Placing limits on the backreactions from inhomogeneities using survey data

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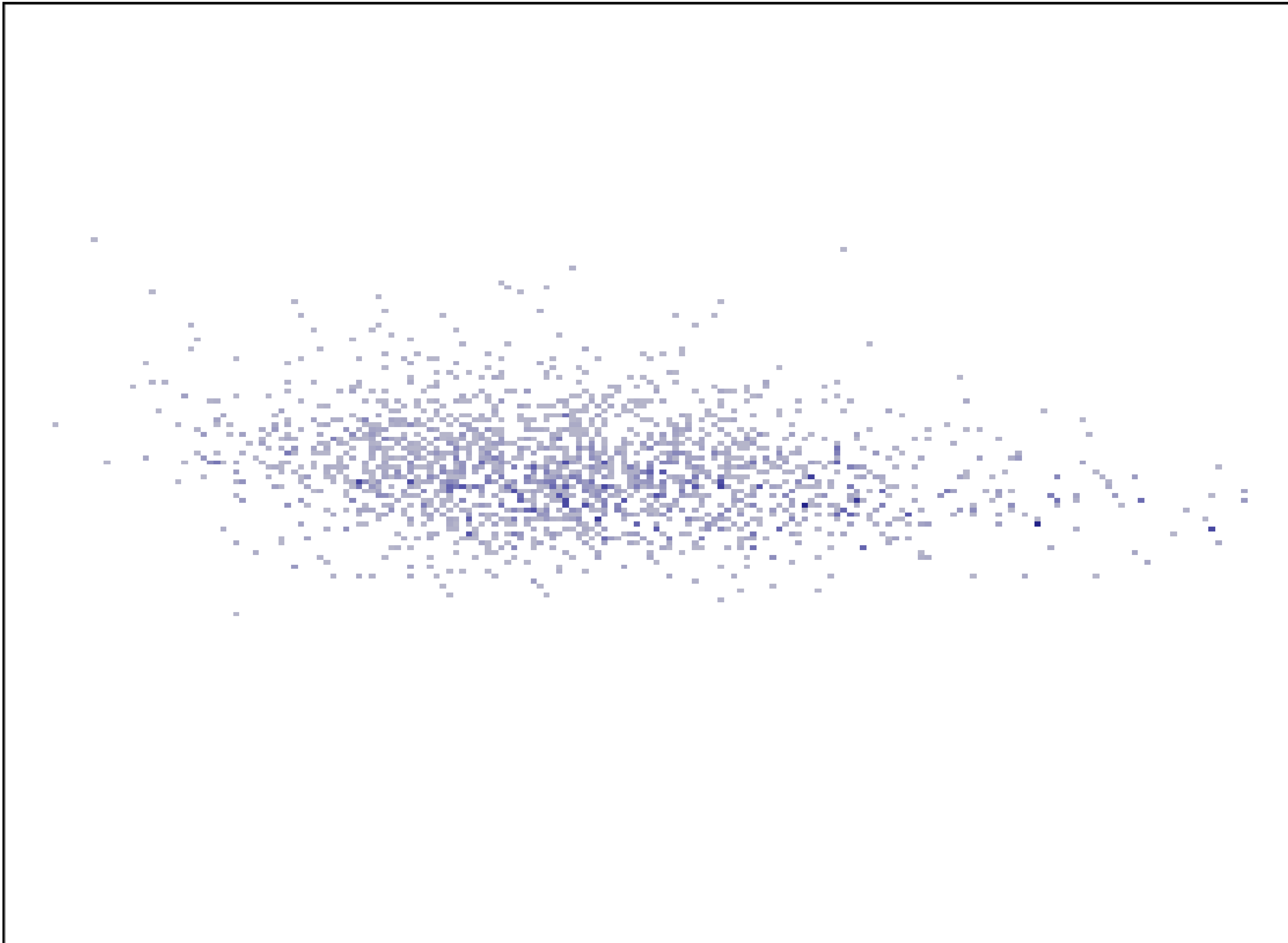
University of Cape Town, March 12 2019



Collaborators

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Korea Institute for Advance Study

Λ-CDM cosmology

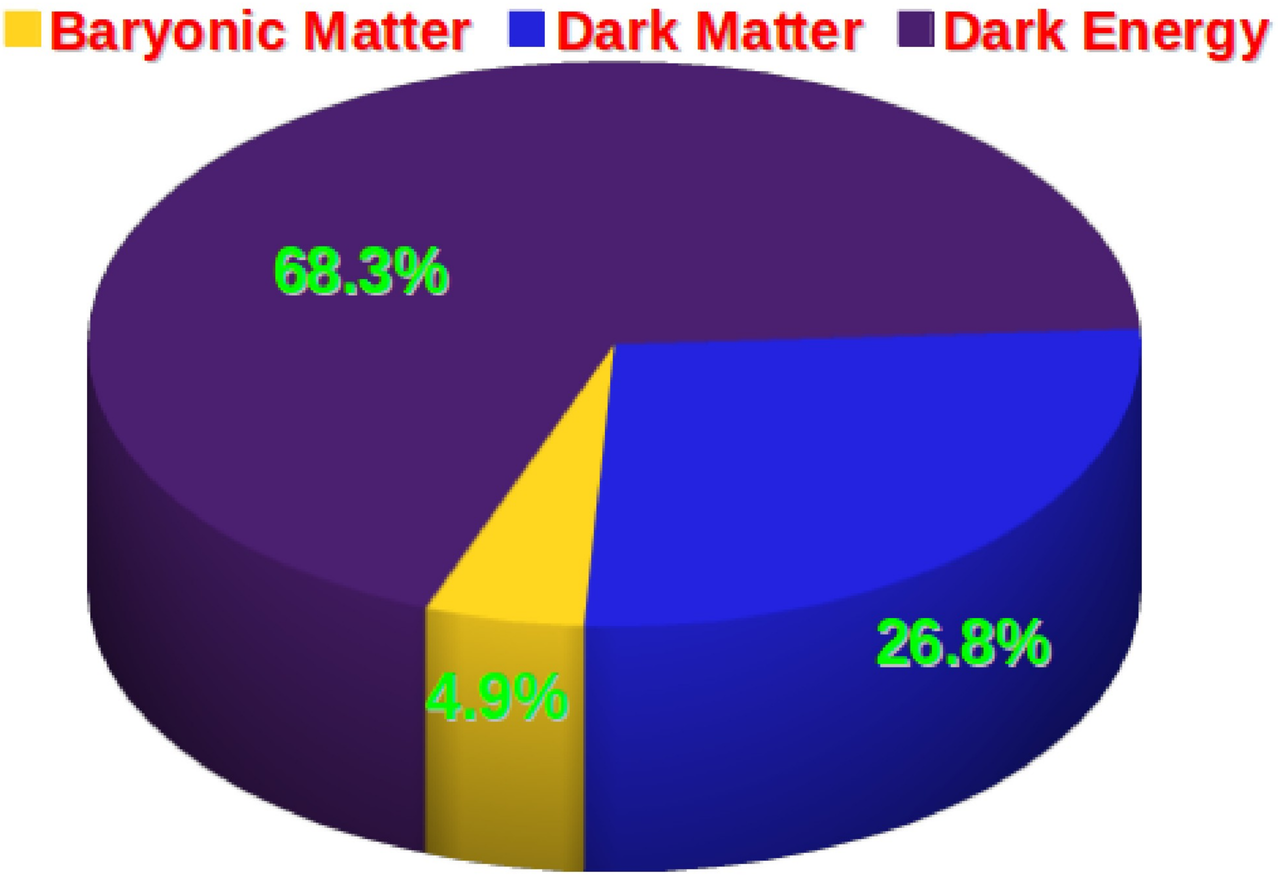
- Based on the following assumptions:
  - General Relativity
    (including a cosmological constant)
  - Isotropy
  - Homogeneity

Cosmological Principle

- → Friedmann-Lemaître-Robertson-Walker metric
- → Friedmann equations

$$\frac{H^2}{H_0^2}=\Omega_\gamma a^{-4}+\Omega_M a^{-3}+\Omega_k a^{-2}+\Omega_\Lambda$$

- Best fit (based on Planck data)

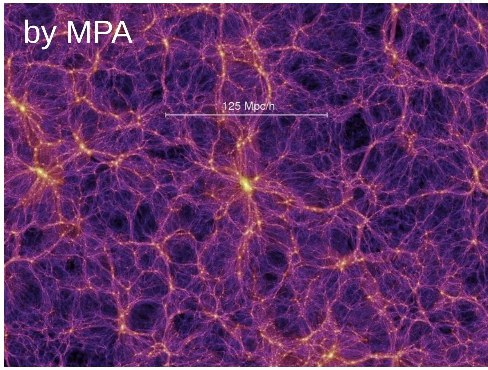


- The present-day universe is dominated by **Dark Energy**

Timescape cosmology

- An inhomogeneous cosmological model postulated in Wiltshire 2007.

- Based on the following assumptions:
  - **General Relativity** (without a cosmological constant)
  - Swiss cheese-like matter distribution
  - No universal cosmological time parameter
  - Modified averaging over inhomogeneities to non-linearities from General Relativity
  - Significant **backreaction** from local **inhomogeneities** (voids and walls)

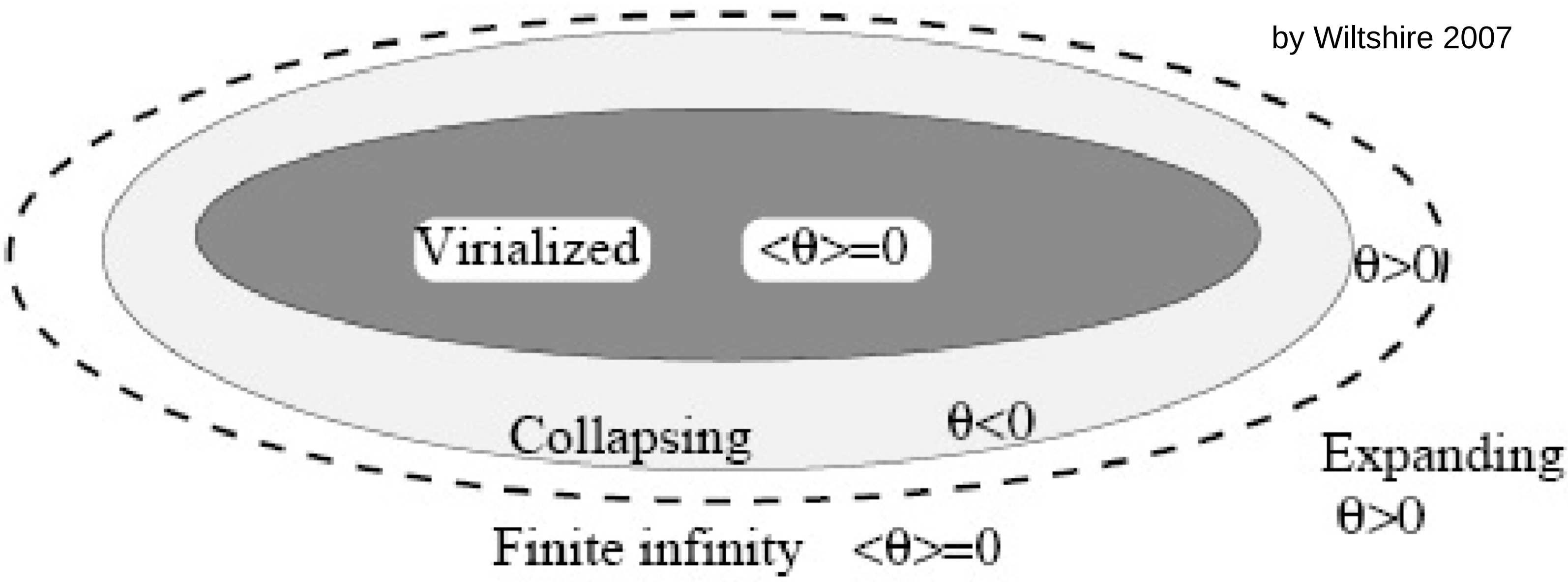


- Two-phase models:
  - **Voids**: close to empty, locally open geometry
  - **Walls**: on average renormalized critical density, locally flat geometry

$$\left(\frac{\dot{\bar{a}}}{\bar{a}}\right)^2+\frac{\dot{f}_V^{\,2}}{9f_V(1-f_V)}-\frac{\alpha^2 f_V^{1/3}(1-f_V)}{\bar{a}^2}=\frac{8\pi G}{3}\bar{\rho}_0\frac{\bar{a}_0^{\,3}}{\bar{a}^3}$$

$$\ddot{f}_V+\frac{\dot{f}_V^{\,2}(2f_V-1)}{2f_V(1-f_V)}+3\frac{\dot{\bar{a}}}{\bar{a}}\dot{f}_V-\frac{3\alpha^2 f_V^{1/3}(1-f_V)}{2\bar{a}^2}=0$$

