Measuring peculiar motions in the local universe

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Collaborators

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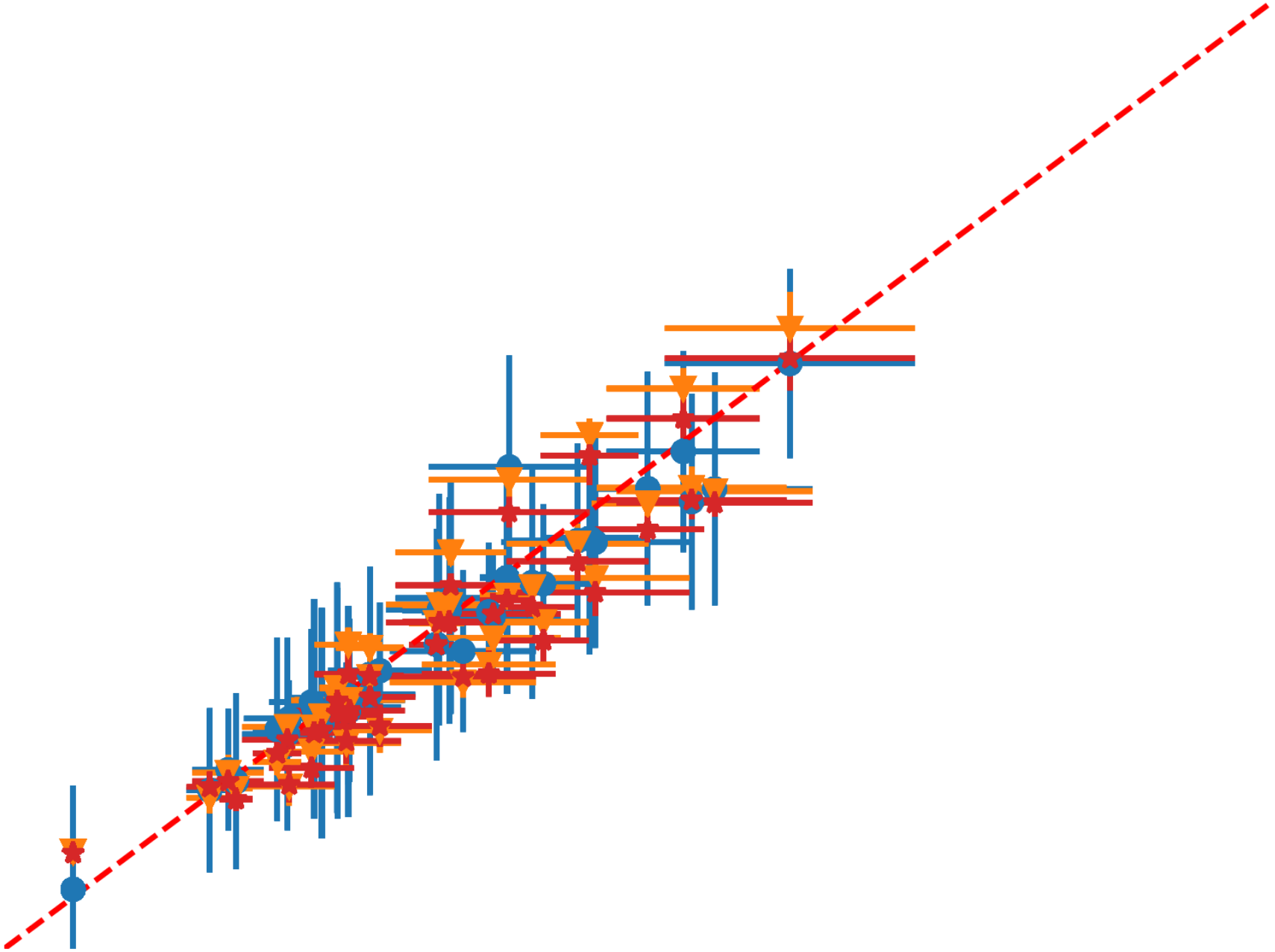
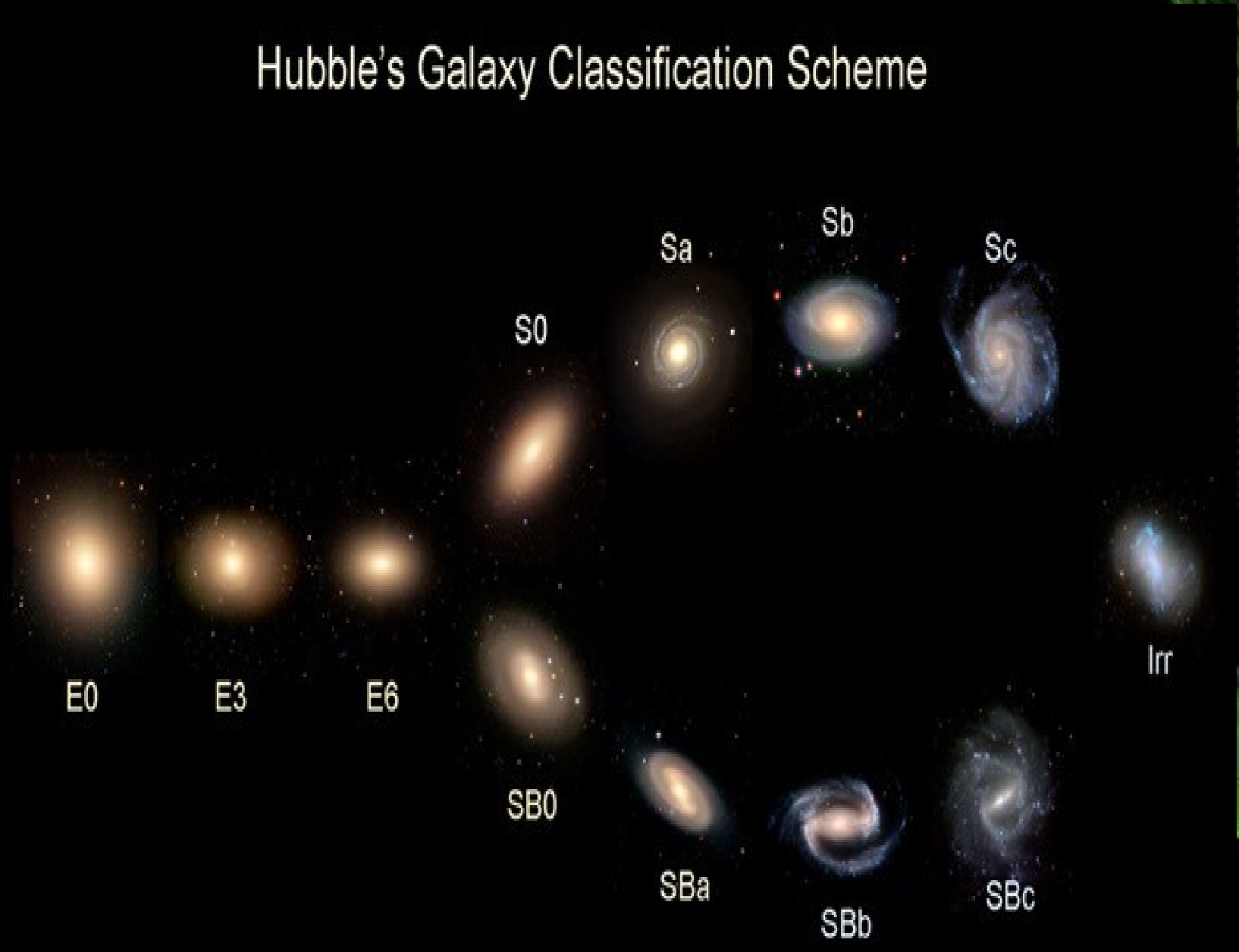
THE UNIVERSITY OF QUEENSLAND AUSTRALIA

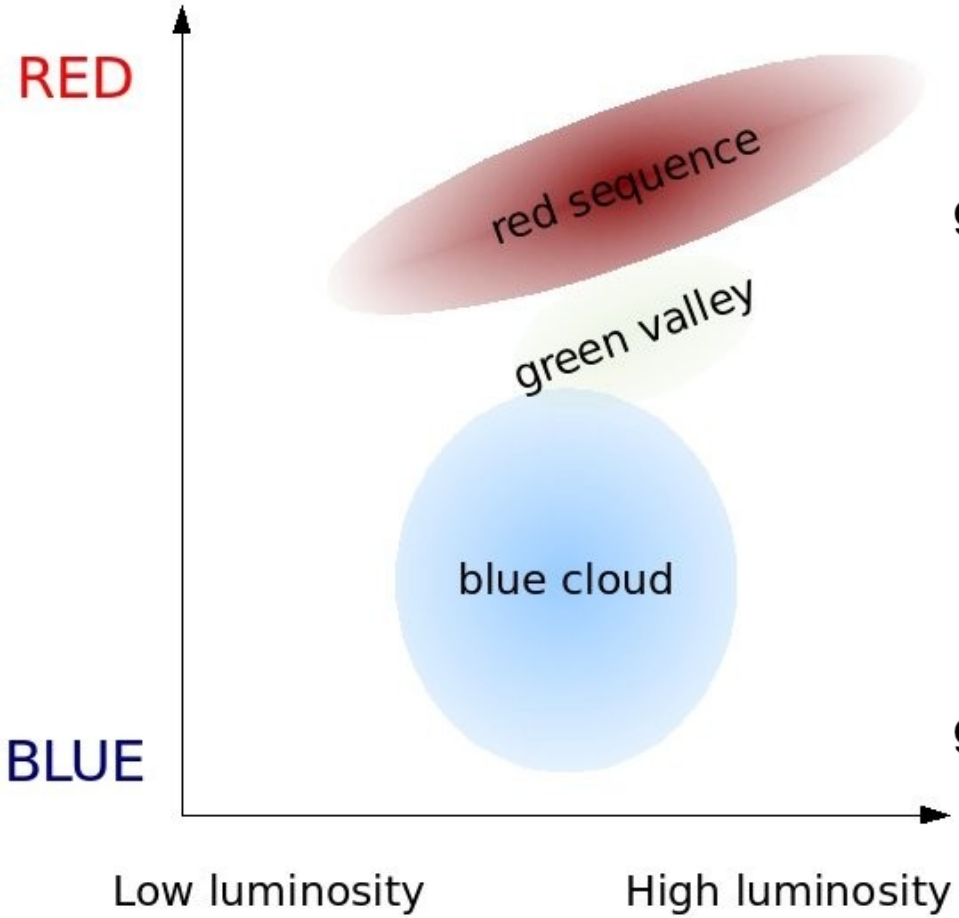


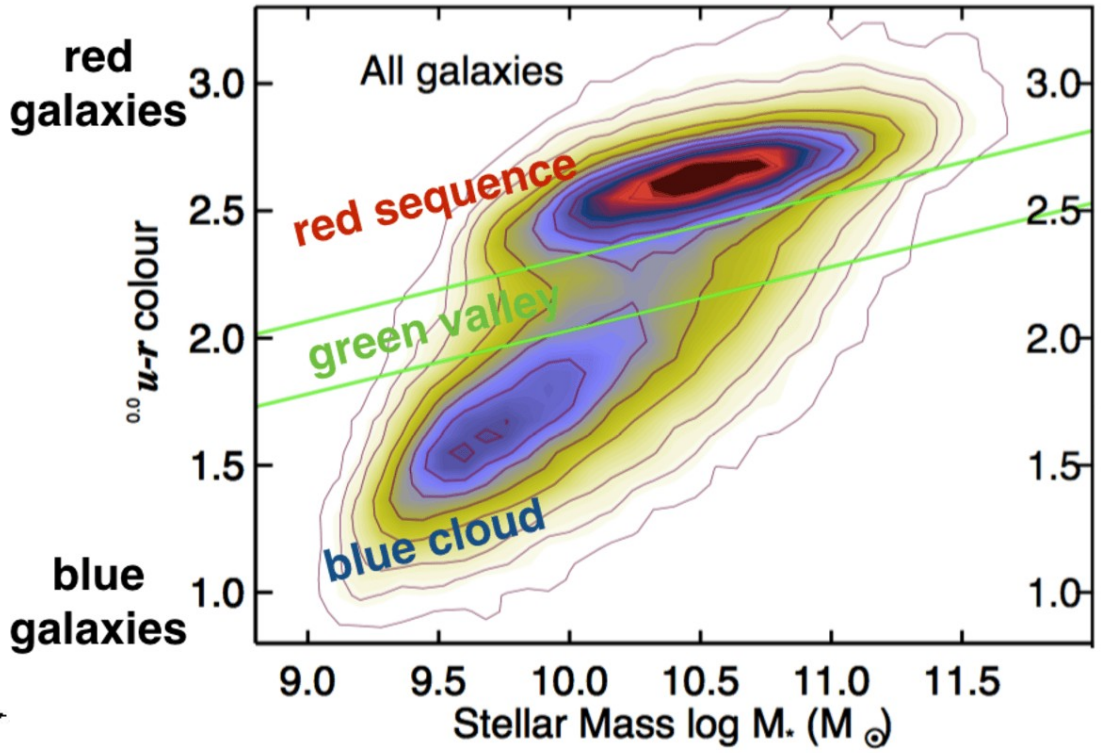
Galaxy Morphology



Colour-magnitude diagram of galaxies

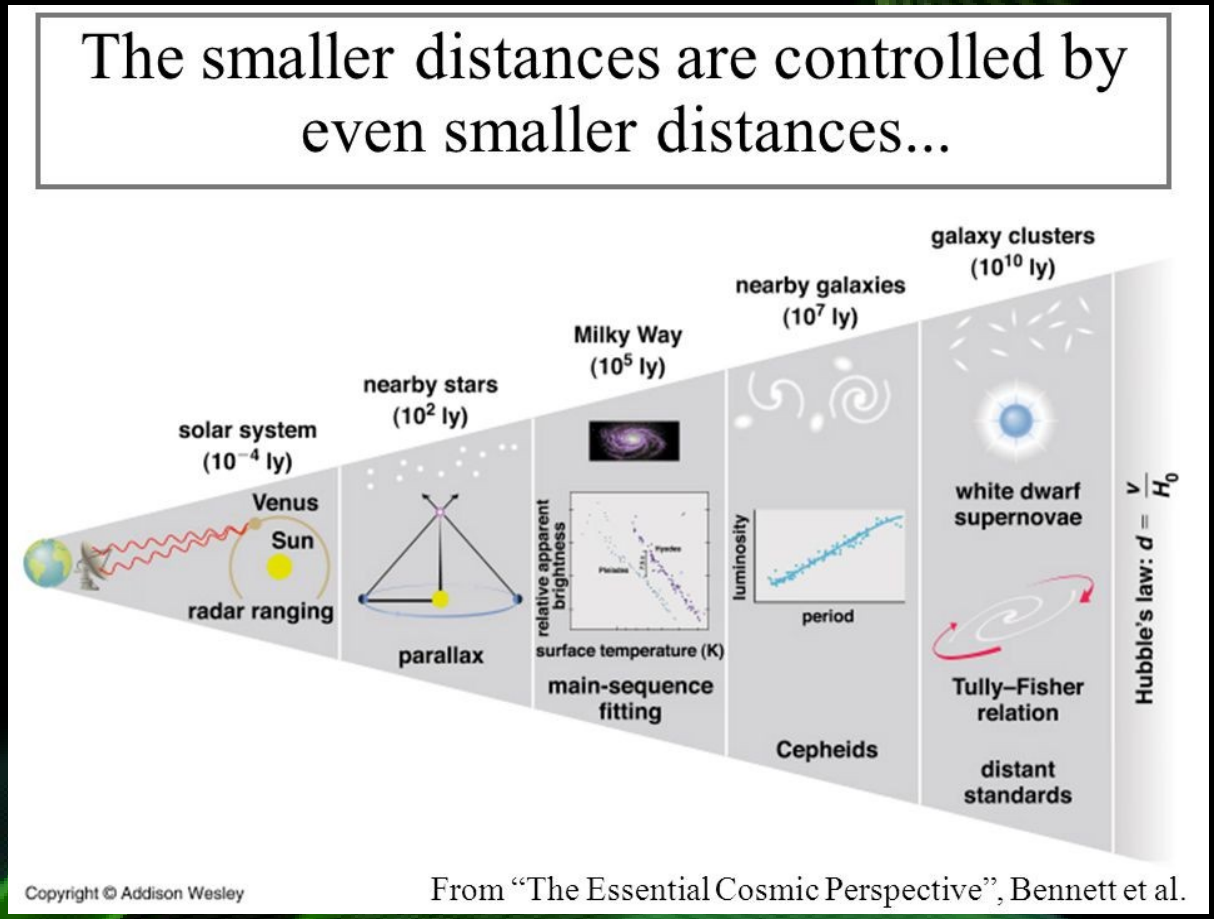
- Red sequence ~ early-type galaxies
- Blue cloud ~ late-type galaxies





