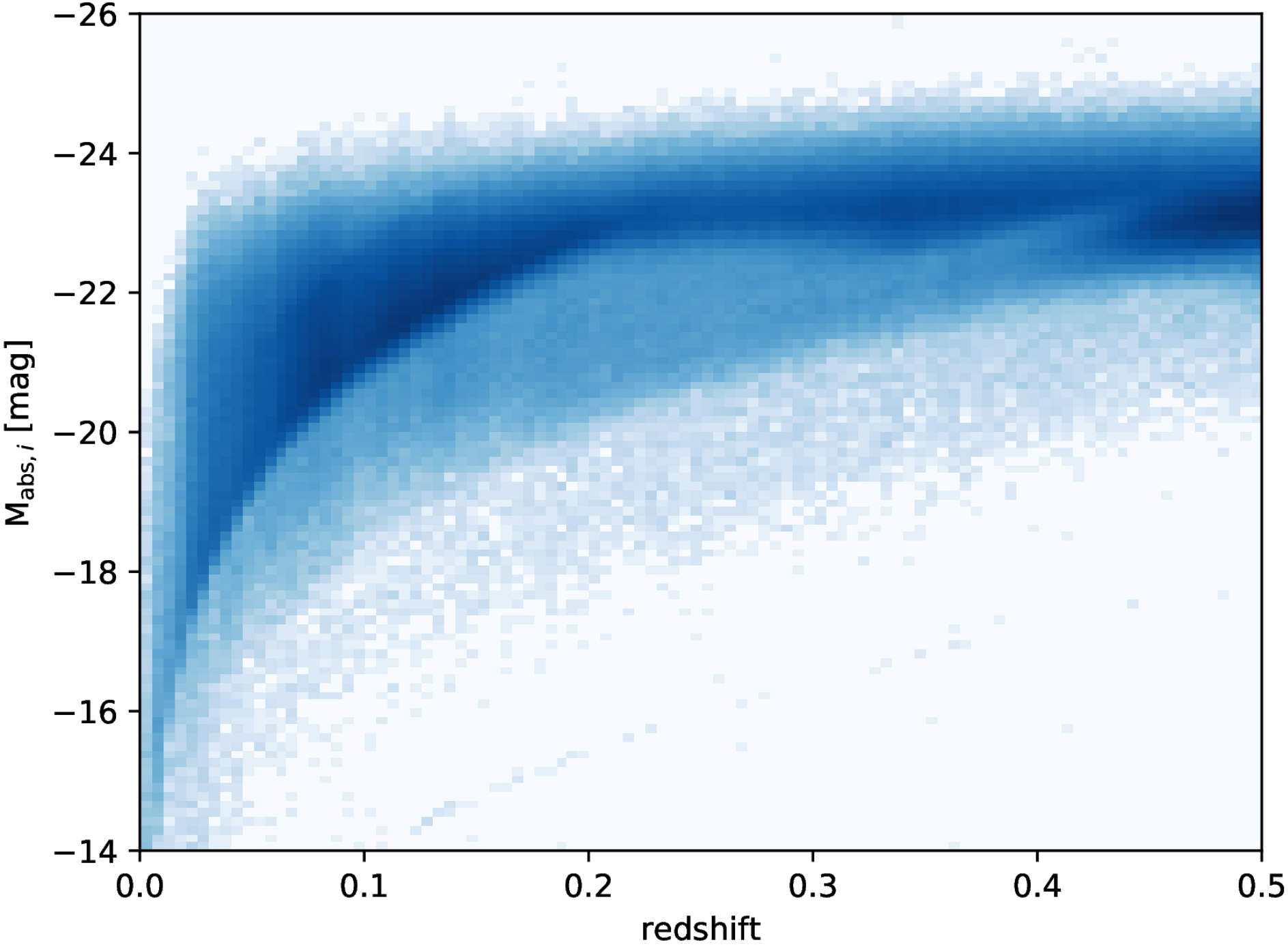

mock catalogues (after fine-tuning)
mock catalogues (before fine-tuning)
observational data
galaxy density [Mpc^{-3}]
10^{-2}
10^{-3}
10^{-4}
0.0
0.1
0.2
0.3
0.4
0.5
redshift

