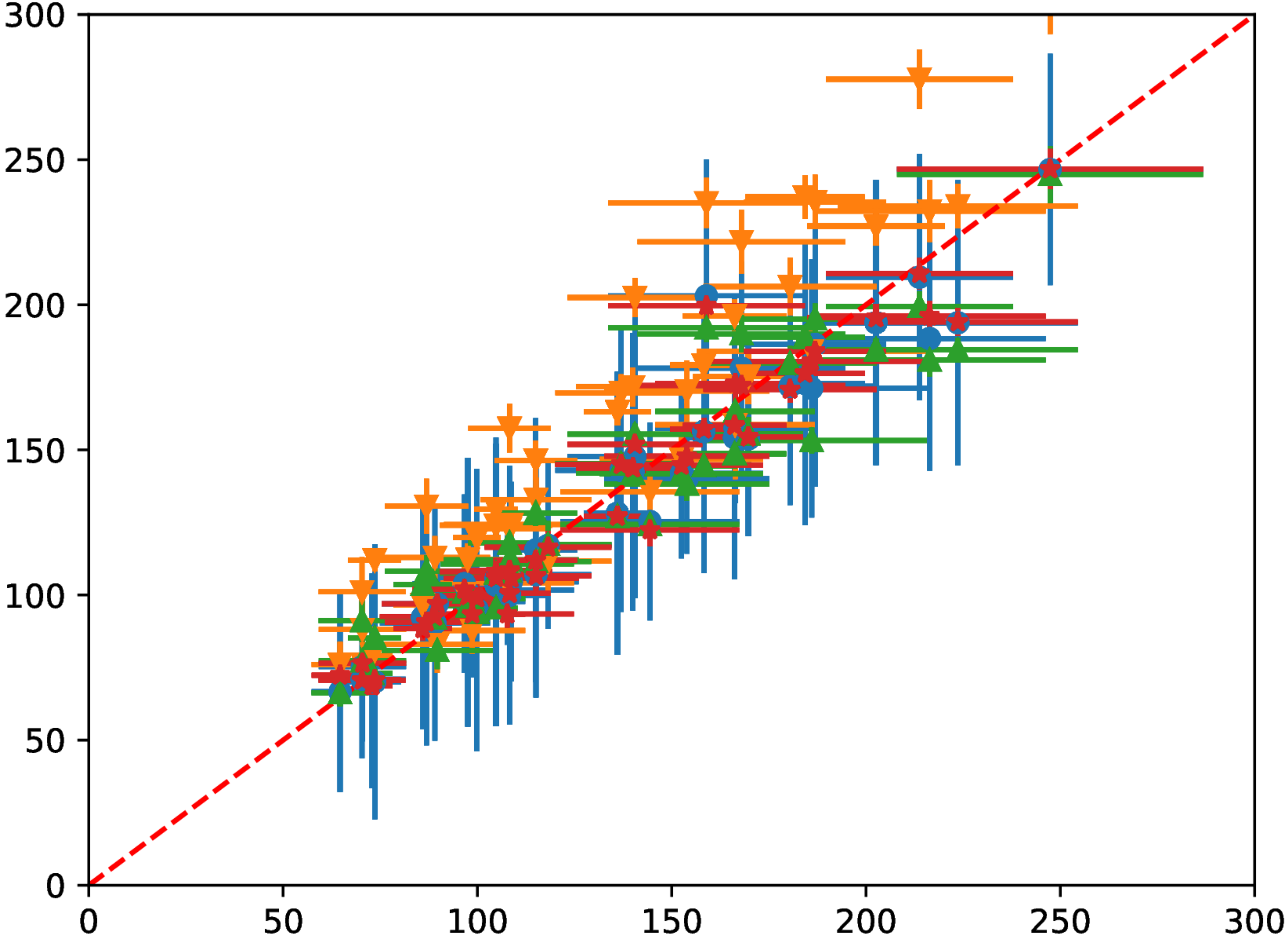
Testing redshift-independent distance indicators with group catalogues

Christoph Saulder
(Korea Institute for Advanced Study)



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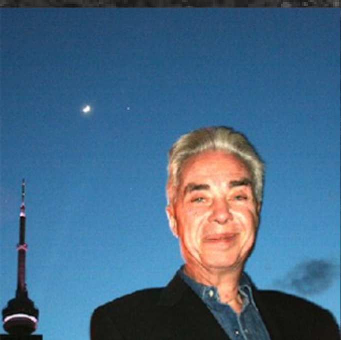
Collaborators

Christoph Saulder (KIAS)



Ian Steer (NED)

Owain Snaith (KIAS)

Changbom Park (KIAS)

KIAS
KOREA INSTITUTE FOR ADVANCED STUDY

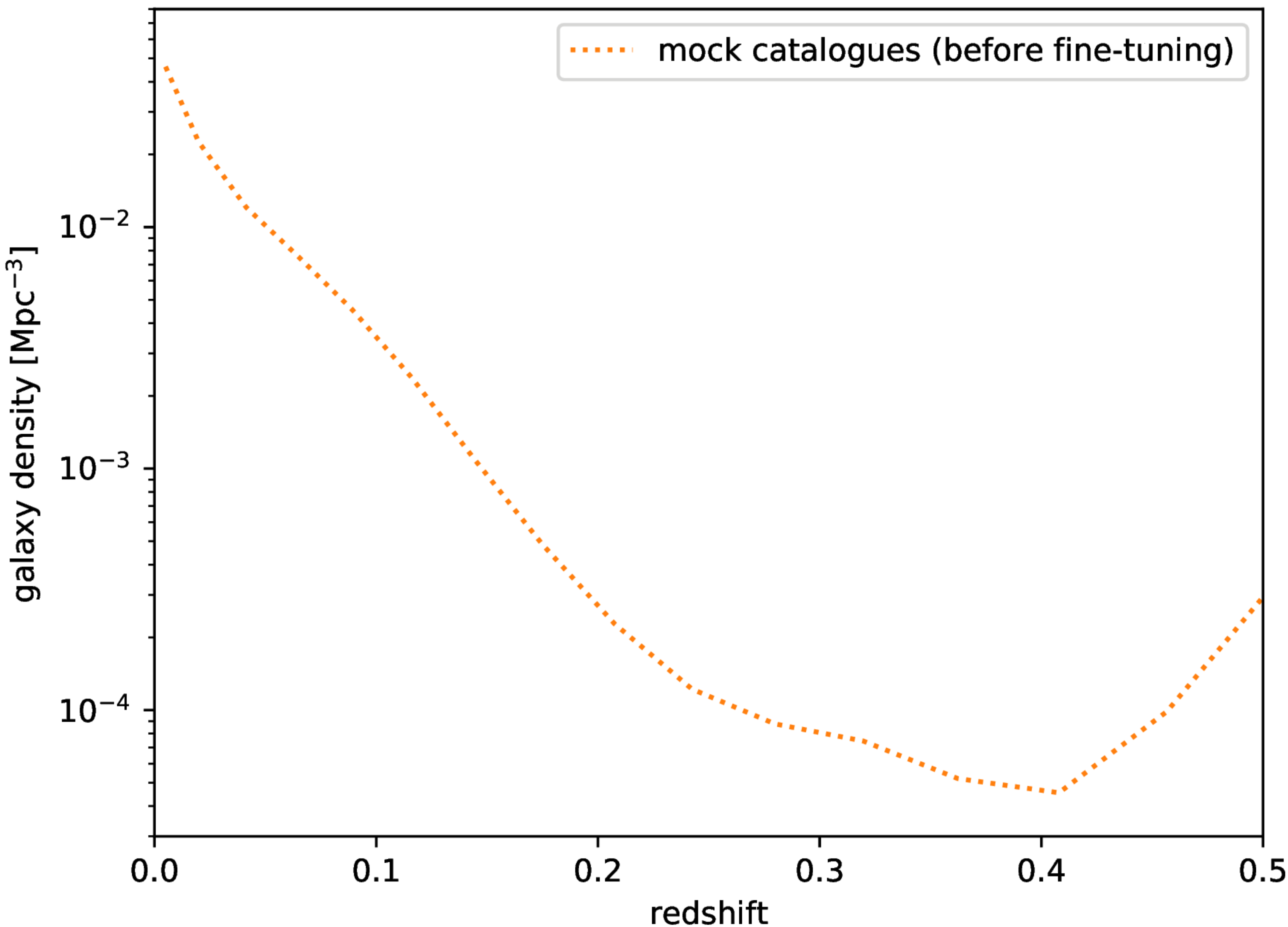
NED

Our group catalogue

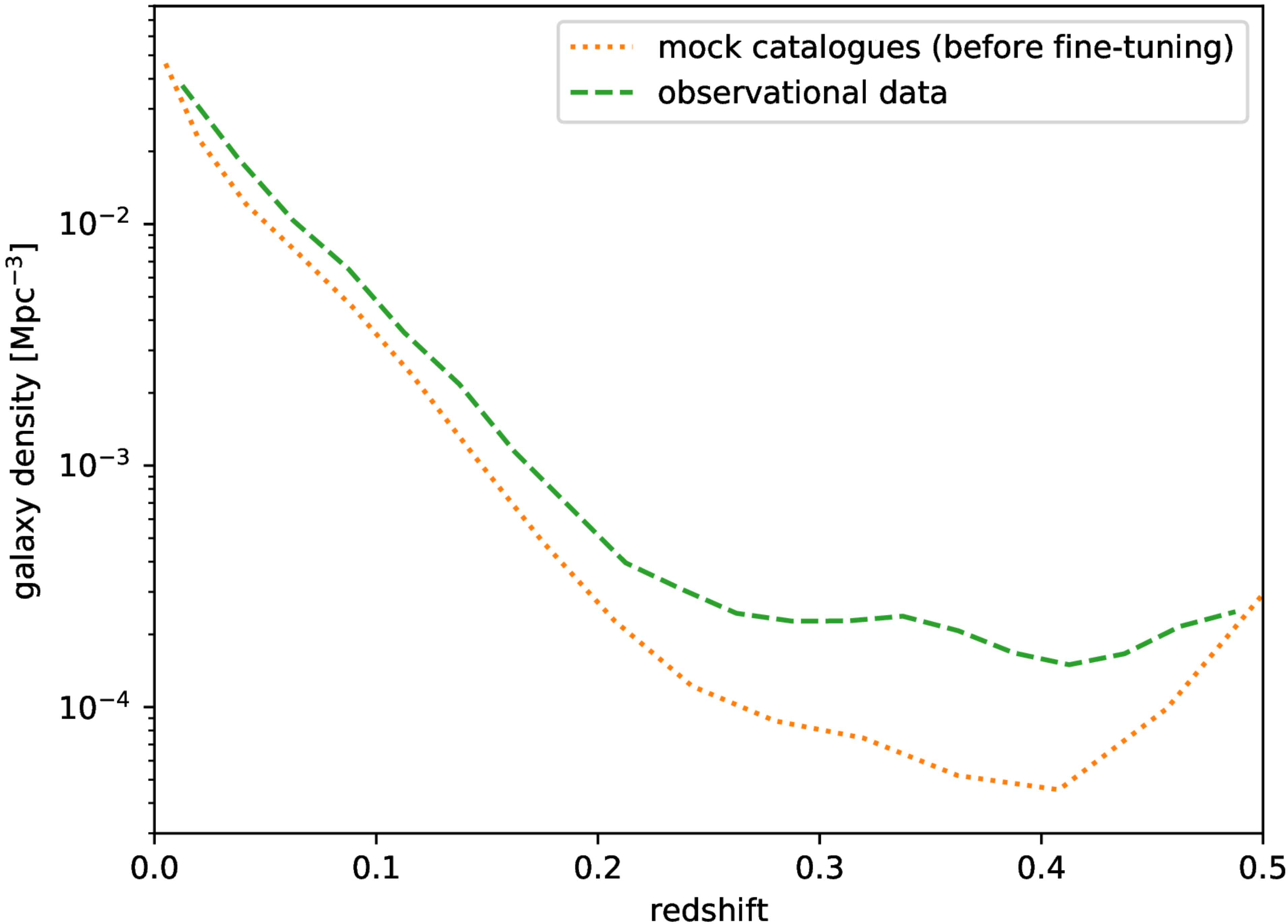
- Improving our special purpose group catalogue from Saulder+2016 and expanding it beyond z=0.1
- SDSS DR15
  - SDSS spectroscopic footprint (9 376 square degree)
  - Redshift up to z=0.5
- 2MRS (2MASS Redshift Survey)
  - Within the SDSS coverage
  - Compensate for the saturation bias of SDSS

Mock catalogues

- FoF group finder
- Calibration of the linking lengths required
- WMAP7 re-run of the Millennium simulation by Guo+2013
  - Snapsots 61 to 46 (z=0.0 to ~0.51)
  - Semi-analytic galaxy models and magnitudes (Guo+2011)
- Magnitute limits and colour cuts for SDSS main galaxy sample, SDSS LRG samples, BOSS low-z sample, CMASS samples, and 2MRS sample



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


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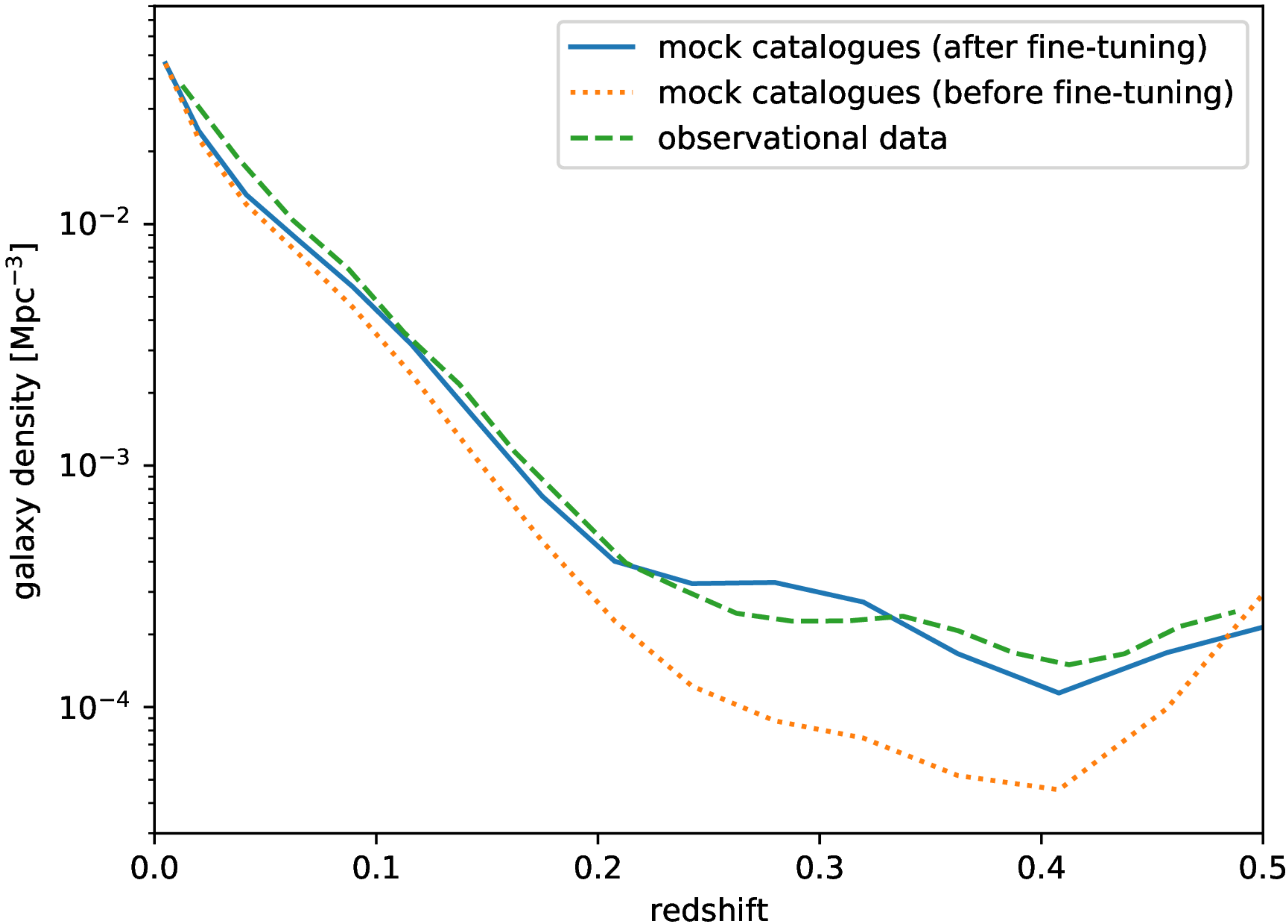
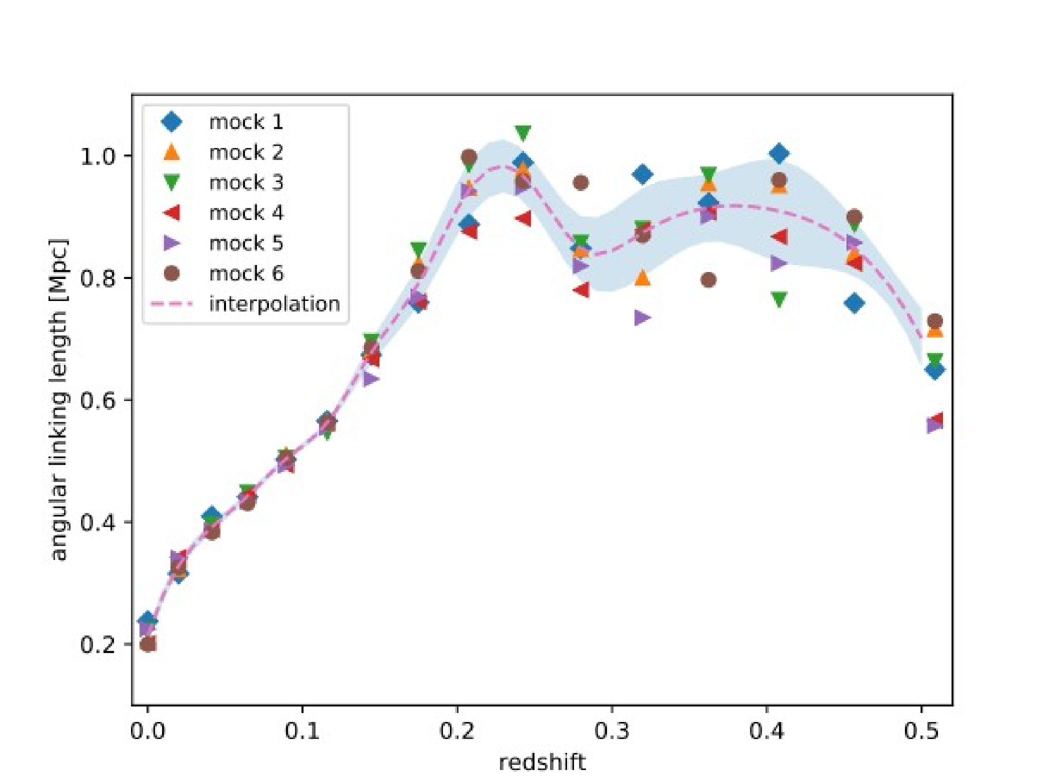
0.5
redshift



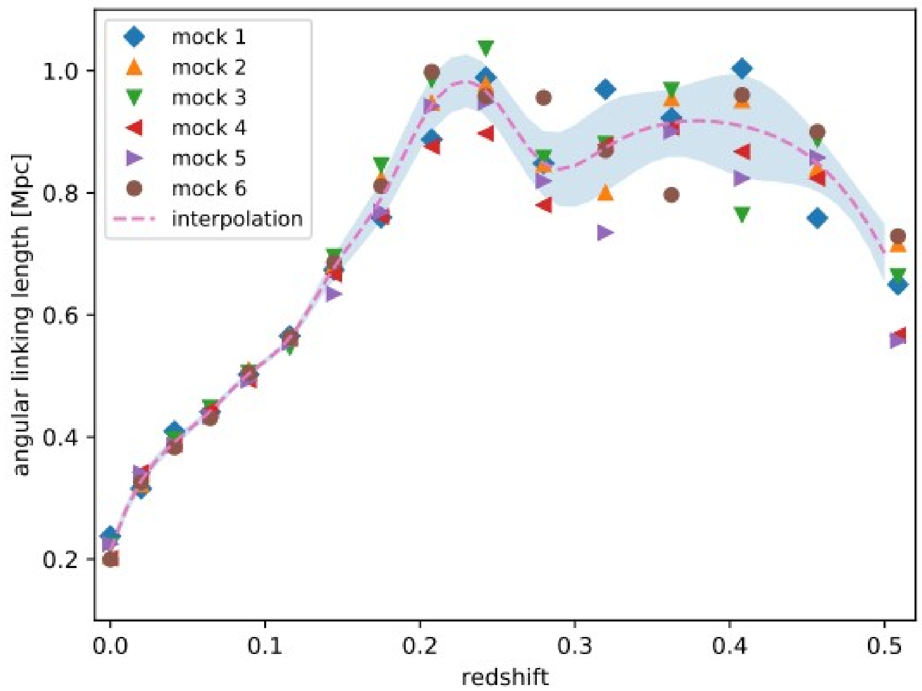
mock catalogues (after fine-tuning)
mock catalogues (before fine-tuning)
observational data
galaxy density [Mpc^{-3}]
10^{-2}
10^{-3}
10^{-4}
0.0
0.1
0.2
0.3
0.4
0.5
redshift

Optimization

- Pre-grid the data before running FoF (following Duarte&Mamon 2014)
- Angular and radial linking lengths optimized for each redshift bin using a cost function based on bijective matches for groups and individual galaxies (Robotham+2011)
- Taking the median value of the 6 (semi-)indepenent mock catalogues and interpolating between the redshifts of the bins