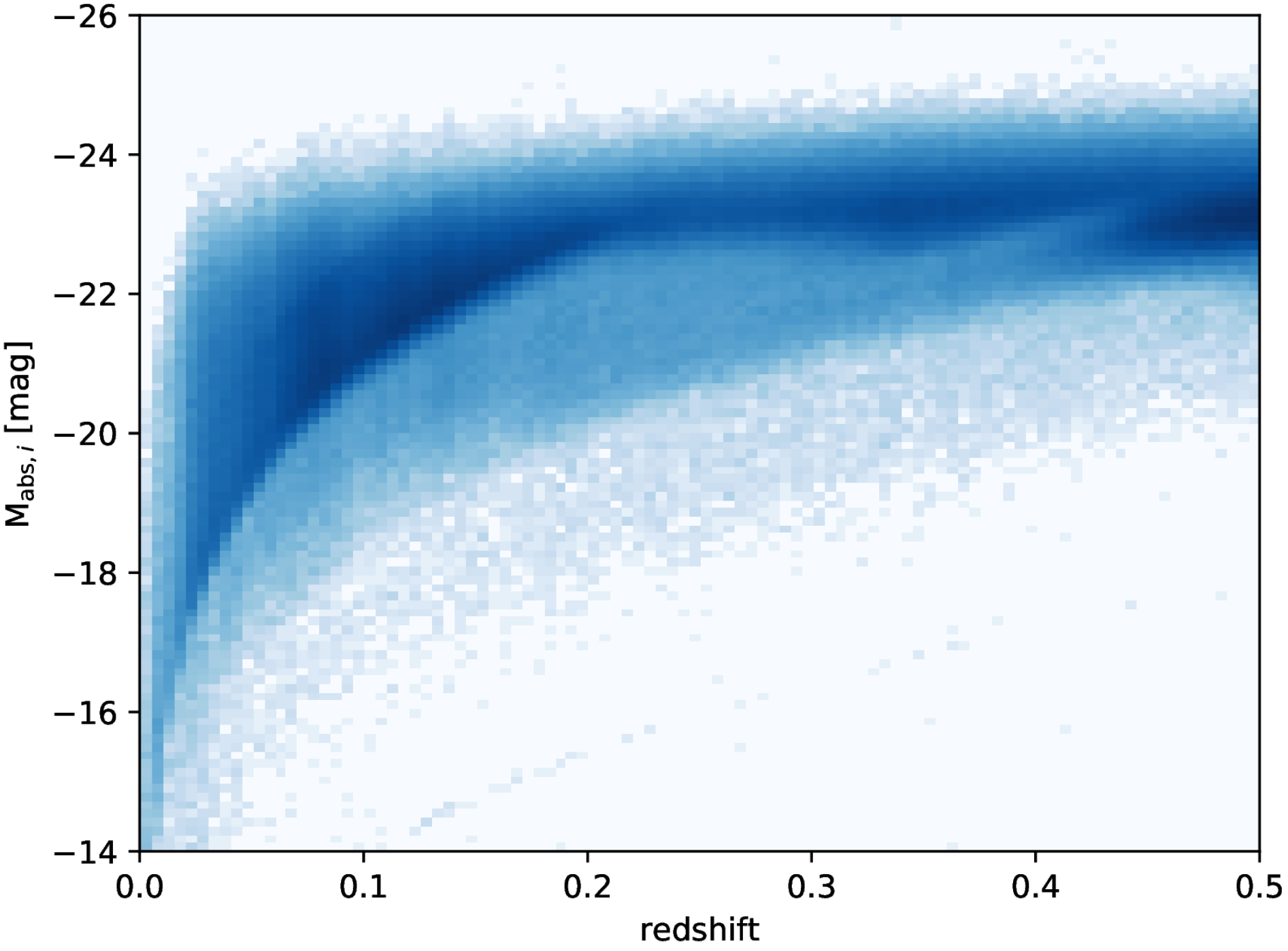
Cosmic distance ladder

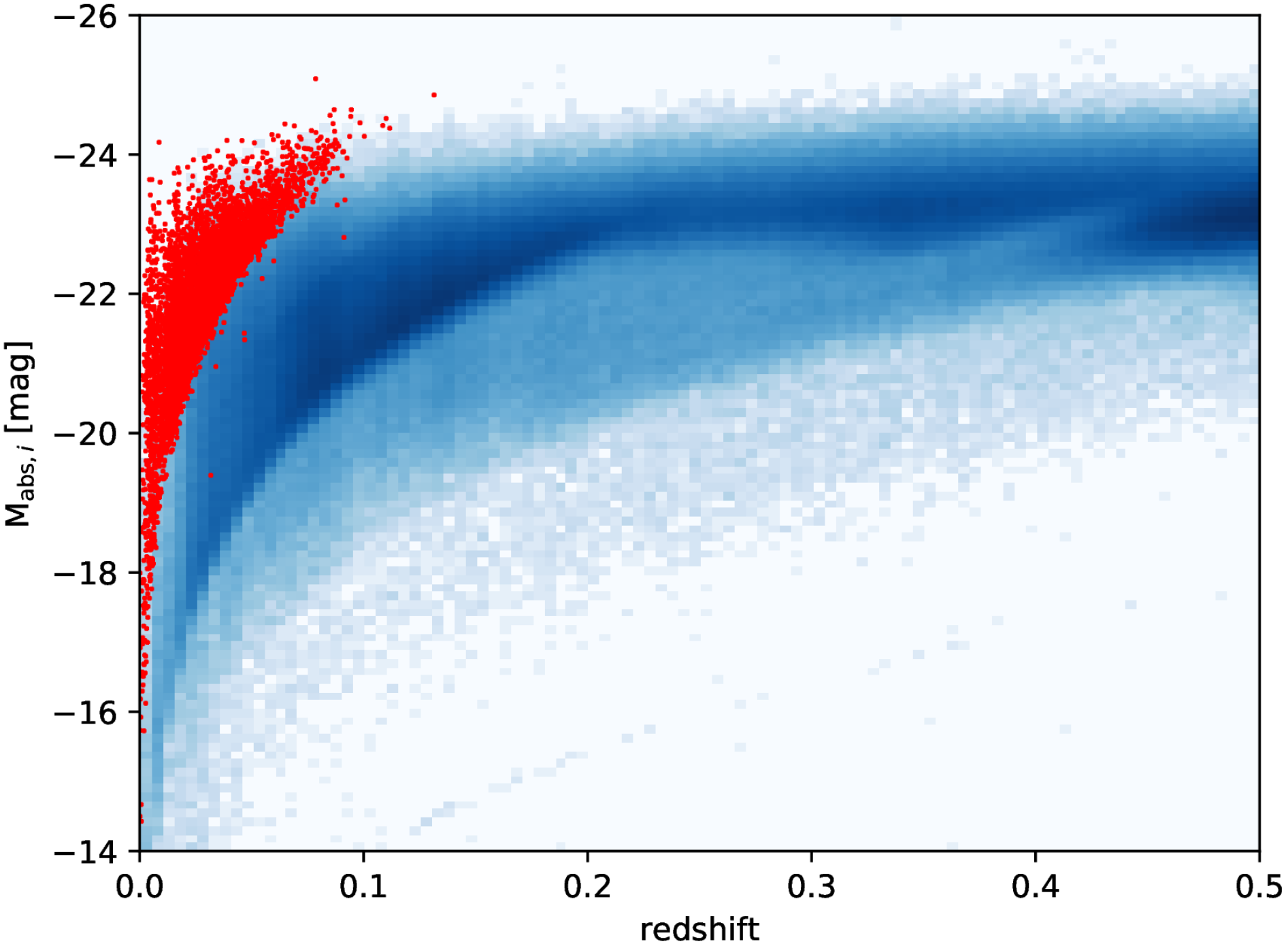
- Standard candles
  - Cepheids
  - Supernovae type Ia
  - ...
- Standard sirens
- Scaling relations
  - Fundamental plane
  - Tully-Fisher relation
  - S_k-relation (?)
  - Tip of the red-giant branch
  - Surface brightness fluctuations
  - ...

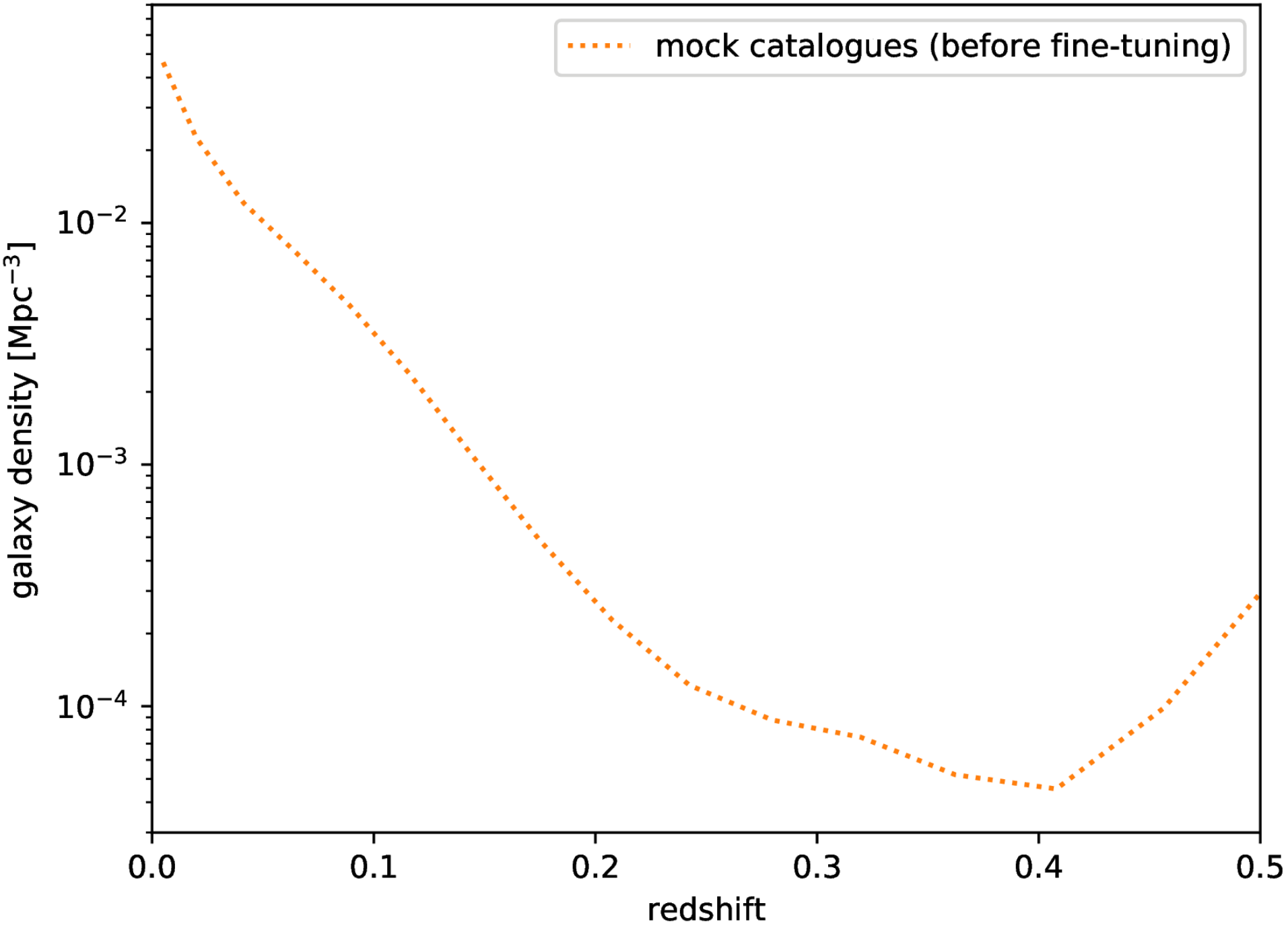


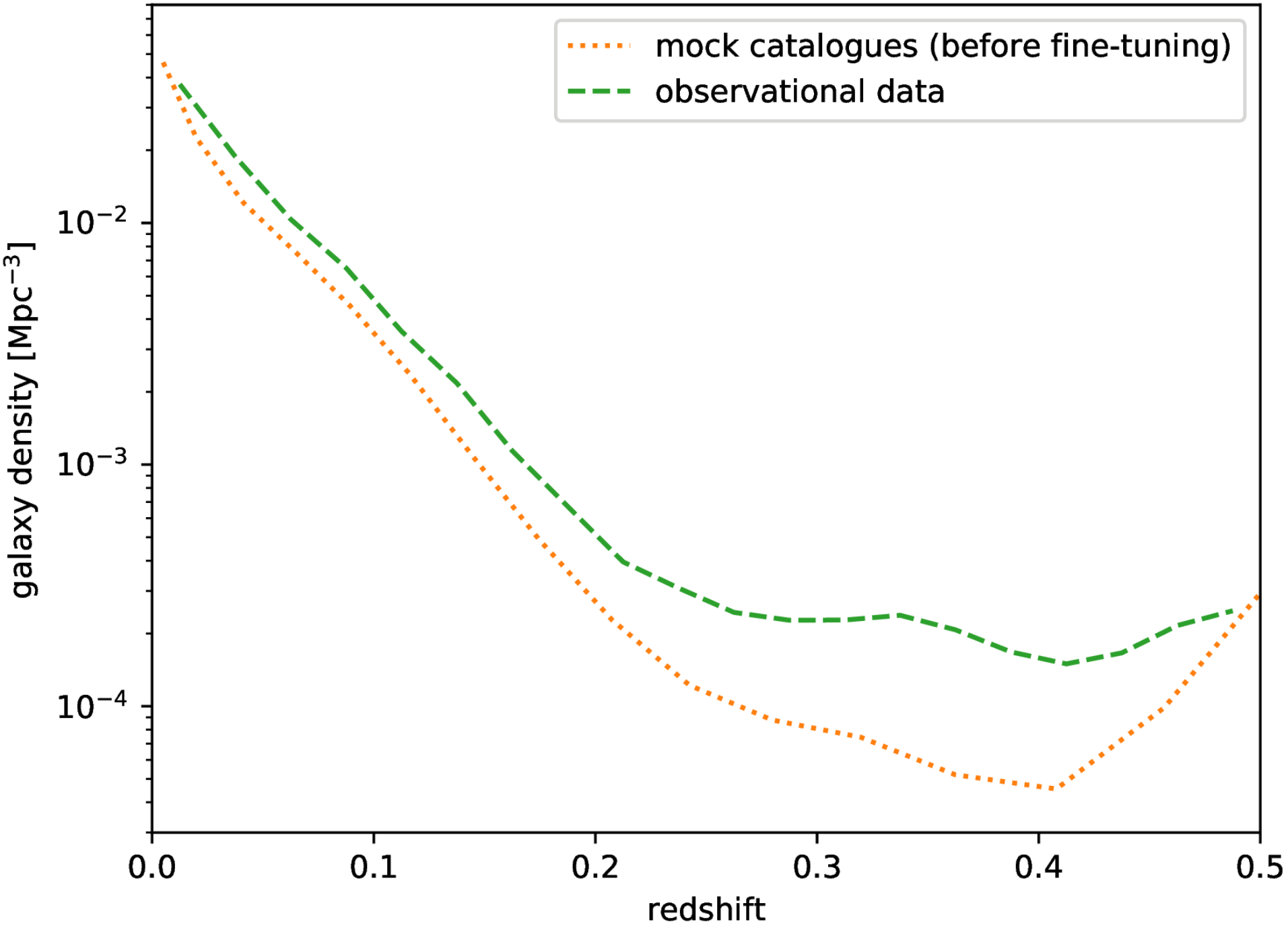
Group catalogue

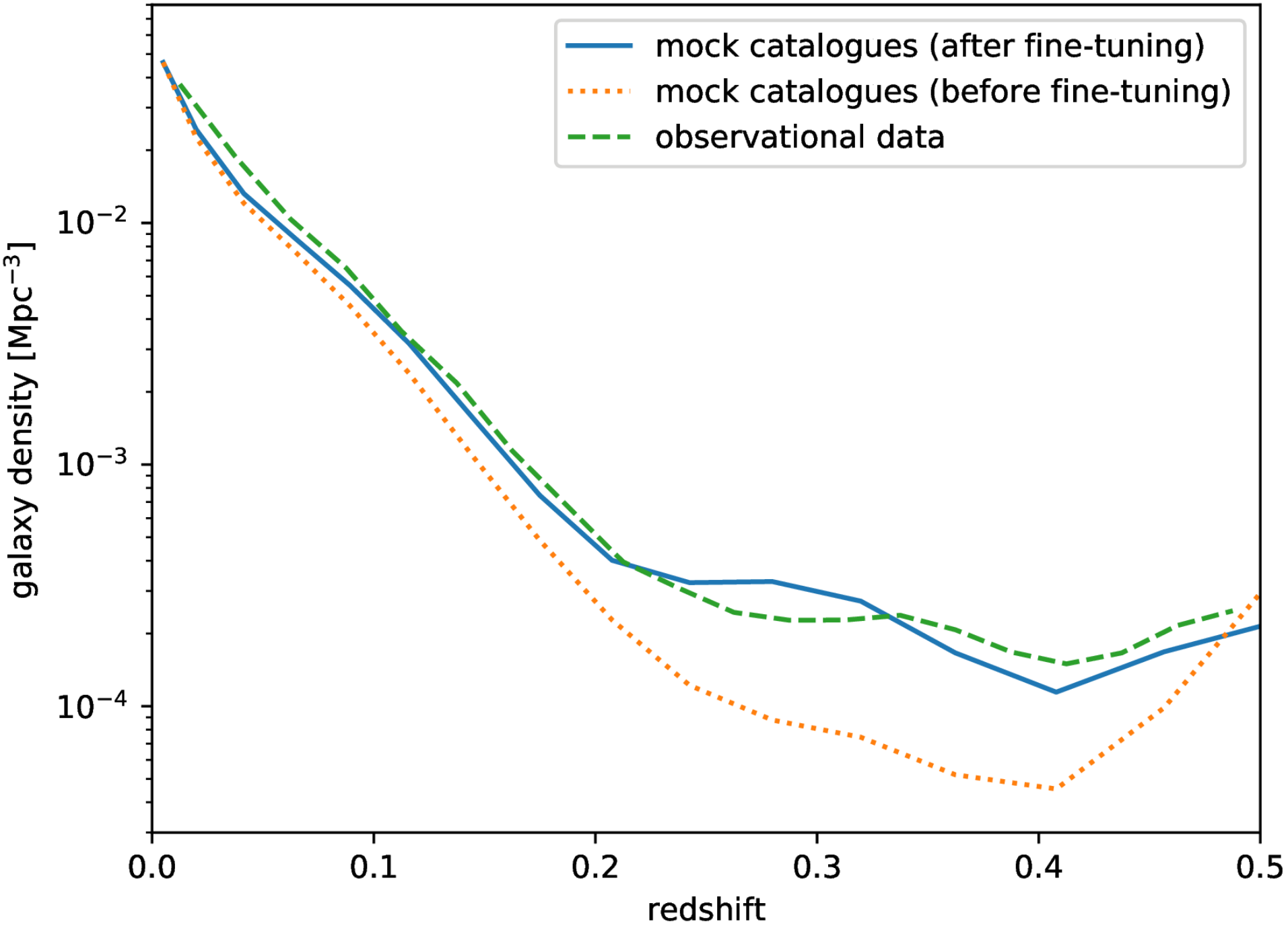
- Improving our special purpose group catalogue from Saulder+2016 and expanding it beyond z=0.1
- SDSS DR15
  - SDSS spectroscopic footprint (9 376 square degree)
  - Redshift up to z=0.5
- 2MRS (2MASS Redshift Survey)
  - Within the SDSS coverage
  - Compensate for the saturation bias of the SDSS main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