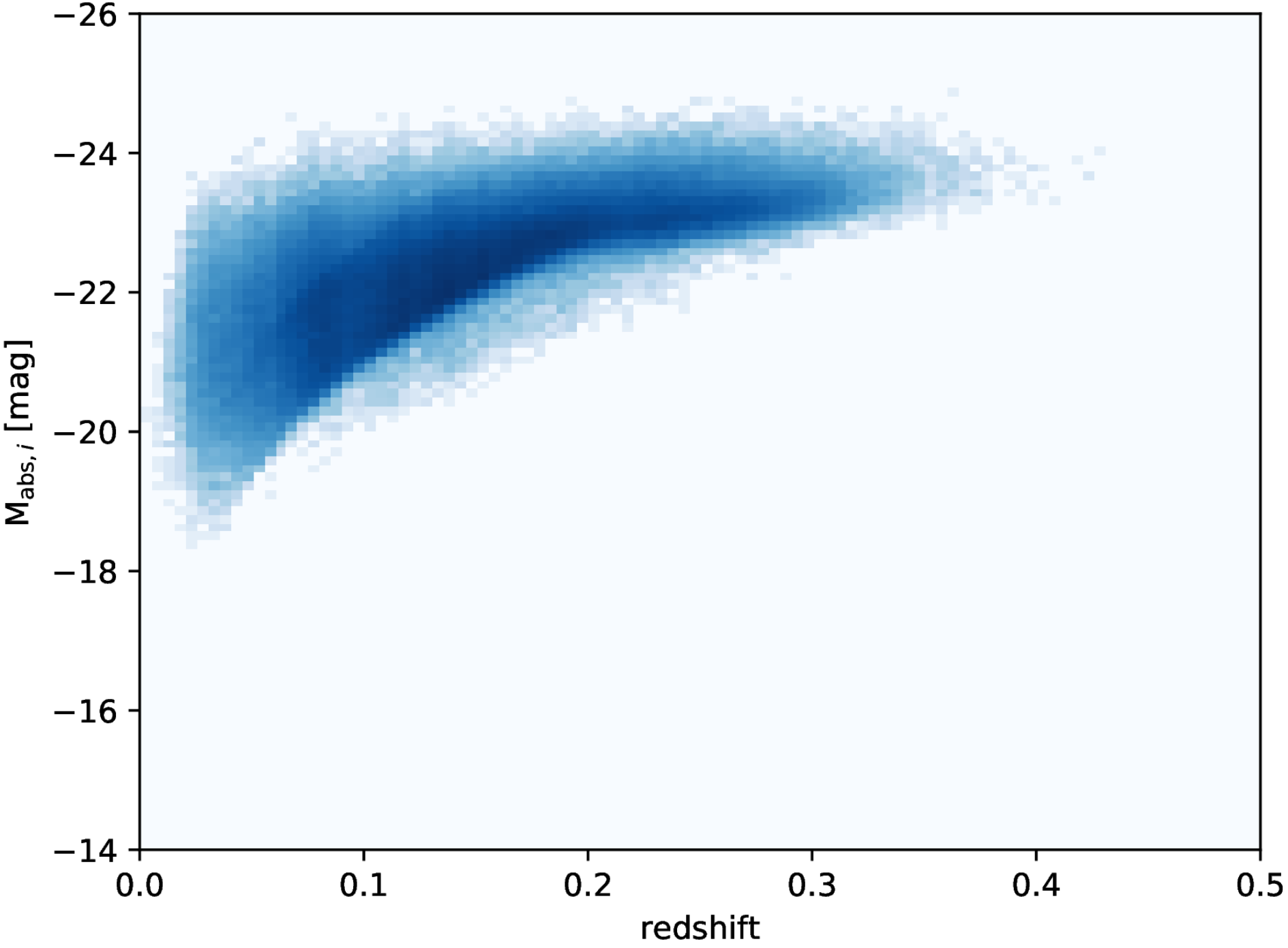

mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation
Robotham S parameter
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
redshift