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


mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation
angular linking length [Mpc]
redshift
0.2
0.4
0.6
0.8
1.0
0.0
0.1
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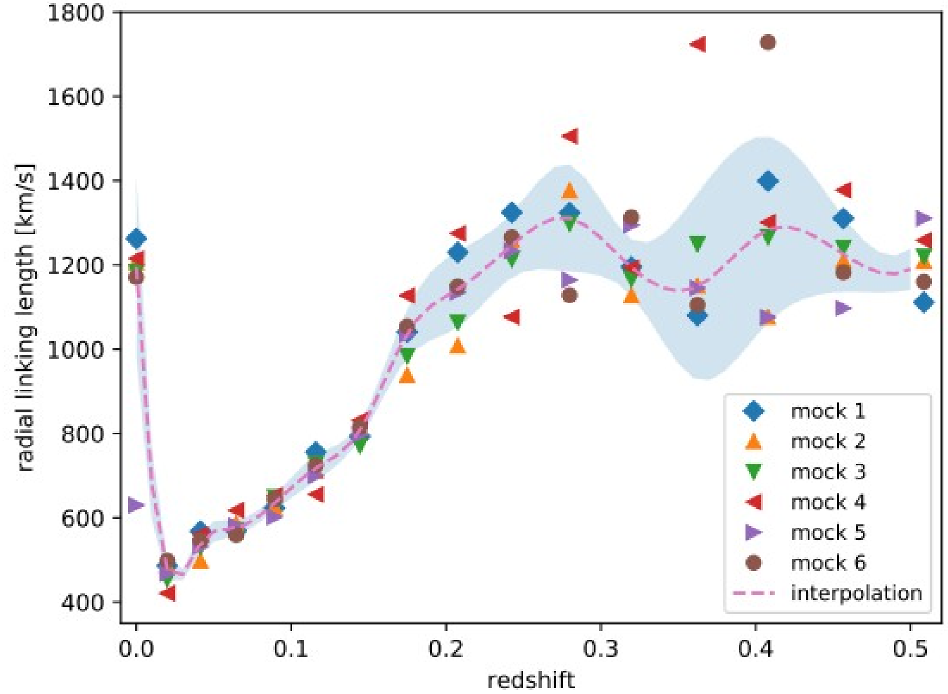
radial linking length [km/s]
redshift
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600
800
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1200
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1600
1800
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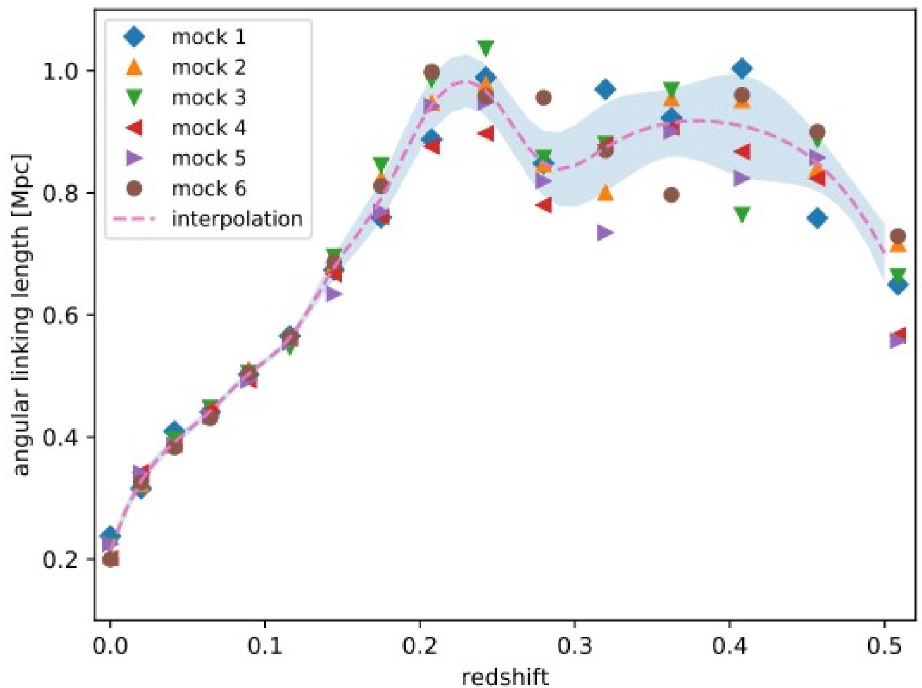
0.2
0.3
0.4
0.5
mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation


angular linking length [Mpc]
redshift
mock 1
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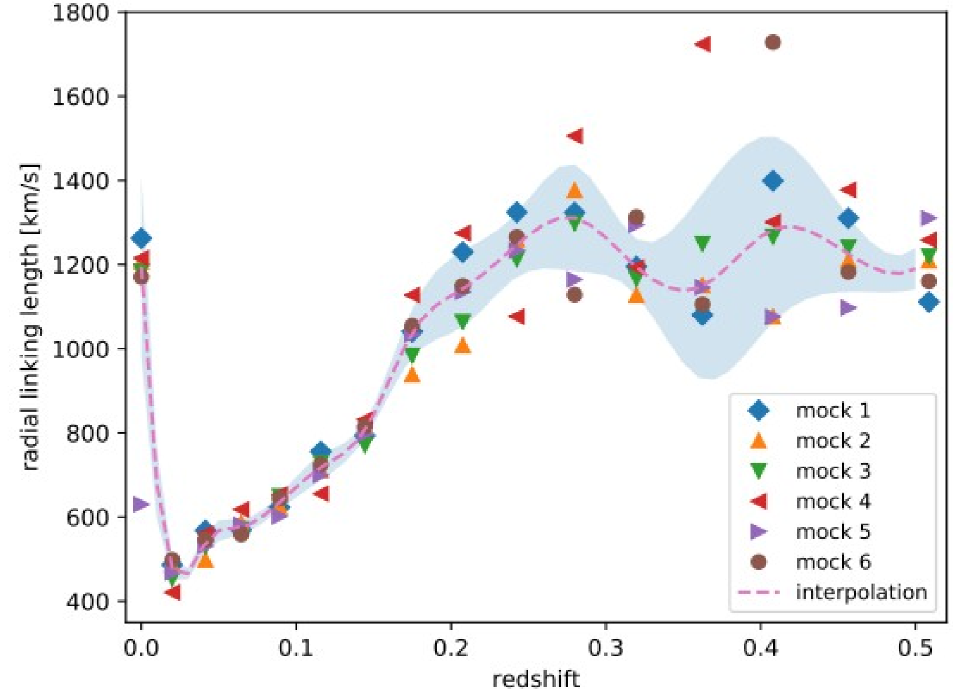
mock 3
mock 4
mock 5
mock 6
interpolation


radial linking length [km/s]
redshift
mock 1
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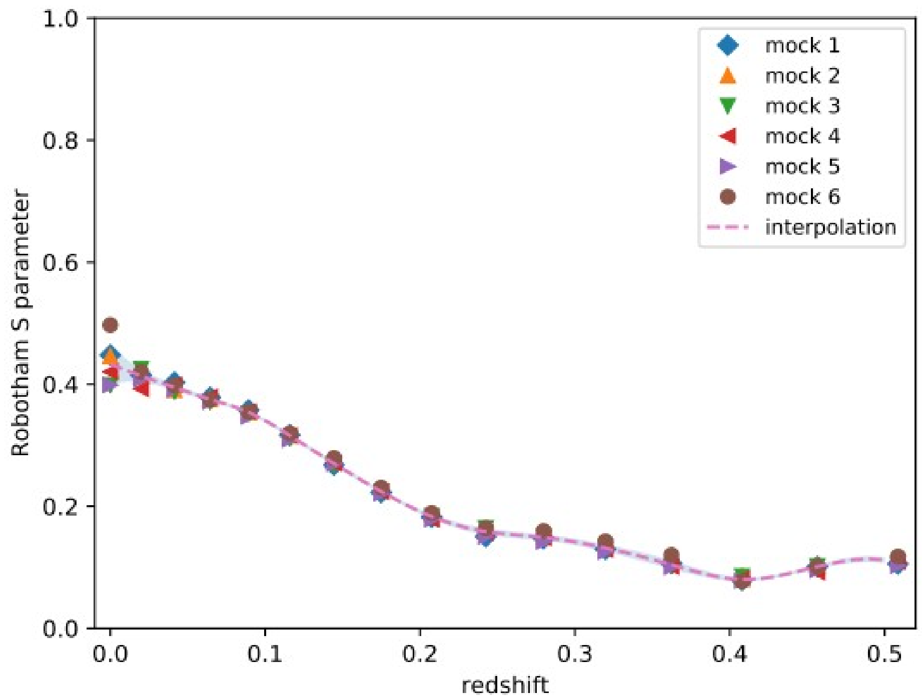
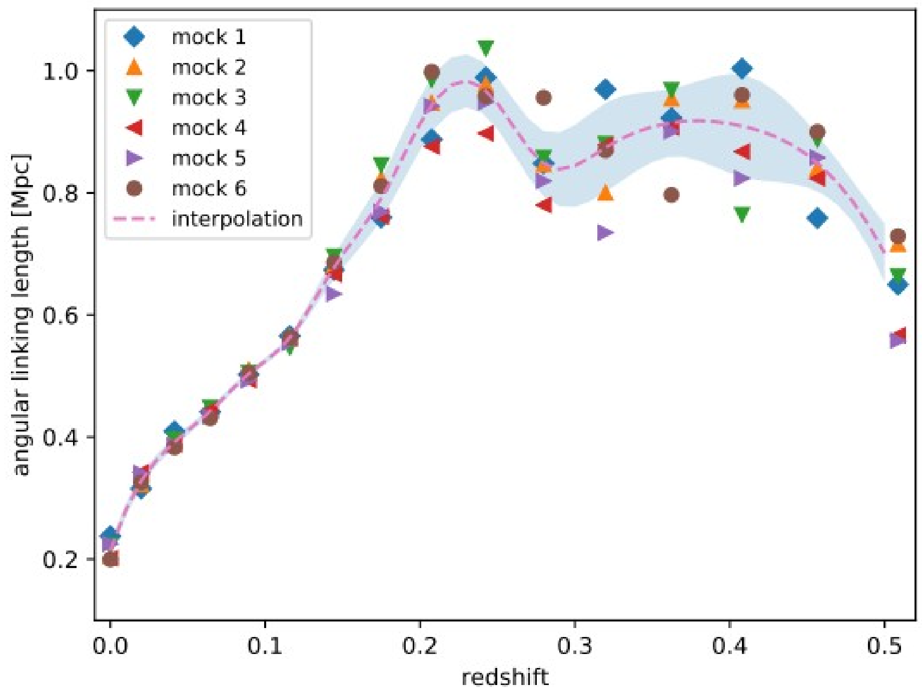
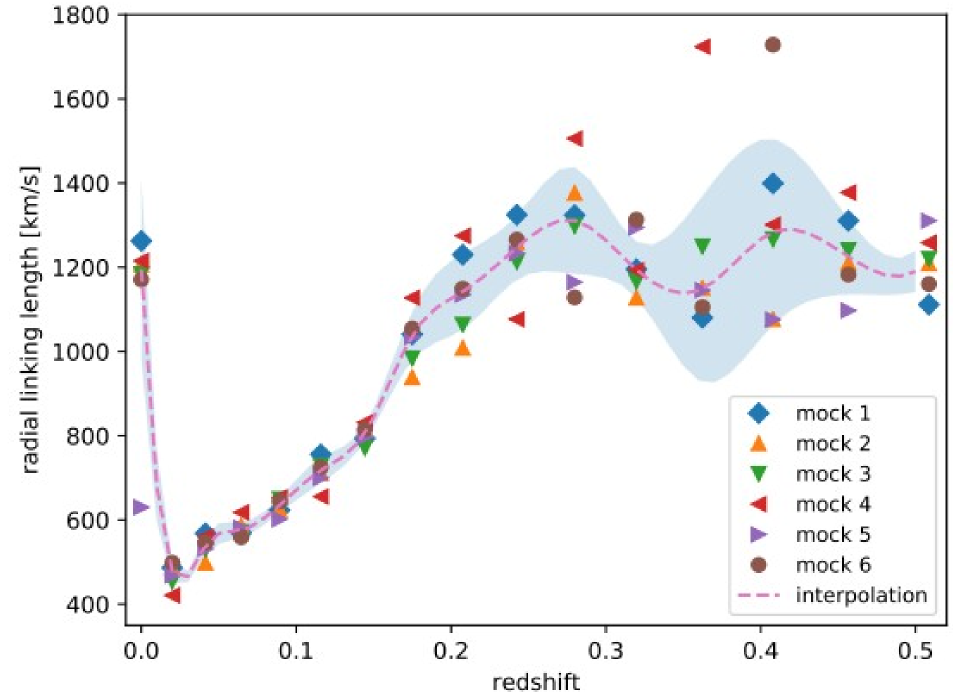
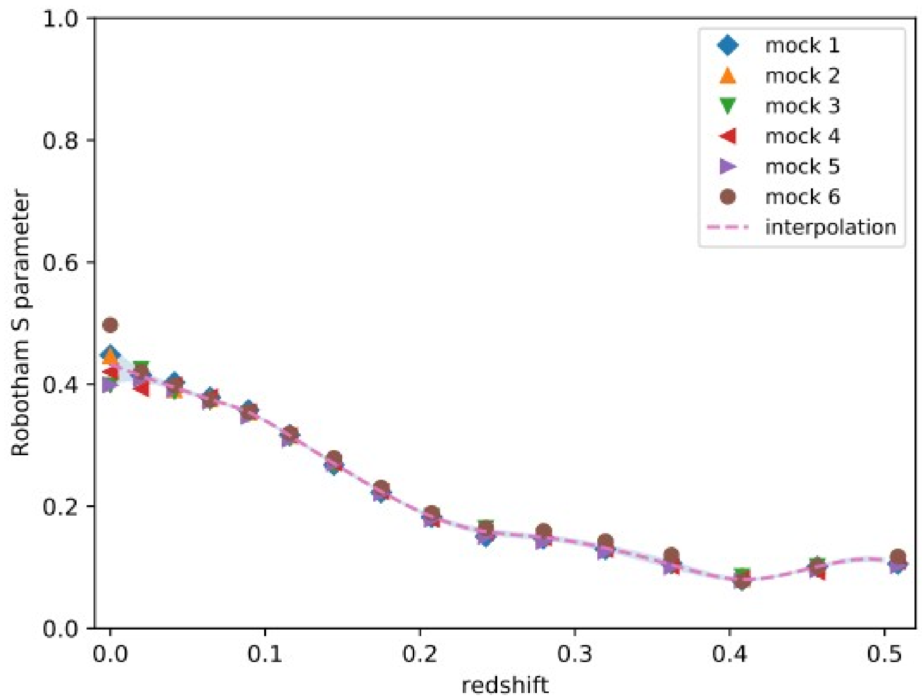
mock 5
mock 6
interpolation


Robotham S parameter
redshift
mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation



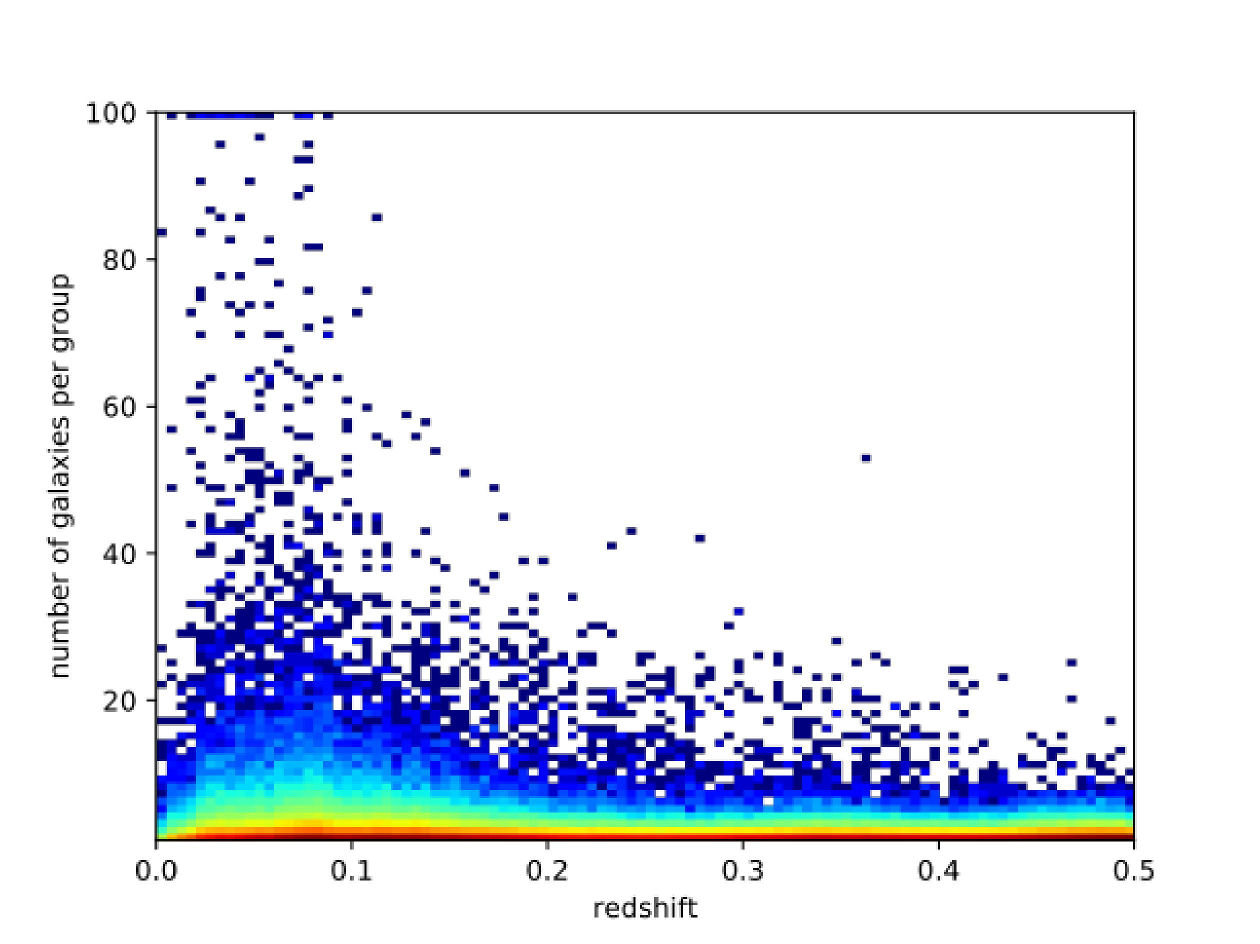




- Works fairly well at lower redshifts
- Issues at higher redshifts due to the sparse sampling and few detectable groups

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



Outlook (group catalogue)

- Further improving the group finder algoritm (membership probabilities)
- Better mock catalogues
- Greater sky coverage: more spectroscopic survey data such as 6dFGS, GAMA, complete 2MRS ... different linking lengths for different areas on the sky
- More data: higher redshifts (focus on big clusters) by using CMASS

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

Our sample of early-type galaxies

- Identifying early-type galaxies in SDSS
  - Red sequence galaxies (colour cuts)
  - Quality of the profile fits (de Vaucoleur profile should fit best)
  - Limits for central velocity dispersions
  - Outlier removal and quality controll
- 318 149 suitable ETGs in SDSS DR15
  - Currently the largest sample ever used for fundamental plane calibrations and applications
  - Previously Saulder+2016 with 121 443 galaxies

Calibrating the traditional fundamental plane

- Applying basic calibrations and corrections to the data retrieved from SDSS
  - Extinction correction (Schlegel maps)
  - K-correction (Chilingarian+2011)
  - (Luminosity) evolution correction (Bernardi+2003, but recalibrated in Saulder+ submitted)
  - Circularized radii
  - Correction for fixed fibre diameters (Jorgensen+ 1995 and Wegner+ 1999)
  - Correction for Tolman effect on surfaces brightnesses

- Calculating the redshift-based distances to these galaxies (using the median redshifts of the groups from our group catalogue)
- Calculating the physical radii of the galaxies
- Direct fit (minimizing the scatter in radii) using least squares
  → fundamental plane coefficients