- Finite infinity regions (Ellis 1984)



by Wiltshire 2007

- Structure formation made the universe inhomogeneous
- Time flows faster in voids than in walls
- → **voids expand faster than walls*** ***from a wall observer's point of view**

Apparent accelerated expansion

without

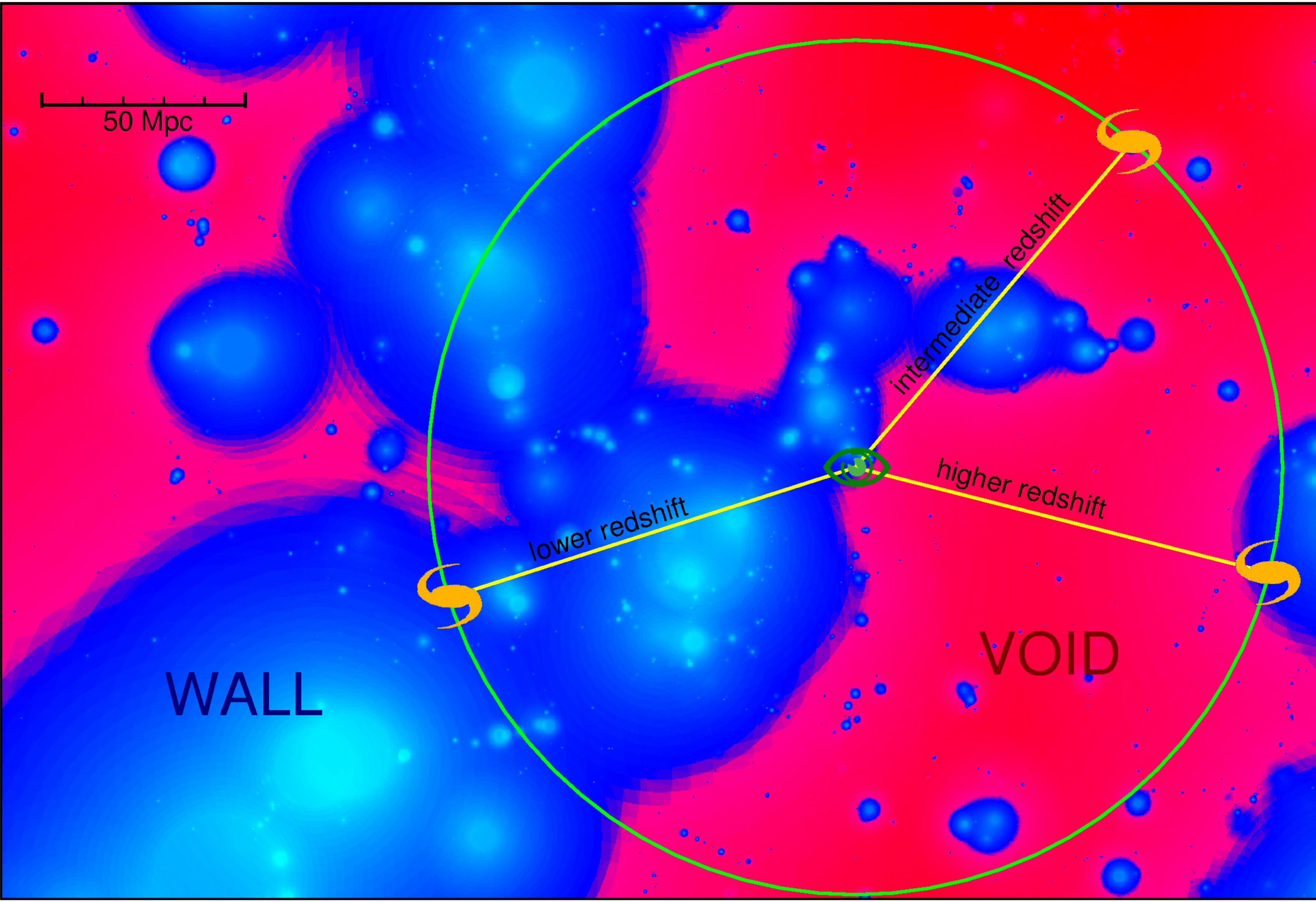
Dark Energy

- Nice theory, isn't it?

  BUT

- Are these backreactions strong enough to explain the cosmic acceleration?
- Exact calculations (beyond two-phase models) are difficult due to the complexity of the equations of General Relativity
- Estimates are ranging from negligible to extremely important (Marra+ 2010, Mattsson+ 2010, Kwan+ 2009, Clarkson+ 2009, Paranjape 2009, van den Hoogen 2010, Kaiser 2017, Buchert 2017, Adamek+ 2019, ...)

Only a test can provide an answer!


50 Mpc
intermediate redshift
higher redshift
lower redshift
VOID
WALL

Designing the test

- Direct measurement of **different expansion rates of voids and walls** (Schwarz 2010, Wiltshire 2011)
- Only be measurable in the local universe (Schwarz 2010)
- Large sample required to get solid statistics (Saulder+ 2012)

- Homogeneous sample with large sky-coverage, sufficient depth and redshift data: **SDSS**

- Redshift-independent distance indicator: **fundamental plane** of early-type galaxies

- Model of the matter distribution in the local universe: **SDSS** supplemented by **2MRS** (because of the saturation bias of SDSS)

- Numerical simulations for mock catalogues: **Millennium simulation**

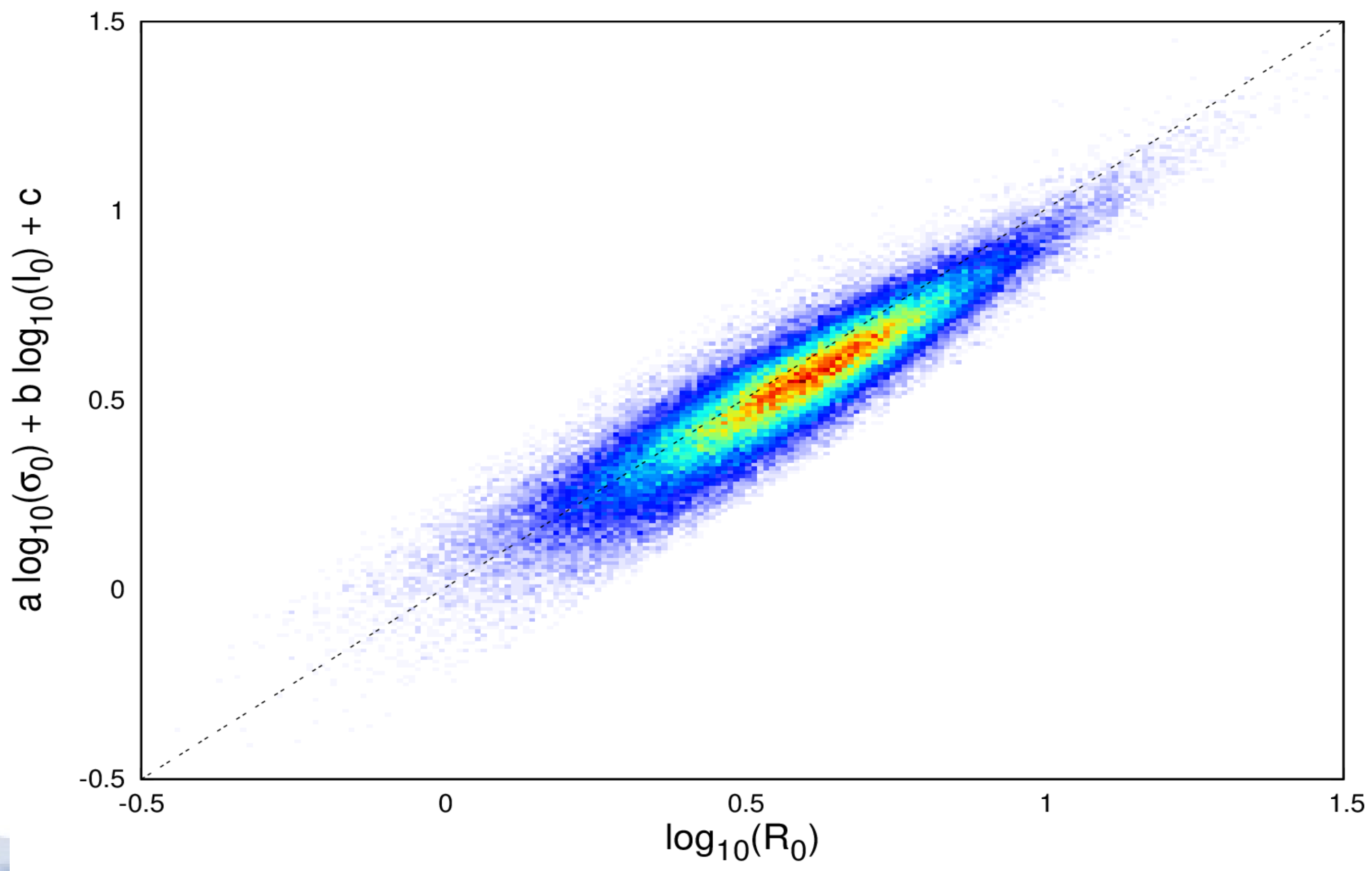
Calibrating the fundamental plane

- Empirical relation for elliptical galaxies

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

- 3 parameters:
  - **physical scale radius** R_0
  - **central velocity dispersion** σ_0 (redshift independent)
  - **surface brightness** μ_0 (redshift independent)
- redshift-independent distance indicator
- Identifying elliptical galaxies in SDSS using **GalaxyZoo** (Linott+ 2008, 2011)

- Largest sample ever (119 085 galaxies from SDSS) to fit the fundamental plane (Saulder+2013, Saulder+2015a)
- **18.5 % distance accuracy** for individual galaxies



Group catalogue

- Model of the local universe
- **SDSS DR12 data + 2MRS data** (to compensate for the saturation bias of SDSS spectroscopy)
- Calibrated (using mock catalogues based on the Millennium simulation) and applied a **modified FoF-algorithm** based on Robotham+ 2011
- Special attention to the completeness and accuracy of group masses