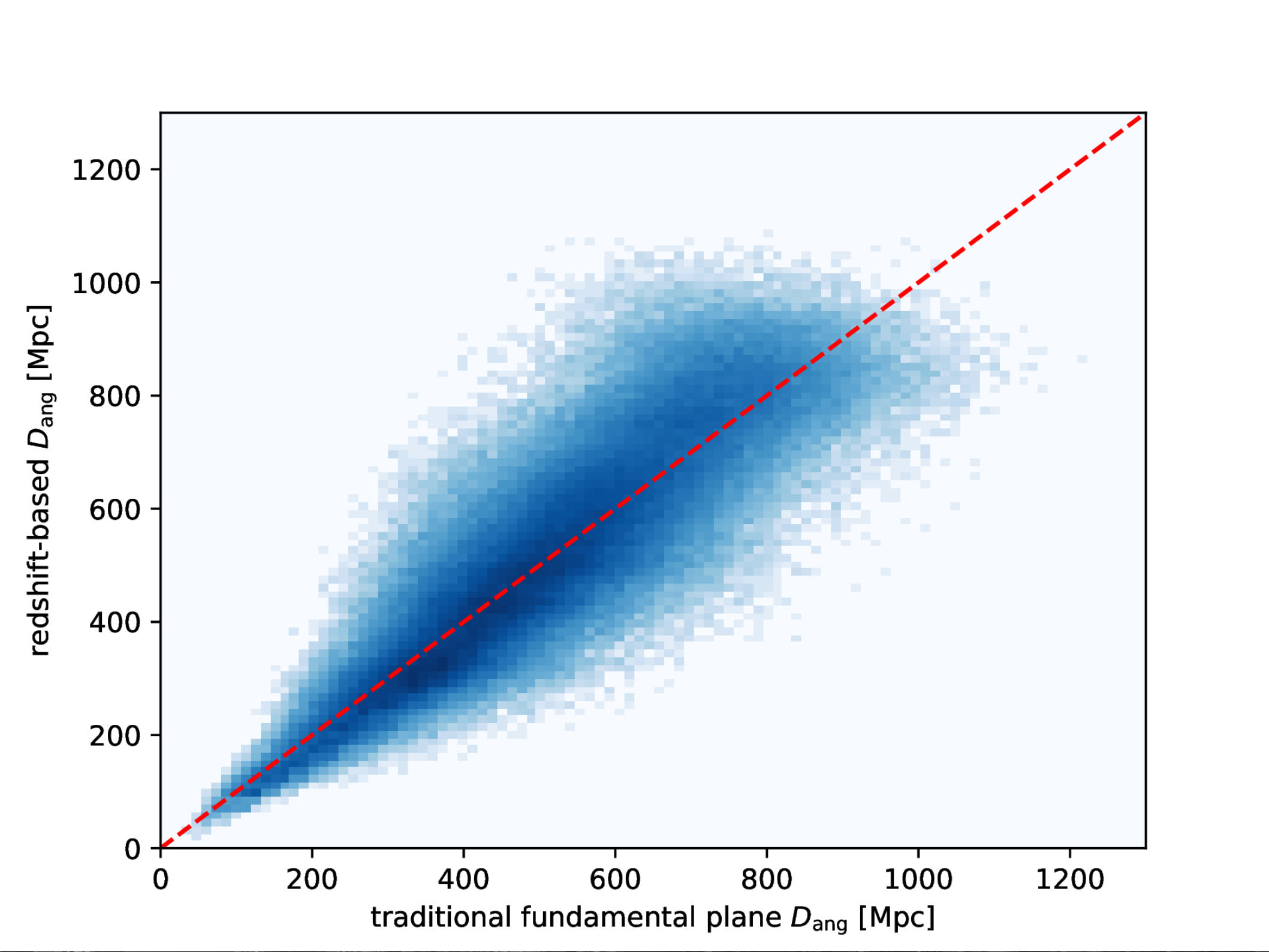

mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation
angular linking length [Mpc]
1.0
0.8
0.6
0.4
0.2
0.0
0.1
0.2
0.3
0.4
0.5
redshift