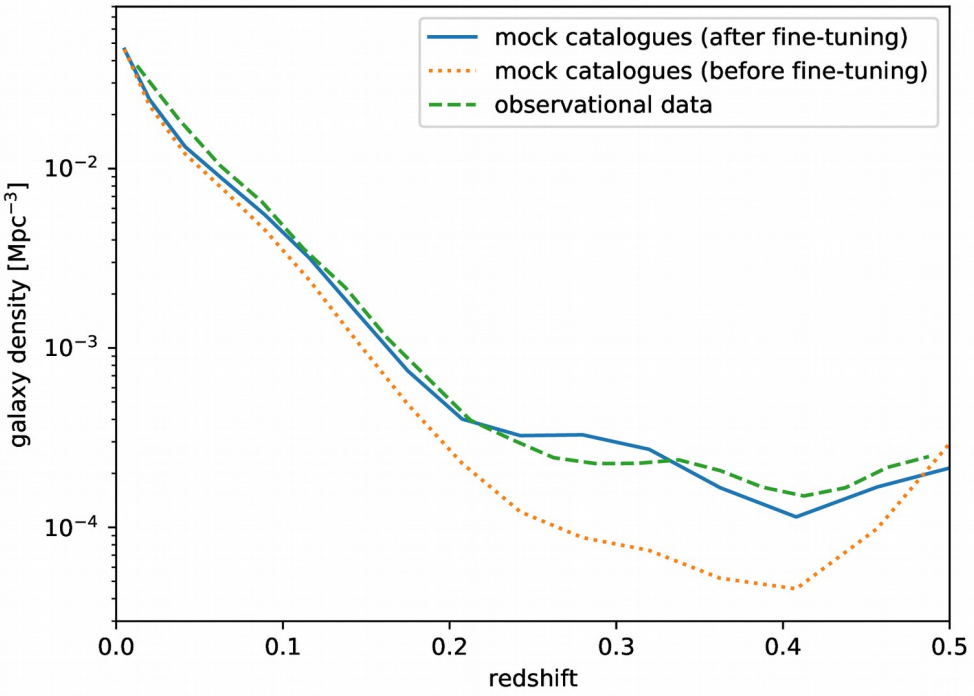

−26
−24
−22
−20
−18
−16
−14
$M_{abs,i}$ [mag]
0.0
0.1
0.2
0.3
0.4
0.5
redshift

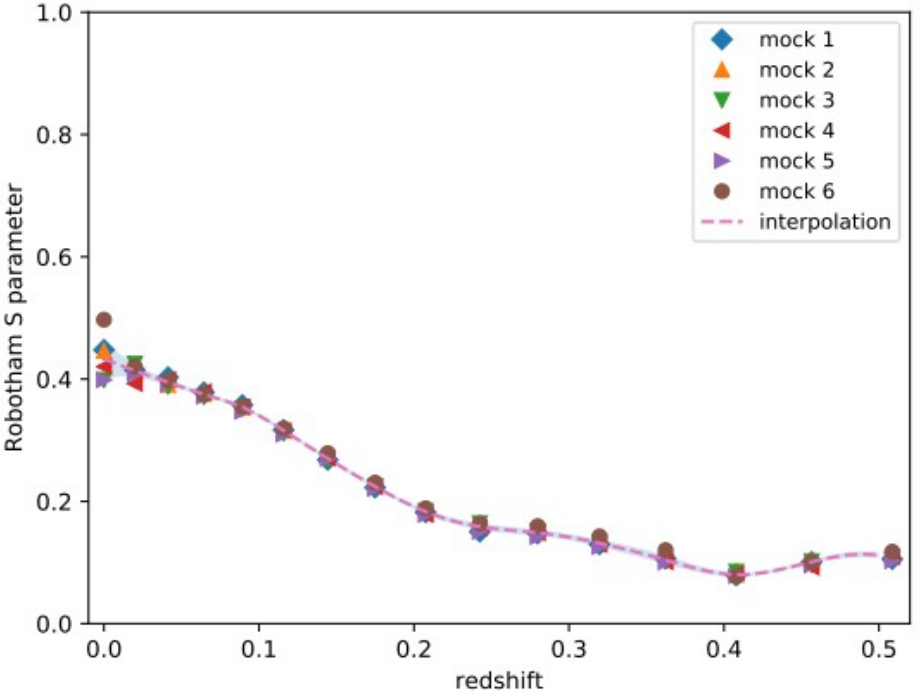

−26
−24
−22
−20
−18
−16
−14
$M_{abs,i}$ [mag]
0.0
0.1
0.2
0.3
0.4
0.5
redshift

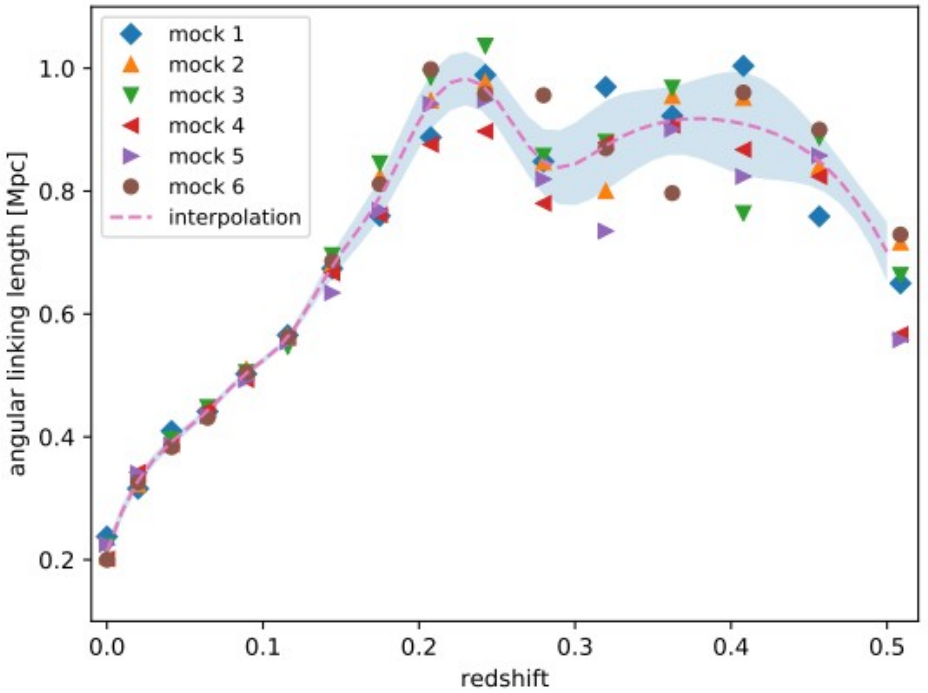

mock catalogues (before fine-tuning)
galaxy density [Mpc^{-3}]
10^{-2}
10^{-3}
10^{-4}
0.0
0.1
0.2
0.3
0.4
0.5
redshift

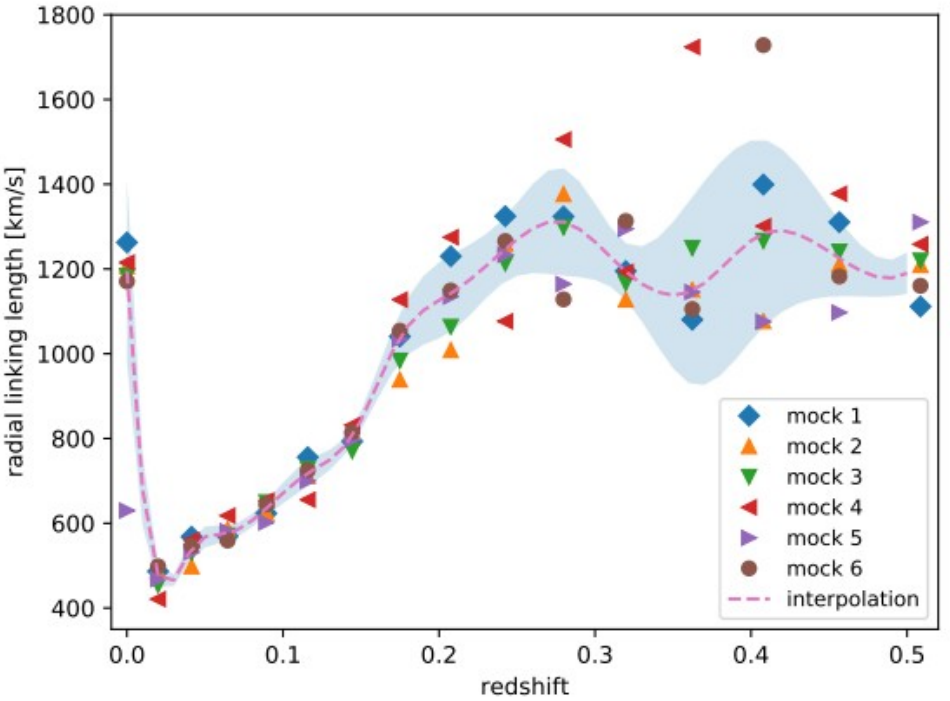

mock catalogues (before fine-tuning)
observational data
galaxy density [Mpc^{-3}]
10^{-2}
10^{-3}
10^{-4}
0.0
0.1
0.2
0.3
0.4
0.5
redshift


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 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

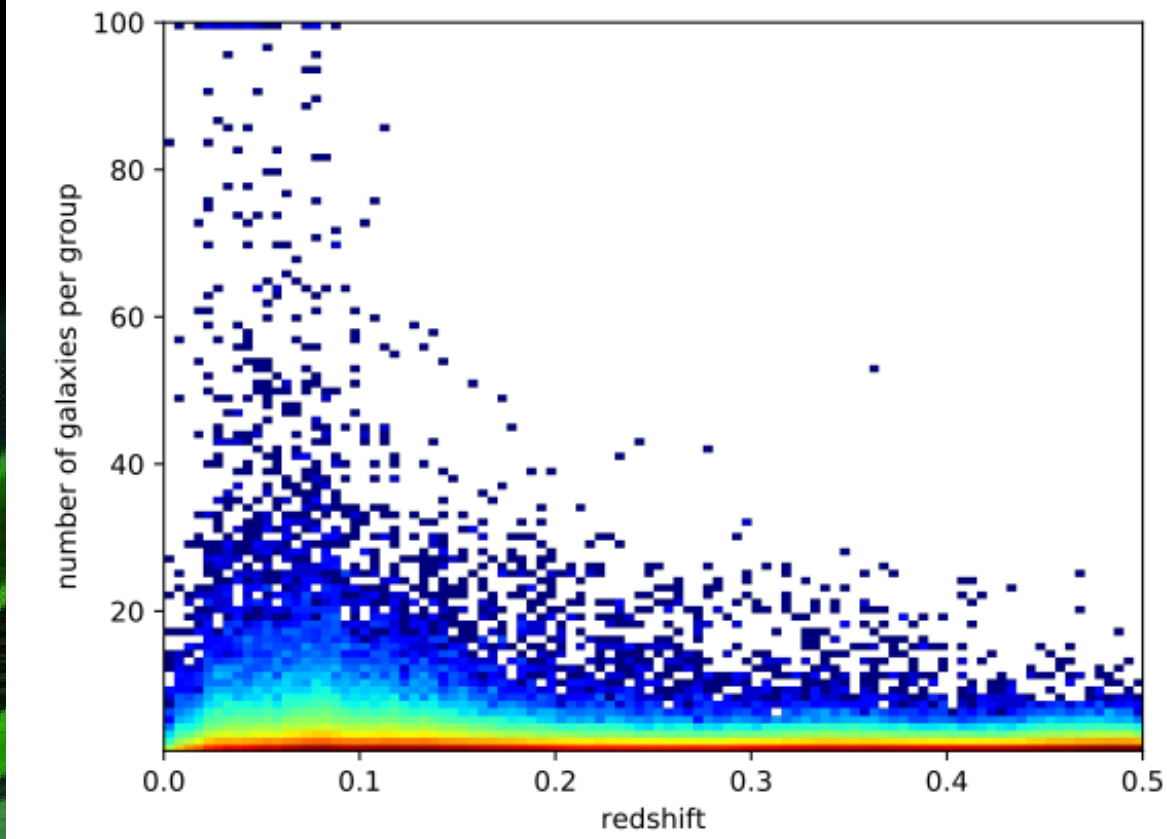

mock 1
mock 2
mock 3
mock 4
mock 5
mock 6
interpolation
Robotham S parameter
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
redshift


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

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)

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

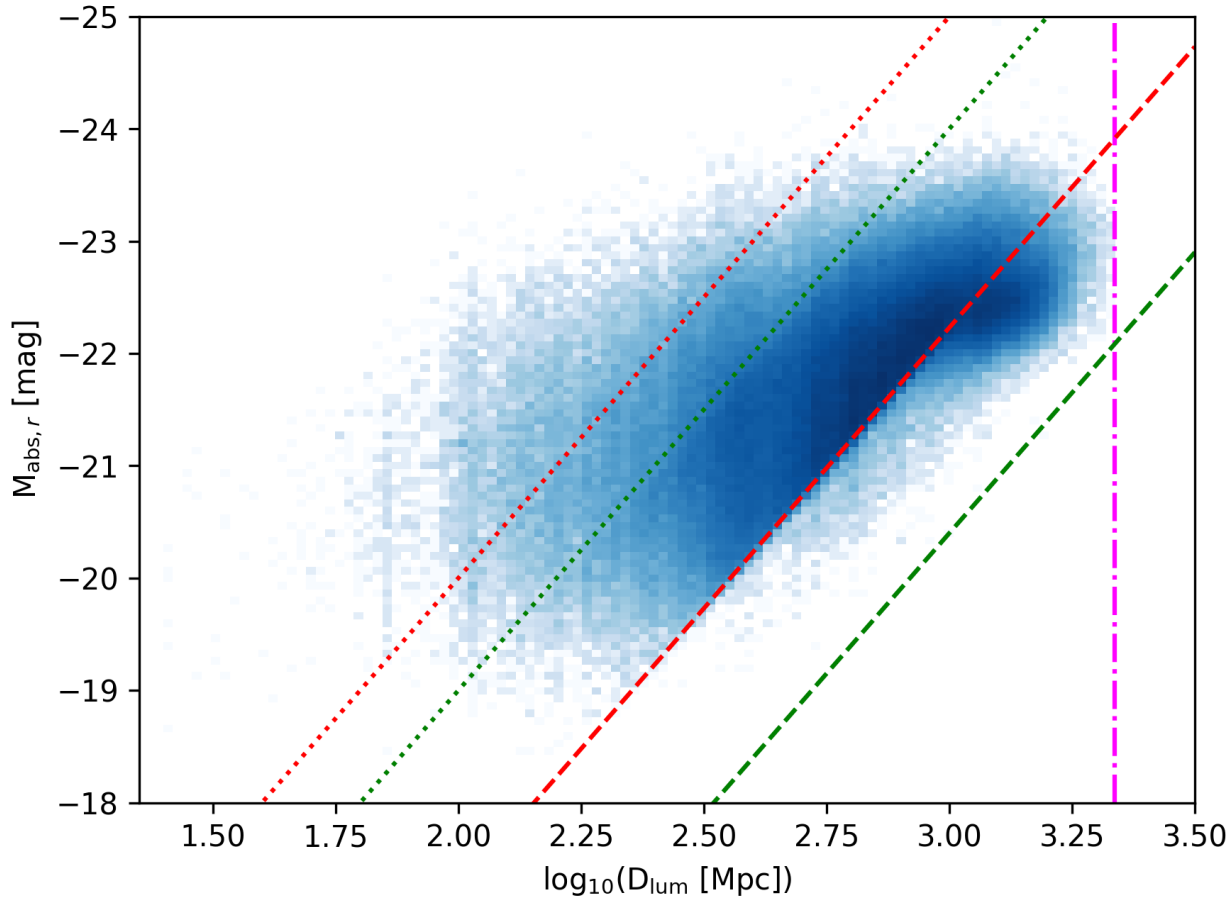
- Standard rod for early-type galaxies
  → comparing observed sizes with predicted sizes
  → angular diameter distances

- 320 309 suitable early-type galaxies in SDSS DR15
  largest dataset every used for the fundamental plane

Sample selection

- Higher likelihood for de Vaucouleurs profile than exponential profile
- Colour cuts
- σ > 100km/s
- Quality controls
- Outlier removal

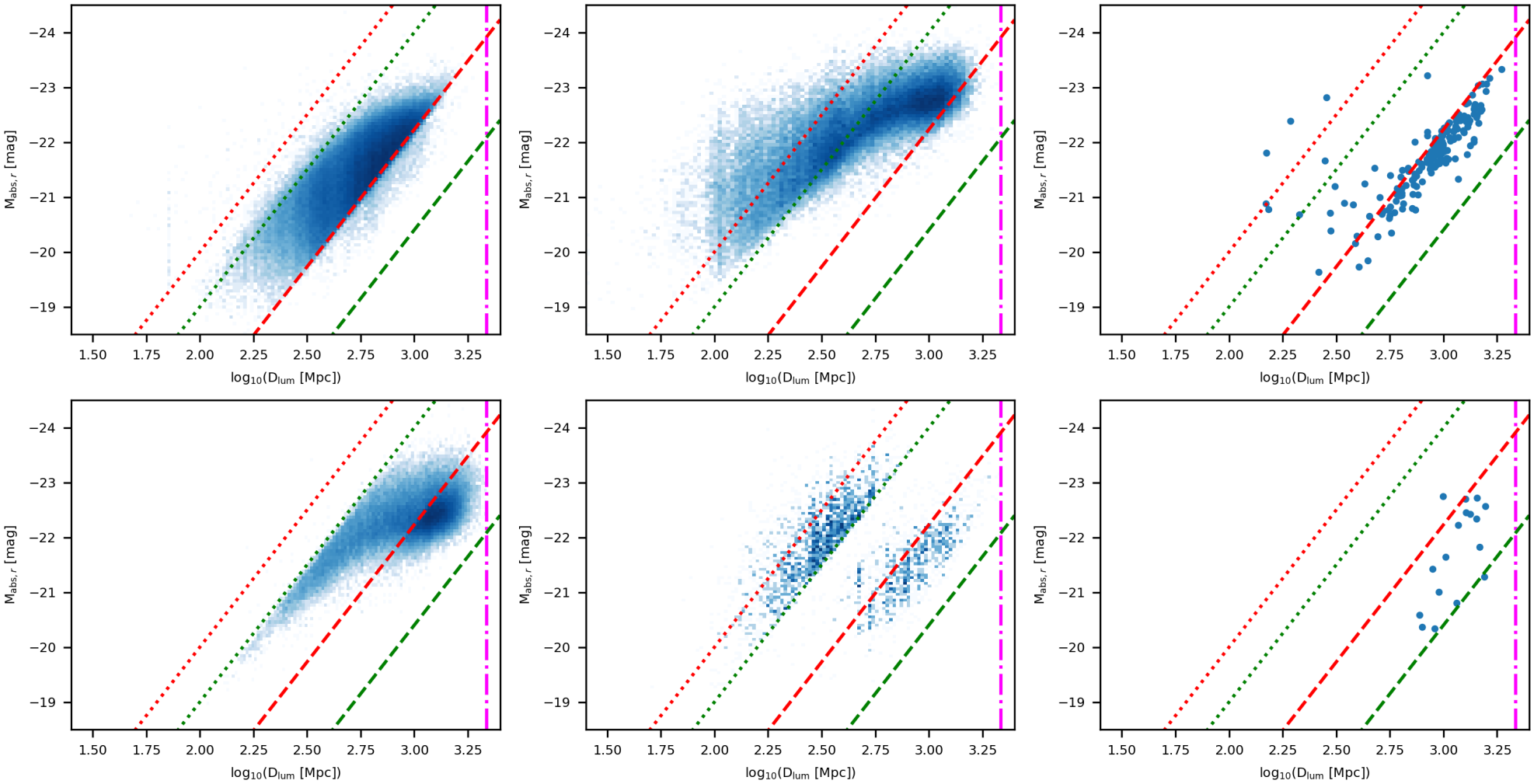
- 320 298 ETGs in SDSS/BOSS



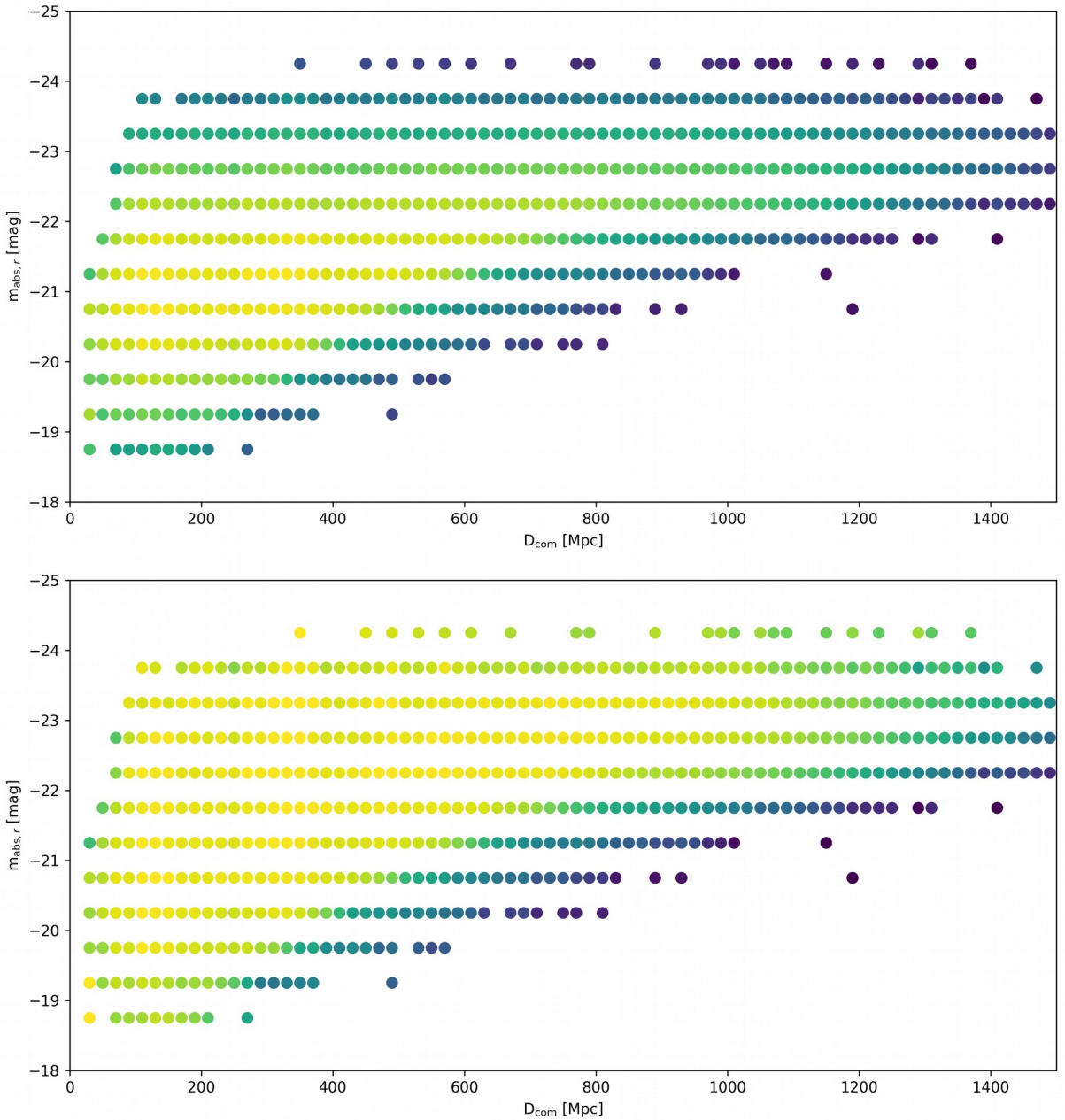
Preparing for the fundamental plane

- Applying basic calibrations and corrections to all the data retrieved from SDSS:
- Corrections for galactic extinction (Schlegel+ 1998)
- K-corrections (Chilingarian+ 2010)
- Evolution corrections for magnitudes (our own based on Bernardi+ 2003), sizes and velocity dispersions (Beifiori+ 2014)
- Correction for Tolman-effect on surface brightnesses
- Corrections for fixed fibre sizes (Jorgensen+ 1995, Wegner+ 1999
- Calculating the fundamental plane parameters:
- R_e, σ_0, and μ_e