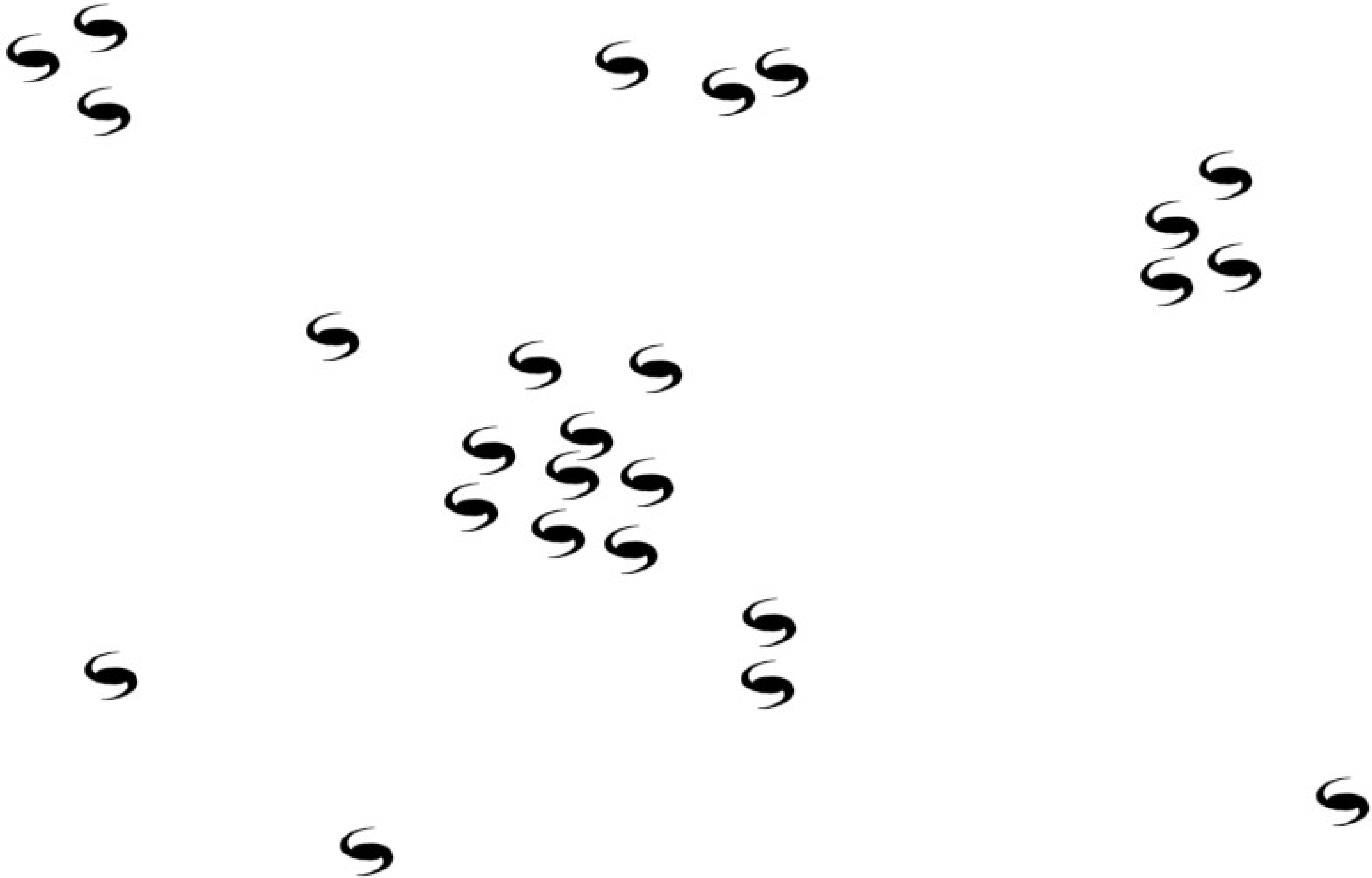
- Also further improve the redshift independent distance measurements

- Four catalogues published in Saulder+ 2016:
  - SDSS group catalogue
  - 2MRS group catalogue
  - SDSS based **fundamental plane distance group catalogue** (using the SDSS group catalogue and the fundamental plane calibrations from Saulder+ 2015)
  - **Catalogue of finite infinity regions** derived from a combination of the SDSS and 2MRS group catalogue

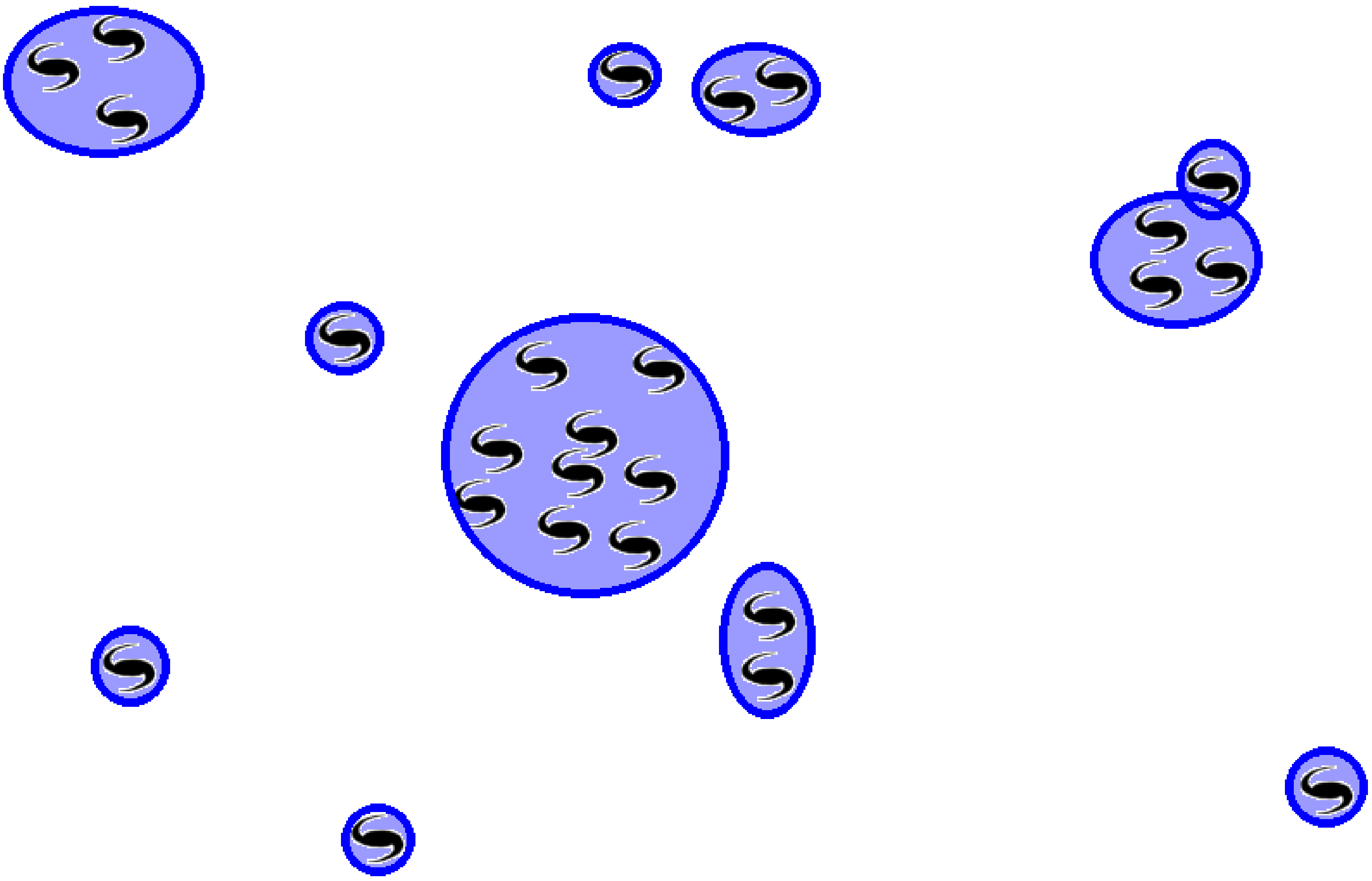
Modelling finite infinity regions

- Merging SDSS and 2MRS group catalogues
- Rescale masses
- Using the group masses to assign **spherical regions** with an **on average re-normalized critical density**.
- Iteratively merging enclosed groups

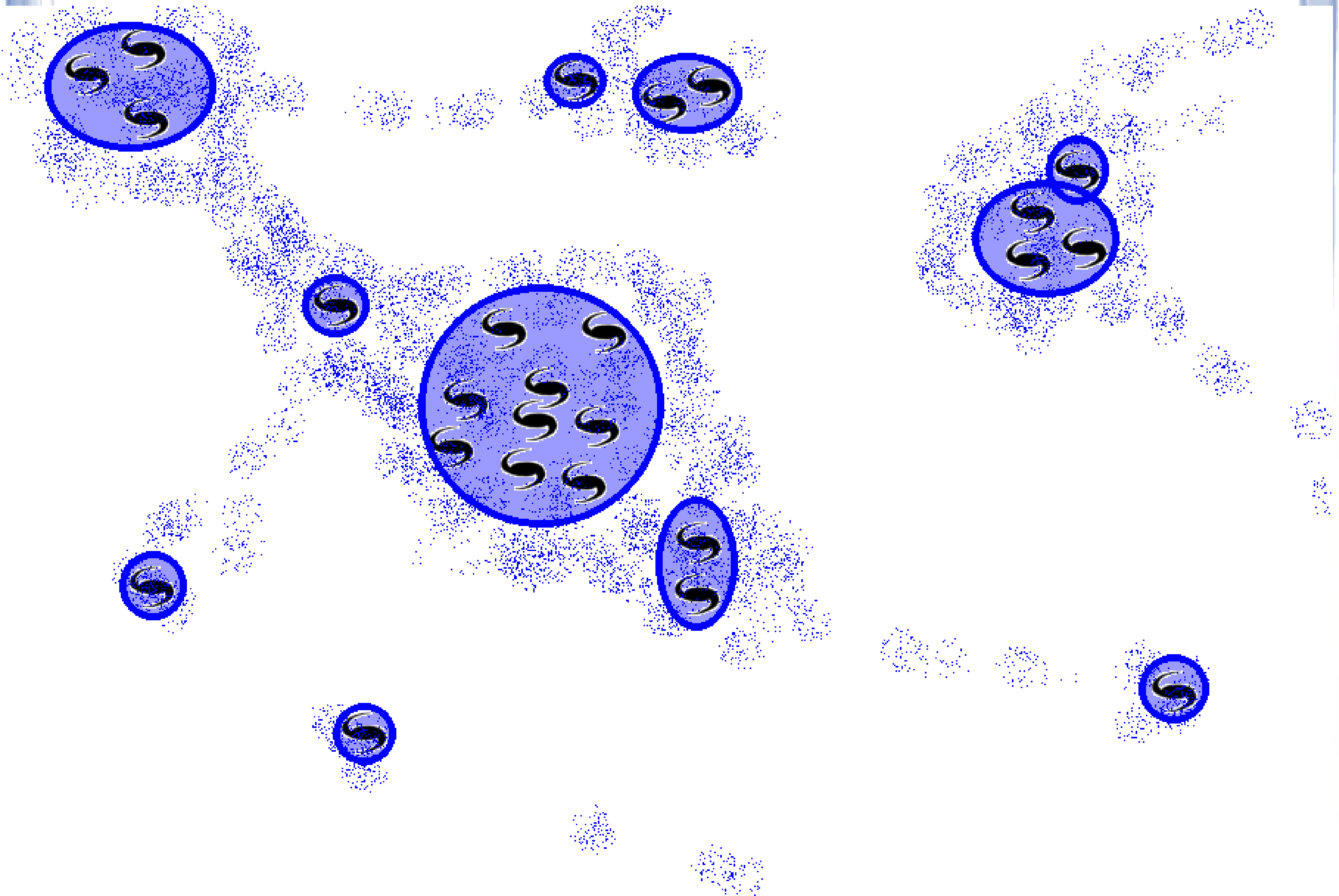
Observed/simulated distribution of galaxies