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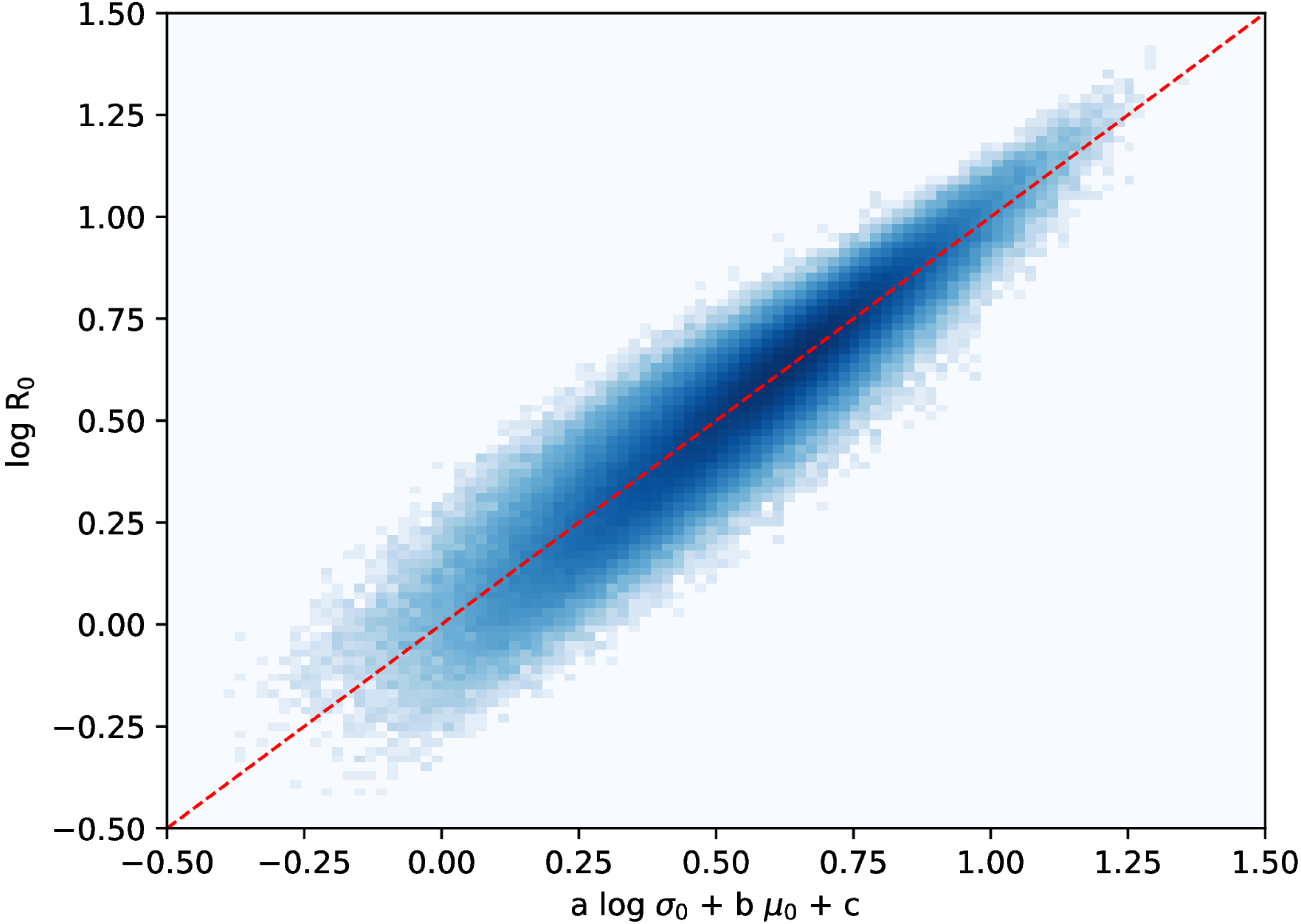
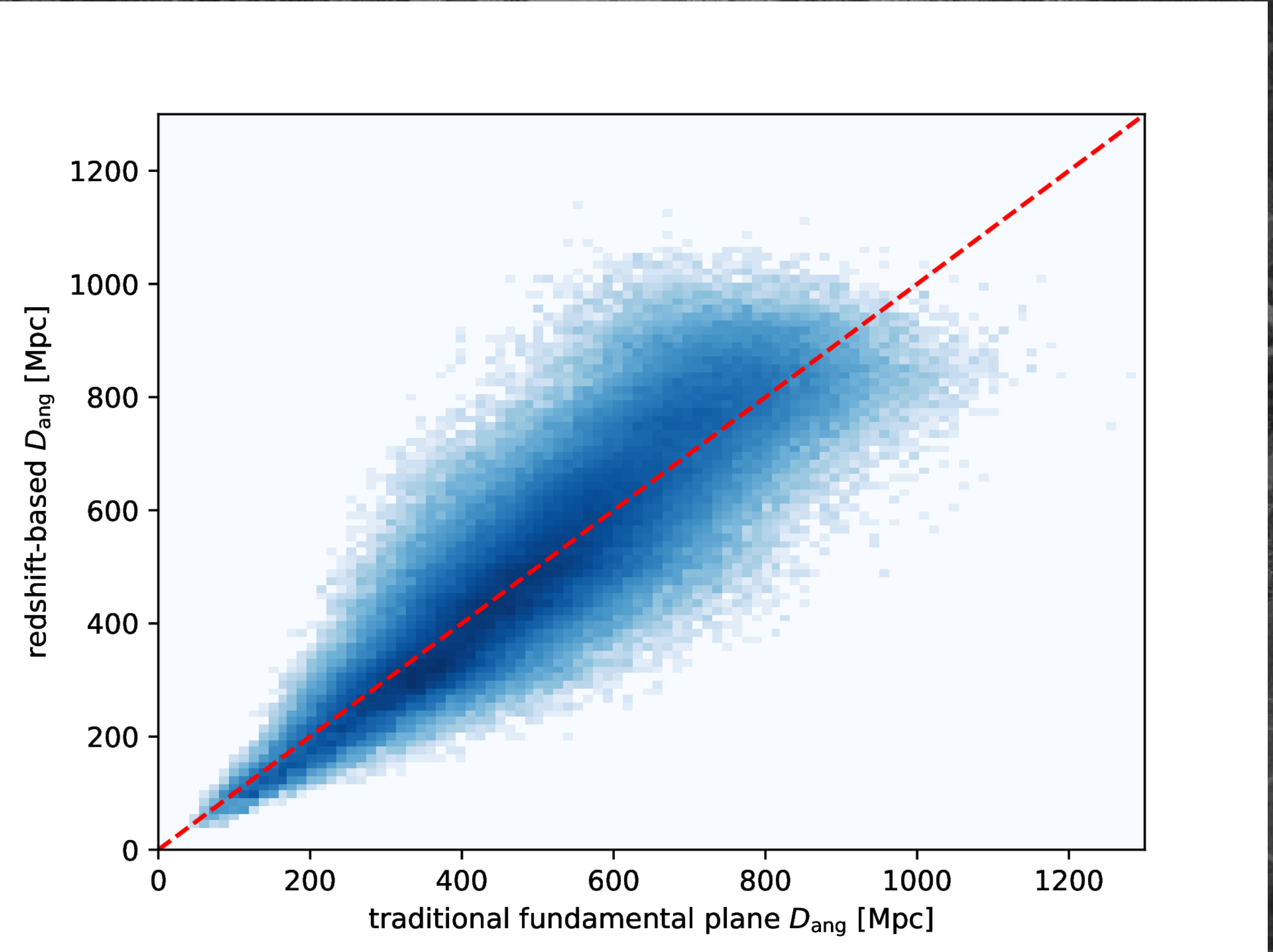
- Calculating the physical radii of the galaxies
- Direct fit (minimizing the scatter in radii) using least squares
  → fundamental plane coefficients
- We INTENTIONALLY did NOT correct for the Malmquist bias (typical done using volume weightening)
- → coefficients will only work for our sample



1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
log R0
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
1.25
1.50
a log σ0 + b μ0 + c

Fundamental plane distances

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

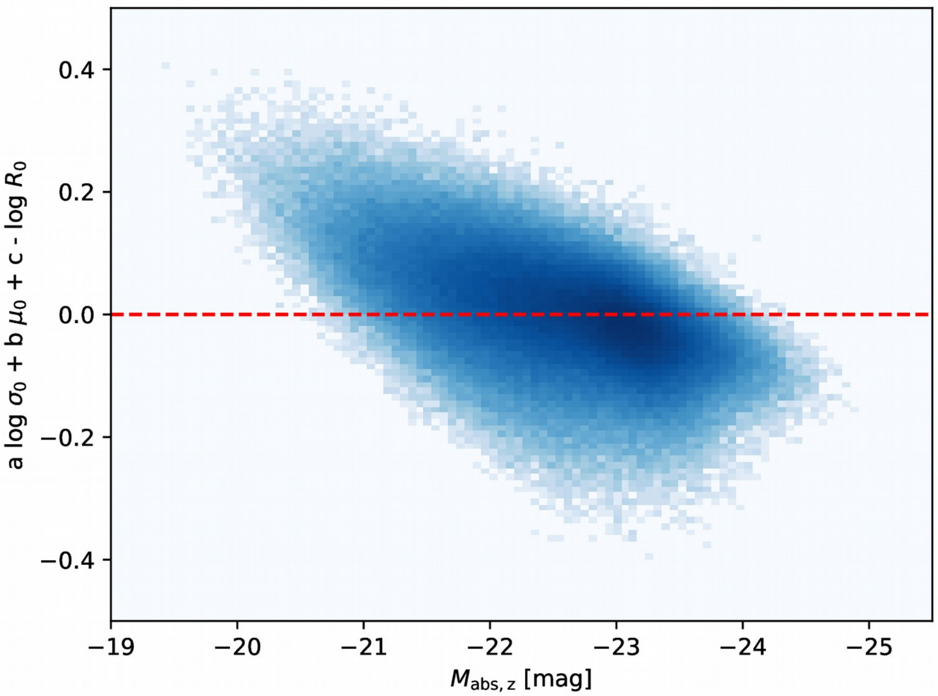


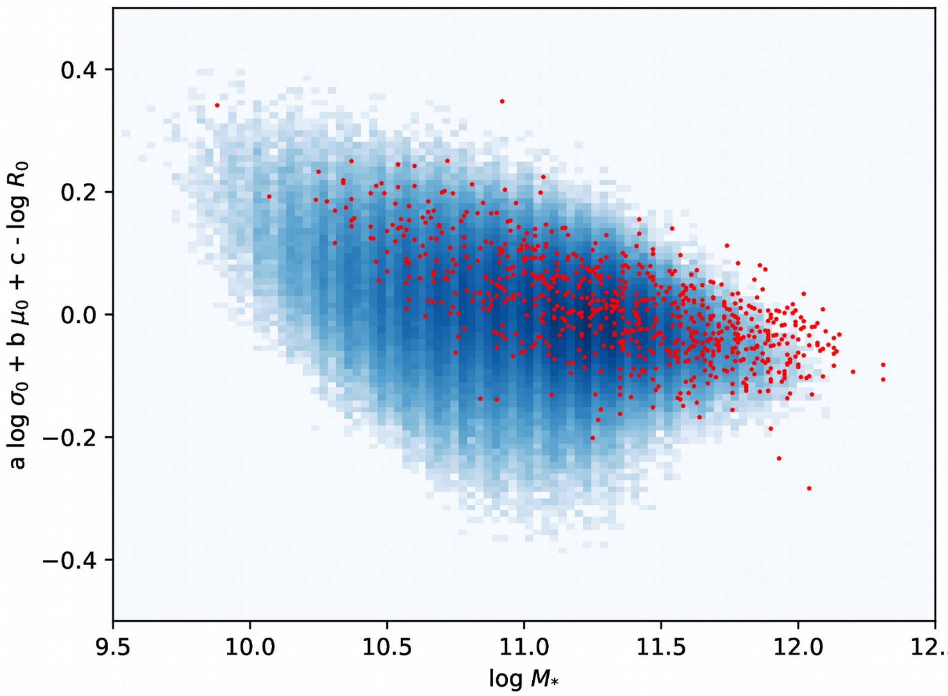
Biases of the traditional fundamental plane

- Hidden redshift dependences
  - Tolman effect correction ~$(1+z)^4$
  - Evolution correction ~ $Q \cdot z$
- 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

Luminosity / stellar mass biases

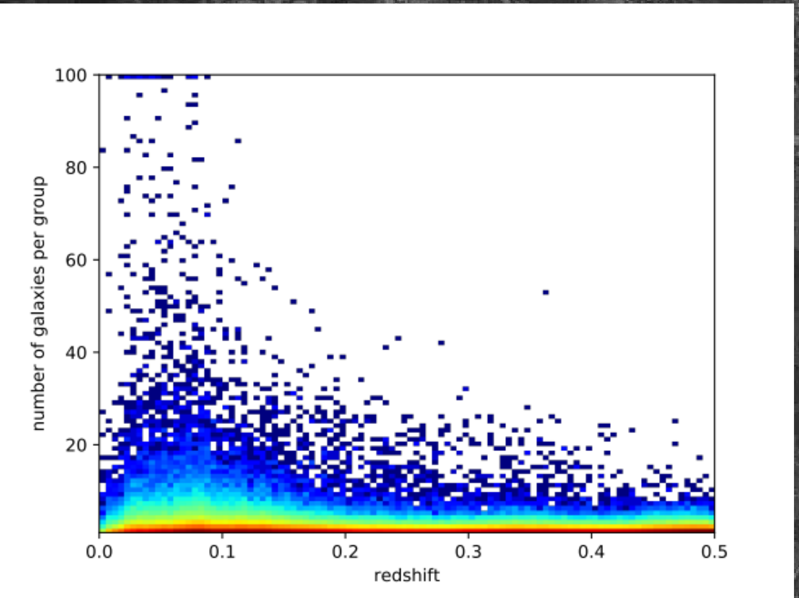
- Intrinsically fainter/brighter galaxies are systematically offset from the fundamental plane
- Stellar masses based on Maraston+ 2009 show the same effect, tighter relation with MaNGA data

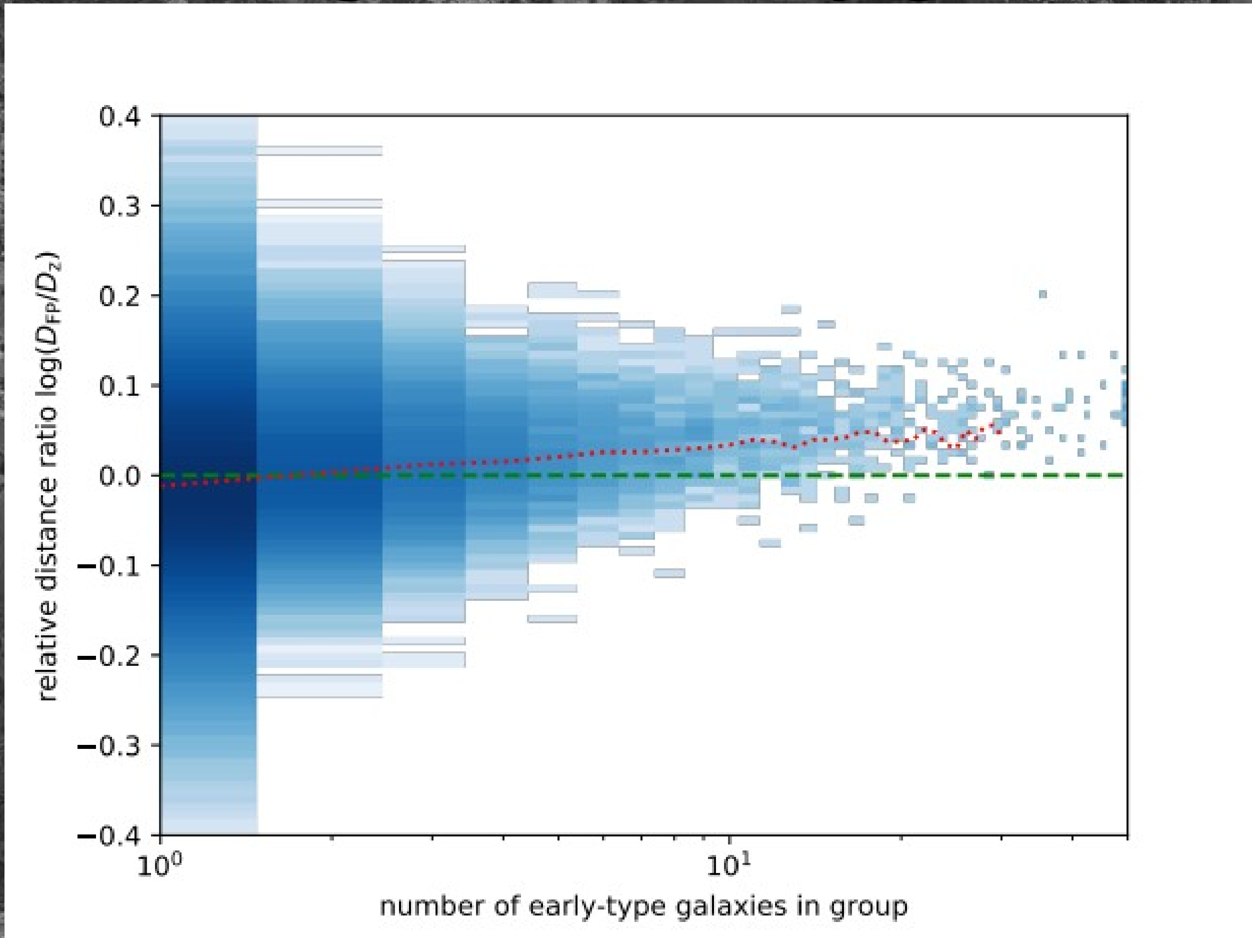




Group bias

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



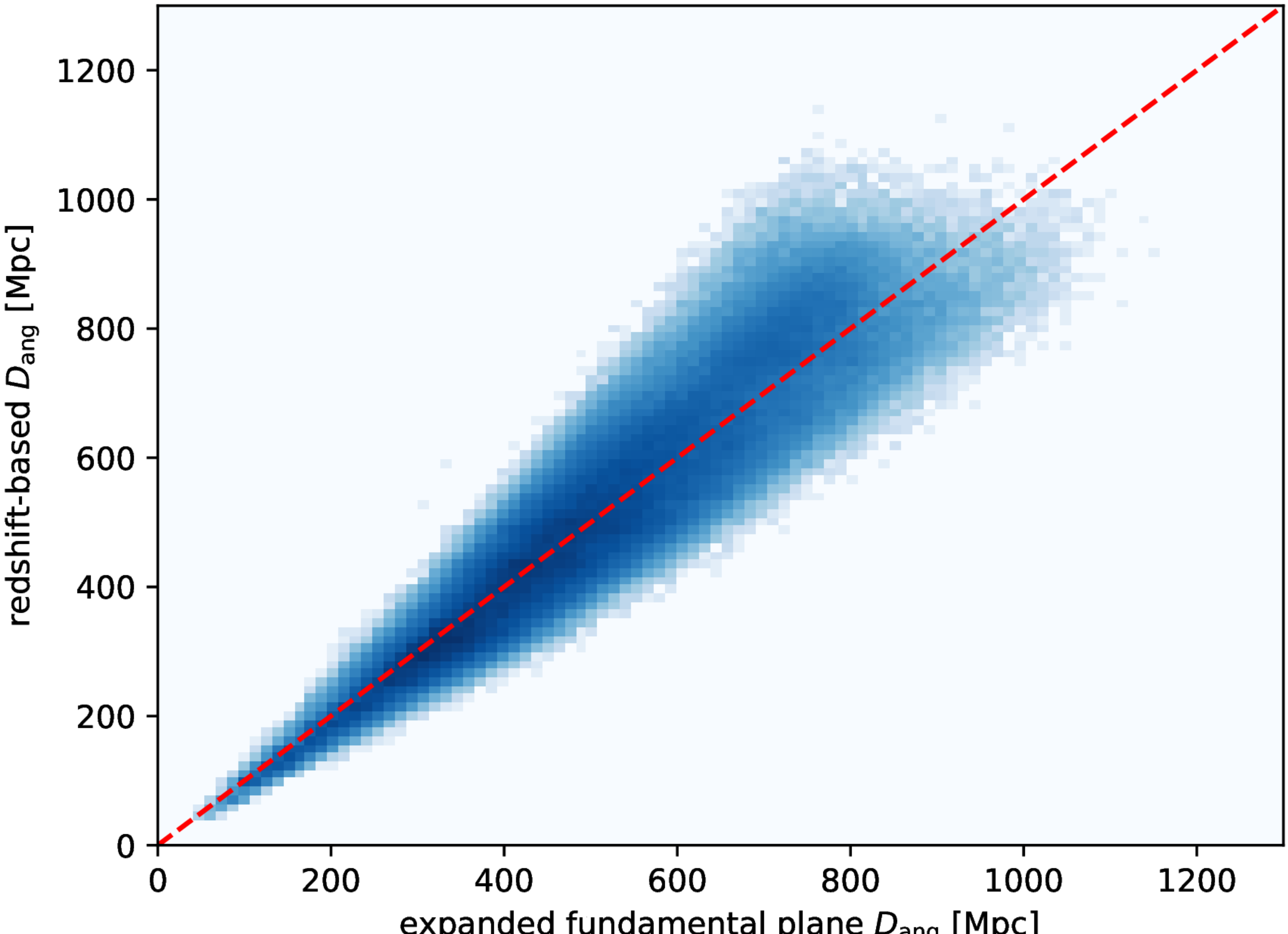


Expanded funamental plane

- 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



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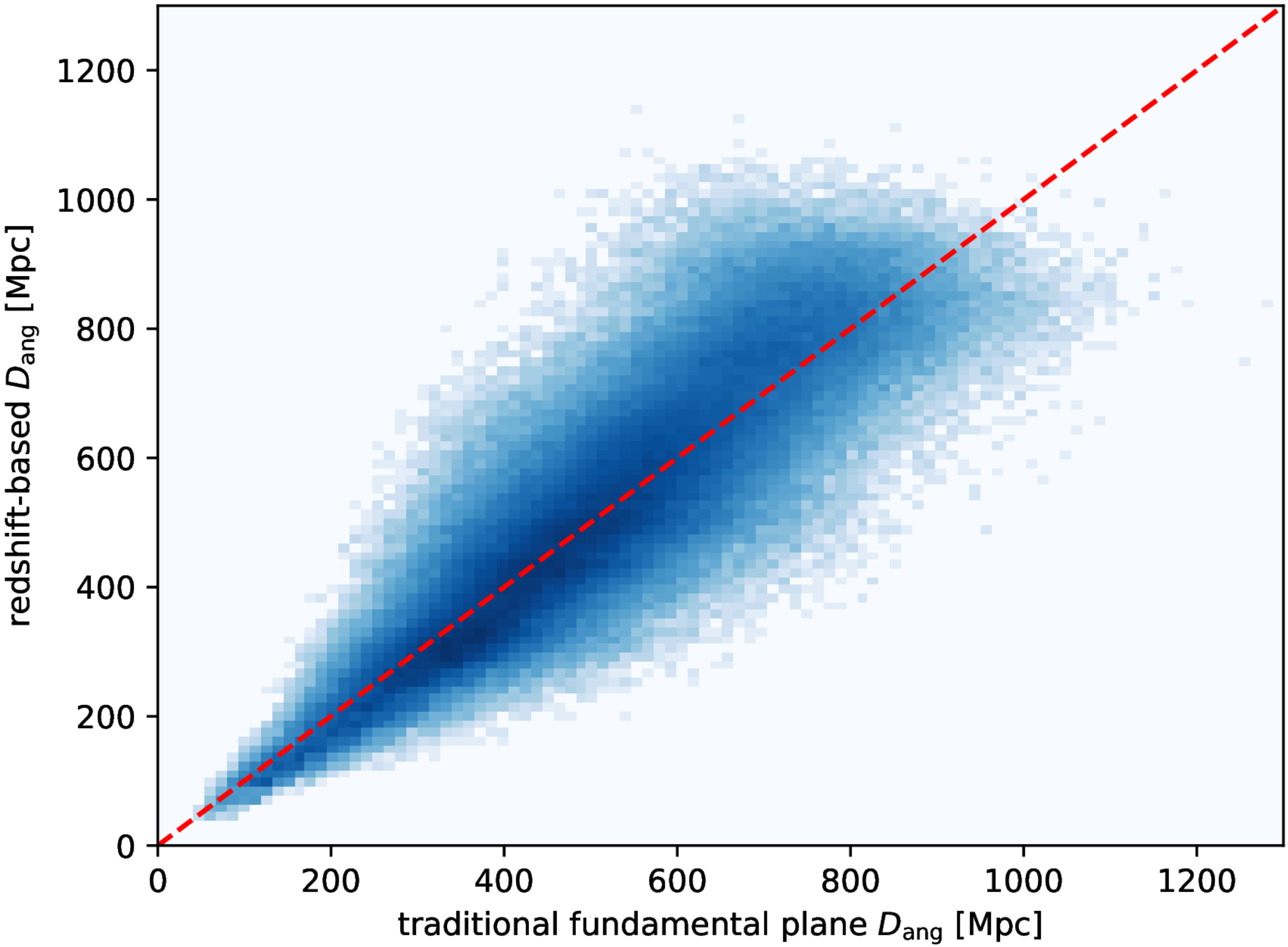
redshift-based D_{ang} [Mpc]
expanded fundamental plane D_{ang} [Mpc]