Subsets of our ETG sample



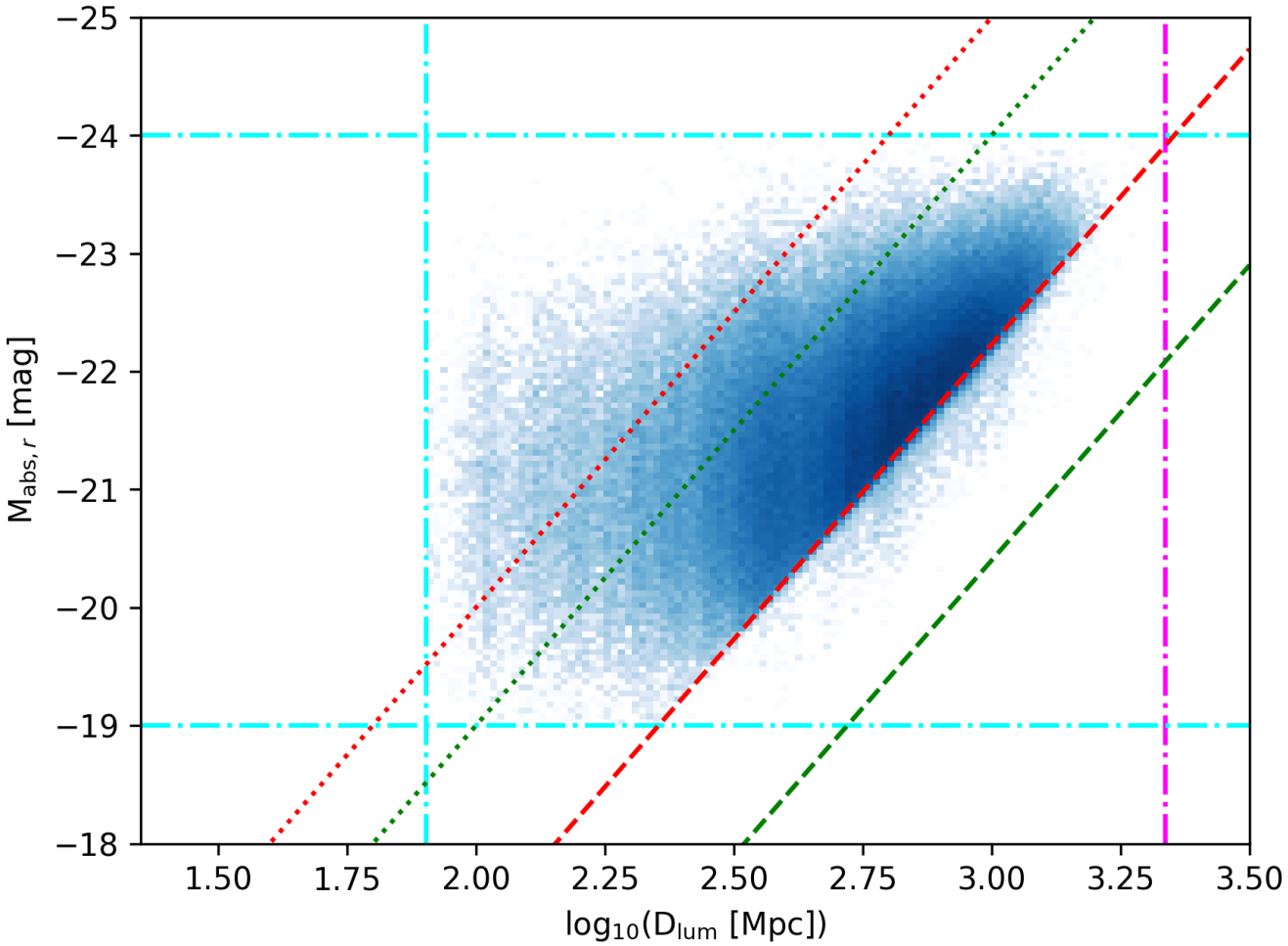
Density and completeness



Calibration sample

- Well-defined subsample based on the SDSS main galaxy sample with additional cuts
- 242 254

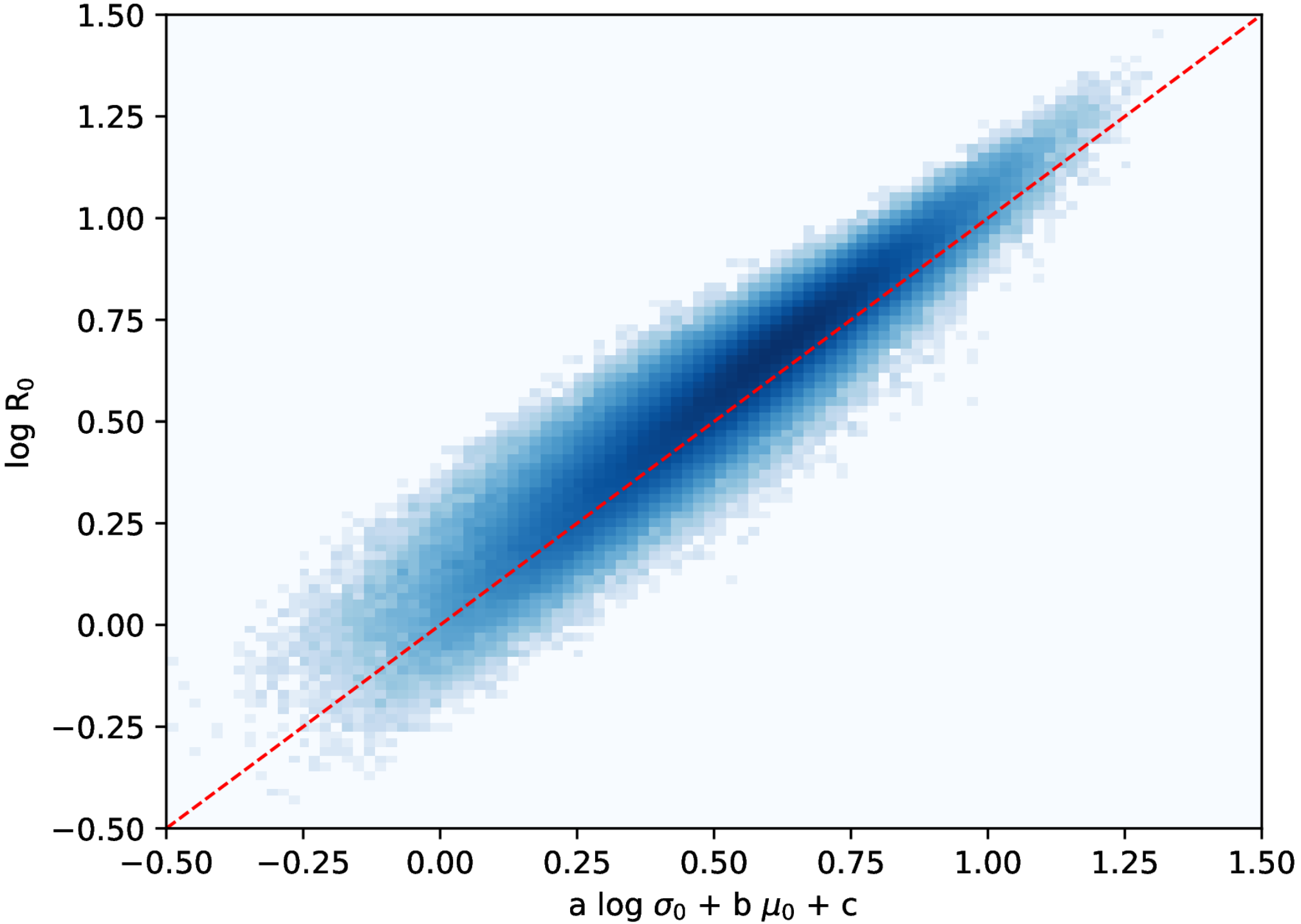
  ETGs



- Using the best method for distance calibrations:
- Direct fit (minimizing the scatter in radii (Sheth&Bernardi 2013)) using least squares
- Volume-weights to adjust for the Malmquist bias
- → fundamental plane coefficients

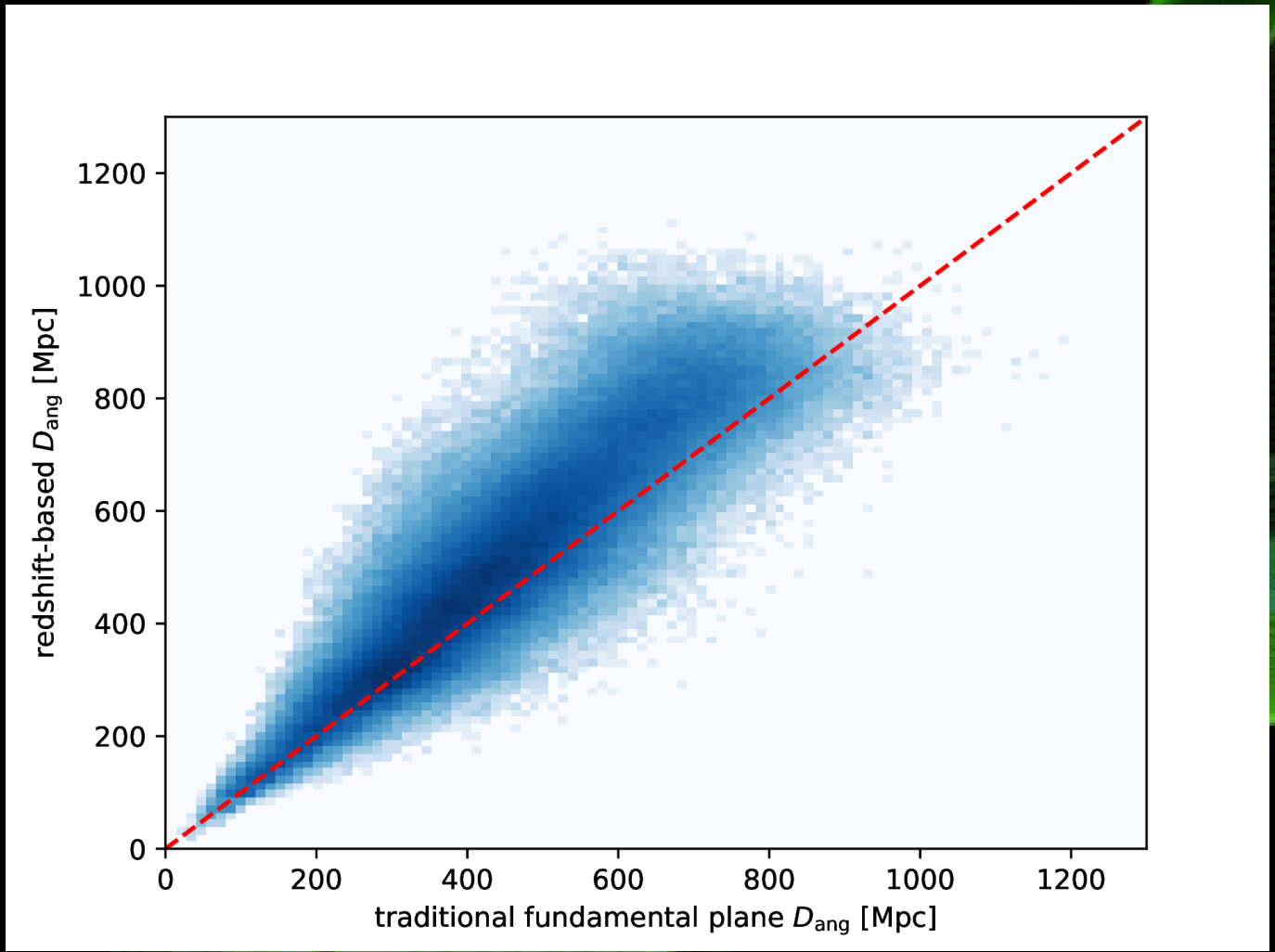
- Applying the coefficients for the entire sample

- Distance accuracy: 20%
- Group catalogue improves it to 18.7%
- 0.2% of it is systematic redshift-dependent bias


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 20.0% without the group catalogue
- Scatter of 18.7% with the group catalogue



Expanded fundamental planes

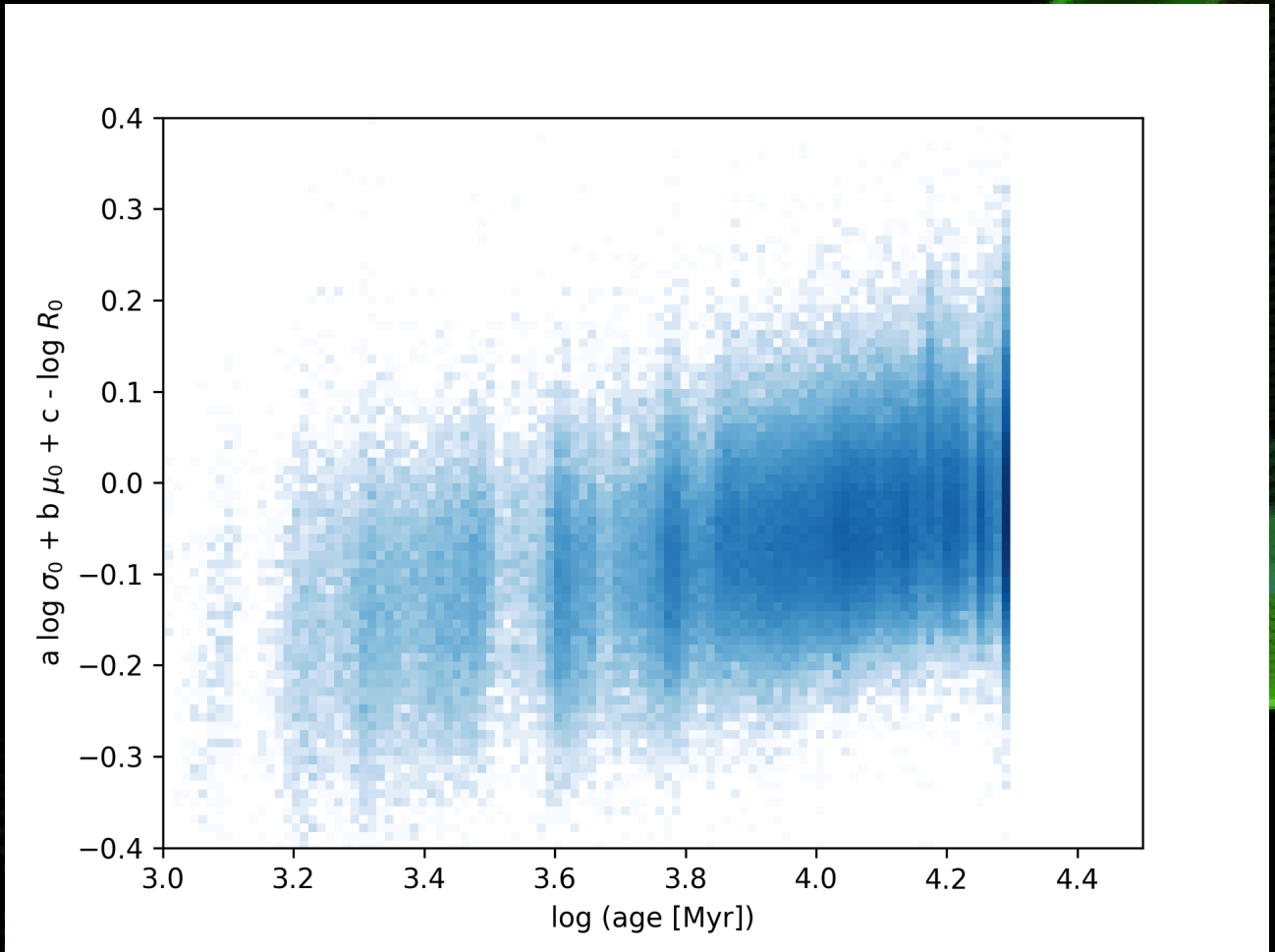
- Additional parameters may contribute to the scatter of the fundamental plane
- Independent parameters are hard to find
- Stellar age the most promising candidate (motivation from both observations (VandeSande+ 2018) and simulations (Lu+ 2019))
- Using the stellar age t_* obtained from simple stellar population models by Chiligarian+ 2016

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

- Subsample of 184 203 galaxies (182 913 of them used for the calibrations)

Age dependence

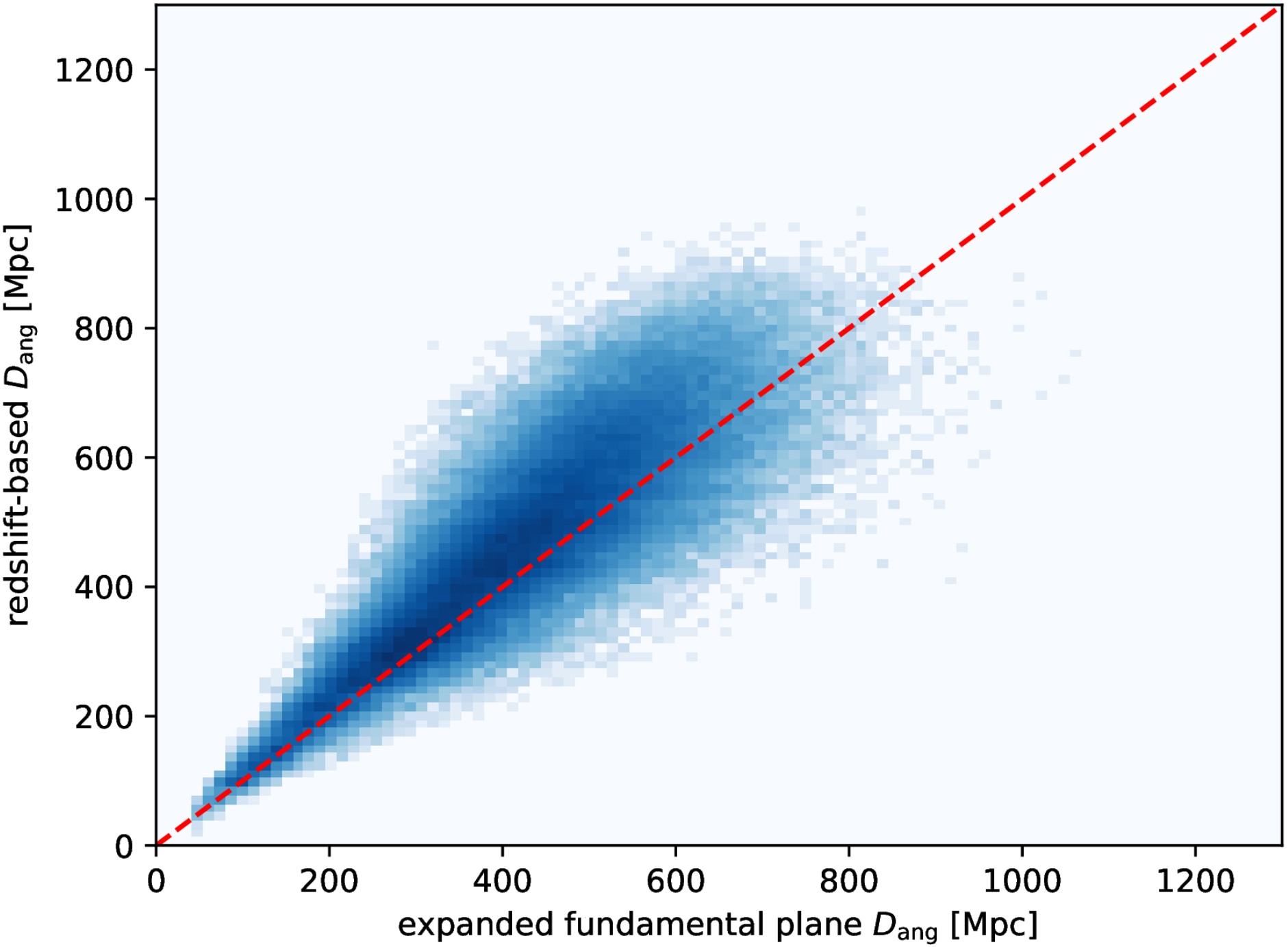
- Clear trends
- Stellar populations contribute to the scatter of the fundamental plane



Does it improve the distance estimates?