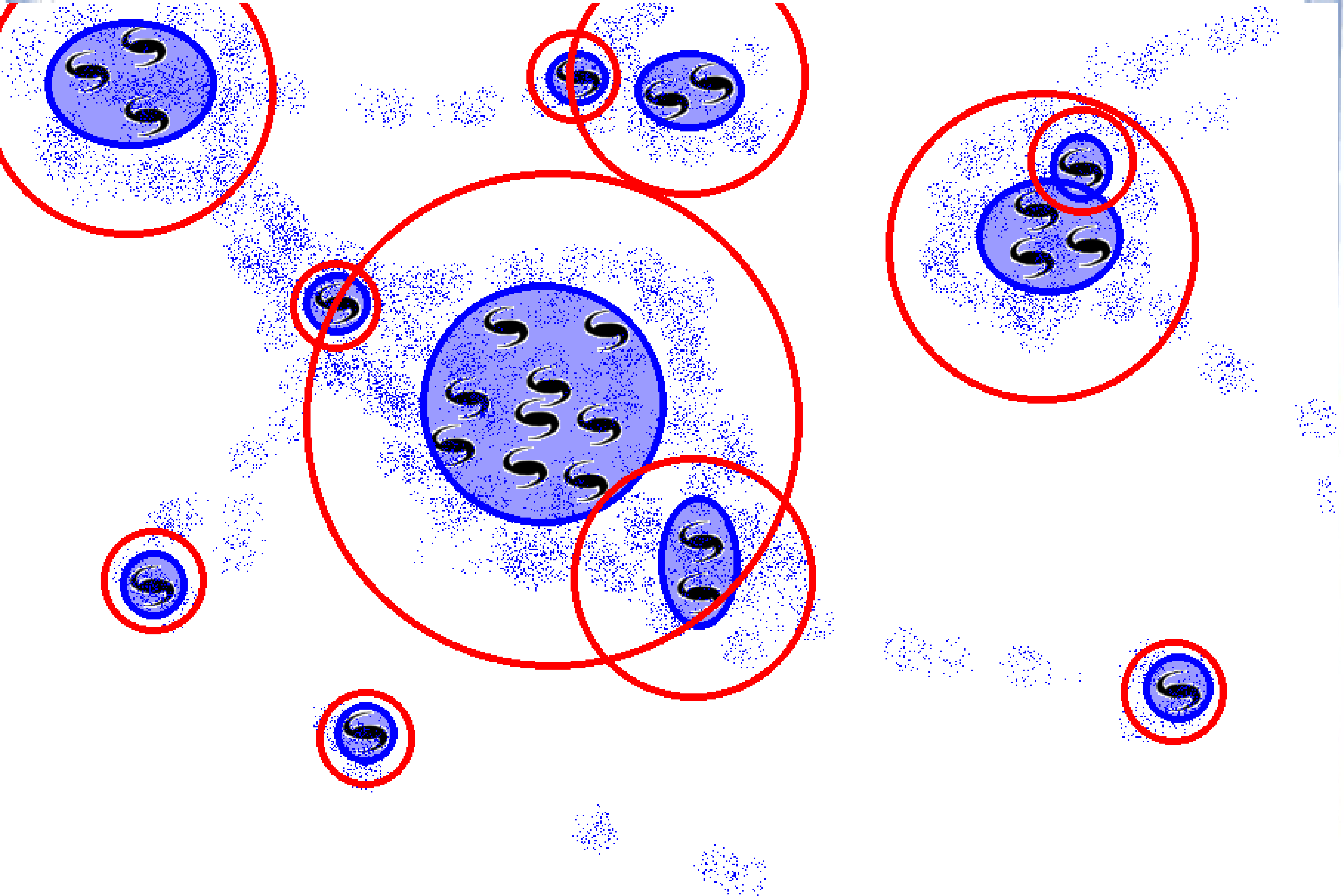
Calculate/use dark matter halos (FoF groups)



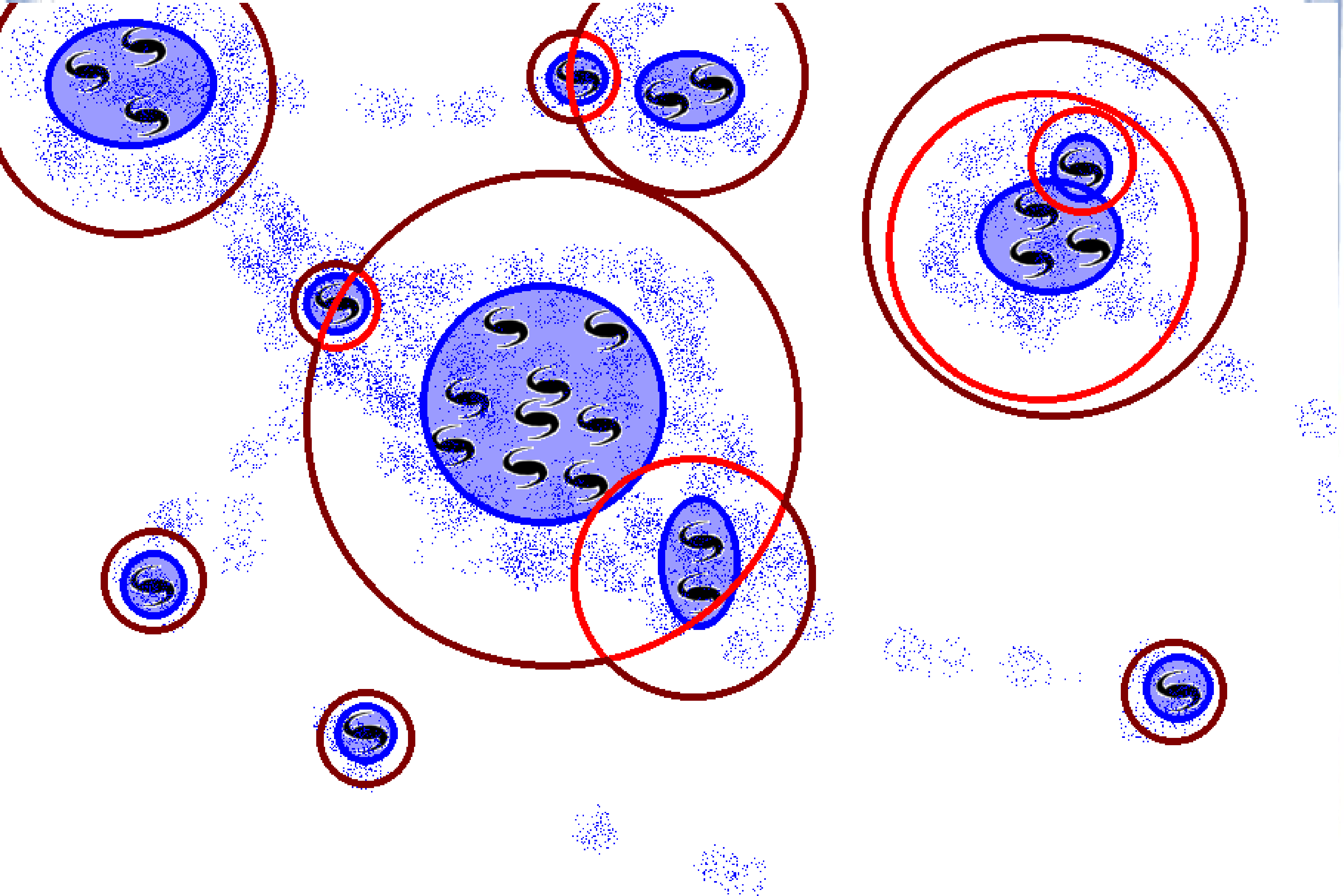
There is also dark matter outside the halos and unbound in the halos.



Assign finite infinity regions using the calibrations from Millimil

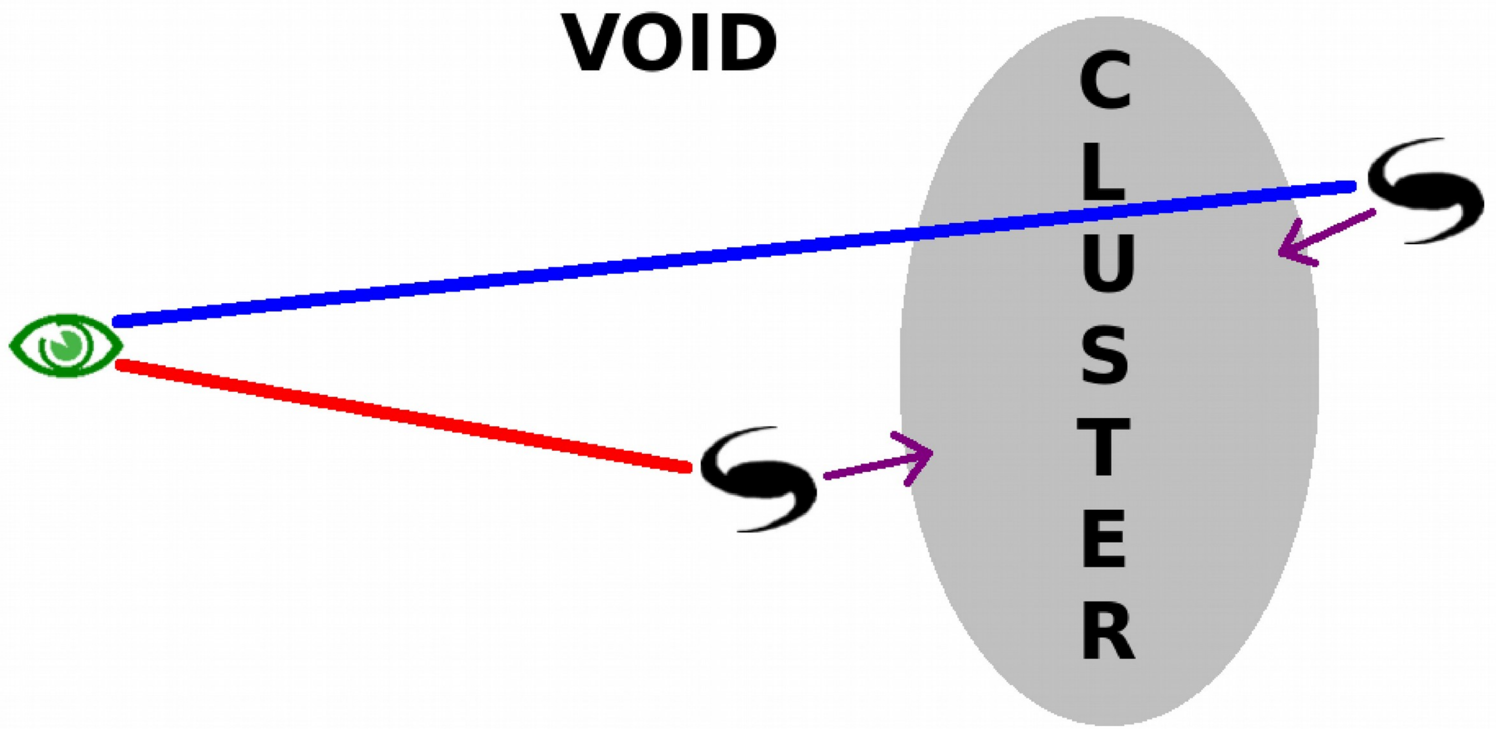


Iteratively merging enclosed finite infinity regions



Mock catalogues

- Consider potential biases, such as coherent infall (Kaiser effect)



- Millennium simulation
- Baseline for comparison to observational data

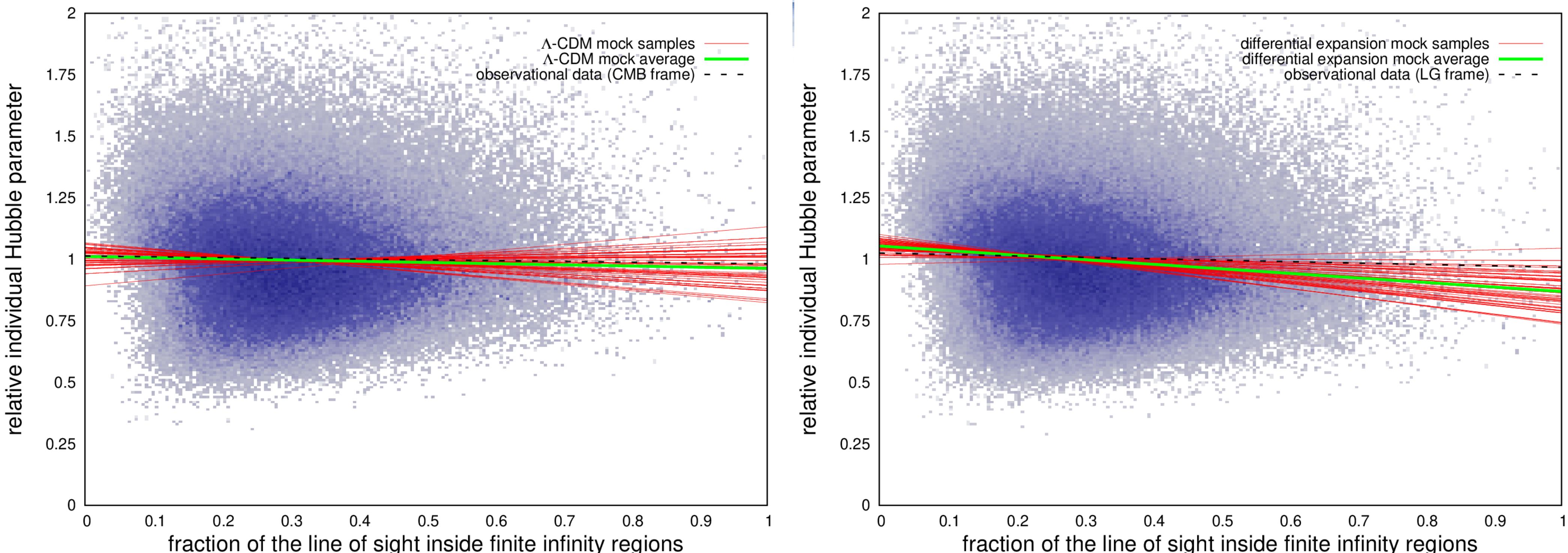
- For both models (Λ-CDM and timescape):
  - For groups and finite infinite regions: same mock catalogues as for the group finder calibration
  - Identifying early-type galaxies in the simulated data and introducing scatter of the fundamental plane
- For approximated timescape cosmology only:
  - Using the complete (unbiased) DM-halo information
  - Introducing different Hubble expansion rates of voids and walls by modifying observed redshift depending on the line of sight matter distribution
- Issues:
  - Dearth of rich groups in the Millennium simulation
  - Artificial introduction of timescape cosmology not ideal