redshift-based D_{ang} [Mpc]
traditional fundamental plane D_{ang} [Mpc]
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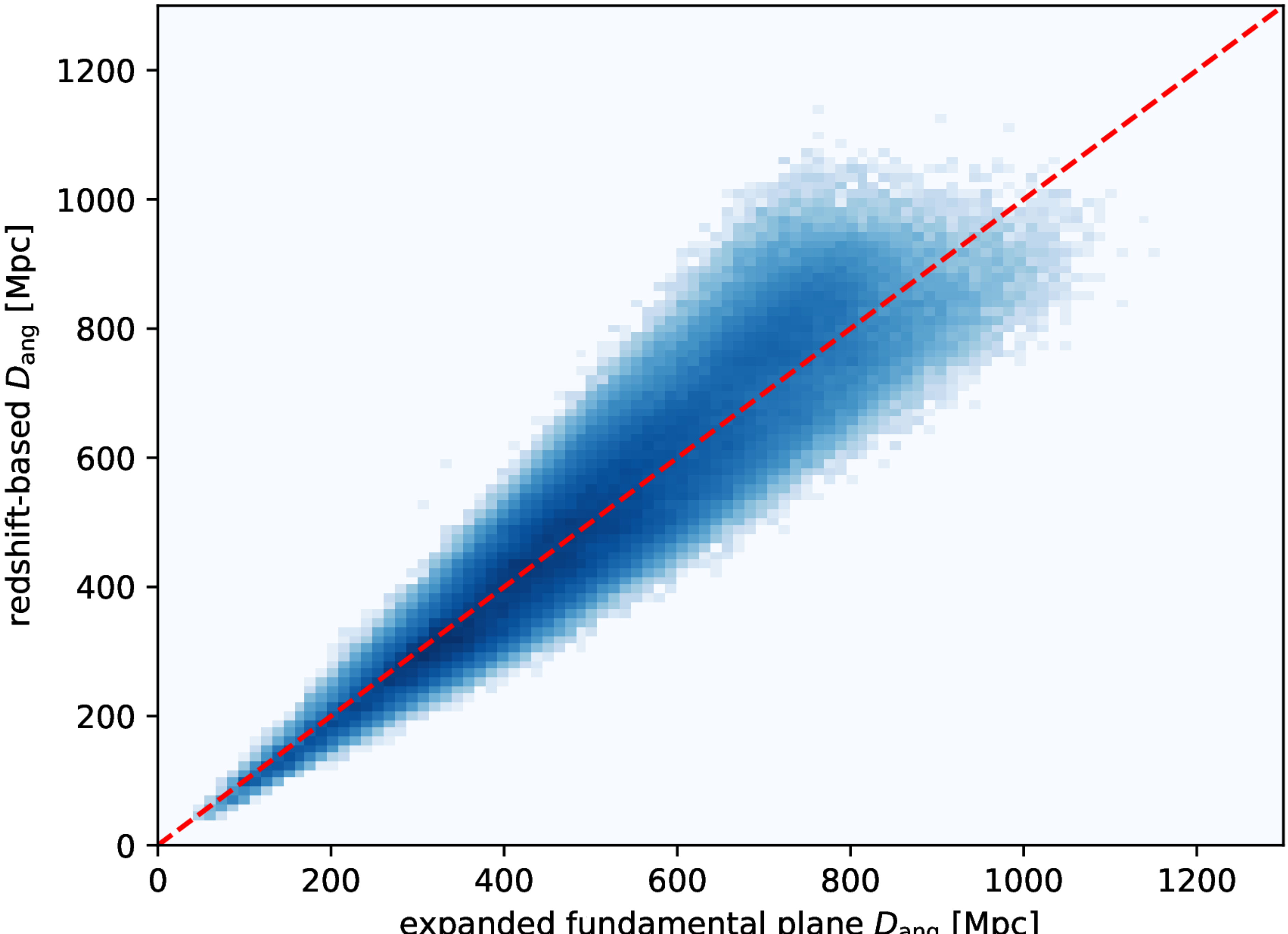
1200
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0
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800
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1200
redshift-based D_{ang} [Mpc]
expanded fundamental plane D_{ang} [Mpc]

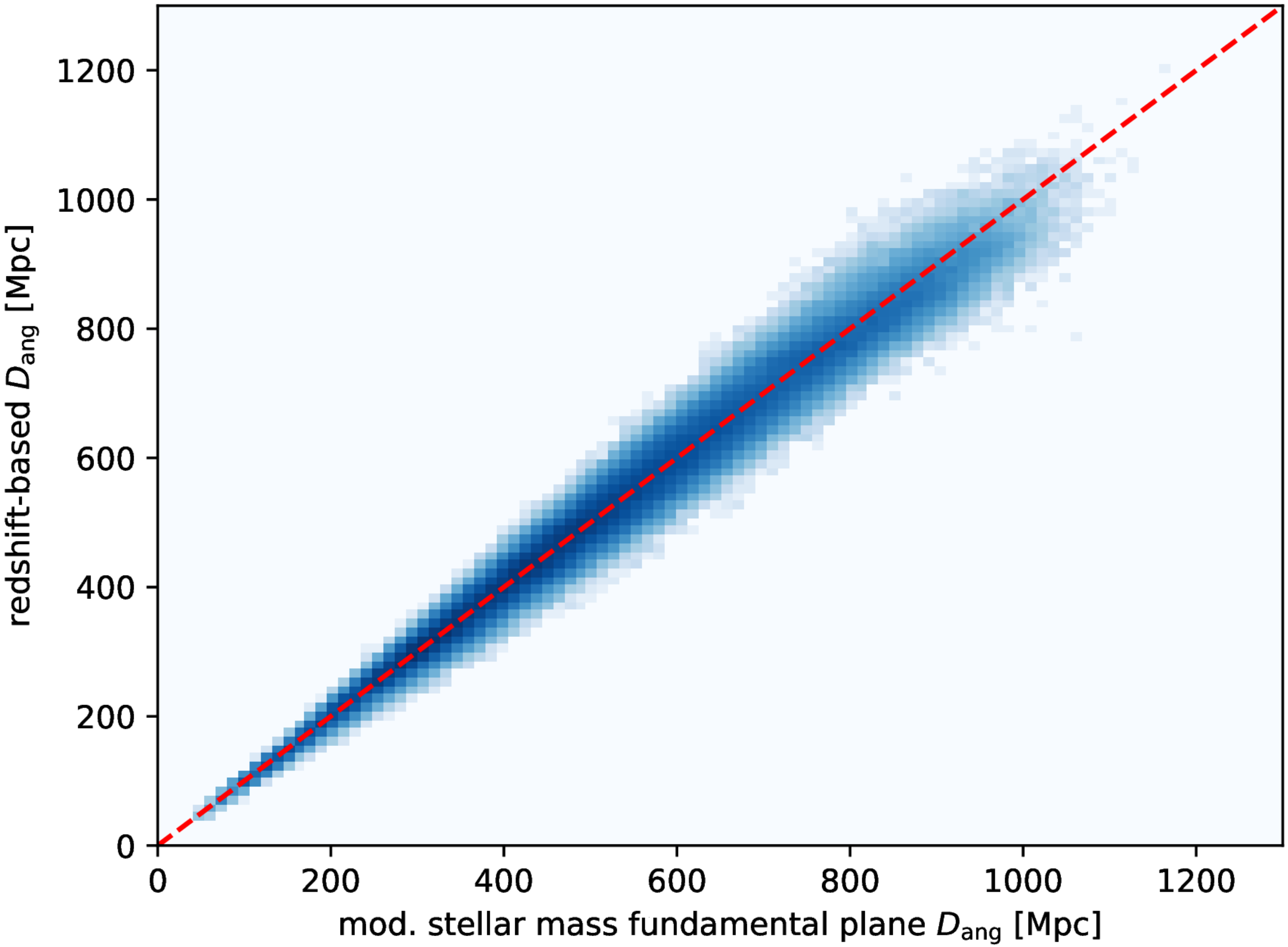
Paying the price

- 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

A mistake and going nuts

- Stellar mass fundamental plane, but wrong
- $\log_{10}(R_0) = a_{msm} \cdot \log_{10}(\sigma_0) + b_{msm}\ \Xi + c_{msm}$

  with $\Xi = \log_{10}(M_*) - f_{opt} \cdot \log_{10}(R_0)$
- f_{opt}=2 („traditional" stellar mass fundamental)
- f_{opt}=6.5 (now, but initially f_{opt}=5)
- Modified stellar mass fundamental plane
- But R_0 in Ξ is obtained from redshift distances



redshift-based $D_{\rm ang}$ [Mpc]
mod. stellar mass fundamental plane $D_{\rm ang}$ [Mpc]
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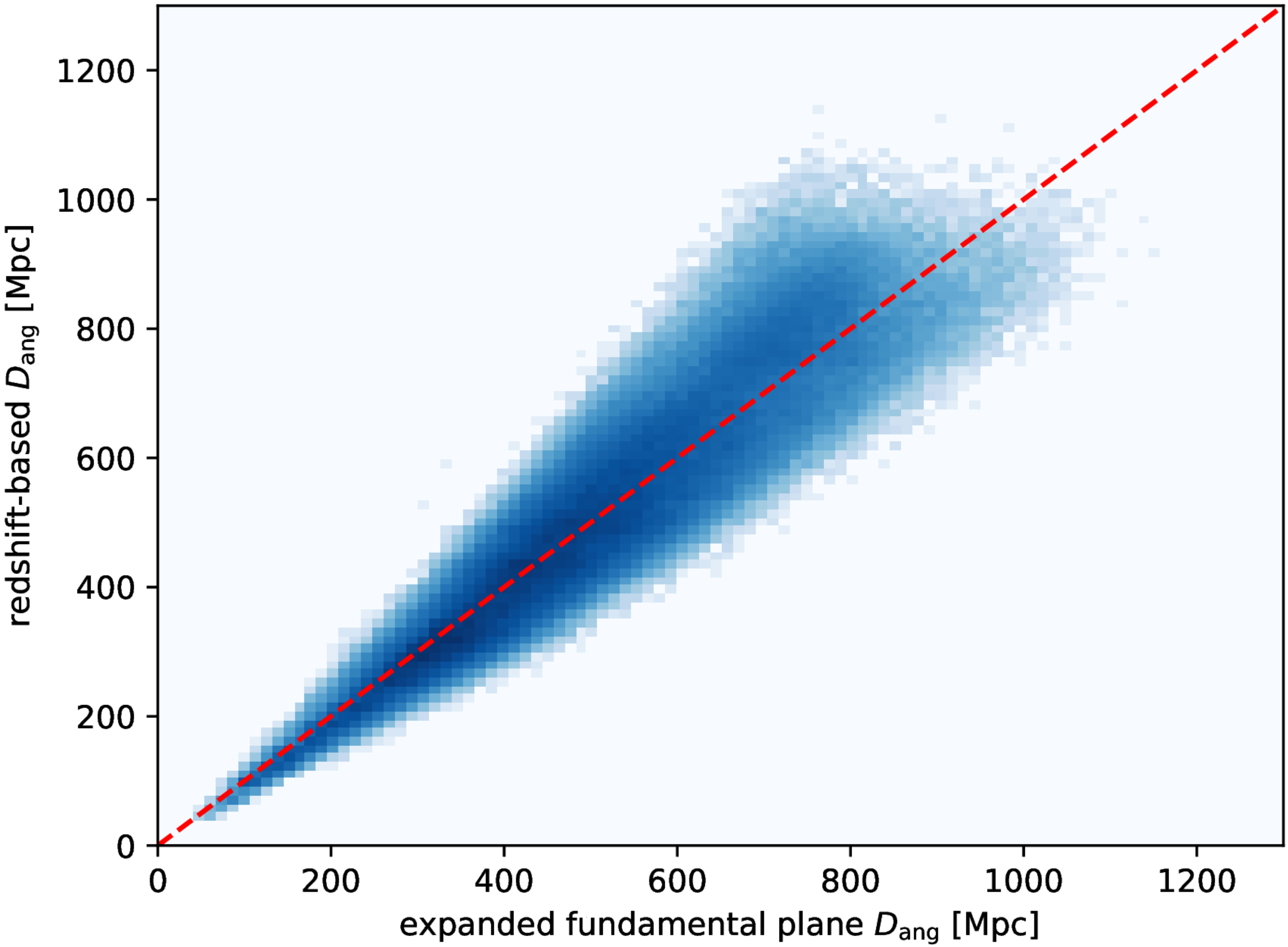

redshift-based D_{ang} [Mpc]
expanded fundamental plane D_{ang} [Mpc]
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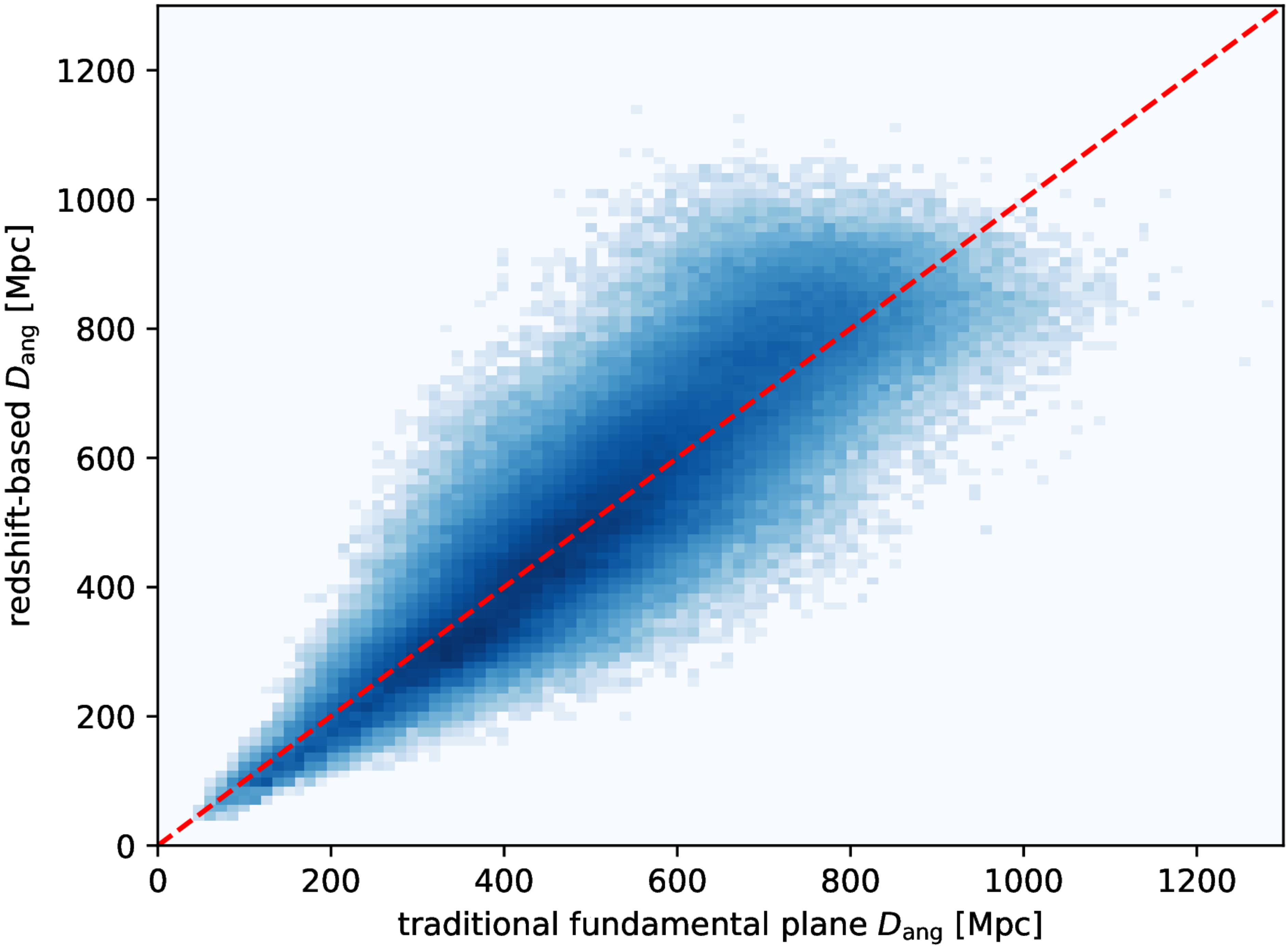

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redshift-based D_{ang} [Mpc]
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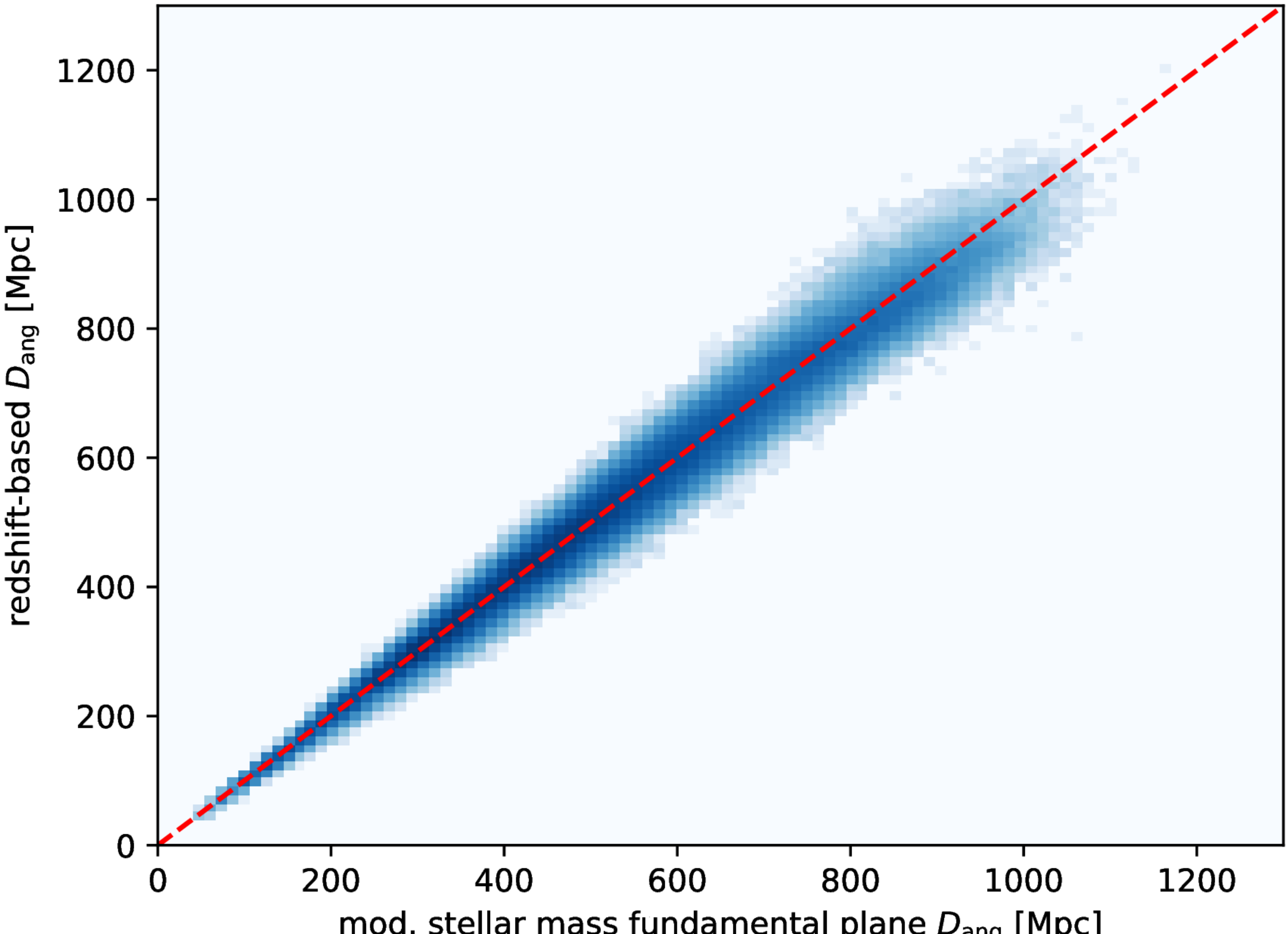
traditional fundamental plane D_{ang} [Mpc]



redshift-based D_{ang} [Mpc]
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800
1000
1200
mod. stellar mass fundamental plane D_{ang} [Mpc]

So, what's the catch?