- Comparison only with the subsample (184 203 galaxies) for which we had stellar ages
- 20.2%/18.9% for the traditional fundamental plane
- 18.8%/17.5% for the expanded fundamental plane

- Marginal improvement, but we still have to test how it effects the biases
- For fair comparison: recalibrate the traditional fundamental plane for the same dataset and only use those galaxies.

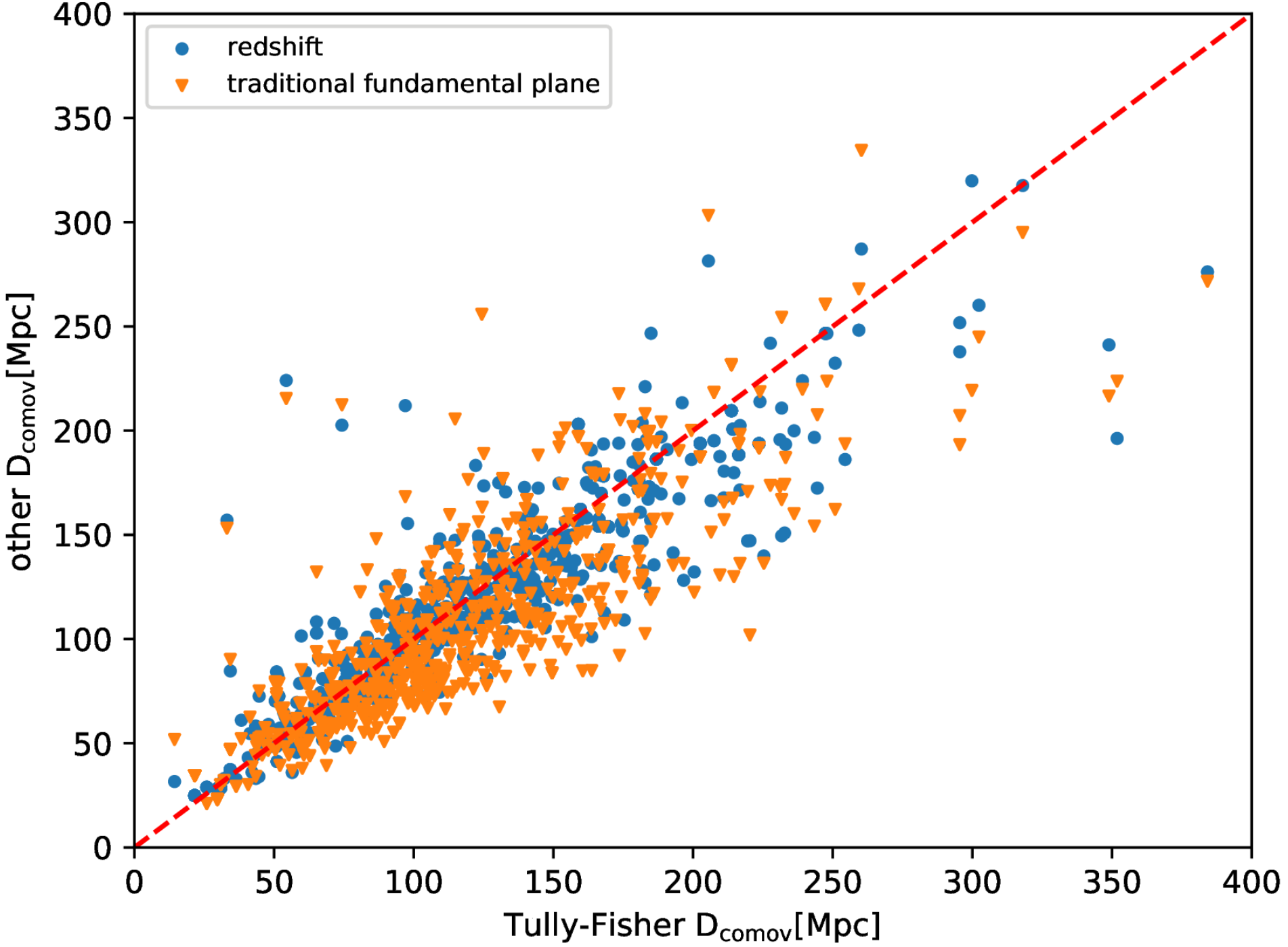

redshift-based D_{ang} [Mpc]
expanded fundamental plane D_{ang} [Mpc]
0
200
400
600
800
1000
1200

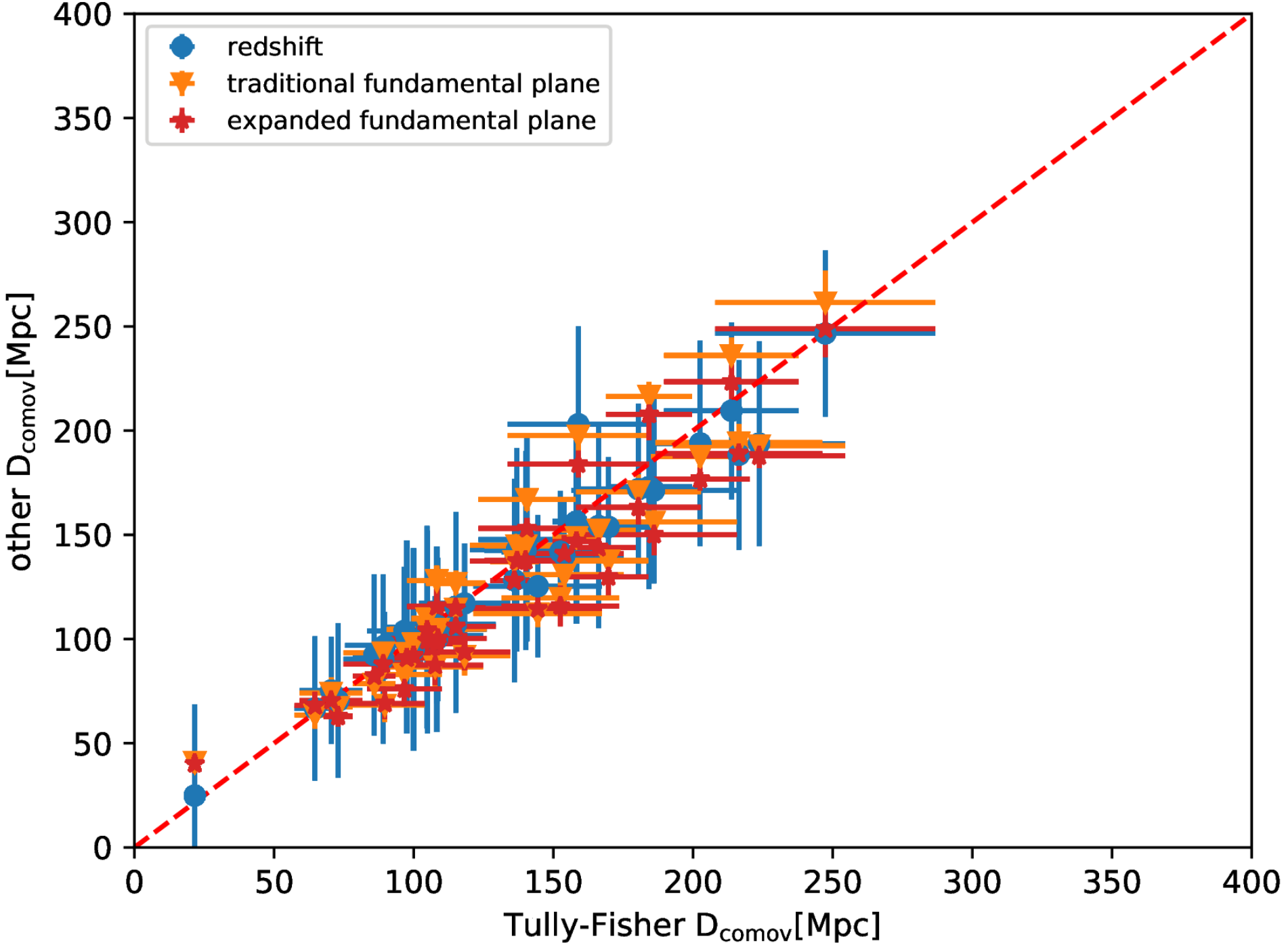
Comparison to the Tully-Fisher relation

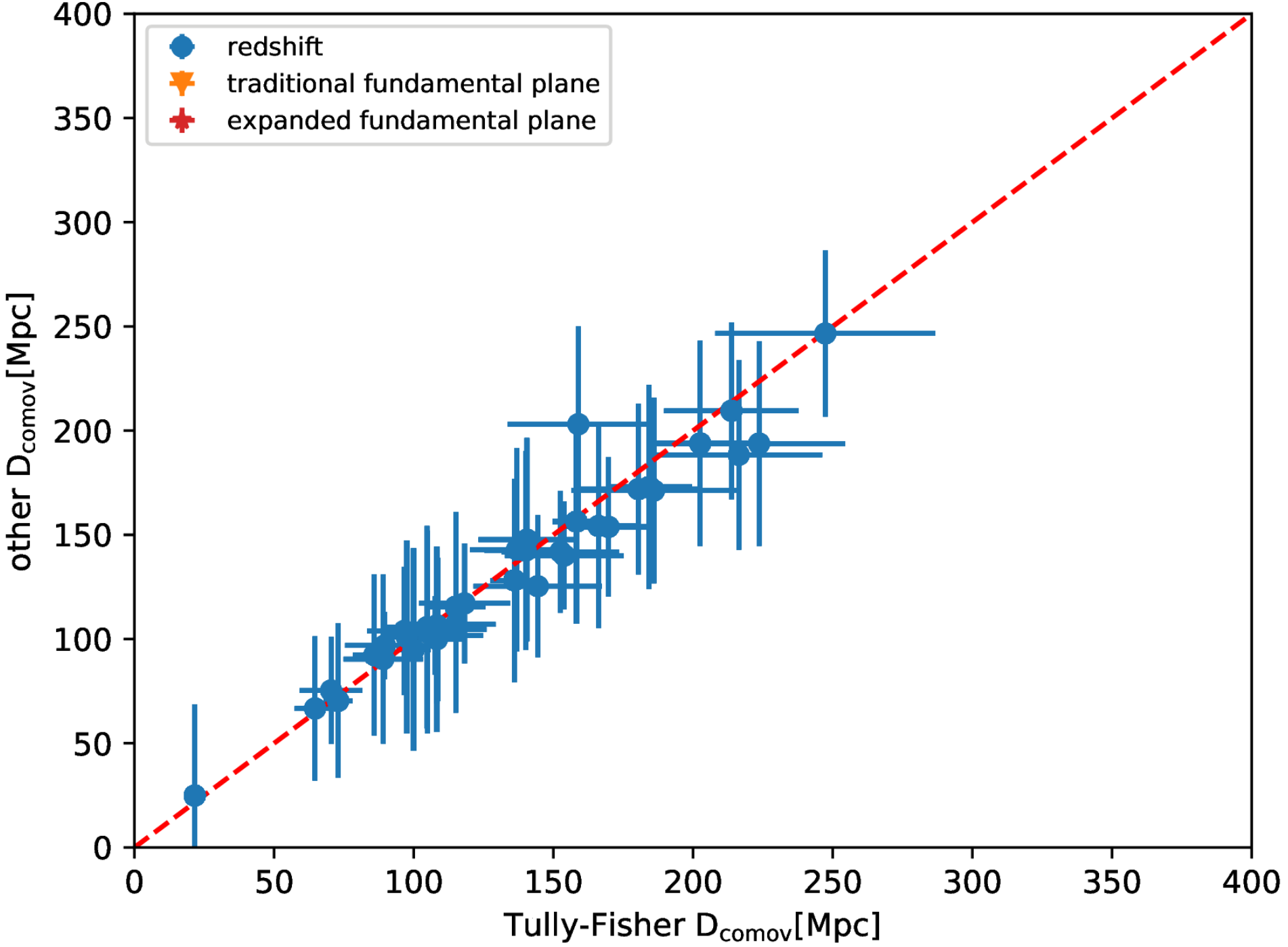
- NASA/IPAC Extragalactic Database (NED)

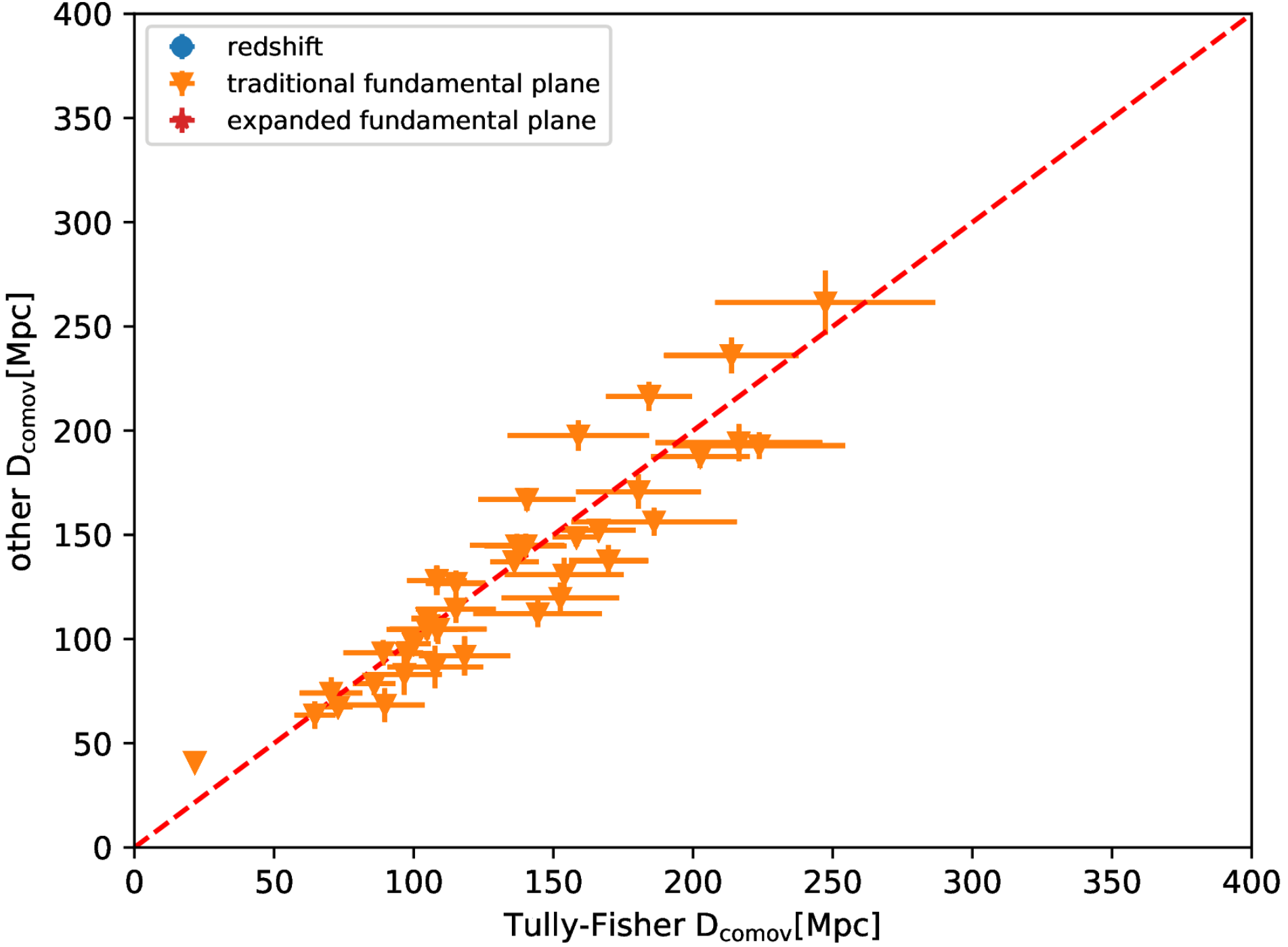
- 20 900 Tully-Fisher relation based distance measurements to 4 481 unique galaxies
- Error weighted average for galaxies that have more than one measurement
- Intrinsic scatter of 23.5%

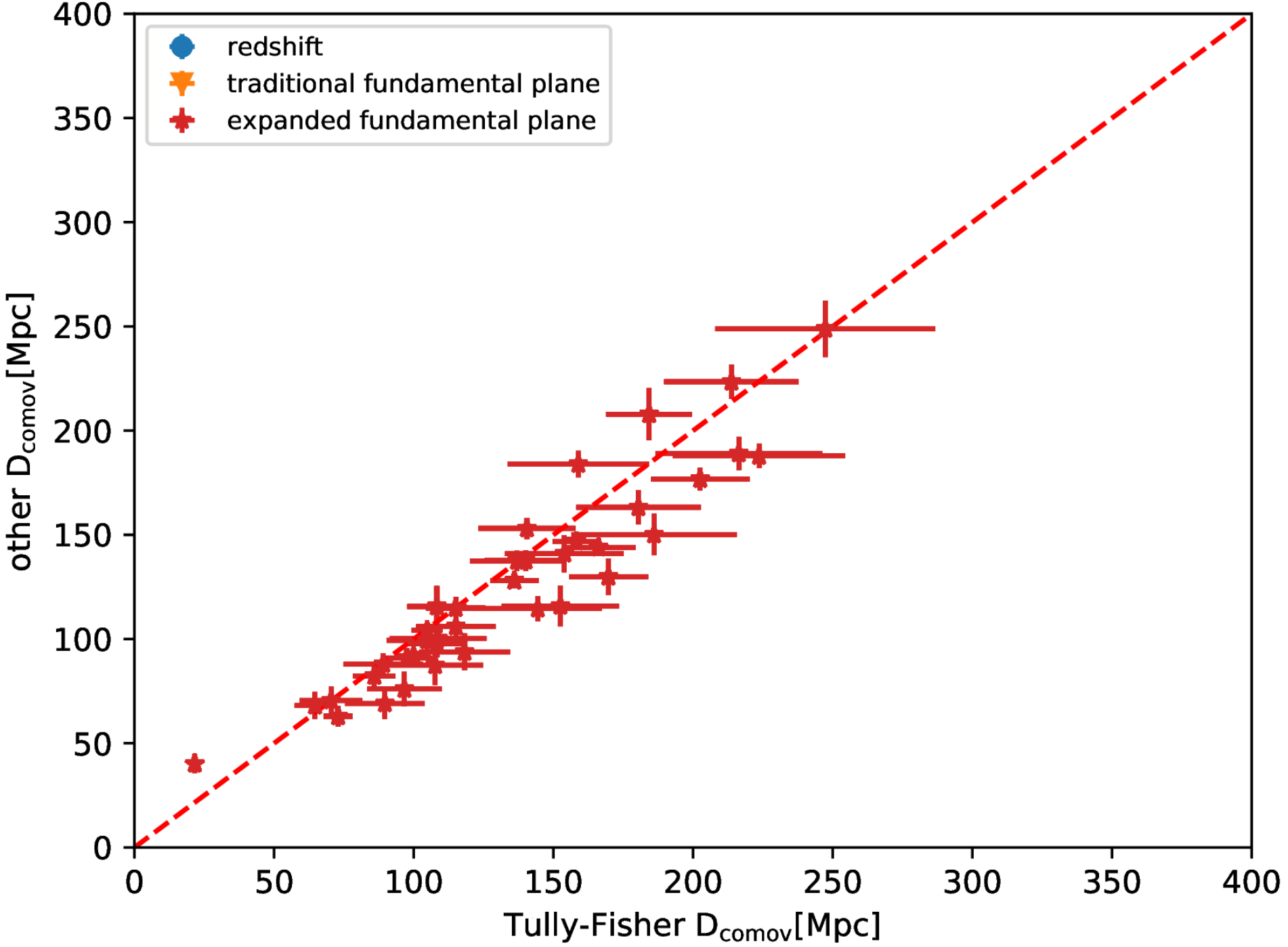
- Using our group catalogue to compare them


redshift
traditional fundamental plane
other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
0
50
100
150
200
250
300
350
400


redshift
traditional fundamental plane
expanded fundamental plane
other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
0
50
100
150
200
250
300
350
400