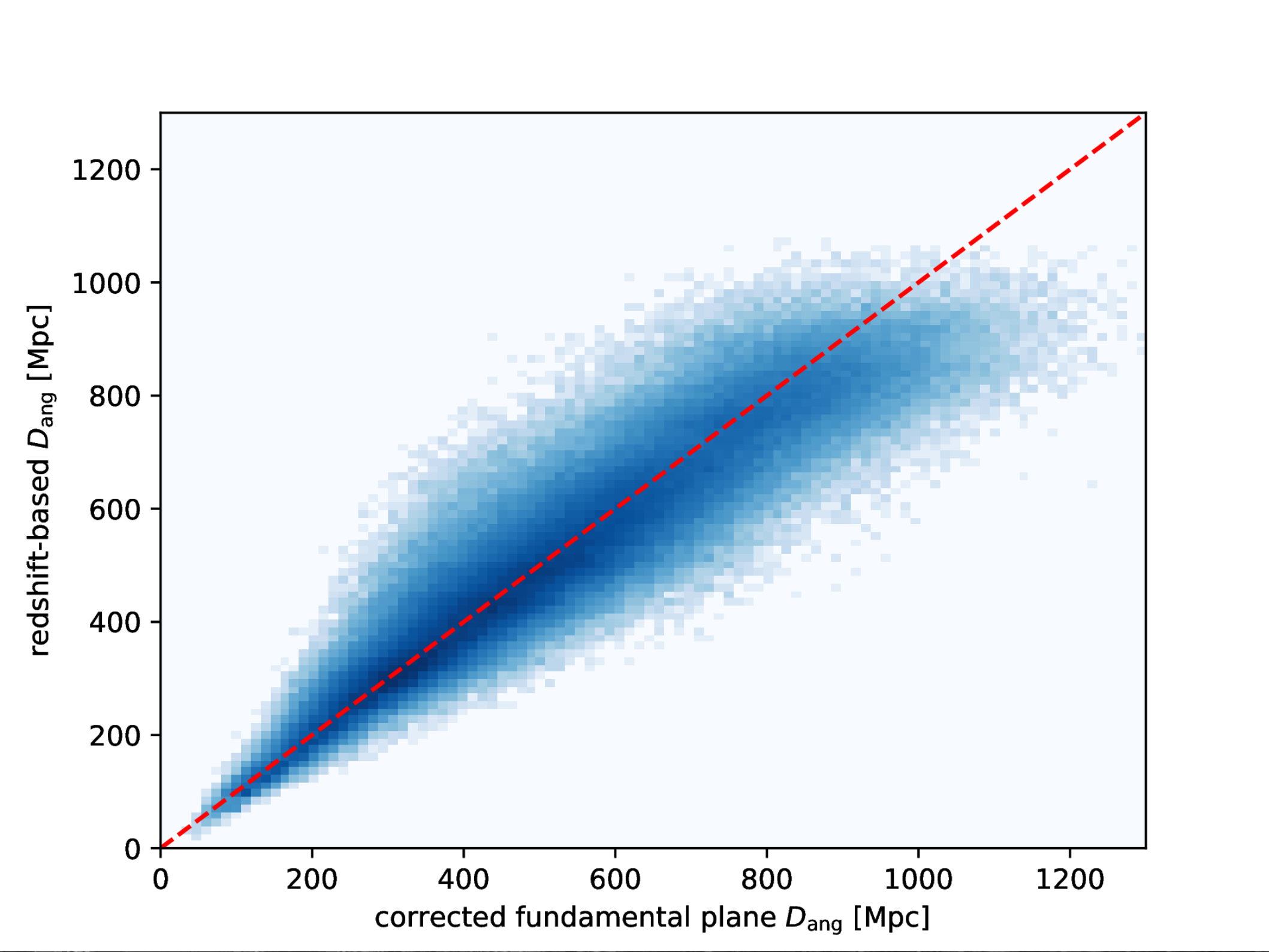

mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation
radial linking length [km/s]
1800
1600
1400
1200
1000
800
600
400
0.0
0.1
0.2
0.3
0.4
0.5
redshift