- Scatter only 5.4% … to good to be true

So, what’s the catch?

- Scatter only 5.4% … to good to be true

- Very explicit redshift-depedence in Ξ (because of R_0)

- Systematic redshift-dependent error between 4.4% (lowest redshifts) and 0.2% (higher redshifts).

- Throw it away?

but there is a surprise!

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

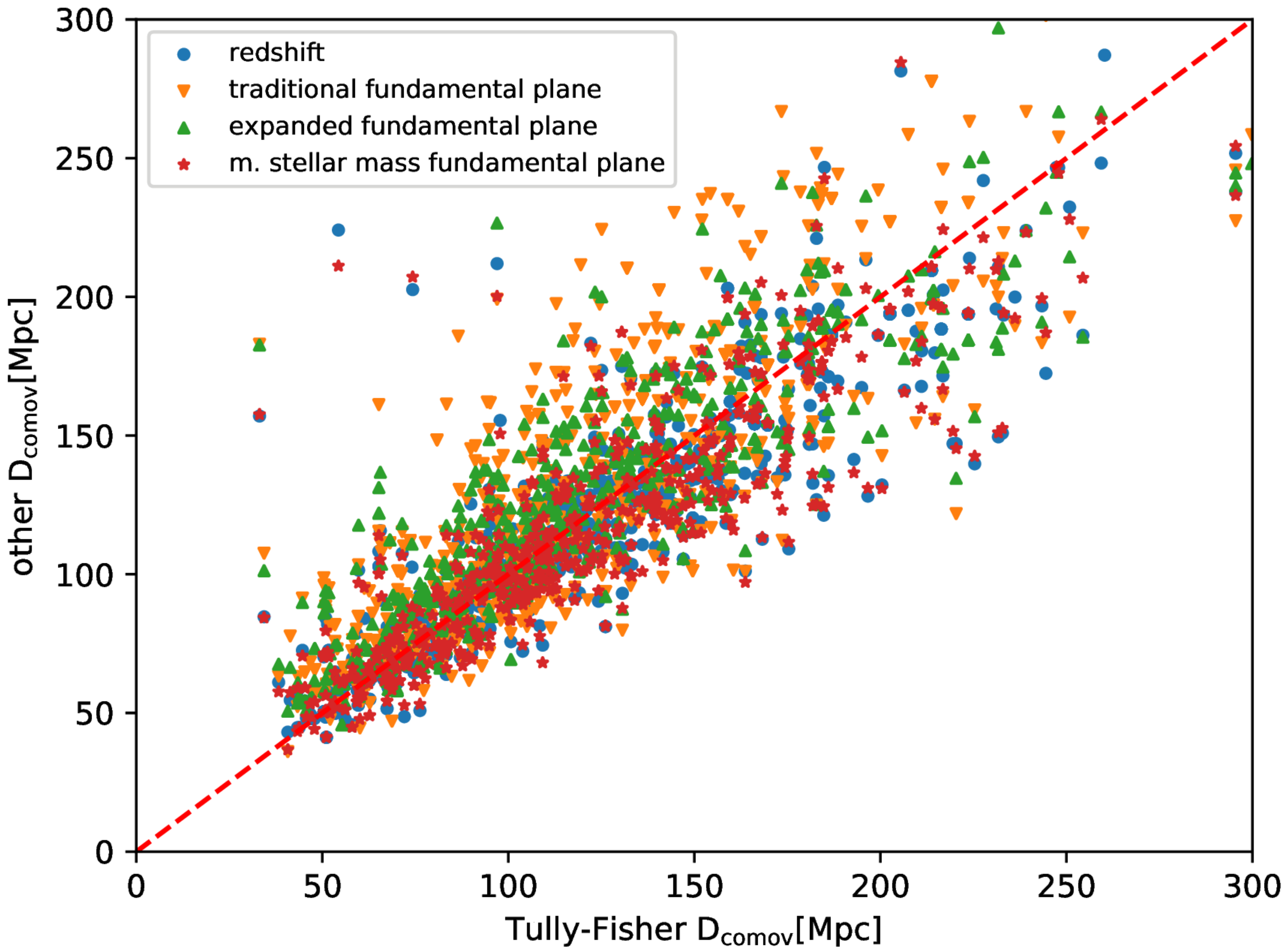
How to compare mutually exclusive samples?

- Late-type galaxies: Tully-Fisher relation
- Early-type galaxies: fundamental plane

How to compare mutually exclusive samples?

- Late-type galaxies: Tully-Fisher relation
- Early-type galaxies: fundamental plane

- Taking advantage of our group catalogue
  - Sizes of groups << distance to groups
  - Compare galaxies within the same groups
  - Trouble with occassional interloopers → increased scatter
  - Focus on rich groups



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
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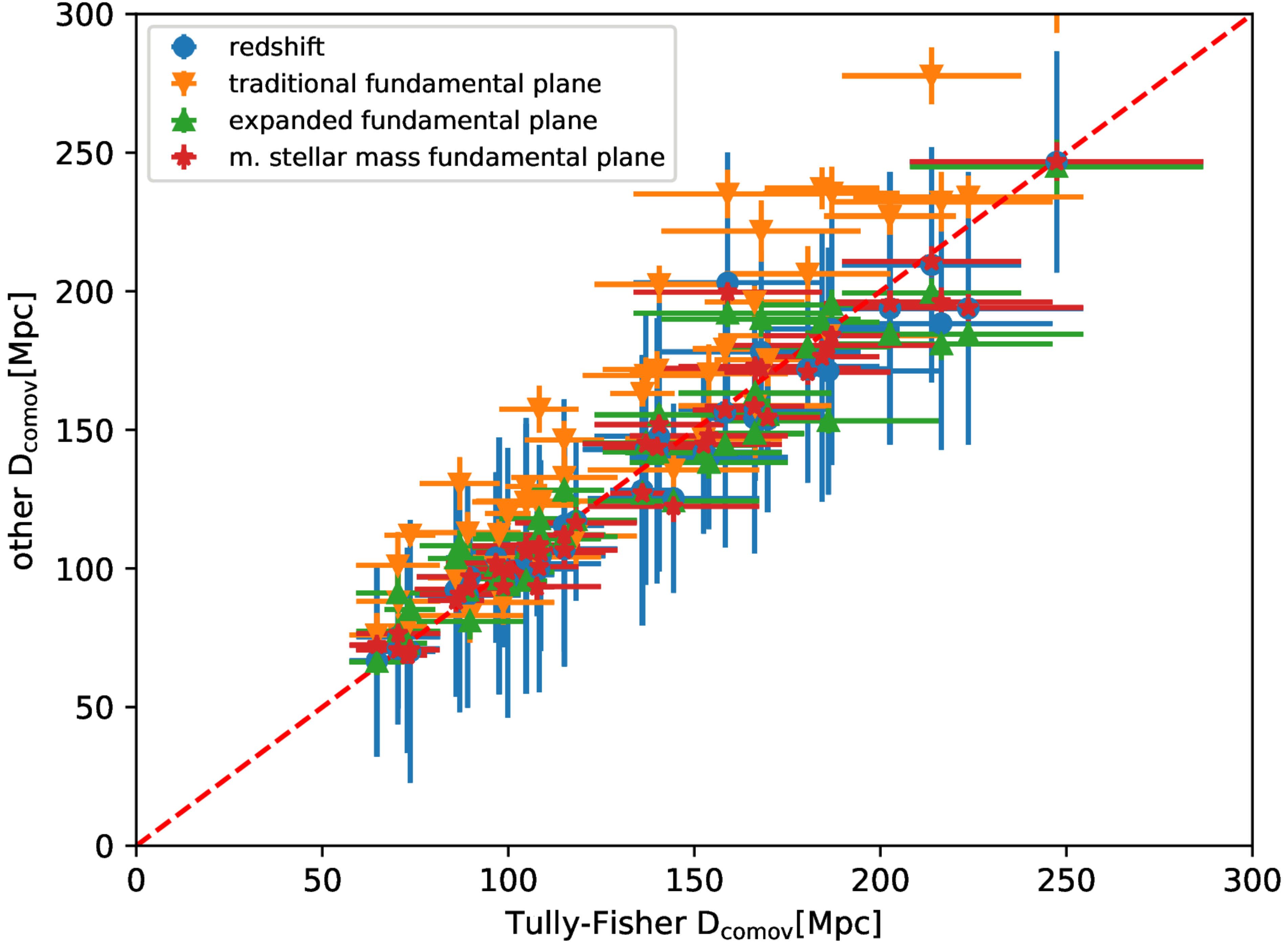

redshift
traditional fundamental plane
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other D_{comov}[Mpc]
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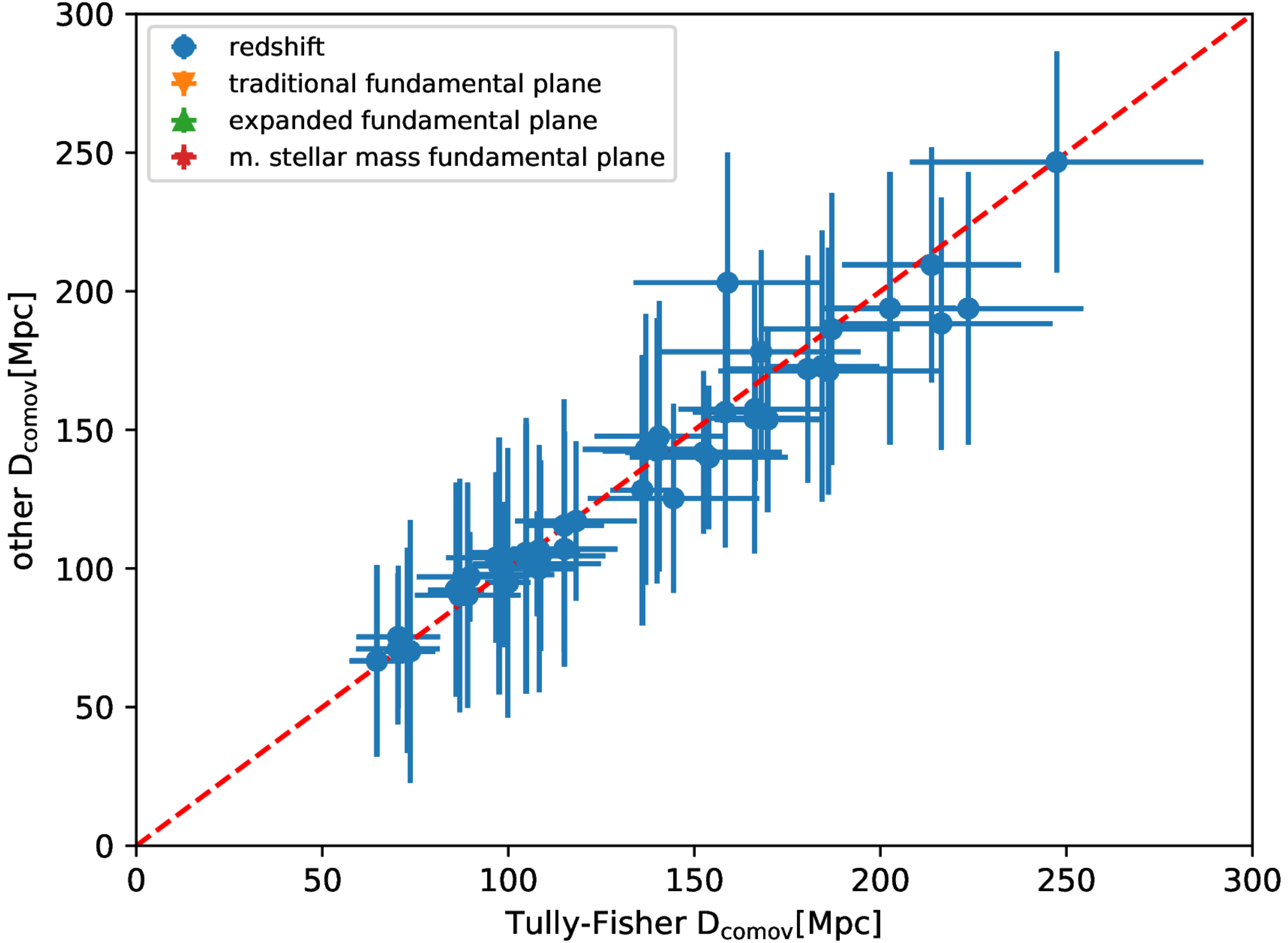
redshift
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Tully-Fisher D_{comov}[Mpc]
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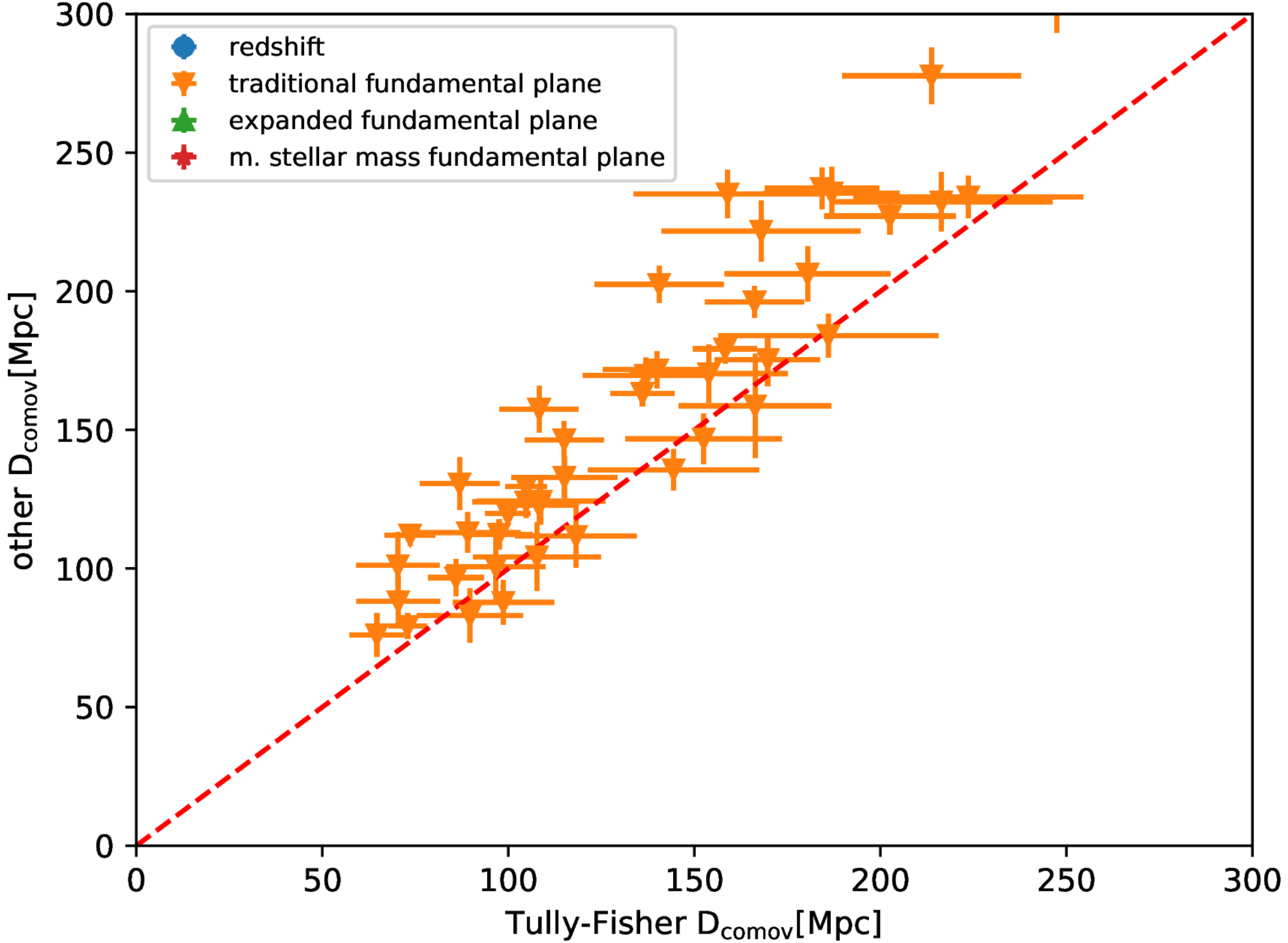

redshift
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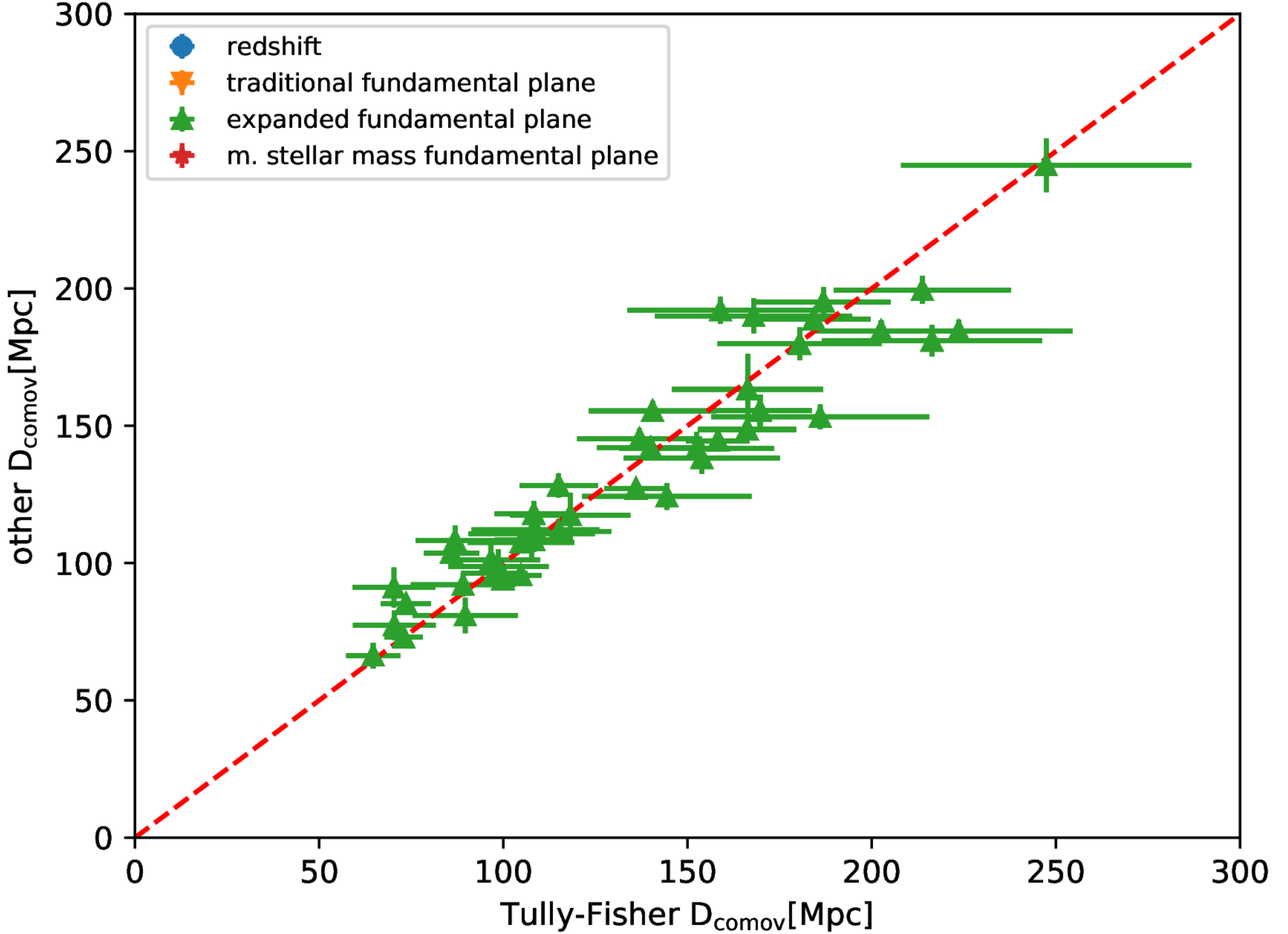