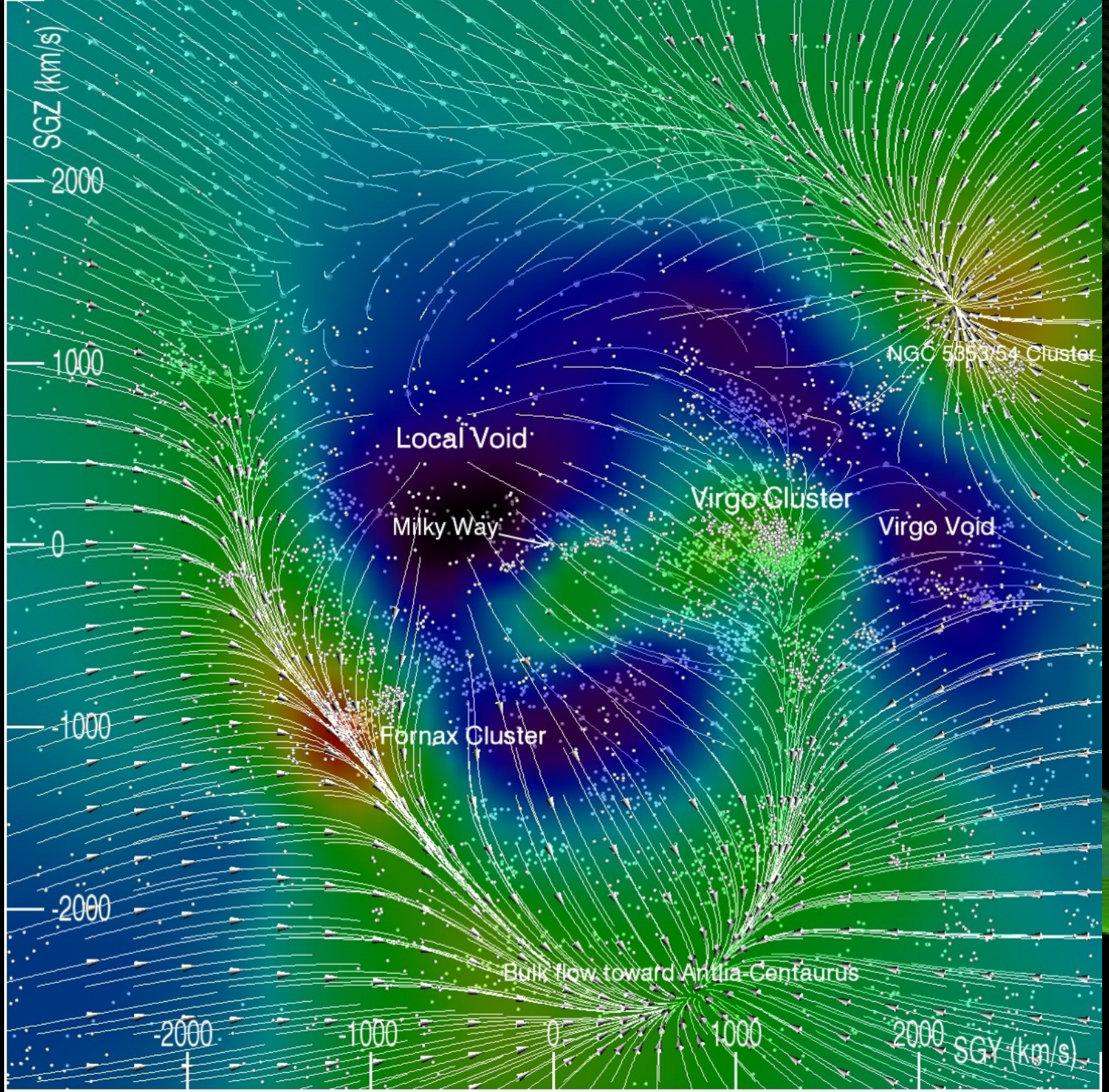

redshift
traditional fundamental plane
expanded fundamental plane
other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
0
50
100
150
200
250
300
350
400

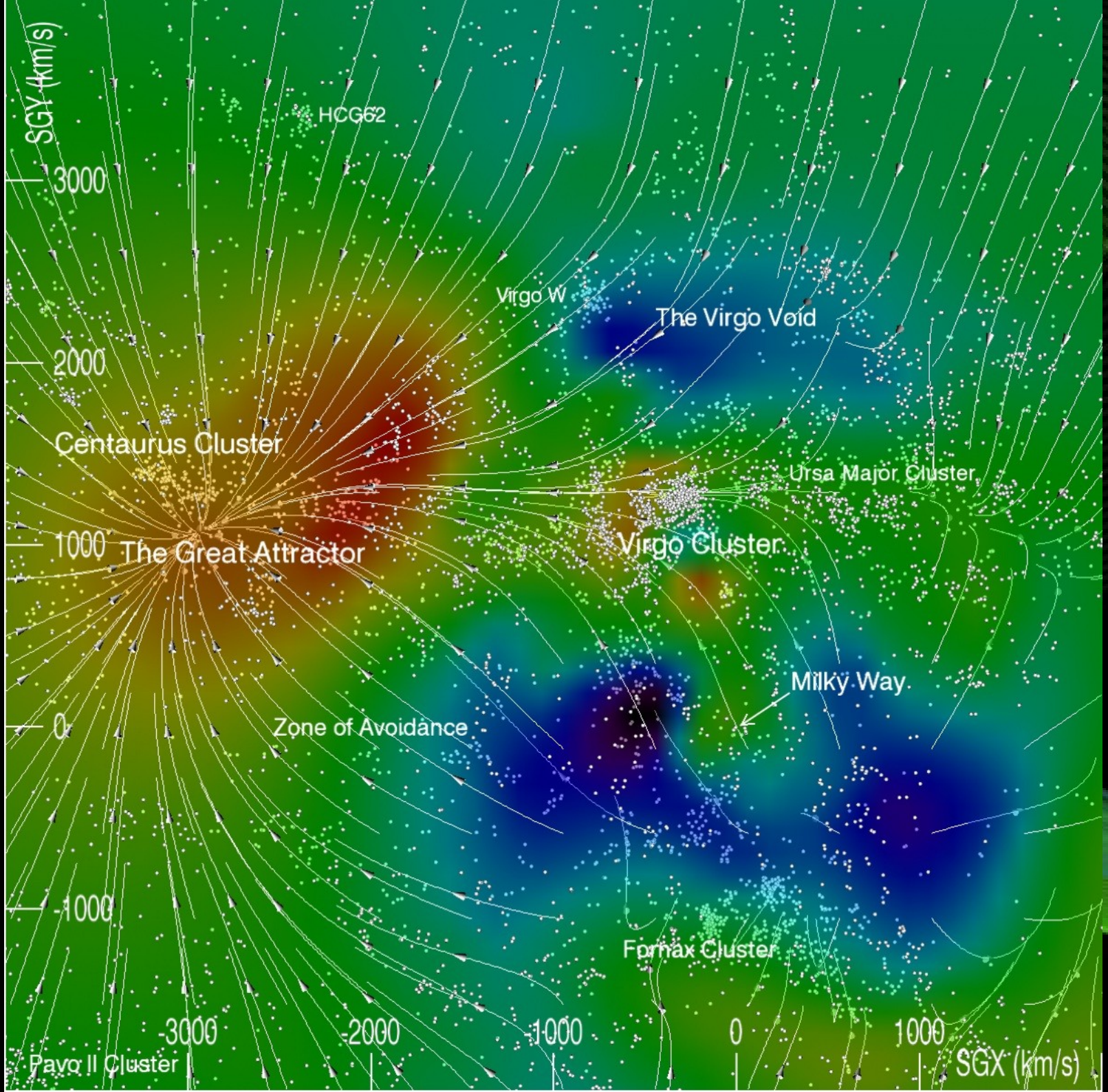

redshift
traditional fundamental plane
expanded fundamental plane
other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
0
50
100
150
200
250
300
350
400


redshift
traditional fundamental plane
expanded fundamental plane
other D_{comov}[Mpc]
Tully-Fisher D_{comov}[Mpc]
0
50
100
150
200
250
300
350
400

CosmicFlows-3 sample

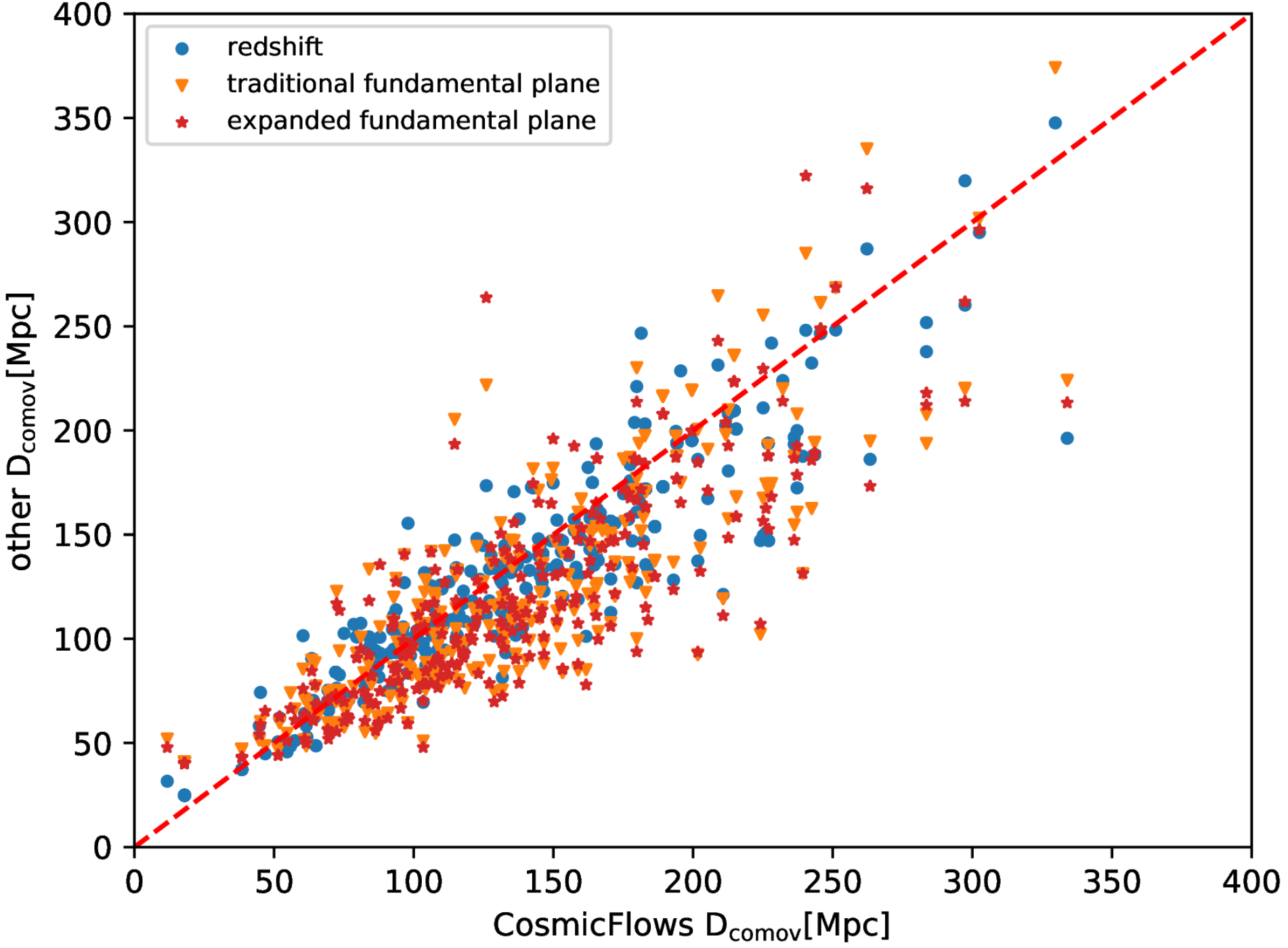
- A well-calibrated sample of distances to 17 669 galaxies in the local universe (Tully+2016)
- Uses a large range of different distance indicators:
  - Tully-Fisher relation
  - surface brightness fluctuations
  - fundamental plane
  - tip of the red giant branch
  - ...
- Fancy visualisations

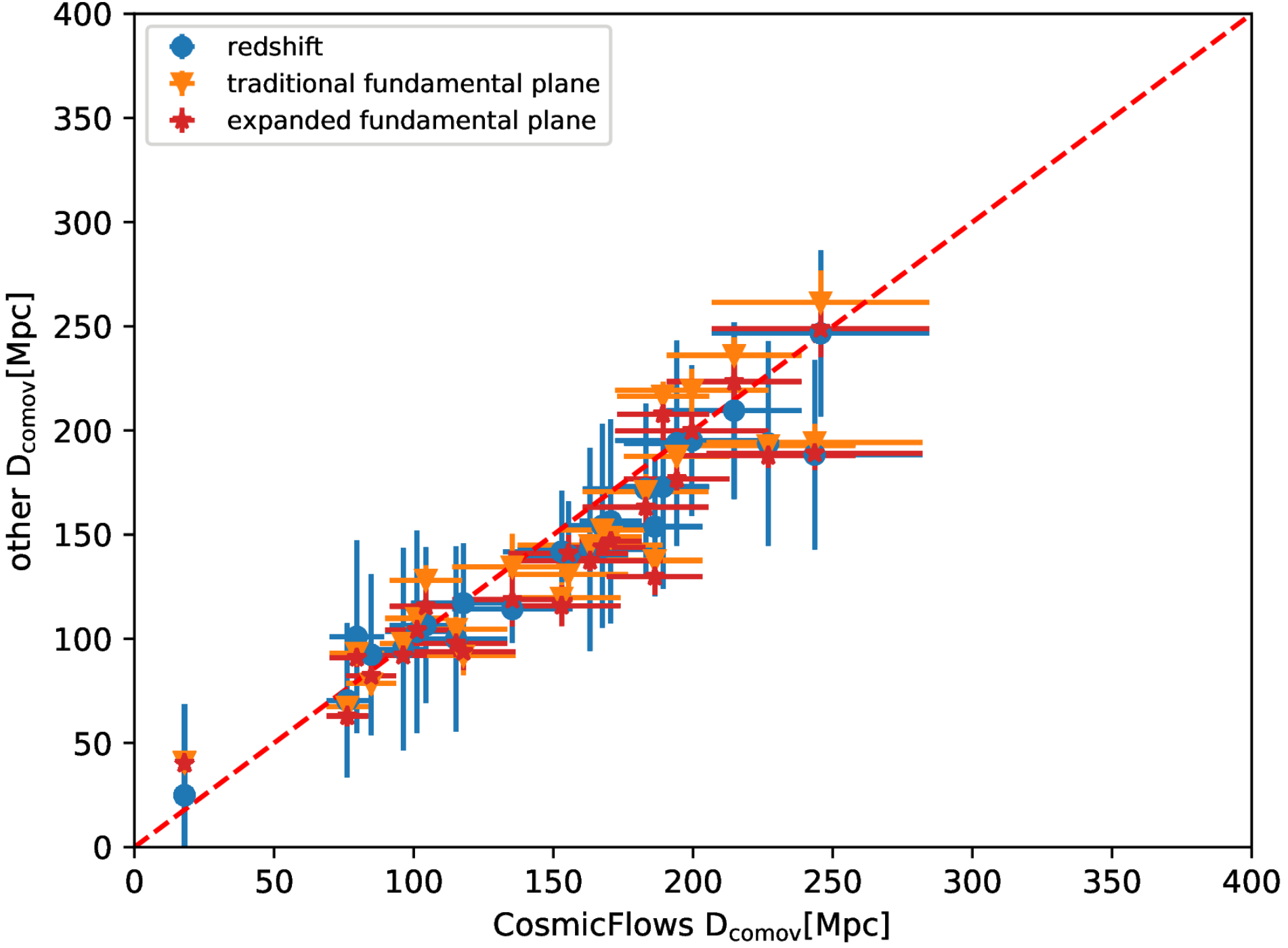

SGZ (km/s)
2000
1000
0
-1000
-2000
Local Void
Milky Way
Virgo Cluster
Virgo Void
NGC 5353/54 Cluster
Fornax Cluster
Bulk flow toward Antlia-Centaurus
-2000
-1000
0
1000
2000
SGY (km/s)

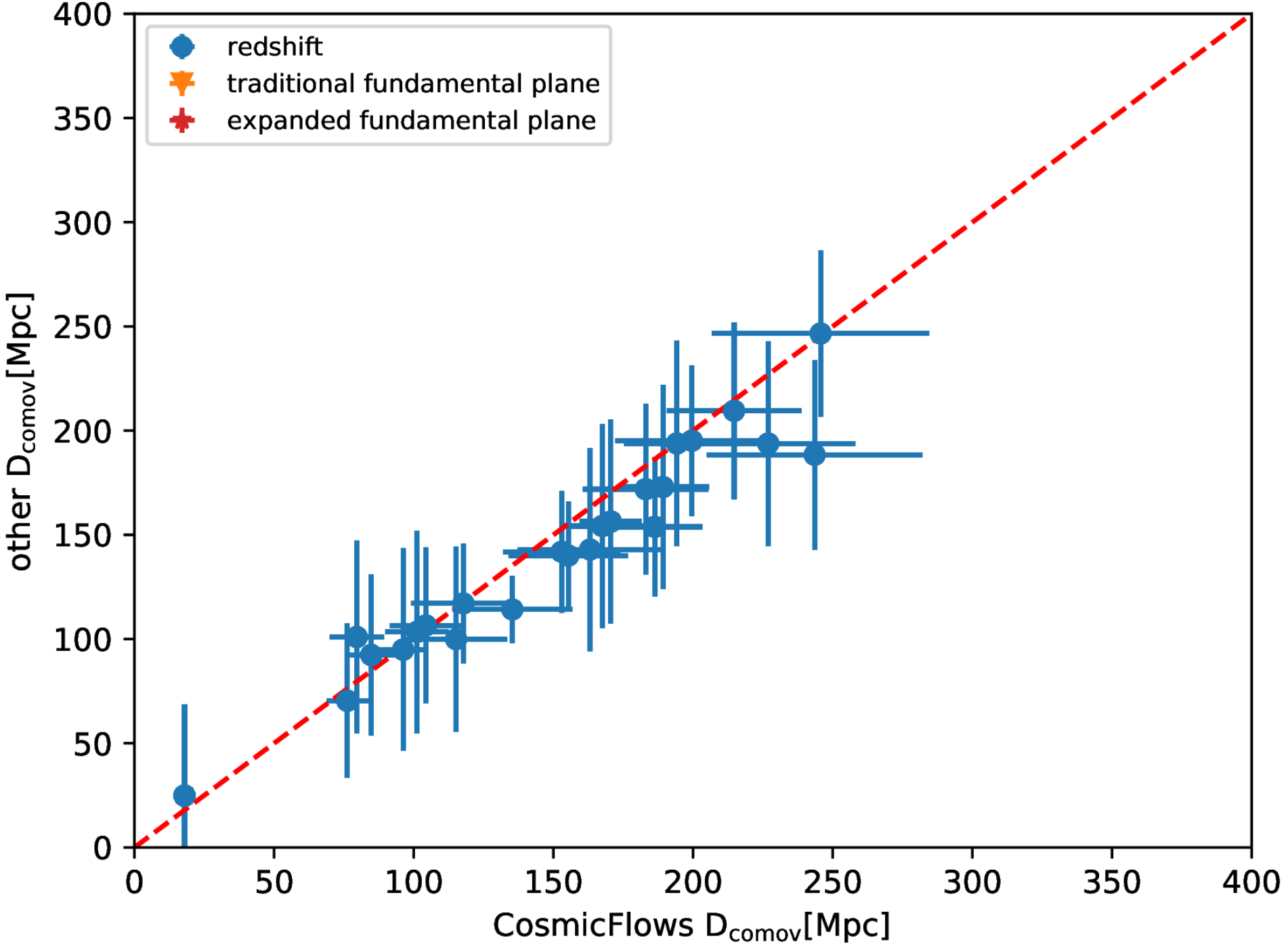

SGY (km/s)
3000
2000
1000
0
-1000
HCG62
Virgo W
The Virgo Void
Centaurus Cluster
Ursa Major Cluster
The Great Attractor
Virgo Cluster
Milky Way
Zone of Avoidance
Fornax Cluster
Pavo II Cluster
-3000
-2000
-1000
0
1000
SGX (km/s)