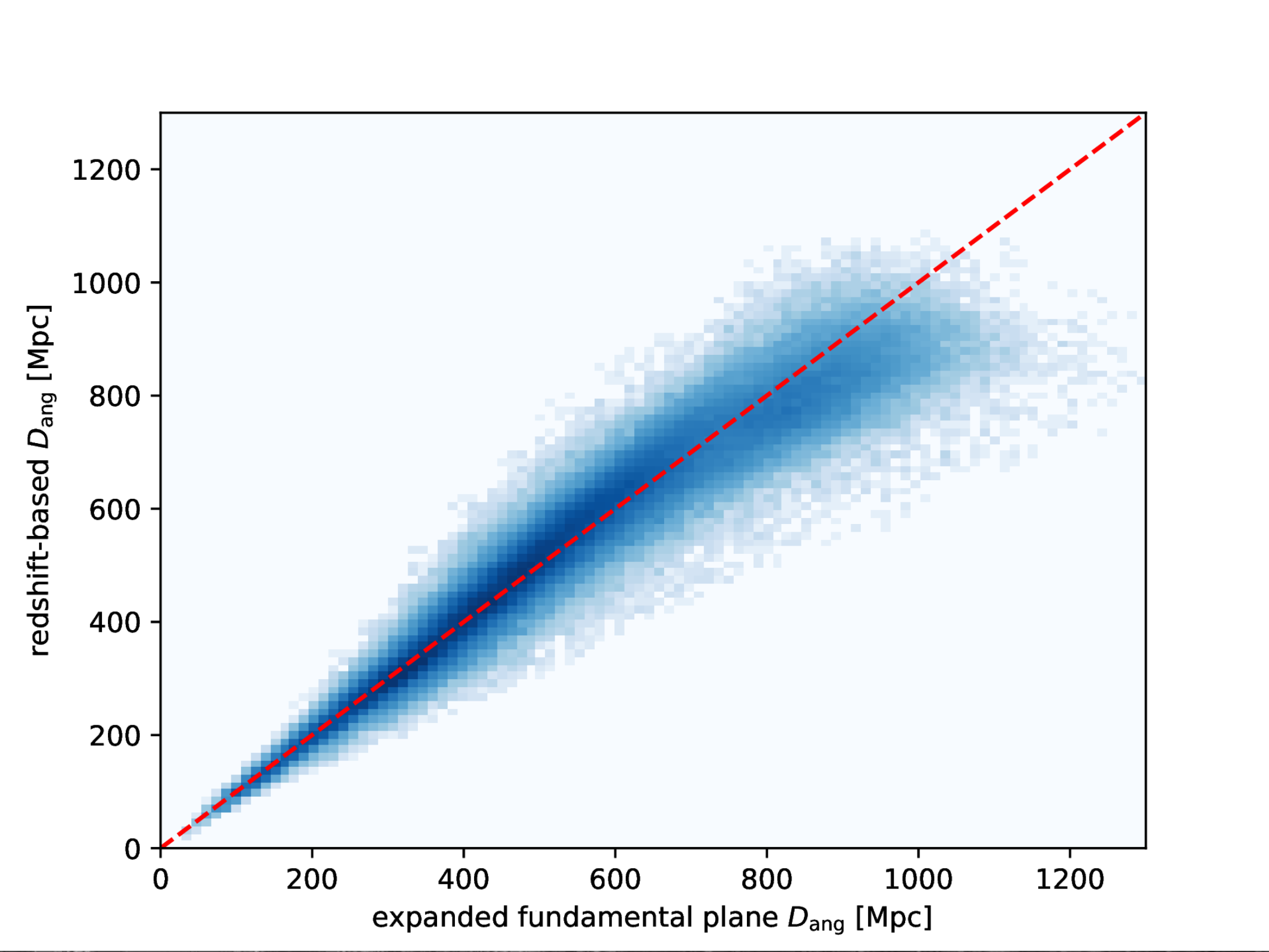

relative distance ratio log(D_{FP}/D_z)
number of early-type galaxies in group
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
10^0
10^1
relative distance ratio log(D_{FP}/D_z)
number of early-type galaxies in group
relative distance ratio log(D_{FP}/D_z)
number of early-type galaxies in group
relative distance ratio log(D_{FP}/D_z)
number of early-type galaxies in group


−26
−24
−22
−20
−18
−16
−14
$M_{abs,i}$ [mag]
0.0
0.1
0.2
0.3
0.4
0.5
redshift


−26
−24
−22
−20
−18
−16
−14
$M_{abs,i}$ [mag]
0.0
0.1
0.2
0.3
0.4
0.5
redshift


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


redshift-based D_{ang} [Mpc]
corrected 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

N/A

- Sorry, I have not prepared a slide for this specific question.