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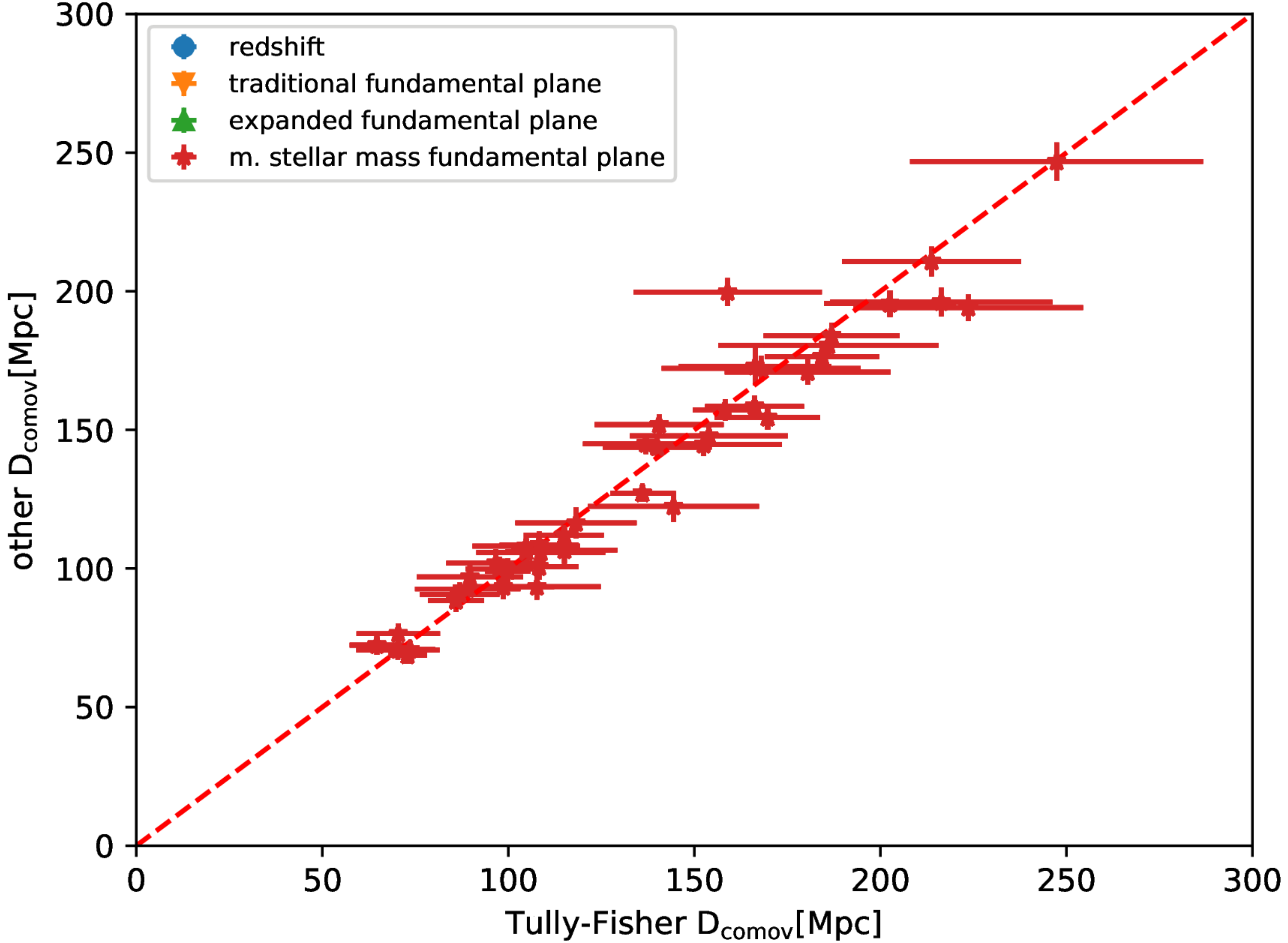

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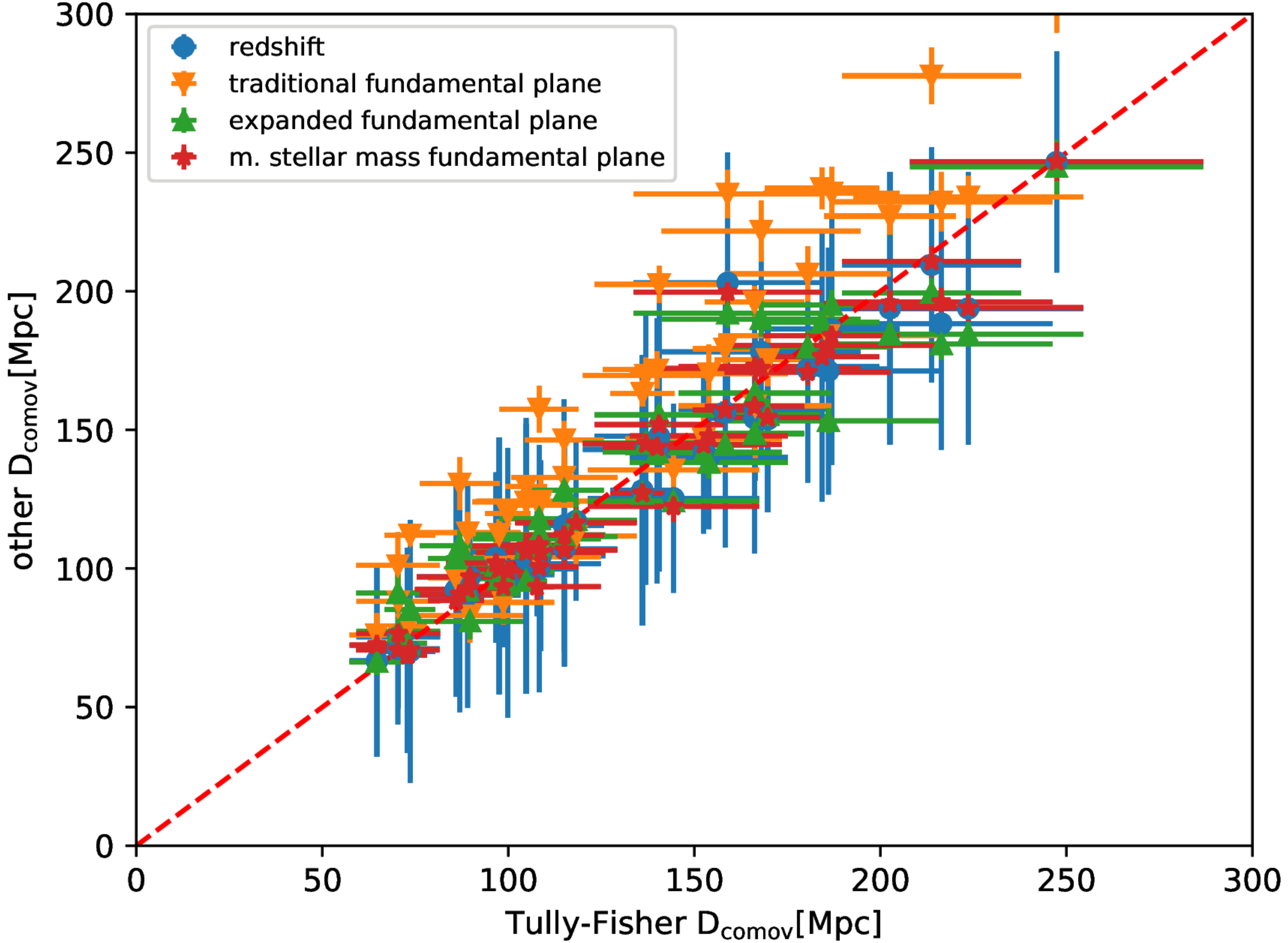

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Tully-Fisher D_{comov}[Mpc]
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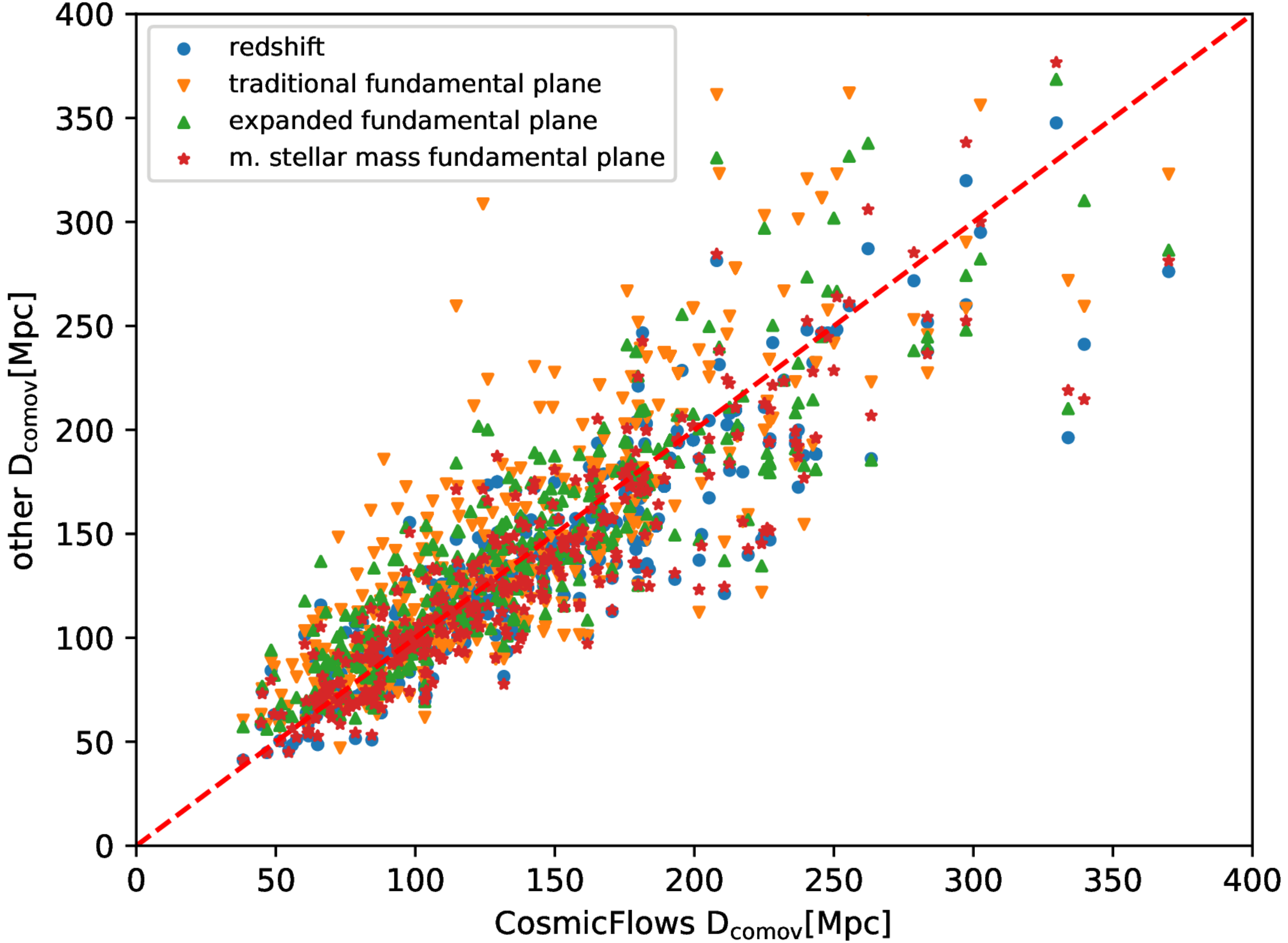
- Systematic off-set of the traditional fundamental plane due to selection effects
- Scatter TF-FP distances: 35.8% / 23.1%
- Scatter TF-expFP distances: 29.7% / 9.7%
- Scatter TF-mSMFP distances: 22.8% / 5.7%
- Scatter TF-redshift distances: 22.9% / 6.0%

- The Tully-Fisher relation distances agree better with the modified stellar mass fundamental plane than with redshifts.

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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CosmicFlows D_{comov}[Mpc]
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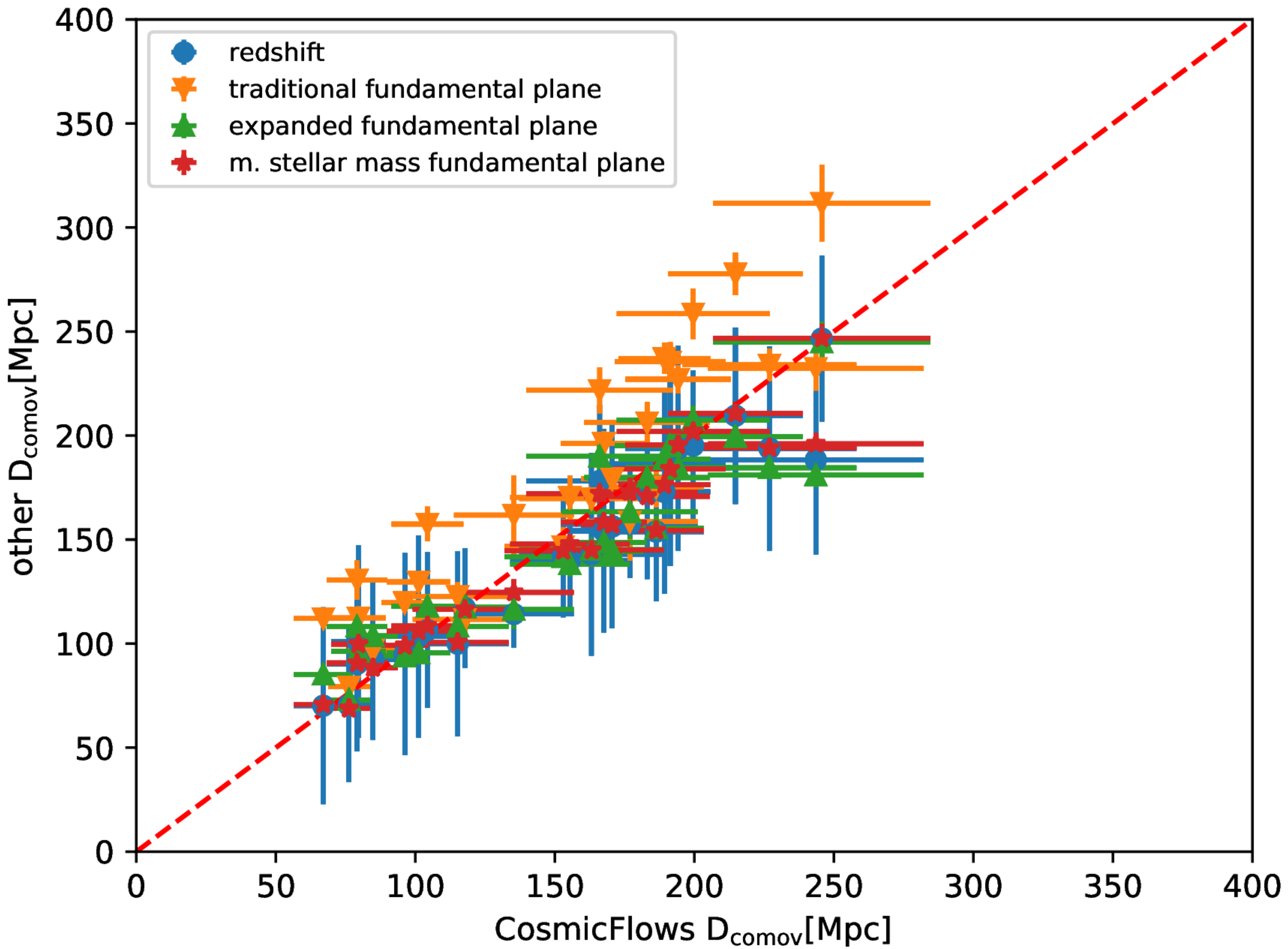

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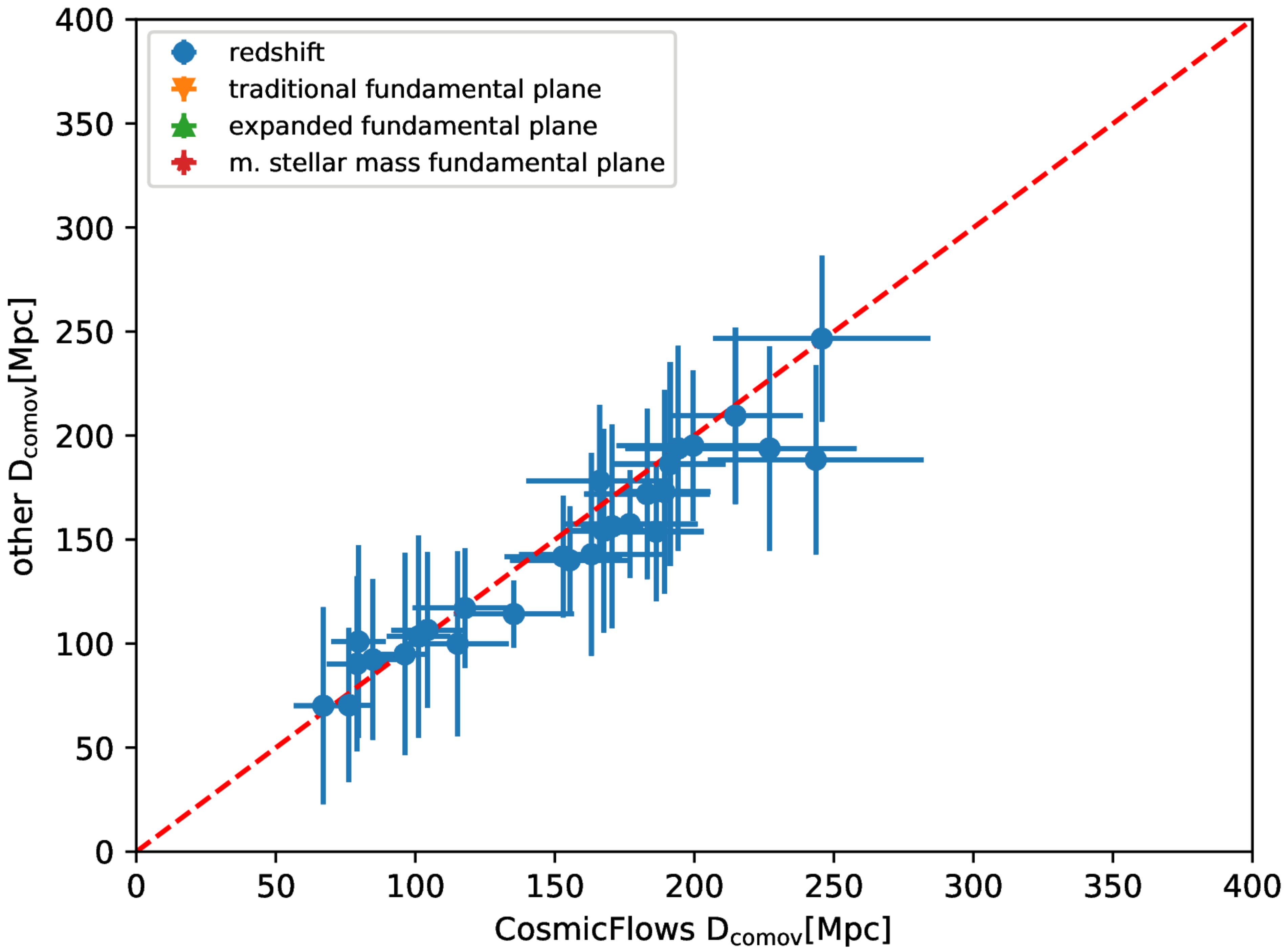

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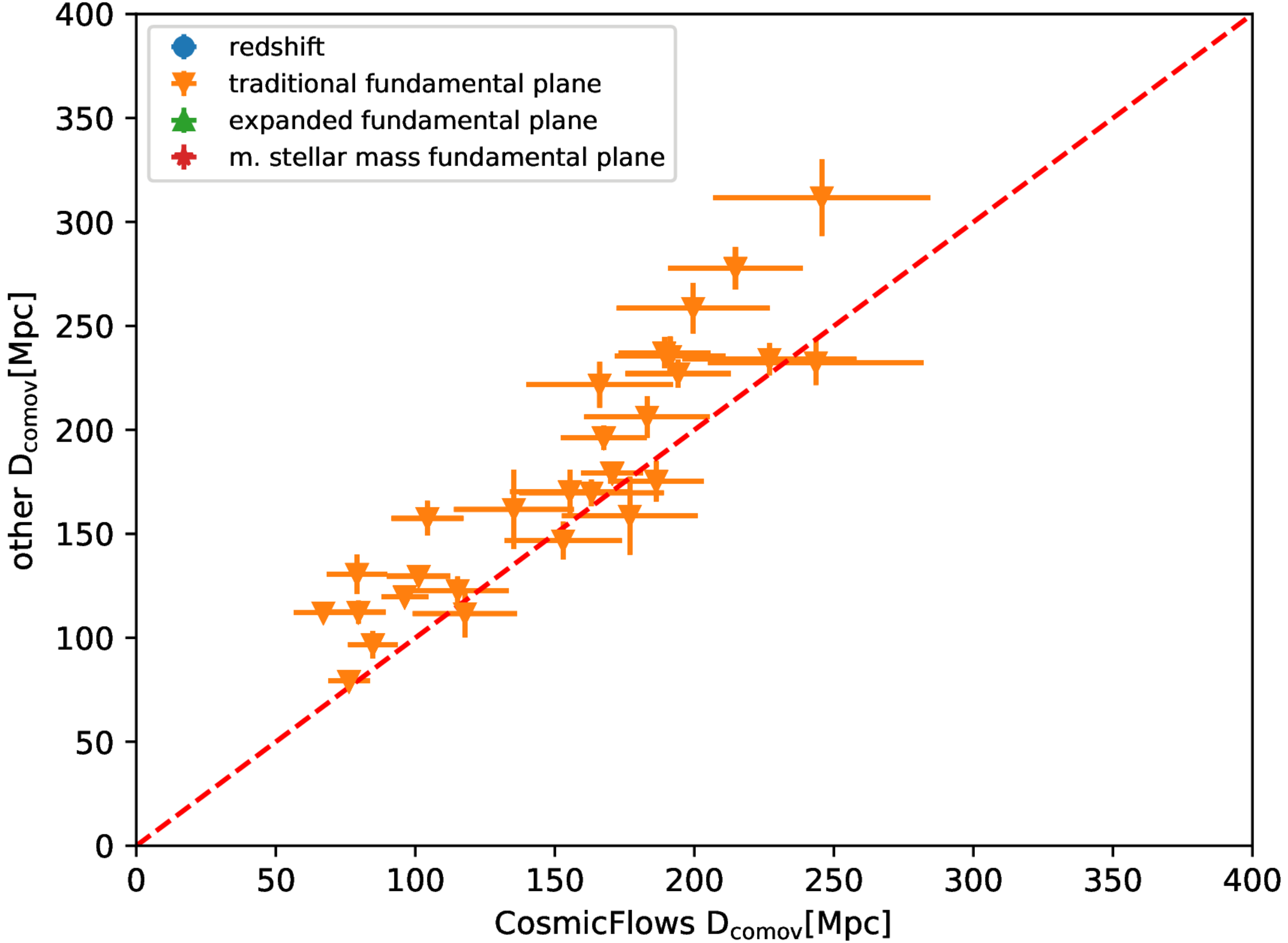