Performing the test

- Calculate "**relative individual Hubble parameters**":
  - Fundamental plane distances to galaxy groups ($z<0.1$)
  - Media redshifts of galaxy groups
  - Normalization for comparability
- Calculate "**fraction of the line of sight within finite infinity regions**":
  - Model of finite infinity regions ($z<0.11$)
  - Line of sight to galaxy groups intersecting them
- For observational data and all mock catalogues

Statistical Analysis

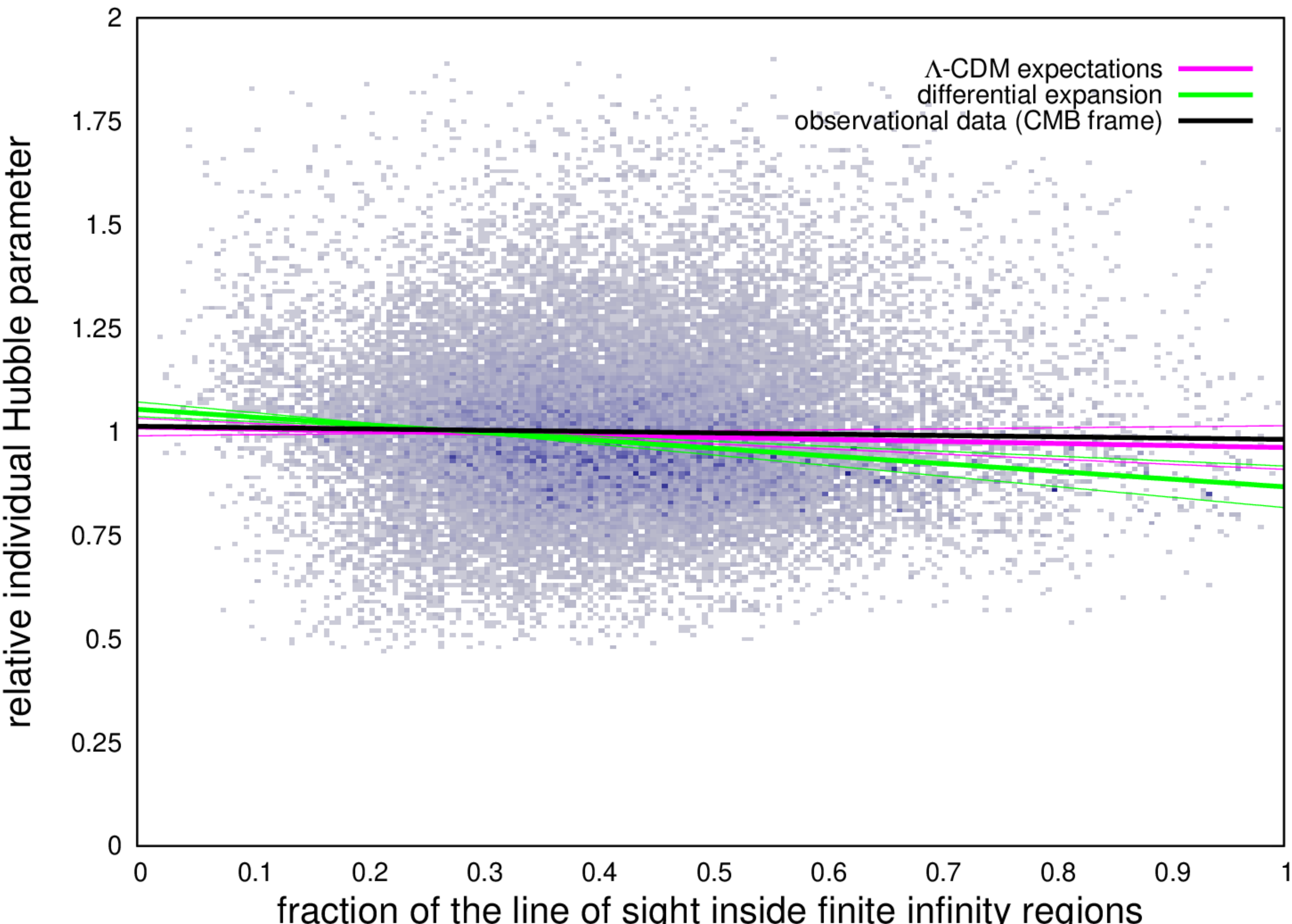
- We have:
  - Observational data (covering about 23% of the sky … almost ¼ of the sky)
  - 8 mock catalogues using Λ-CDM cosmology (each covering ⅛ of the sky)
  - 8 mock catalogues using timescape cosmology (each covering ⅛ of the sky)
- For comparability: all 64 (36 unique) **combinations of two mock catalogues** (of the same cosmology) → ¼ sky coverage



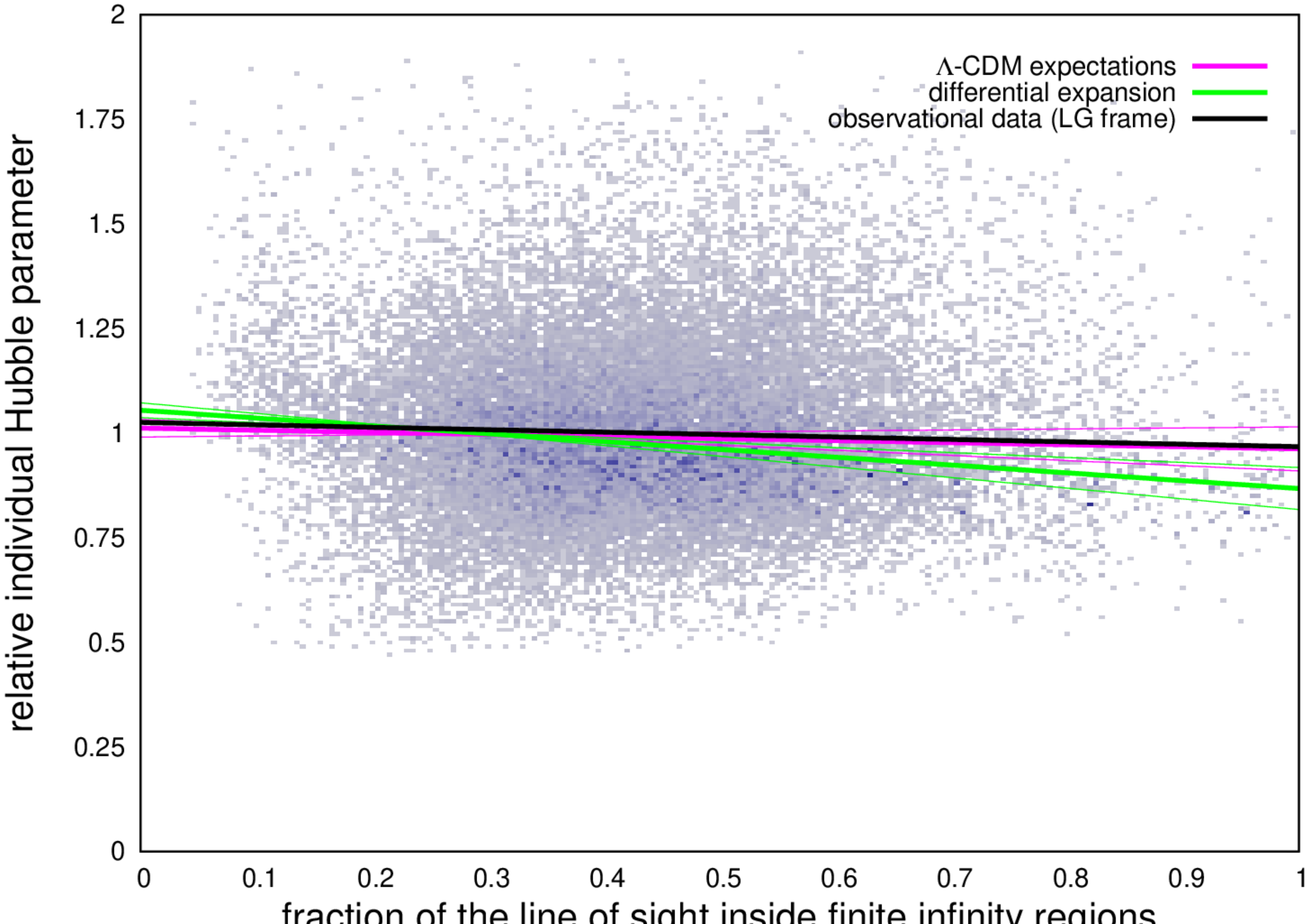
- **High variability** between the combined mock catalogues of the same cosmology (σ_k = 0.025/0.023 vs. ($k_{\Lambda\text{-CDM}}$-$k_{\text{diff.exp}}$) = 0.20)
- Large scatter in the relative individual Hubble parameters

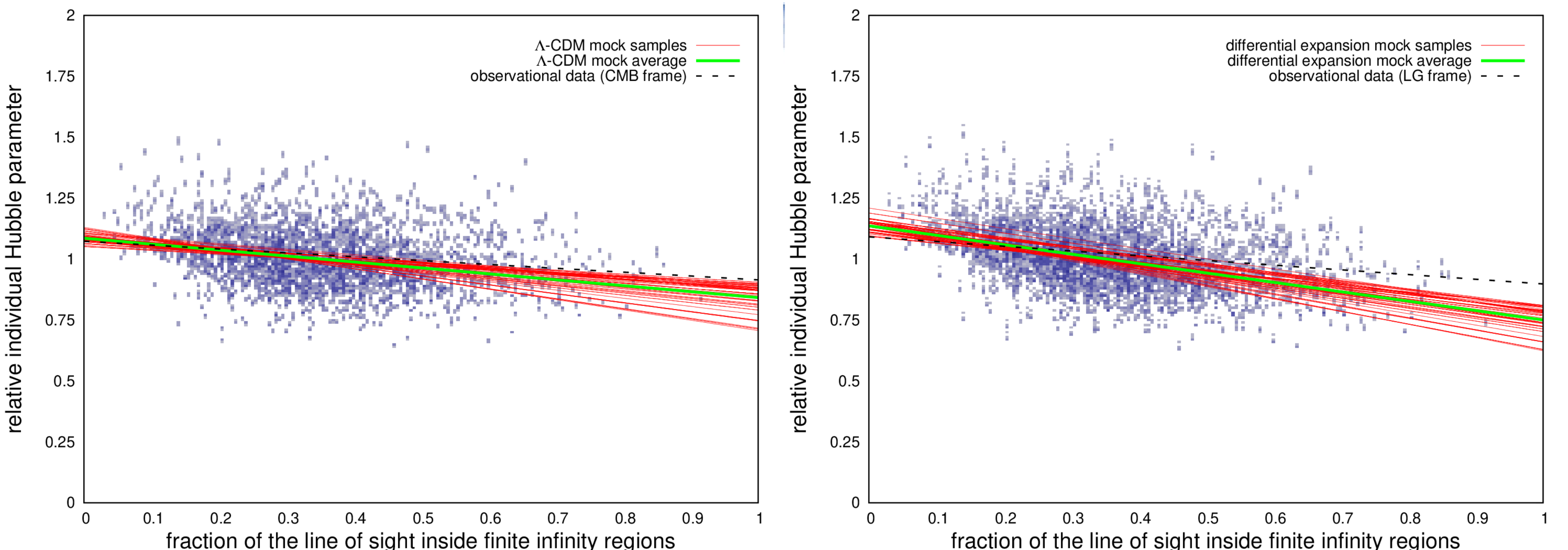
→ uncertainty in fundamental plane distances