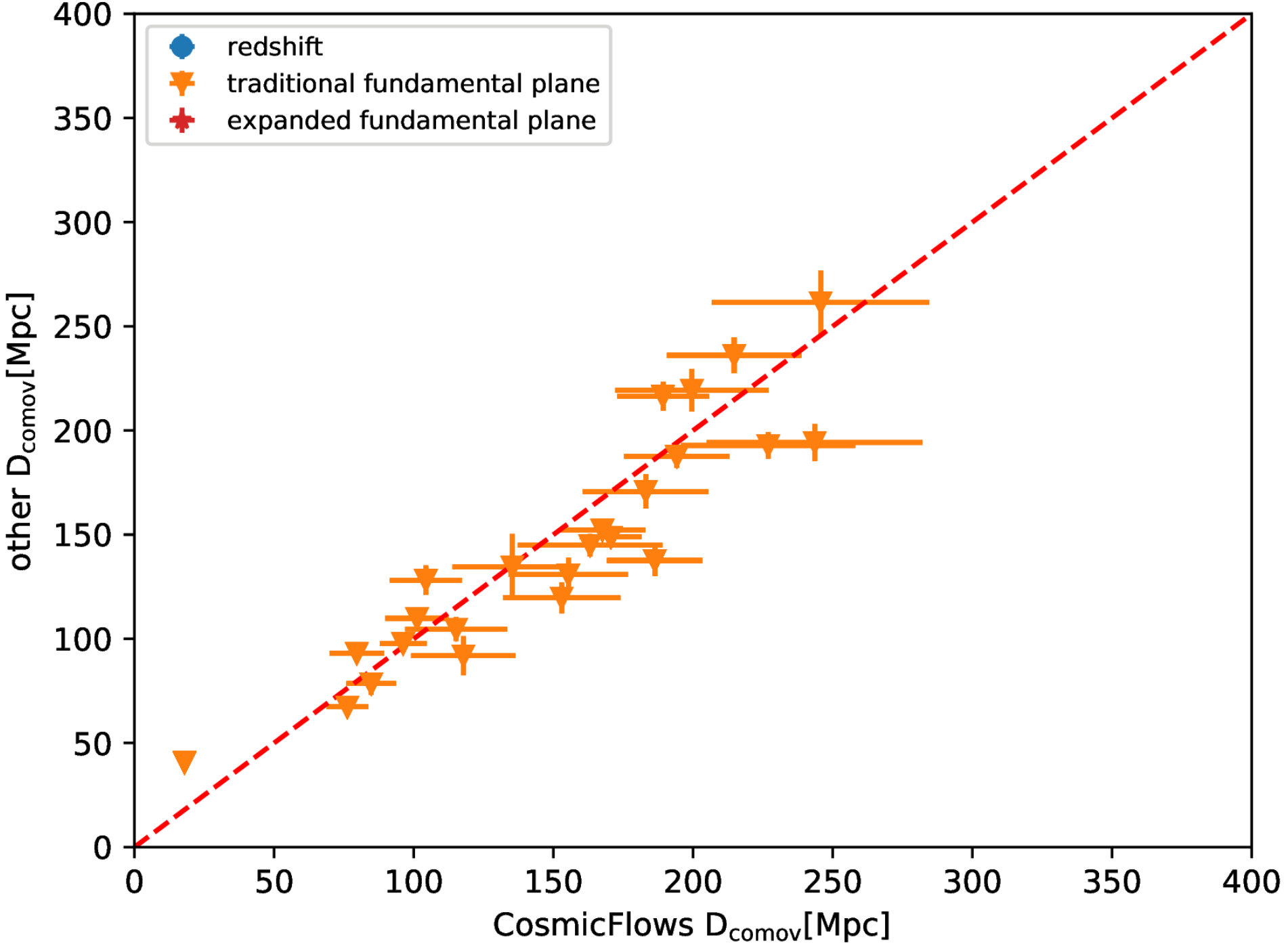
Comparison to the CosmicFlows-3 sample

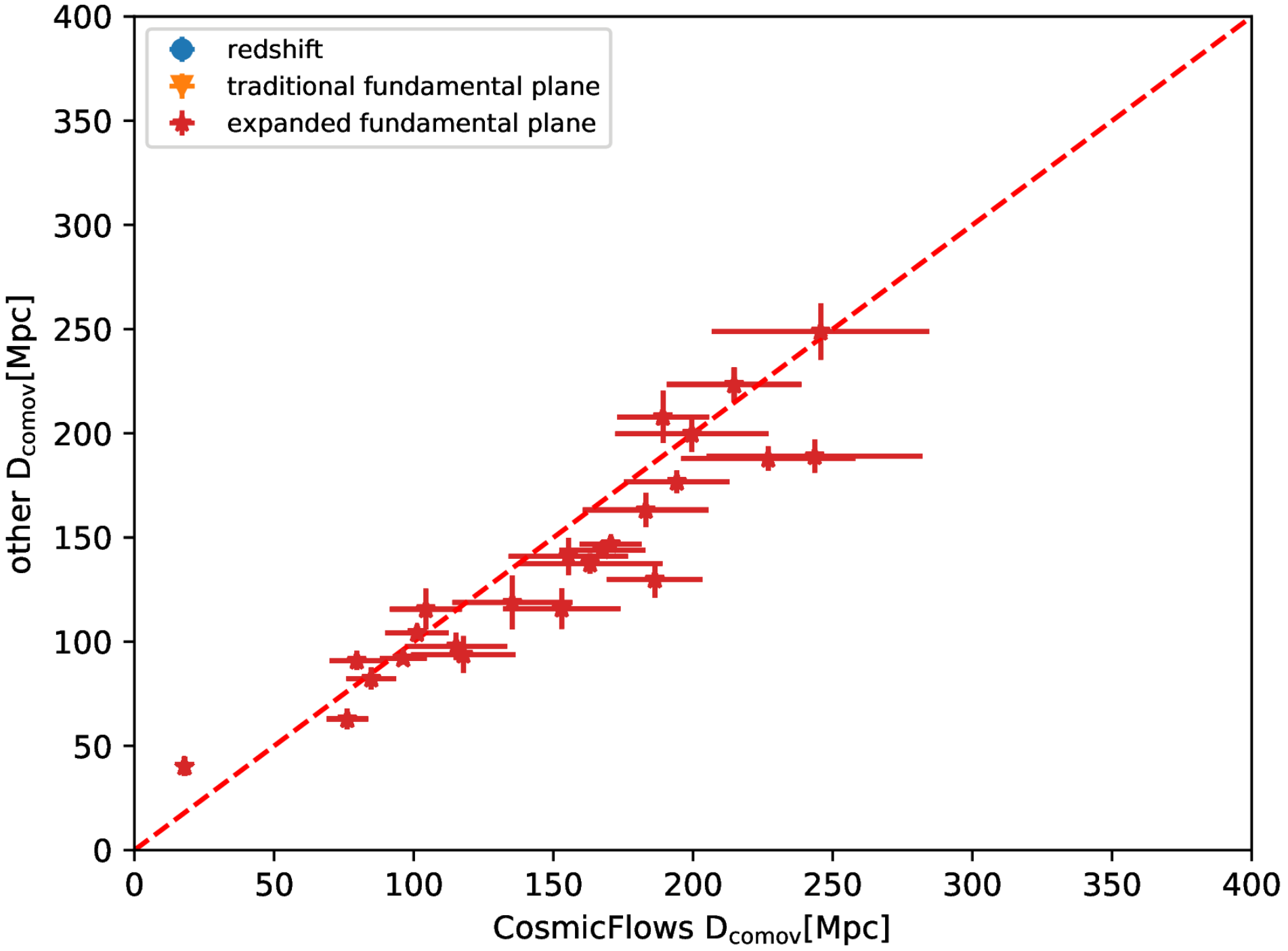
- We exclude their fundamental plane data
- Using our group catalogue to compare the samples
- Rescaling their cosmology to fit the one assumed by our calibrations
- Notable issue: they used the LG rest frame, we used the CMB rest frame


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


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

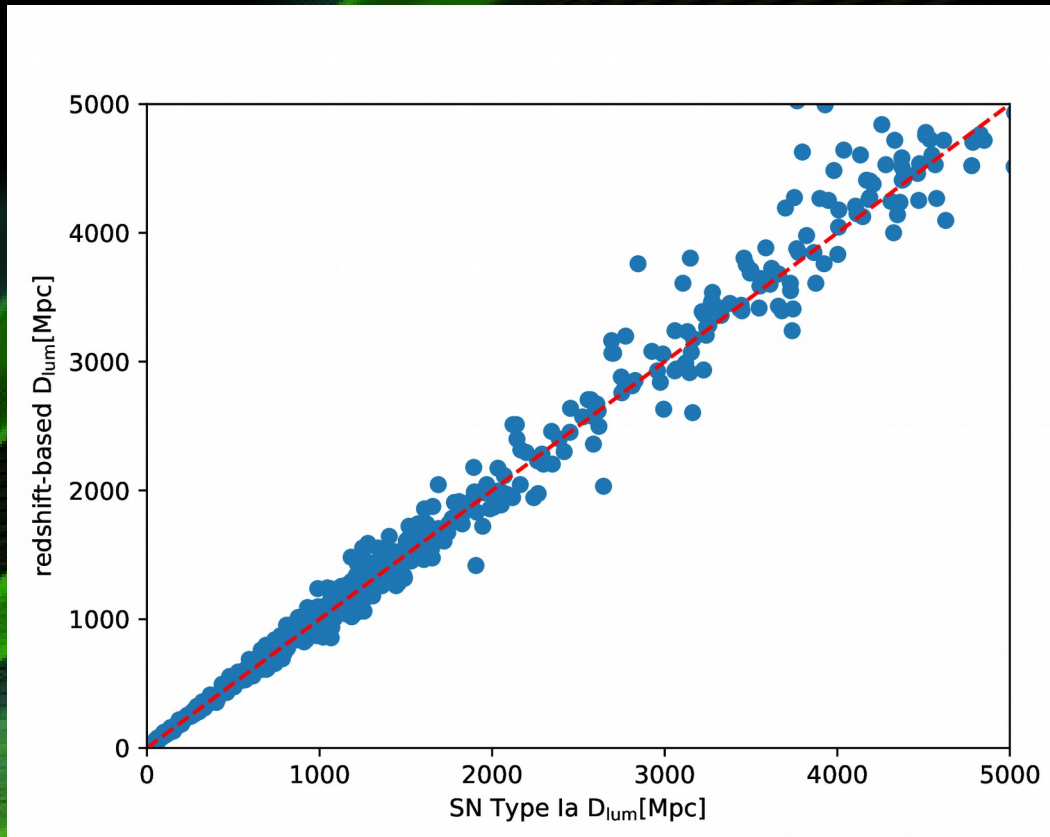

redshift
traditional fundamental plane
expanded fundamental plane
other D_{comov}[Mpc]
CosmicFlows D_{comov}[Mpc]
0
50
100
150
200
250
300
350
400

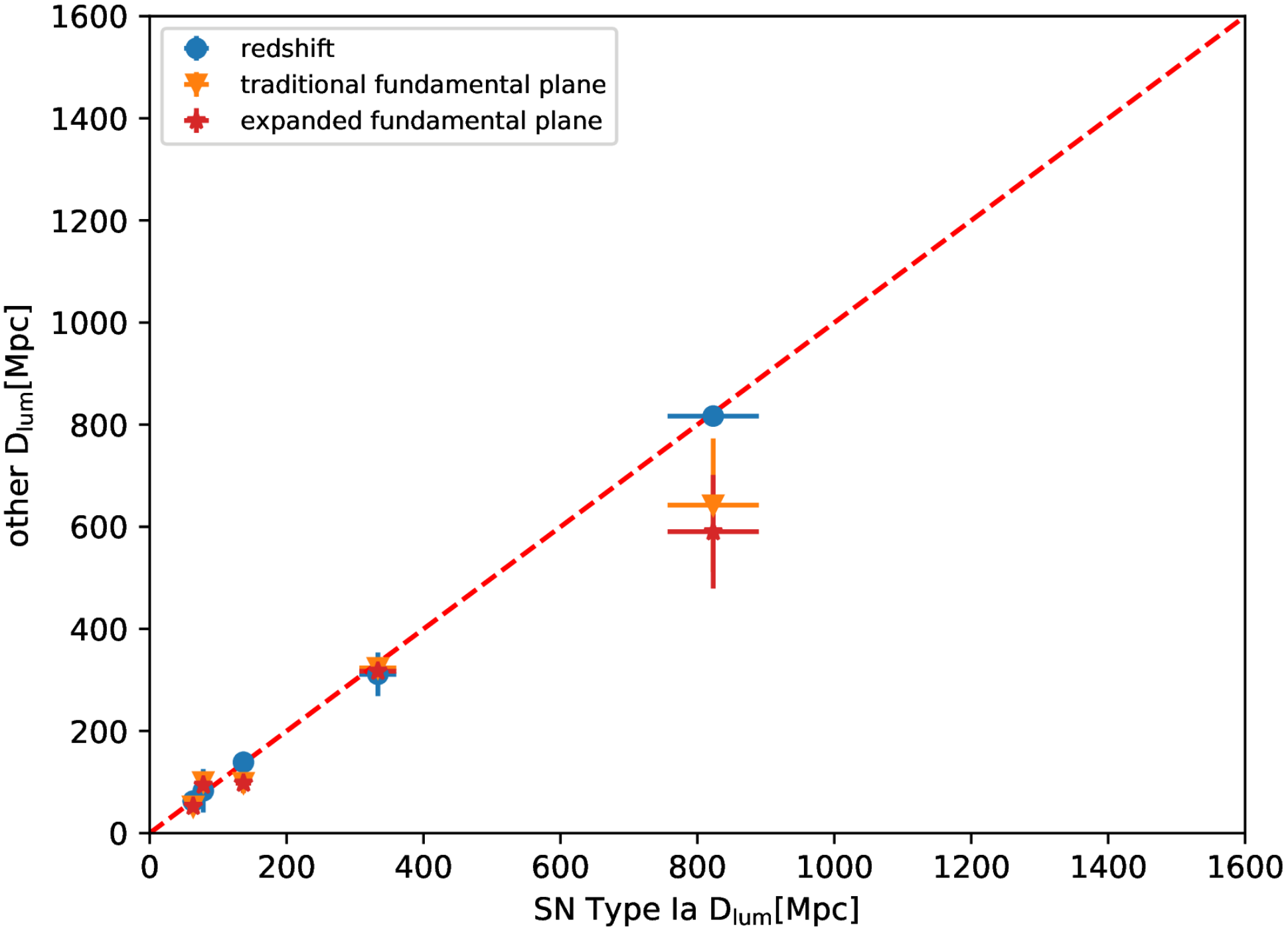

redshift
traditional fundamental plane
expanded fundamental plane
other D_{comov}[Mpc]
CosmicFlows D_{comov}[Mpc]
0
50
100
150
200
250
300
350
400


redshift
traditional fundamental plane
expanded 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 supernovae in our ETGs
- Scatter of supernova distances about ~8%