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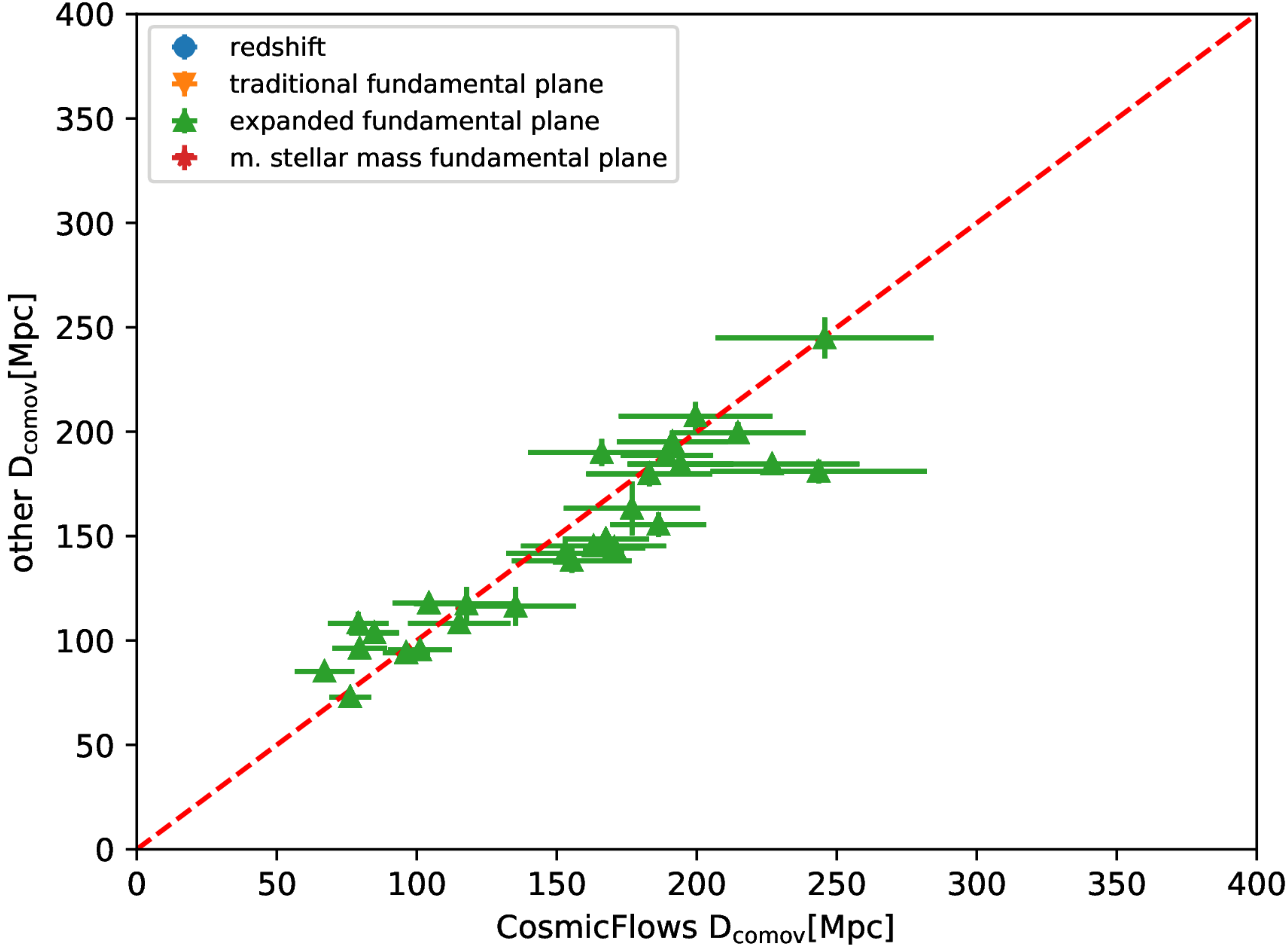
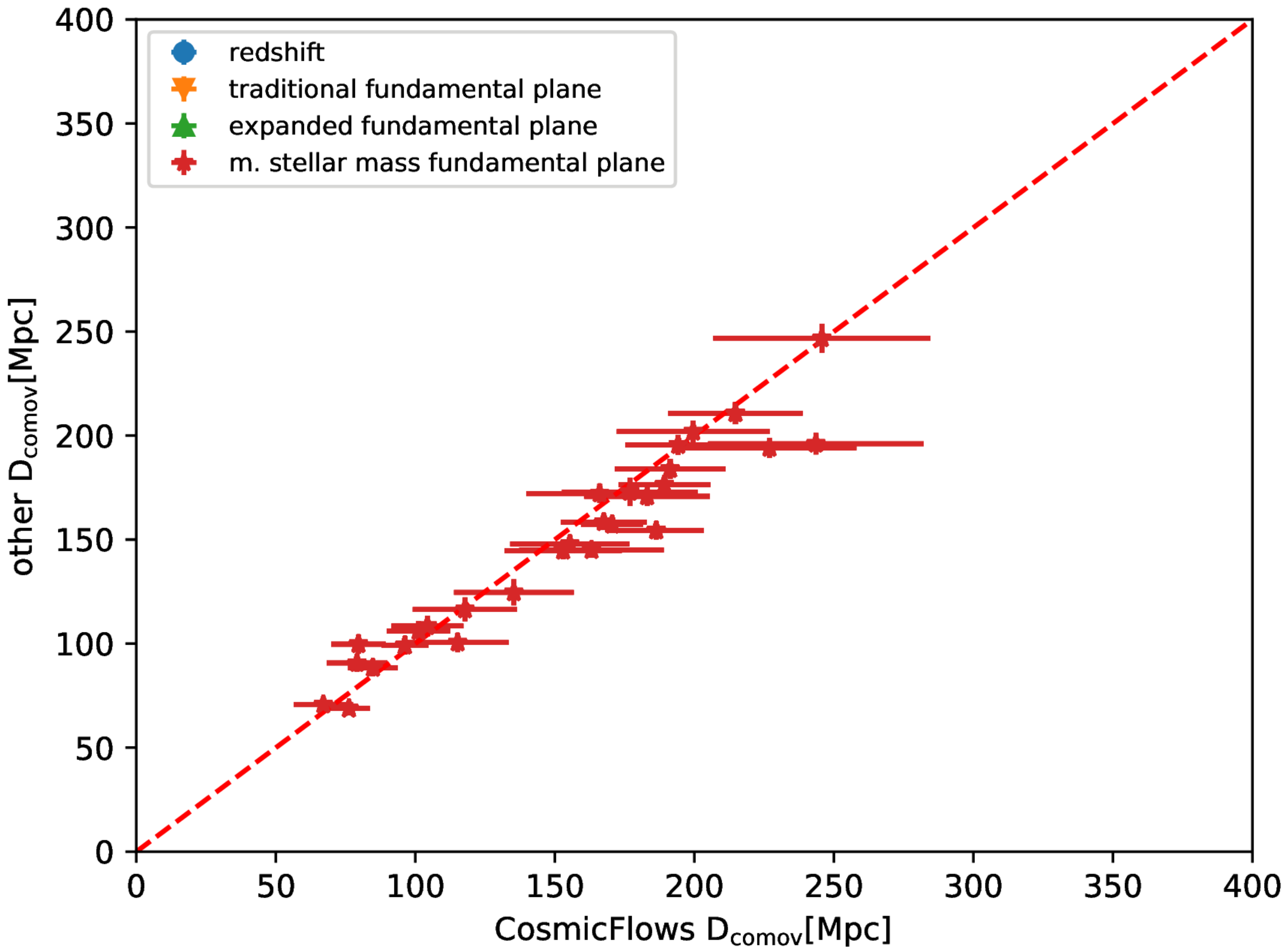
350
400


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



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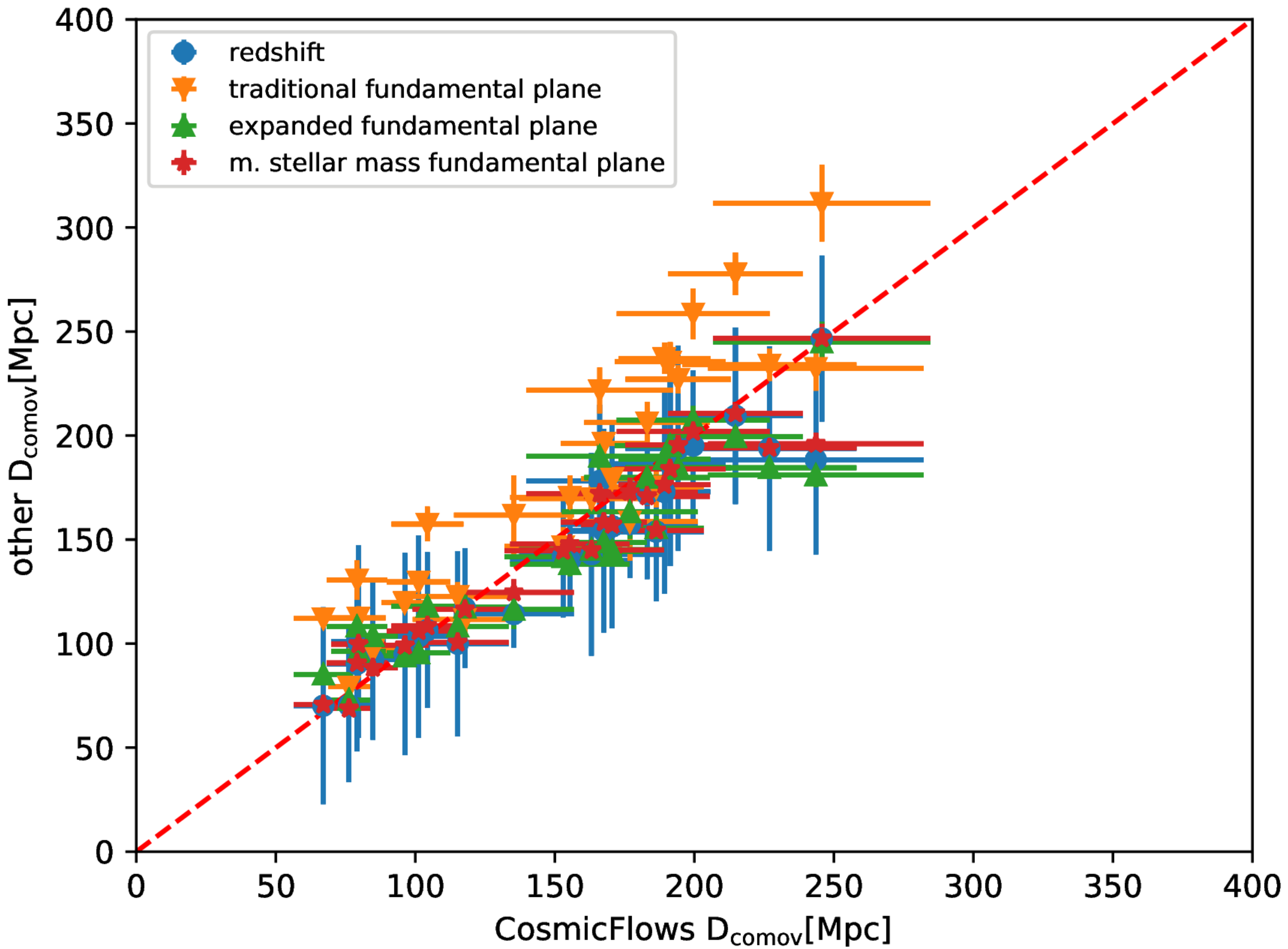


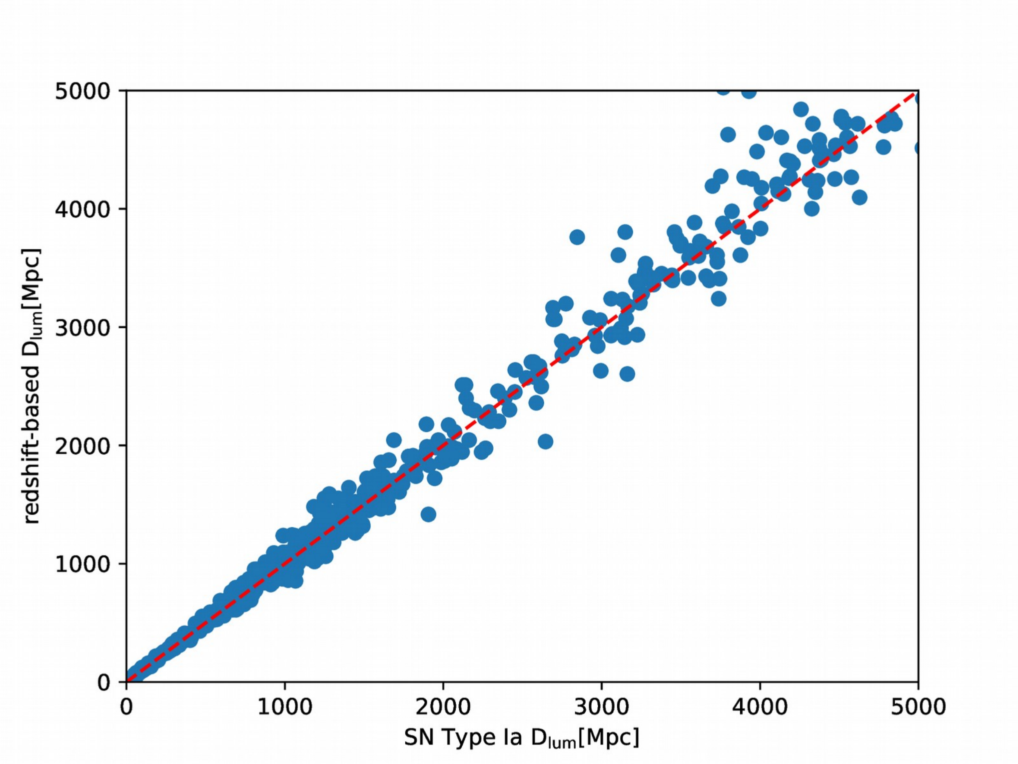
redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{comov}[Mpc]
CosmicFlows D_{comov}[Mpc]
0
50
100
150
200
250
300
350
400

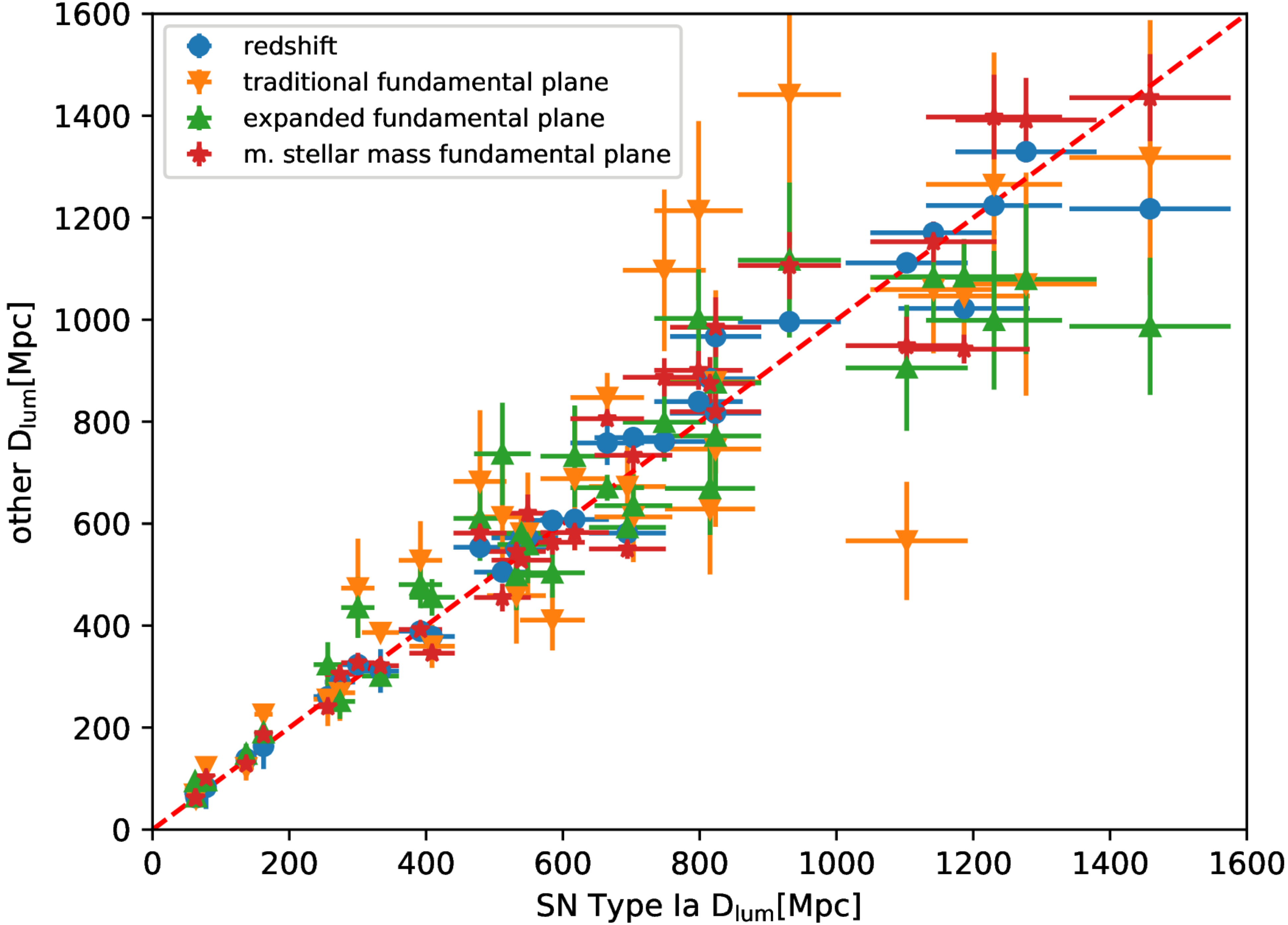
- Scatter CF3-FP distances: 28.5% / 24.6%
- Scatter CF3-expFP distances: 20.5% / 13.4%
- Scatter CF3-mSMFP distances: 16.1% / 9.1%
- Scatter CF3-redshift distances: 15.7% / 10.1%