- Observational data → close to Λ-CDM (in CMB-frame)



Observational data → close to Λ-CDM (in LG-frame)

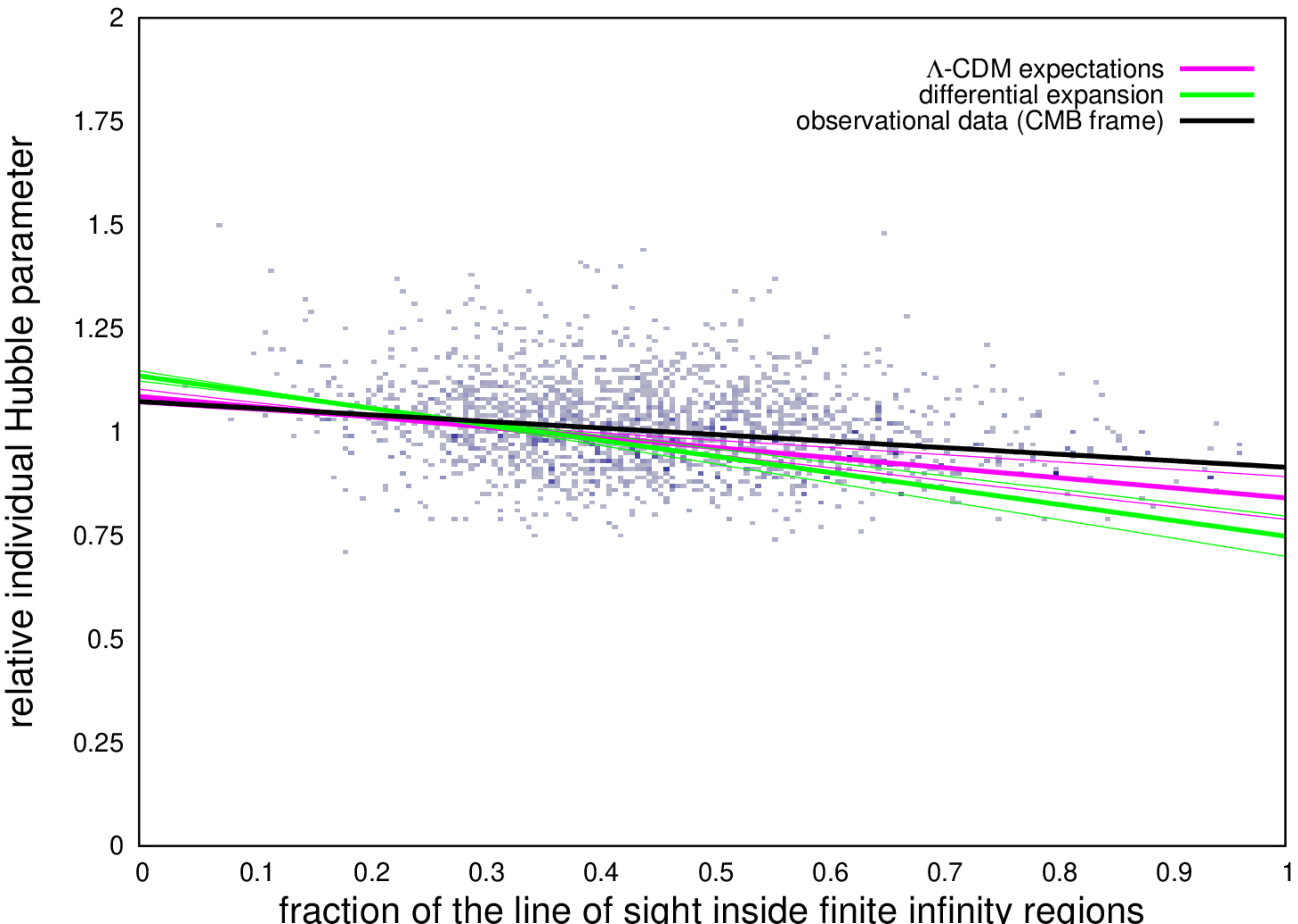




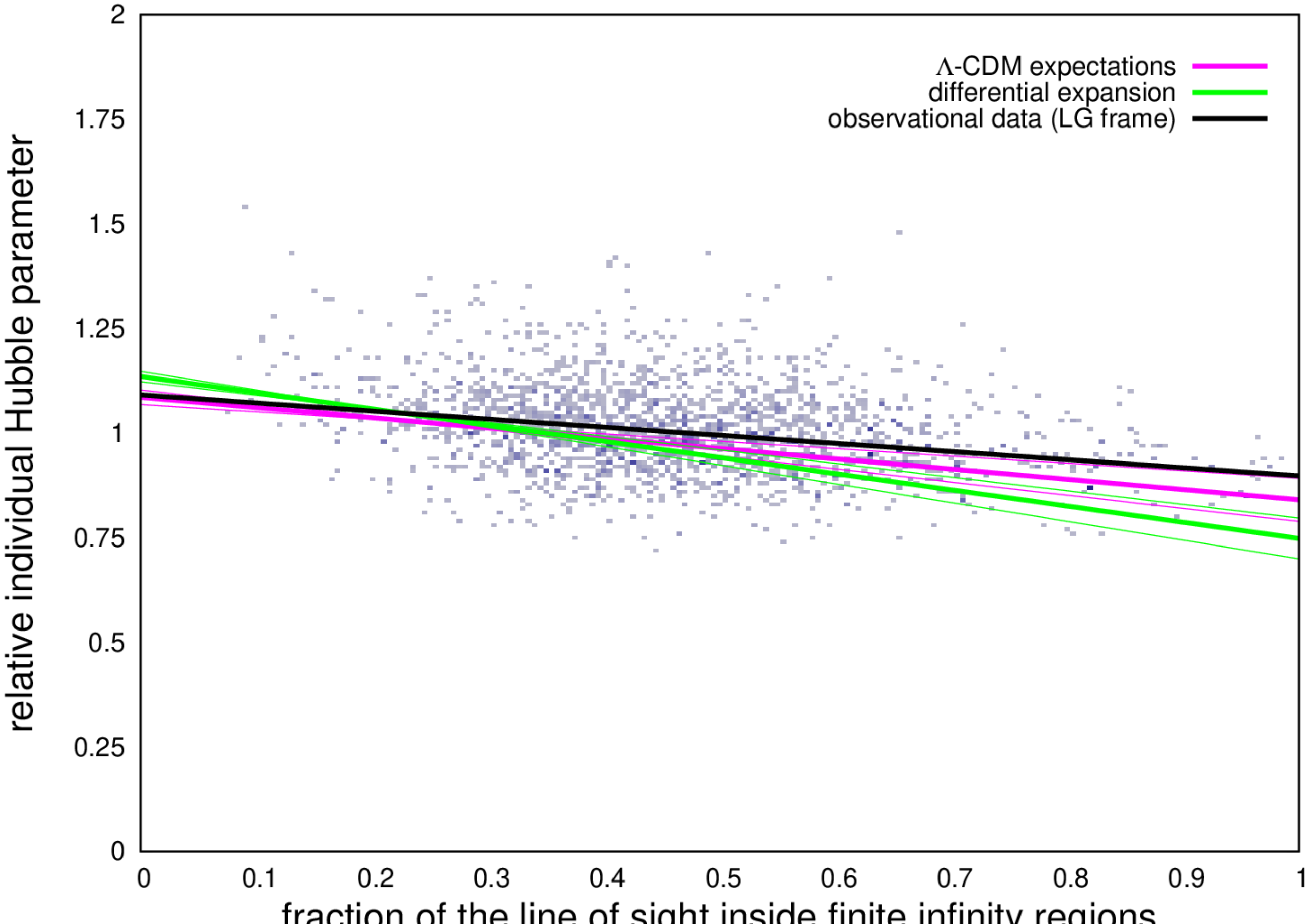
- Introduce additional selection criteria:
  - Distance limit: ~400 Mpc (≙ redshift 0.1)
  - **At least 3 early-type galaxies per group**

- Scatter slightly reduced (σ_k = 0.023/0.020), but also number of groups

- Observational data → timescape is 11-σ outlier (CMB frame)



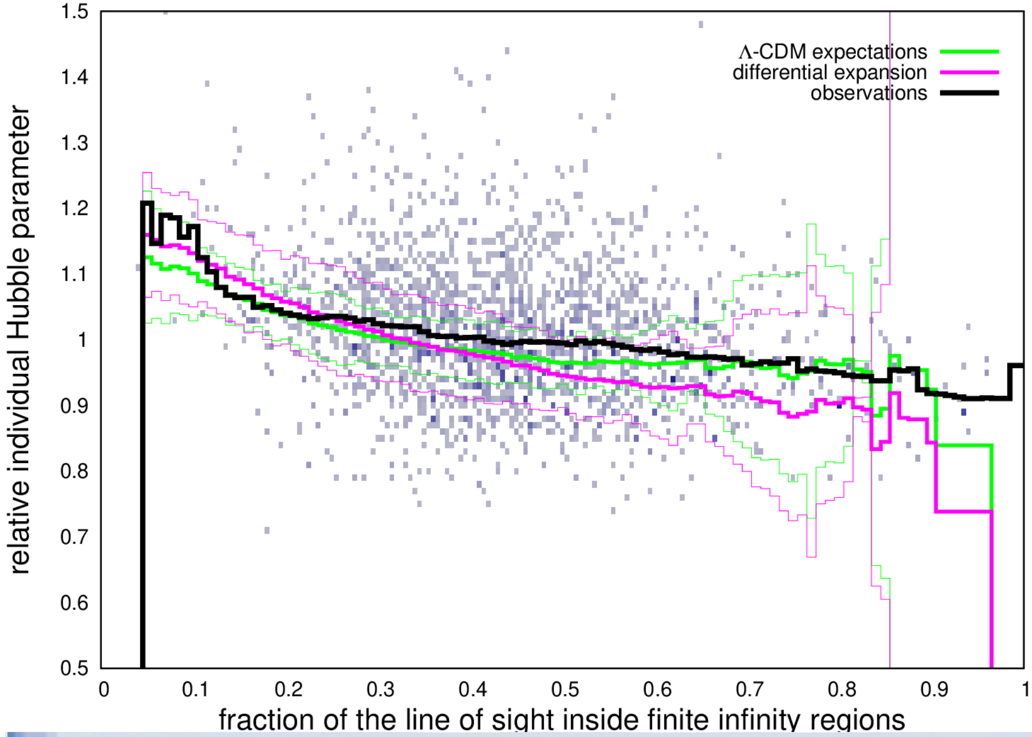
Observational data → timescape is 9-σ outlier (LG frame)