redshift
traditional fundamental plane
expanded fundamental plane
other D_{lum}[Mpc]
SN Type Ia D_{lum}[Mpc]
0
200
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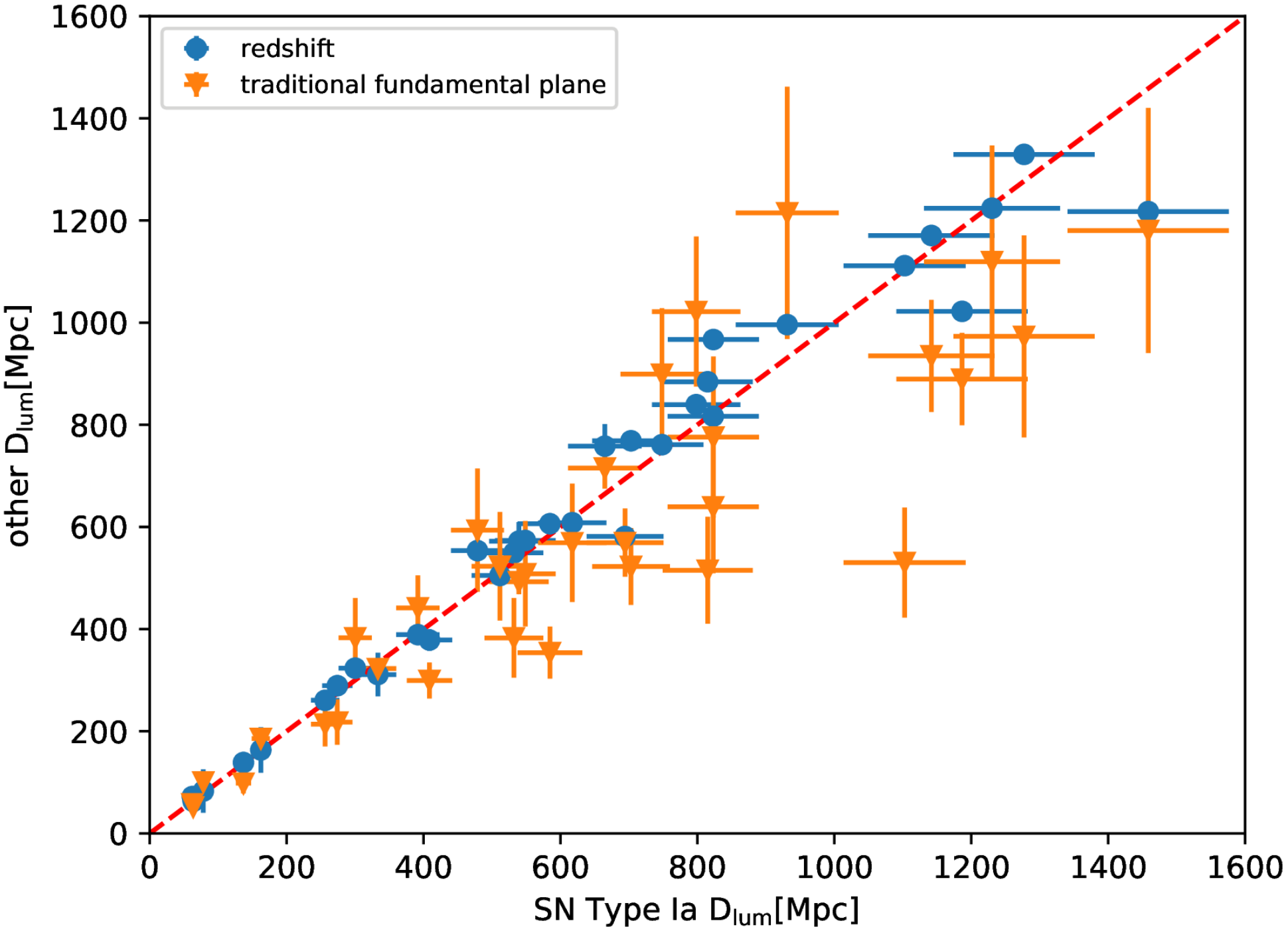
redshift
traditional fundamental plane
other D_{lum}[Mpc]
SN Type Ia D_{lum}[Mpc]
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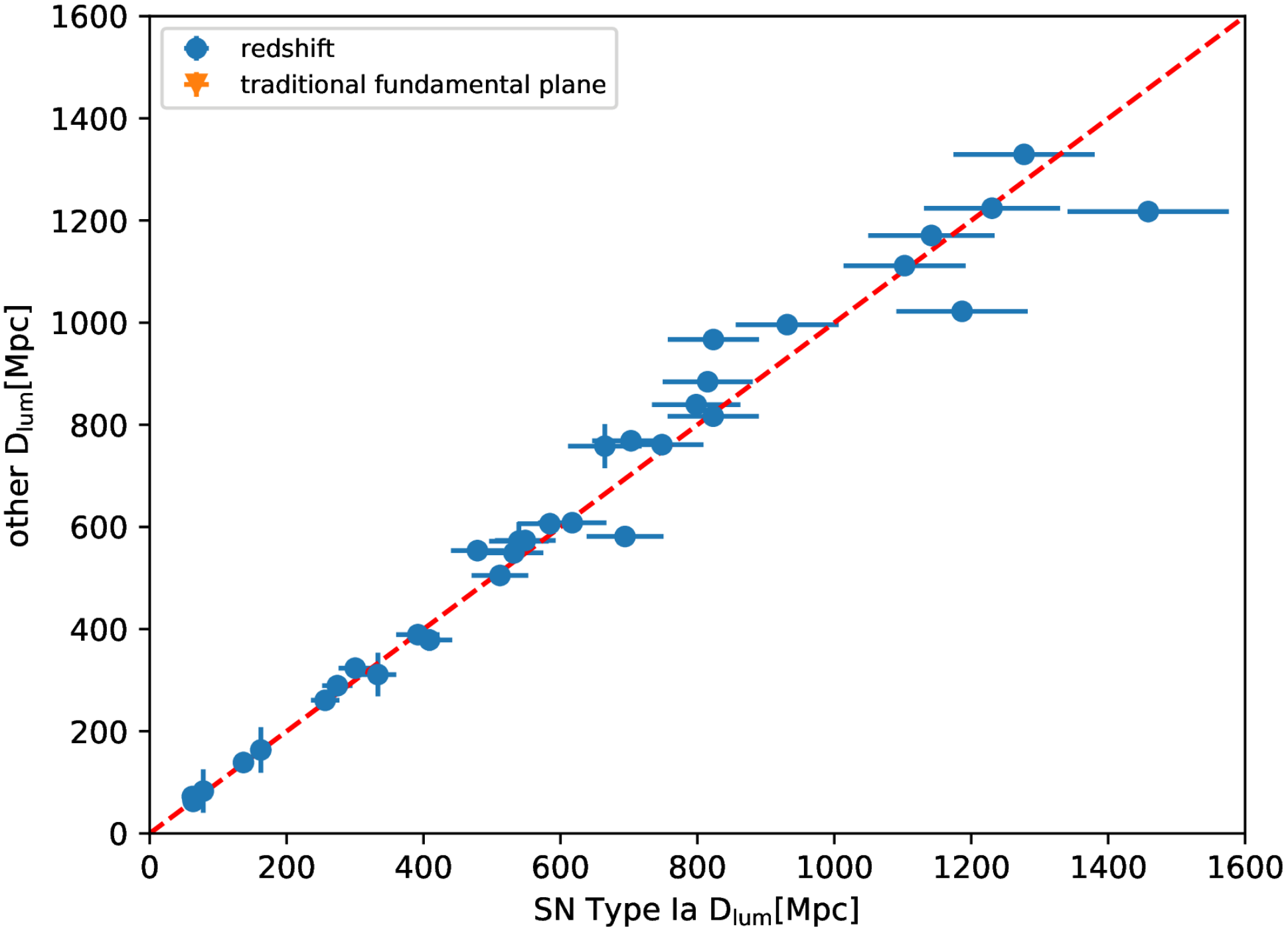
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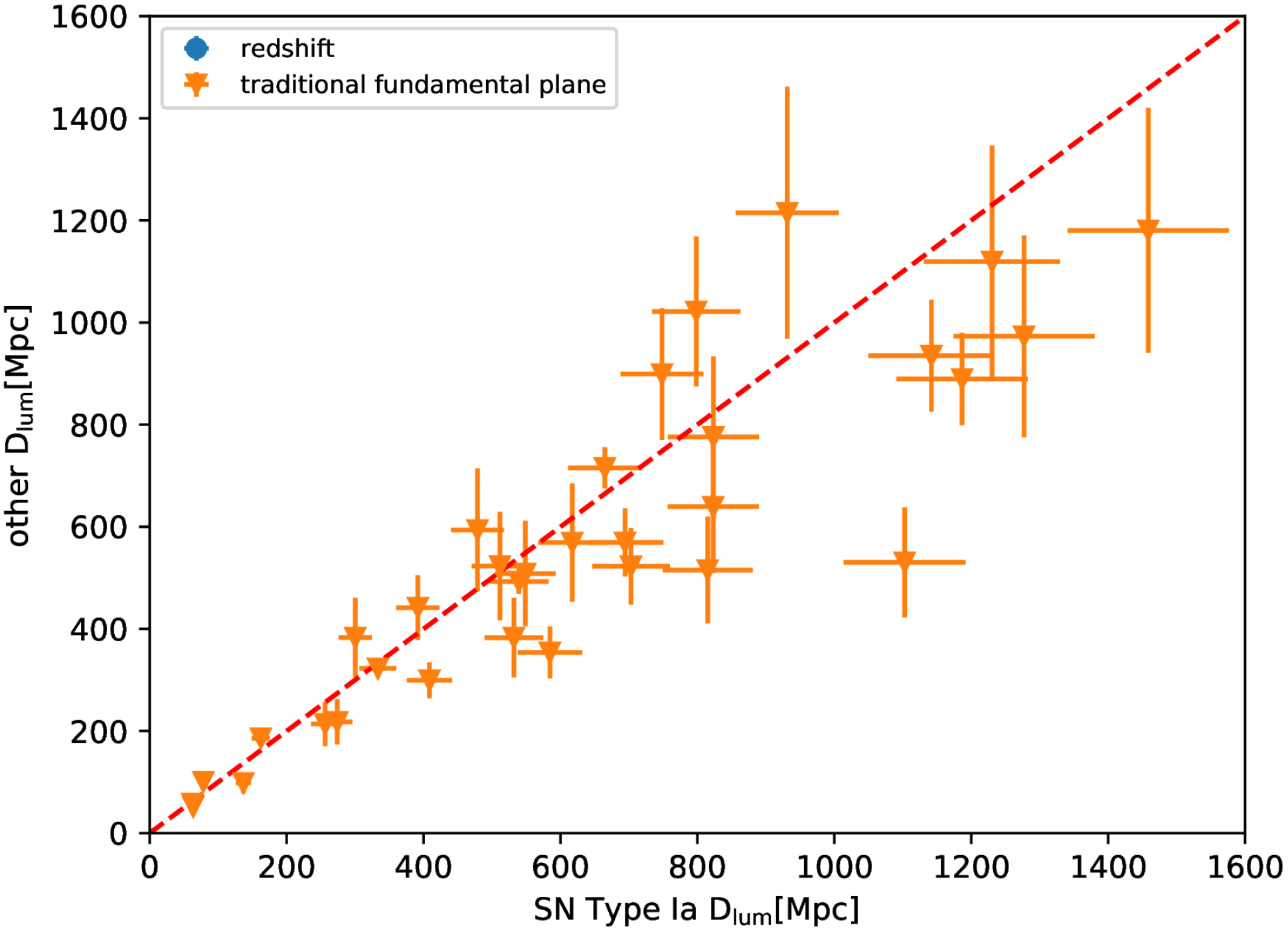
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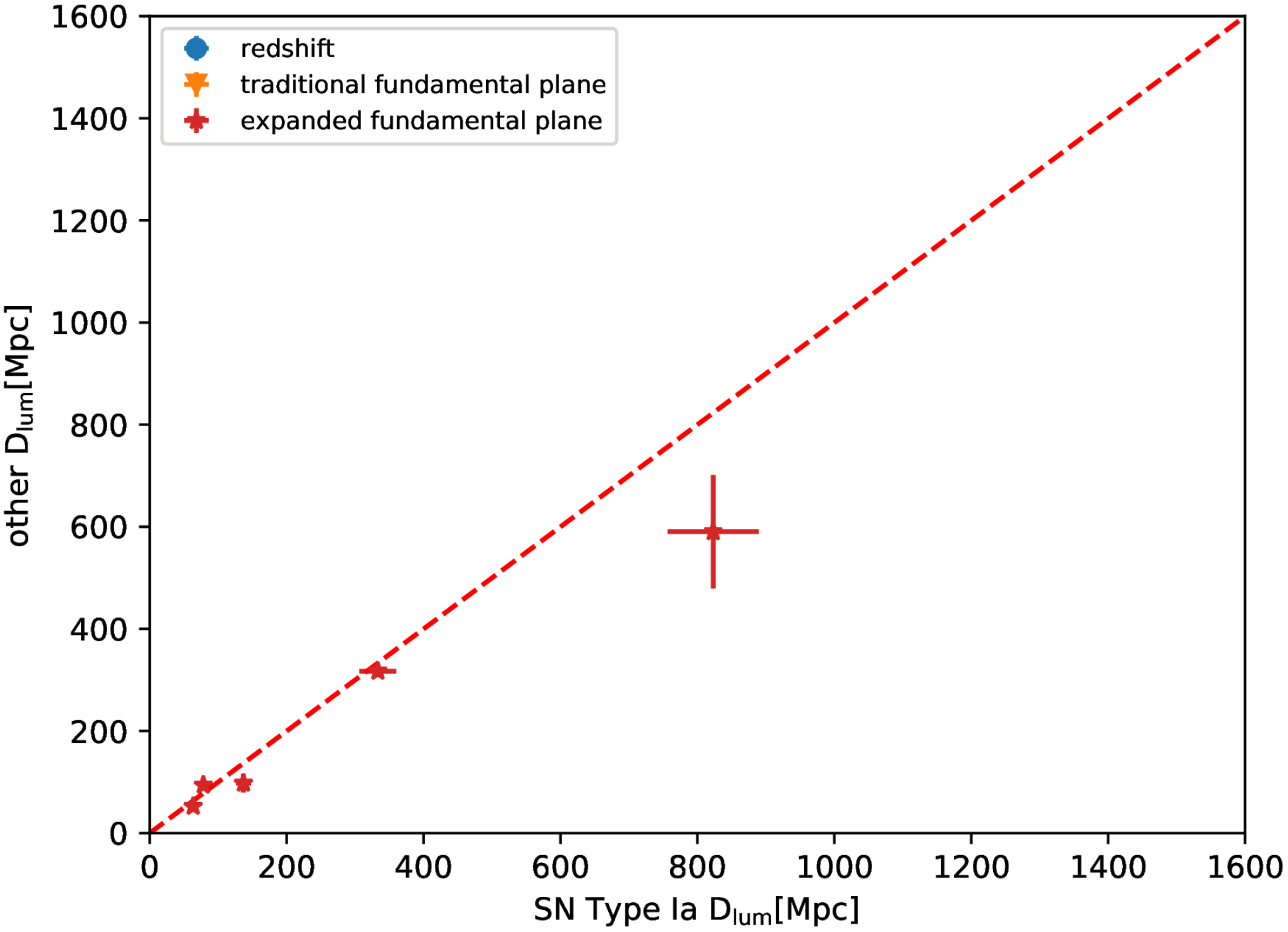
redshift
traditional fundamental plane
expanded fundamental plane
other D_{lum}[Mpc]
SN Type Ia D_{lum}[Mpc]
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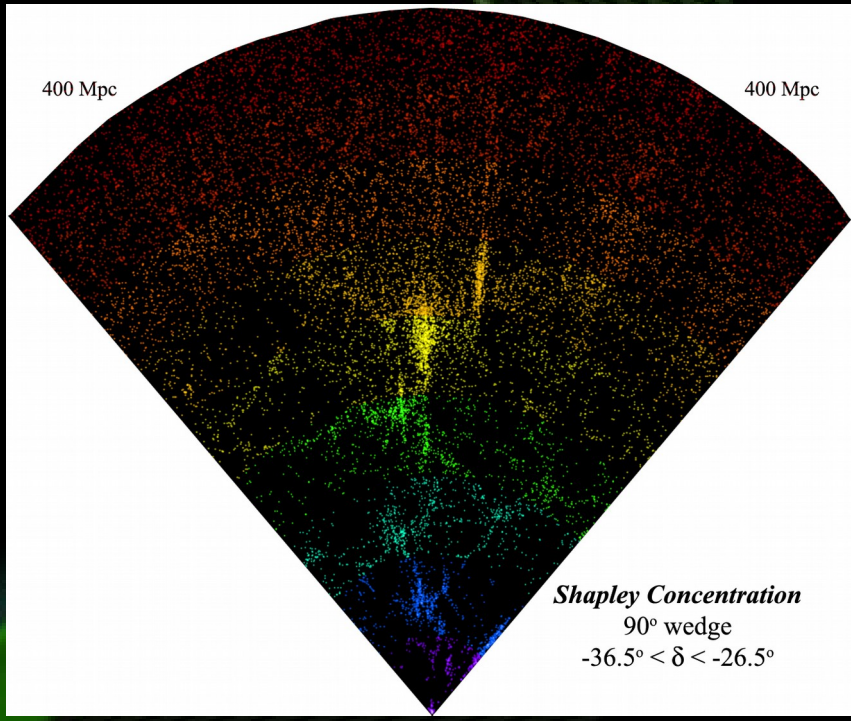
Statistics

- Tully-Fisher comparison:
  - Redshifts: 32.1%, 8.0% (rich groups)
  - Traditional fundamental plane: 30.7%, 15.8%
  - For the subsample: 37.5%, 19.2%
  - Expanded fundamental plane: 35.6%, 18.2%
- CosmicFlows-3 comparison:
  - Redshifts: 20.2%, 13.1%
  - Traditional fundamental plane: 30.7%, 23.2%
  - For the subsample: 32.5%, 29.6%
  - Expanded fundamental plane: 30.9%, 28.9%
- Supernovae Type Ia comparison:
  - Redshifts: 8.4%
  - Traditional fundamental plane: 22.9%

Peculiar Motions



by Thomas Jarrett (IPAC/Caltech)

- Galaxies are not sitting still
- Motion induced by gravity of other galaxies/clusters/...
- Redshift space distortions:
- Finger of God effect (random motion inside clusters)
- Kaiser effect (coherent infall into clusters)

- Scatter around the homogeneous Hubble flow

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 redshift-independent distance indicator and redshift measurements
- Lots of systematic biases need to be considered

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

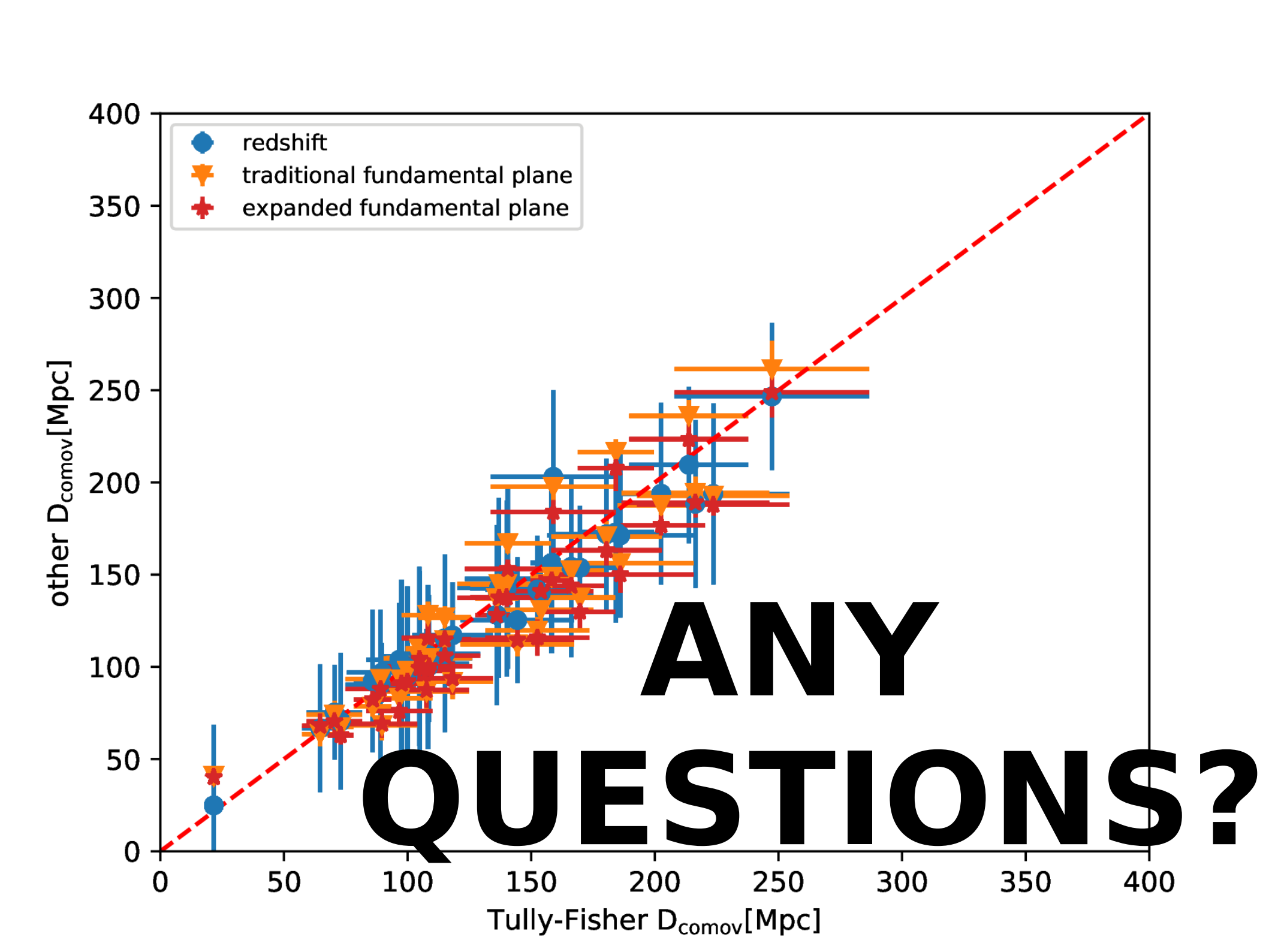
- 6dFGSv (Springob+ 2014)
  - Uses the fundamental plane
  - Only Southern hemisphere (6dFGS follow-up)
  - Recently reworked data: Howlett+ 2017, Qin+ 2018, Howlett+ 2019

Our goal

- Providing an extended self-consistent peculiar velocity model for the Northern hemisphere
- Complementary to the 6dFGSv
- Using the methods of Howlett+ 2019 on our data to supplement their catalogue.
- Help to reduce directional issues with their data
- Study the momentum power spectrum (with Park C.)
- Correlations with clusters found using other methods (with Schwarz D.)

Summary

- Group catalogue covering ~1 500 000 galaxies
- ~320 000 traditional fundamental plane distances
- ~184 000 expanded fundamental plane distances
- Largest self-consistent set of redshift-independent distances ever produced
- Improvements due to expansion of the fundamental plane not as big as hoped
- Comparison to Tully-Fisher relation, CosmicFlows-3, and Supernova Type Ia distances
- Peculiar motion data is work in progress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ANY
QUESTIONS?