- More or less the same as for the Tully-Fisher relation distances

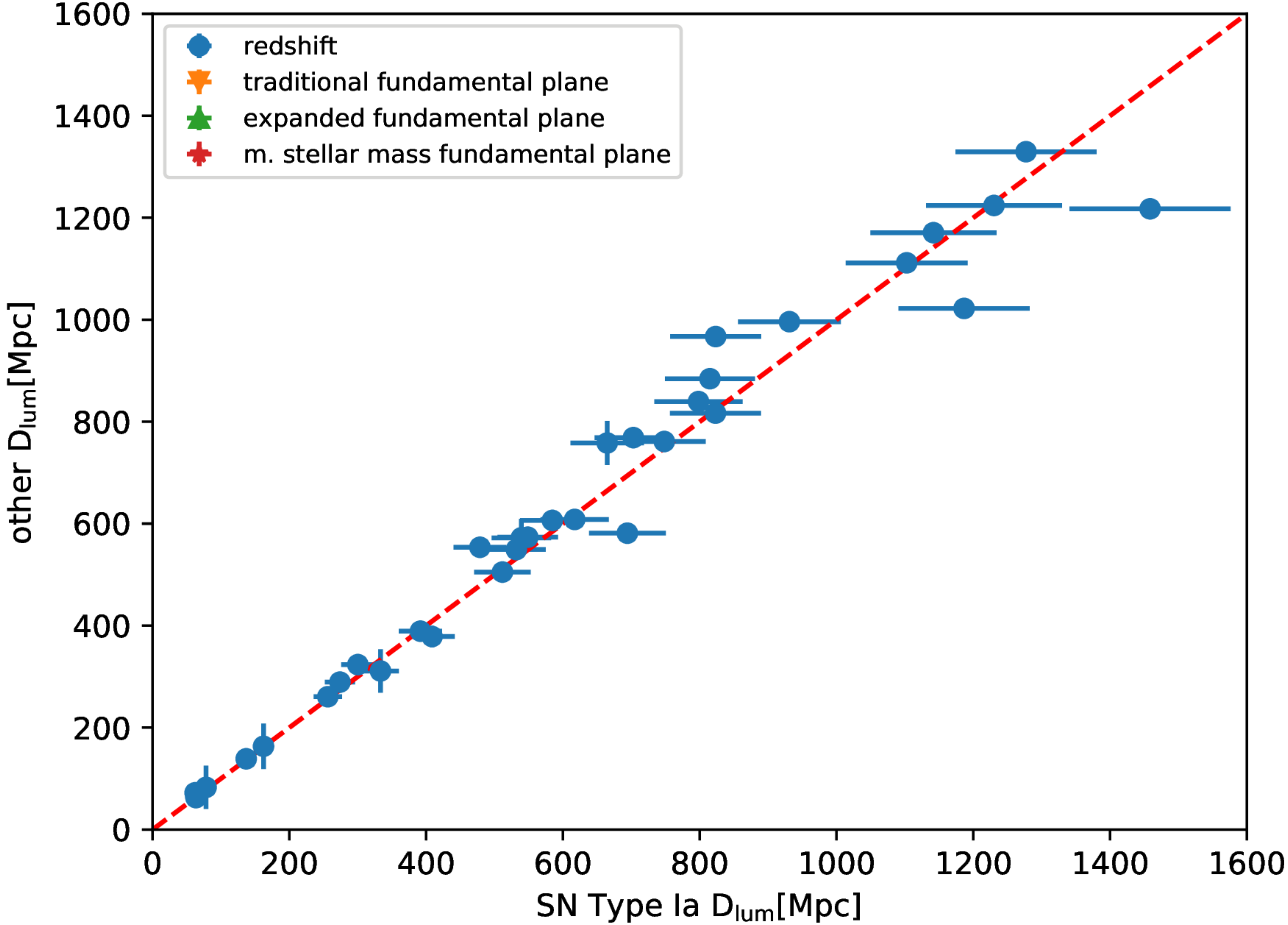
Comparison to supernovae Type Ia

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

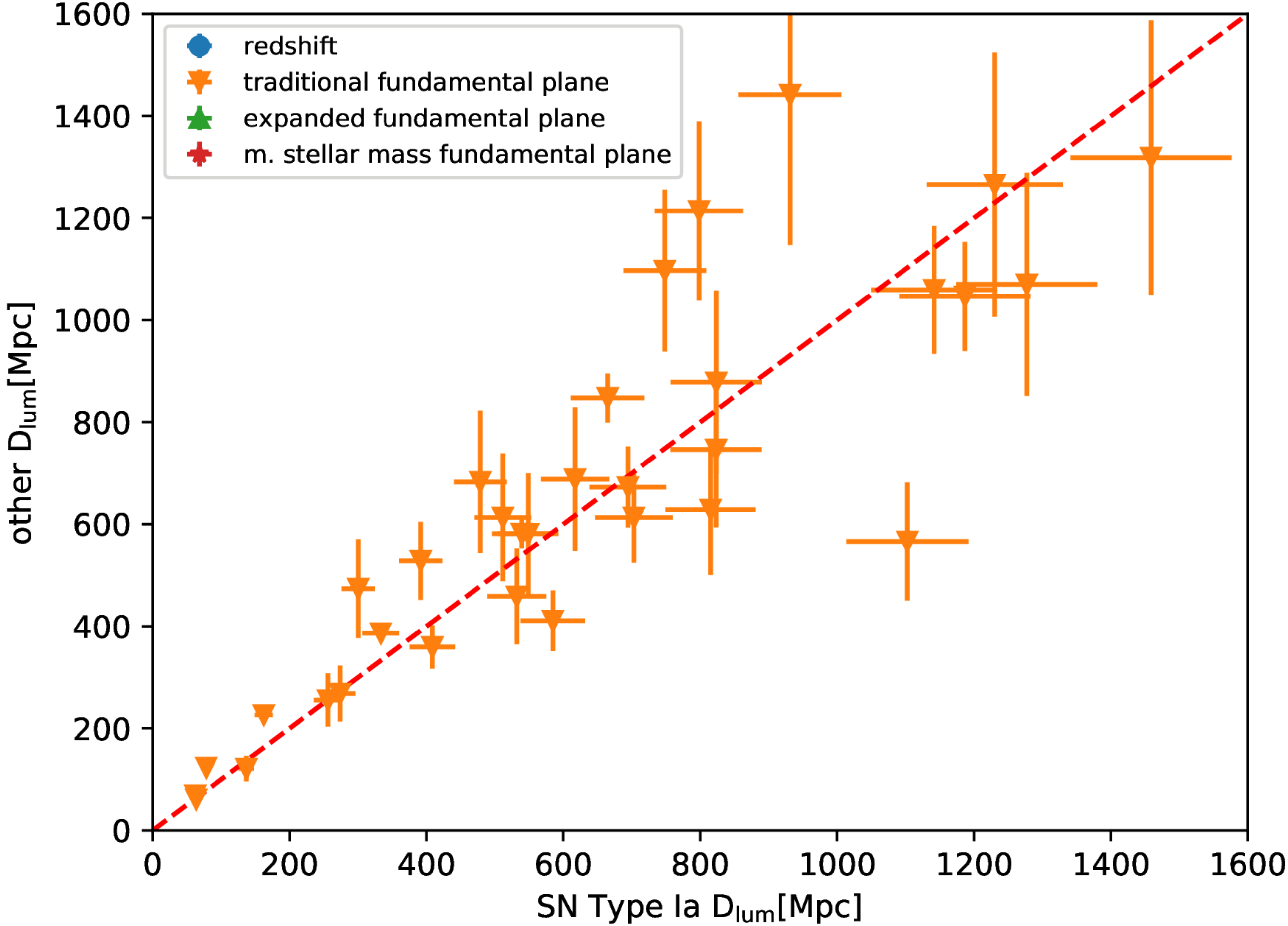




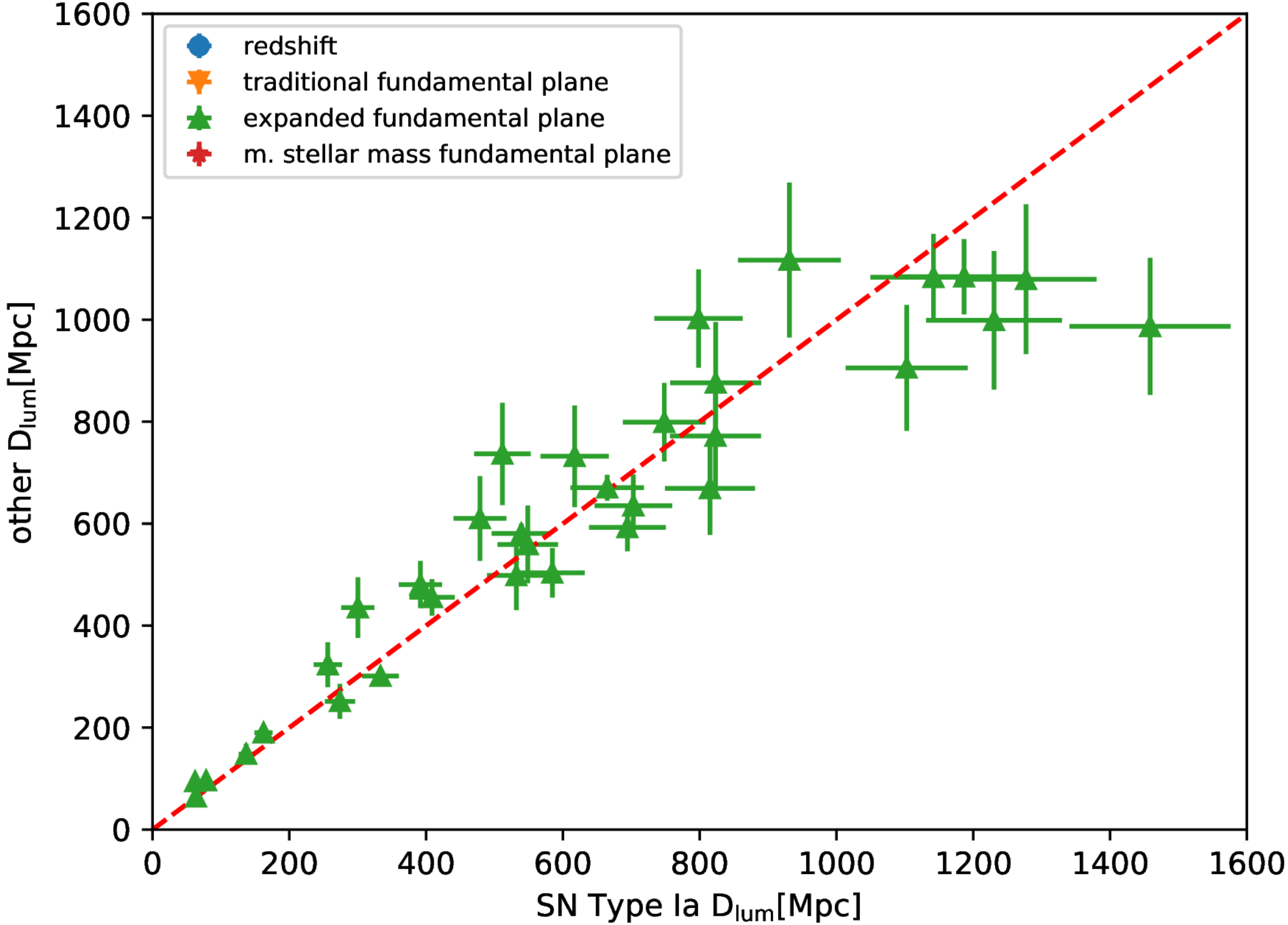
redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
0
200
400
600
800
1000
1200
1400
1600
other D_{lum}[Mpc]
SN Type Ia D_{lum}[Mpc]



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]
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]
0
200
400
600
800
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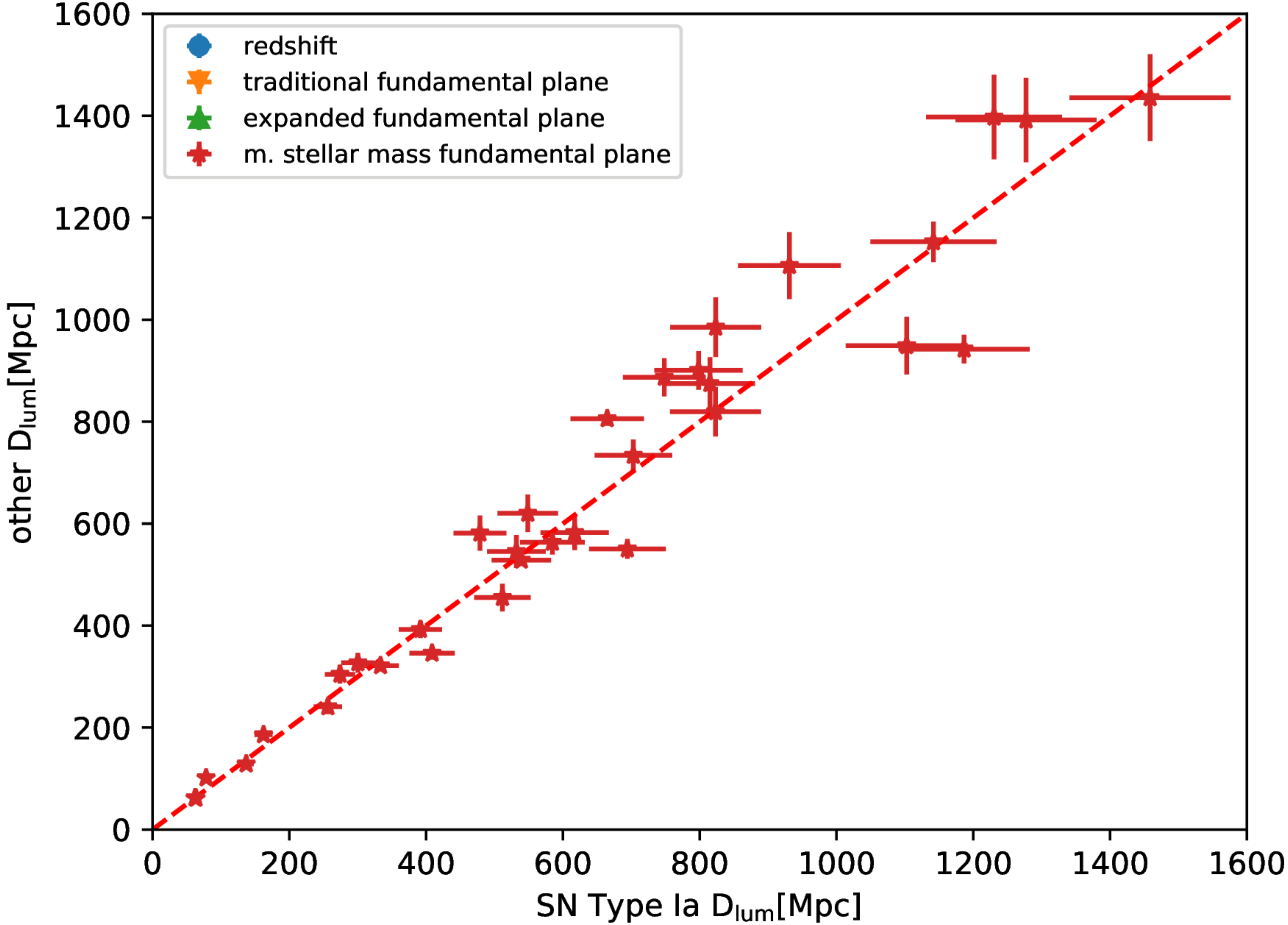
1200
1400
1600



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expanded fundamental plane
m. stellar mass fundamental plane
other D_{lum}[Mpc]
SN Type Ia D_{lum}[Mpc]
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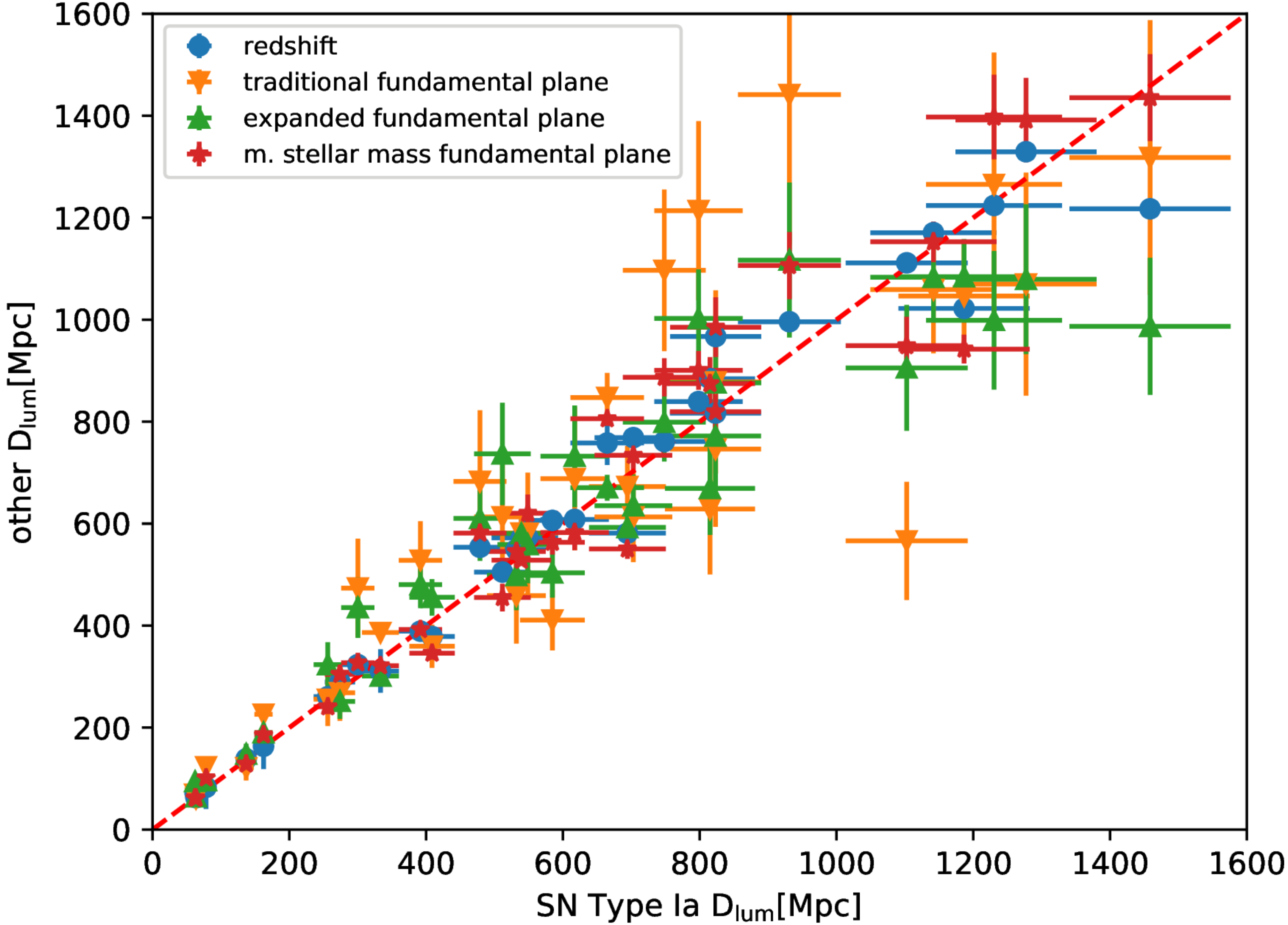


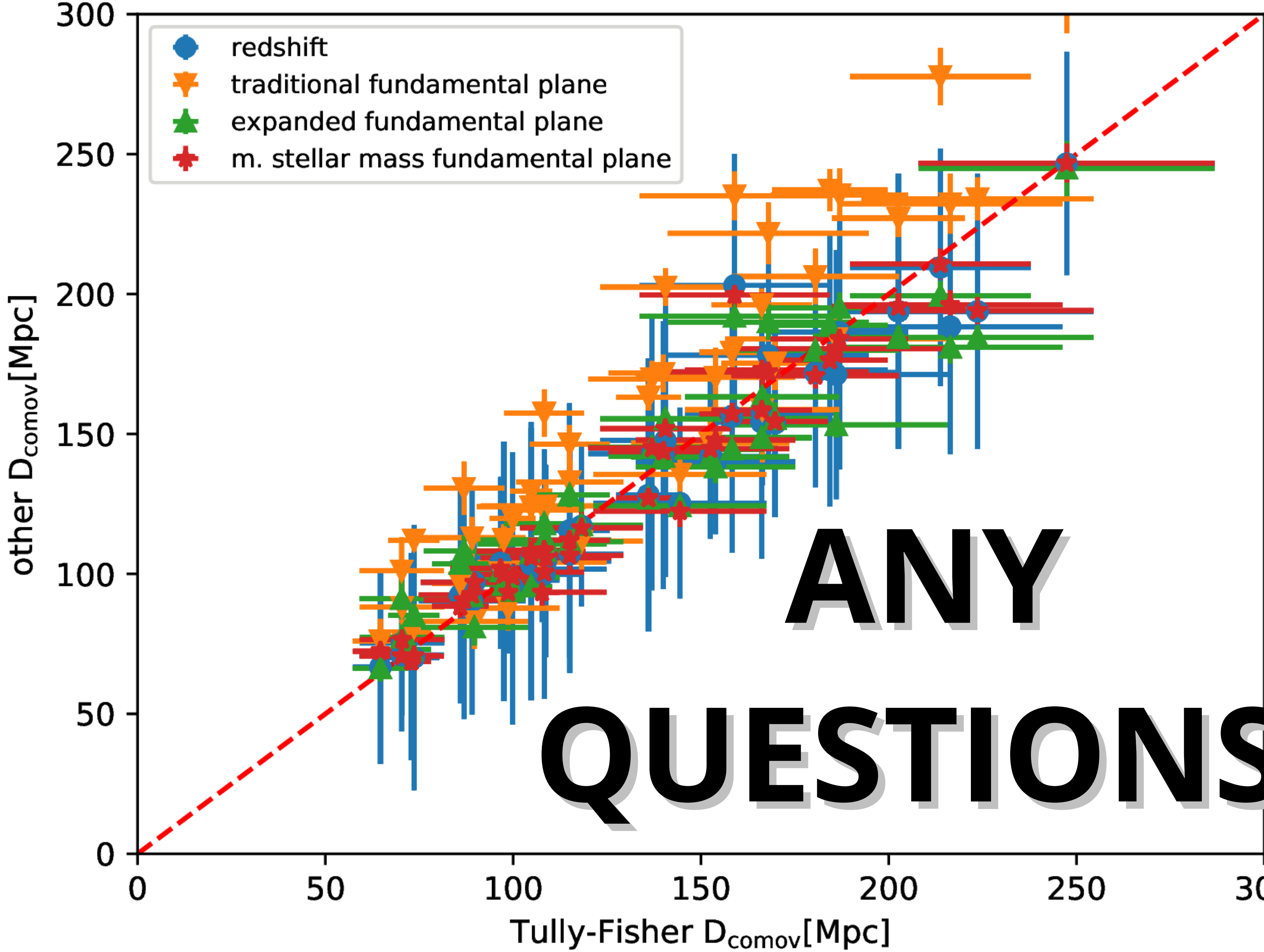
redshift
traditional fundamental plane
expanded fundamental plane
m. stellar mass fundamental plane
other D_{lum}[Mpc]
SN Type Ia D_{lum}[Mpc]
0
200
400
600
800
1000
1200
1400
1600

- Scatter SNIa-FP distances: 28.1%
- Scatter SNIa-expFP distances: 20.8%
- Scatter SNIa-mSMFP distances: 12.9%
- Scatter SNIa-redshift distances: 8.4%

- Strange offeset for expanded fundemental plane distances at higher redshifts
- Modified steller mass fundamental plane does NOT agree better with supernova type Ia distances (in contrast to TF and CF3)

Summary

- Group catalogue covering ~1 500 000 galaxies
- ~320 000 fundamental plane distances
- Covering the entire SDSS spectroscopic footprint as far as a redshift of 0.5
- Various fundamental plane calibrations with different biases
- Comparison to Tully-Fisher relation, CosmicFlows-3, and Supernova Type Ia distances
- Presented in Saulder+, submitted



ANY QUESTIONS?