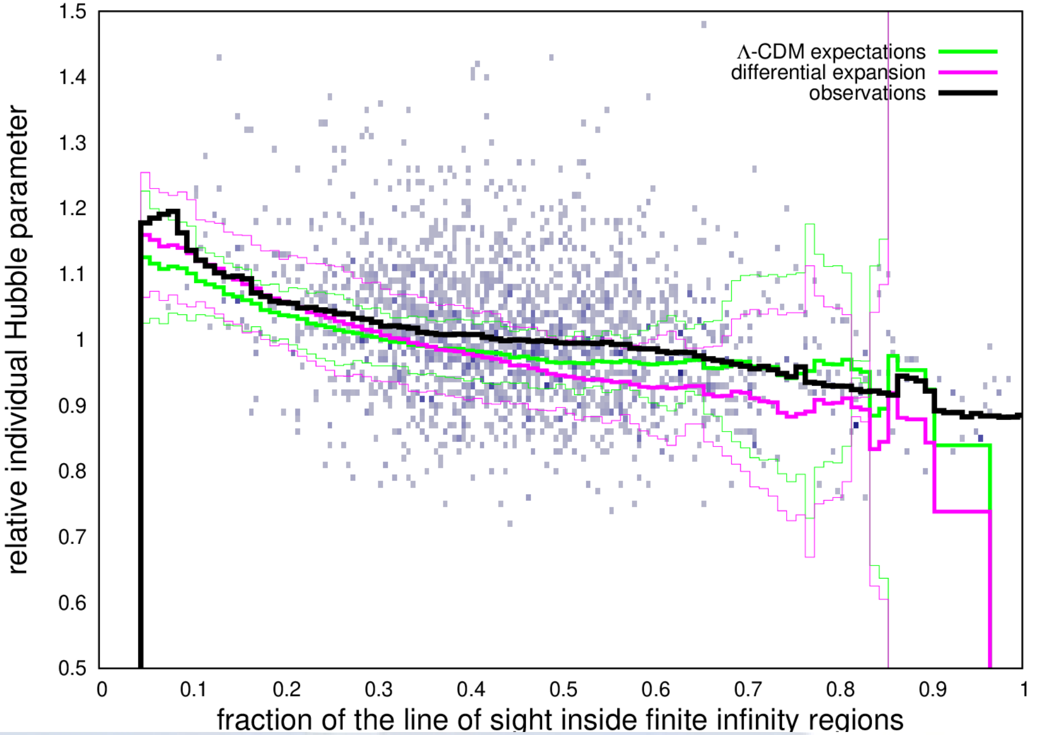


- **Observations are within ~3-σ of Λ-CDM**
- Observations agree best with the mock catalogues with the flattest gradient (highest average finite infinity region fraction … also observations have a similarly high fraction)
- Observations are clear outliers for the approximated timescape cosmology (differential expansion model)
- LG rest frame agrees better with the observations than the CMB rest frame (for both theories)

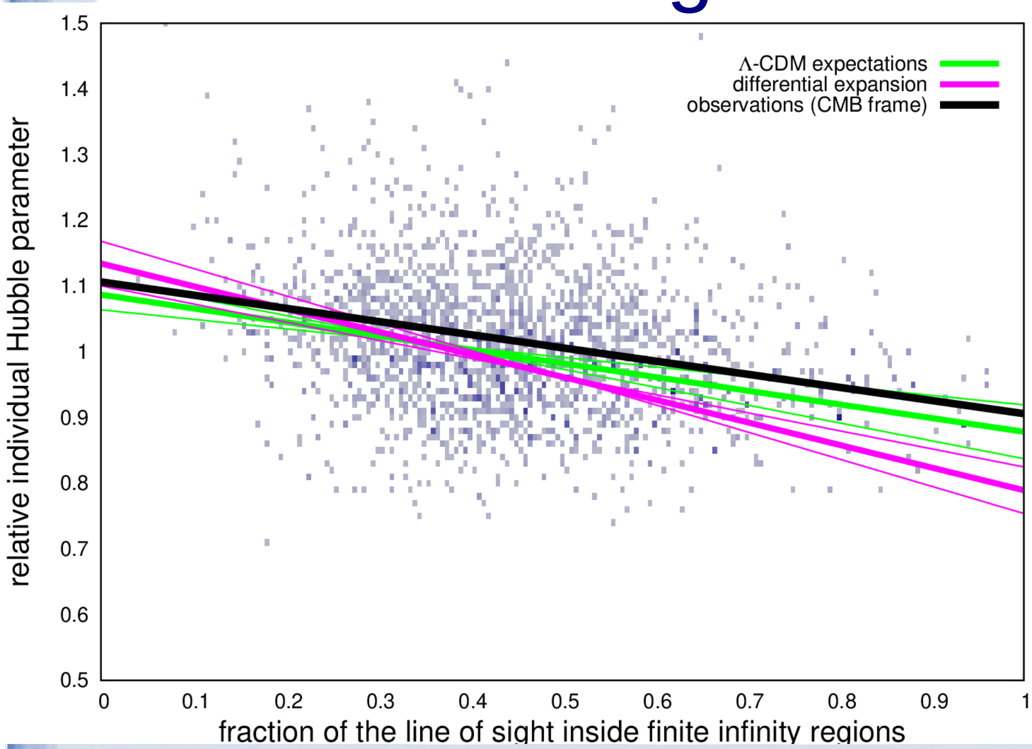
- additional tests for our data

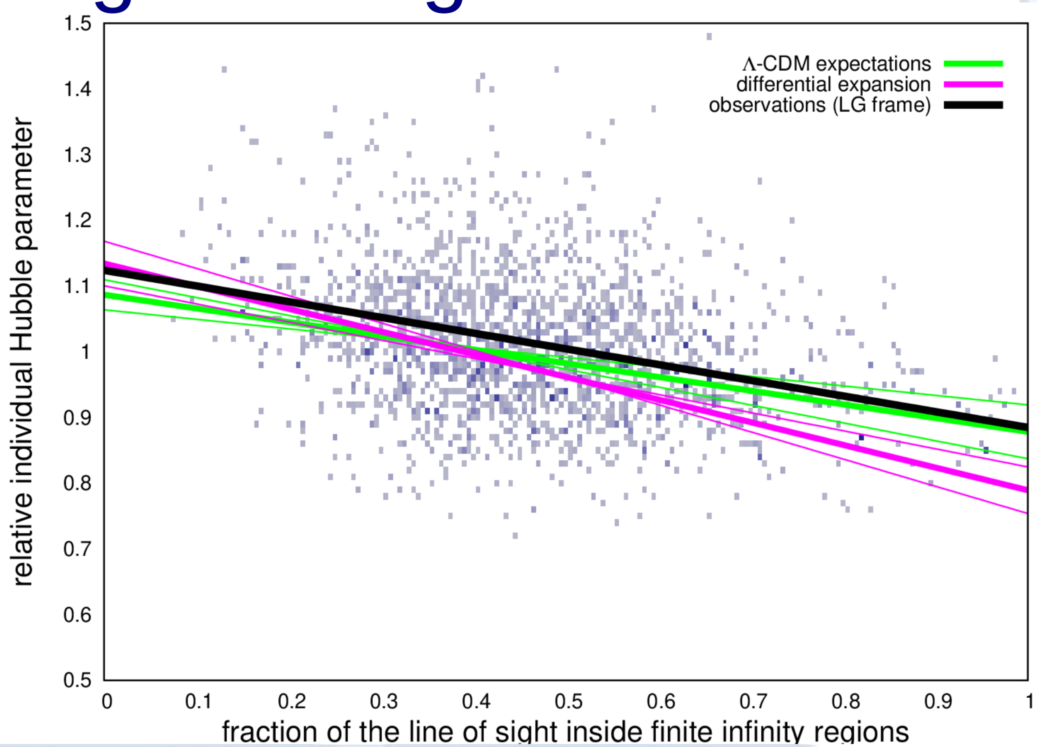
- Studying the data in bins
- Most bins agree better with Λ-CDM than with our timescape approximation.
- Some strange features in the case of mostly void line of sights … but very few galaxies.





- Fits to the bins yield similar results as the direct fits to the data
- We also tried a Kolmogorov-Smirnov test, which yielded low probabilities for both models, but better results for Λ-CDM
- A ξ^2 test also prefers Λ-CDM … especially one mock catalogue with a high average fi fraction



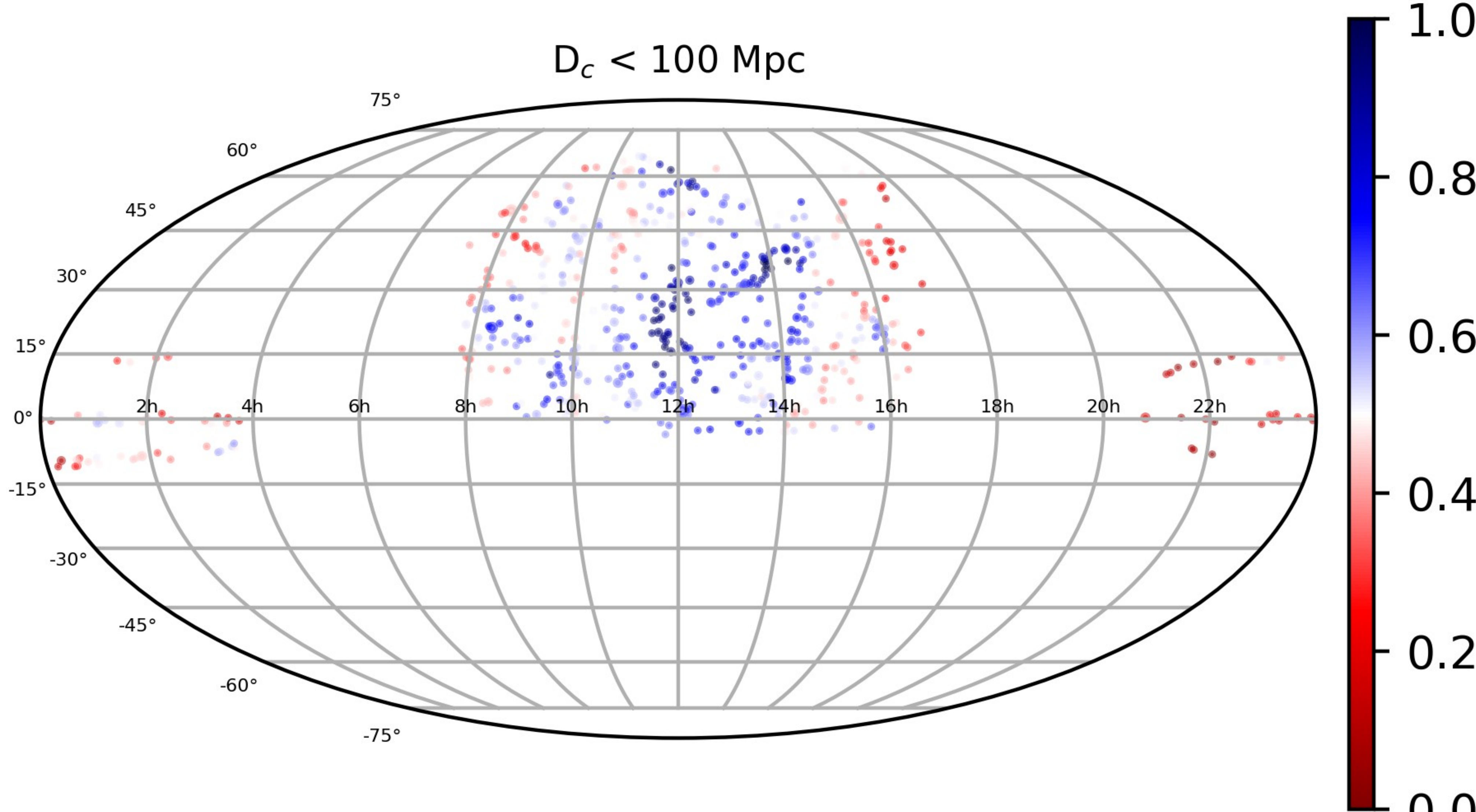


Summary of our Results

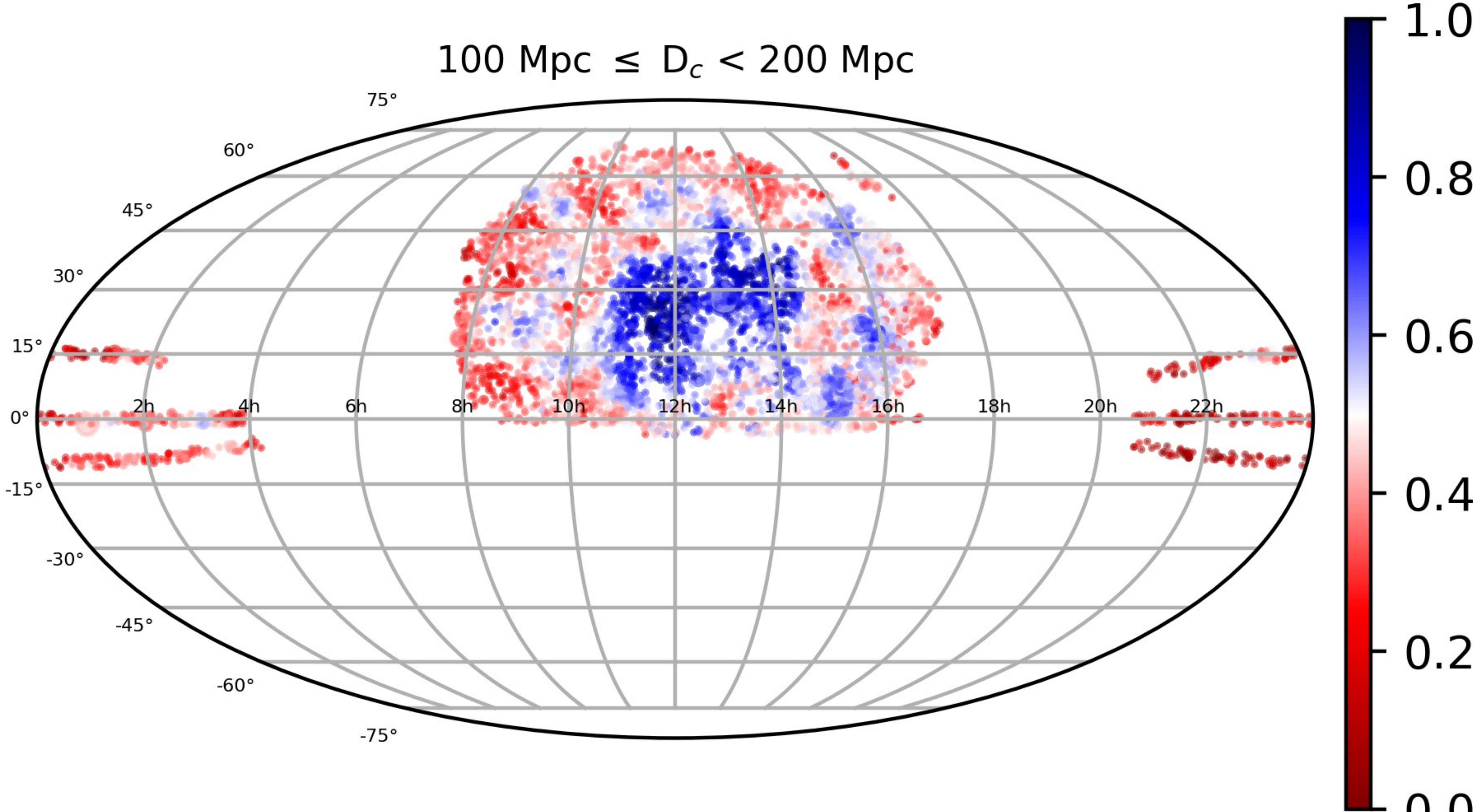
- Observations lie about 3-σ **above the average Λ-CDM predictions**, far **away from the timescape model** in the case of the direct fits
- Fits on binned data yield good agreements with Λ-CDM predictions, while timescape cosmology lies at a 2-σ level
- LG rest frame consistently gives slightly better results for timescape cosmology
- Scatter in the mock catalogues also depends on the average fraction of finite infinity regions … **closer to the observational value, better agreement of the gradient**

Open issues

- **Dearth of rich groups** in the Millennium simulation and slightly dated cosmological parameters
- **No** fully self-consistent numerical **simulation** using **timescape cosmology** (work in progress (Rácz+2017))
- Finite infinity regions are only approximated
- Possible **systematic effects** from using the **fundamental plane** (Joachimi+ 2015, Saulder+ 2016, Saulder+ submitted)
- **Limited sky coverage** (no test for antipodal correlations)

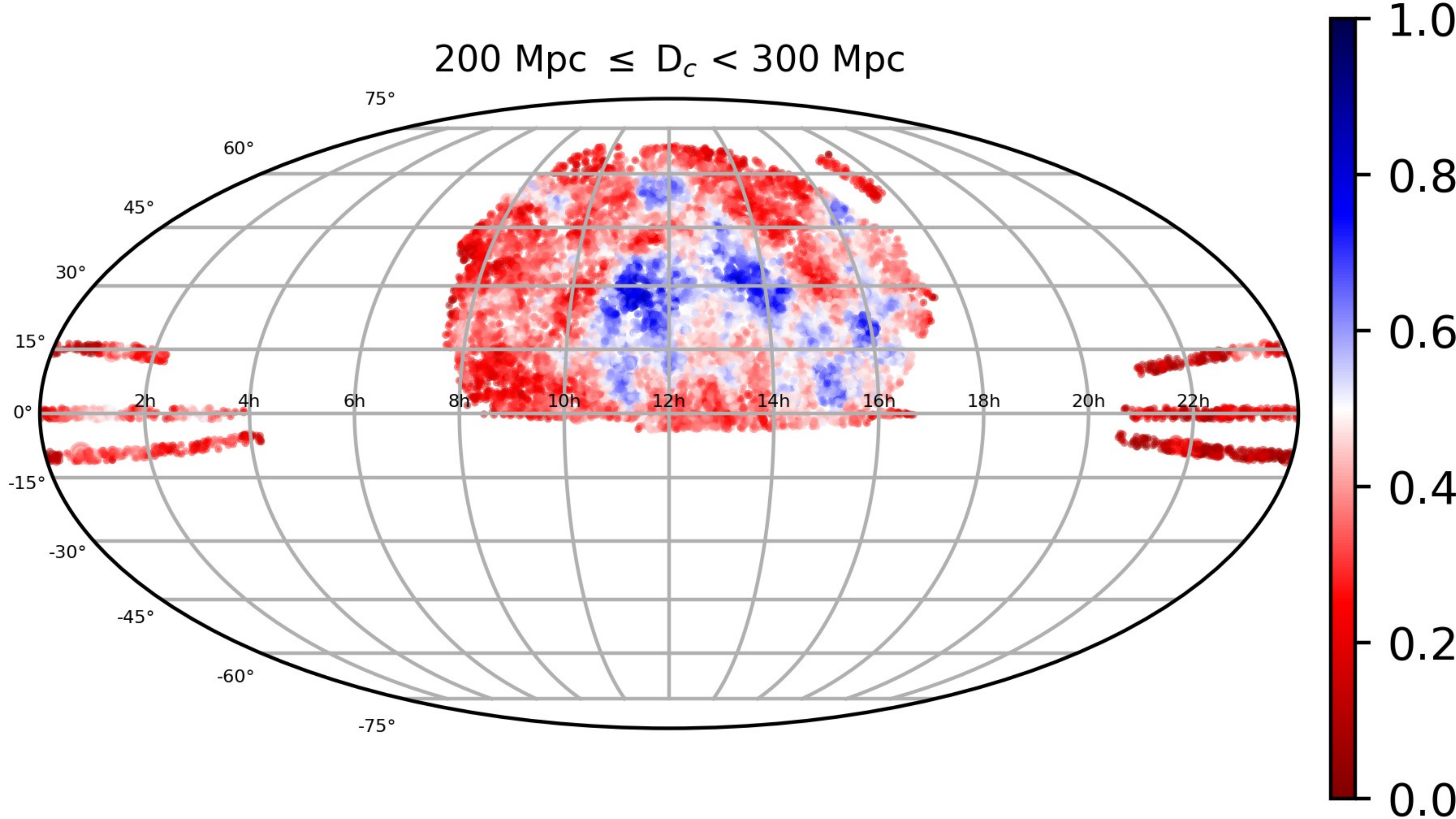


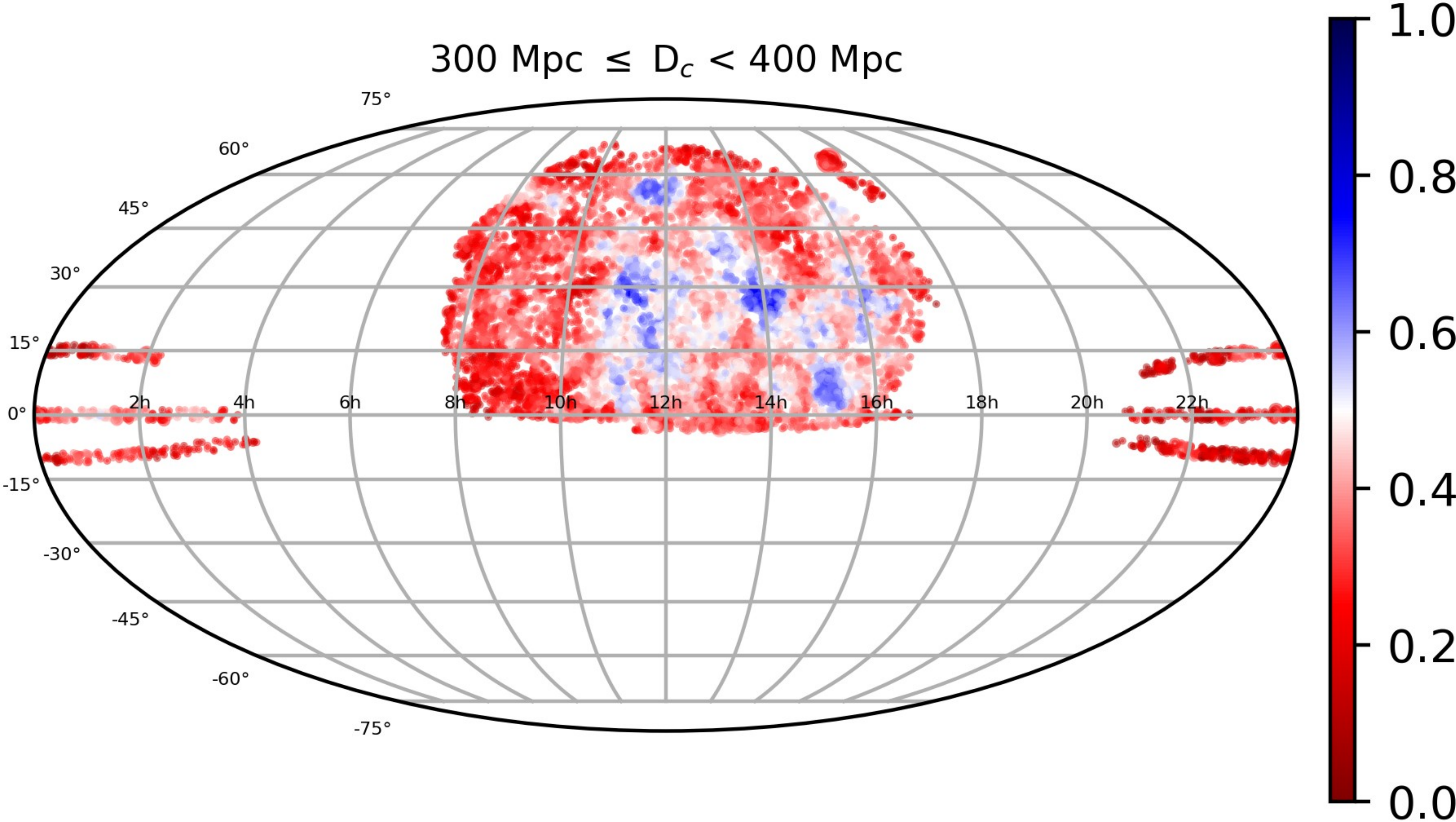
D$_c$ < 100 Mpc
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h
1.0
0.8
0.6
0.4
0.2
0.0

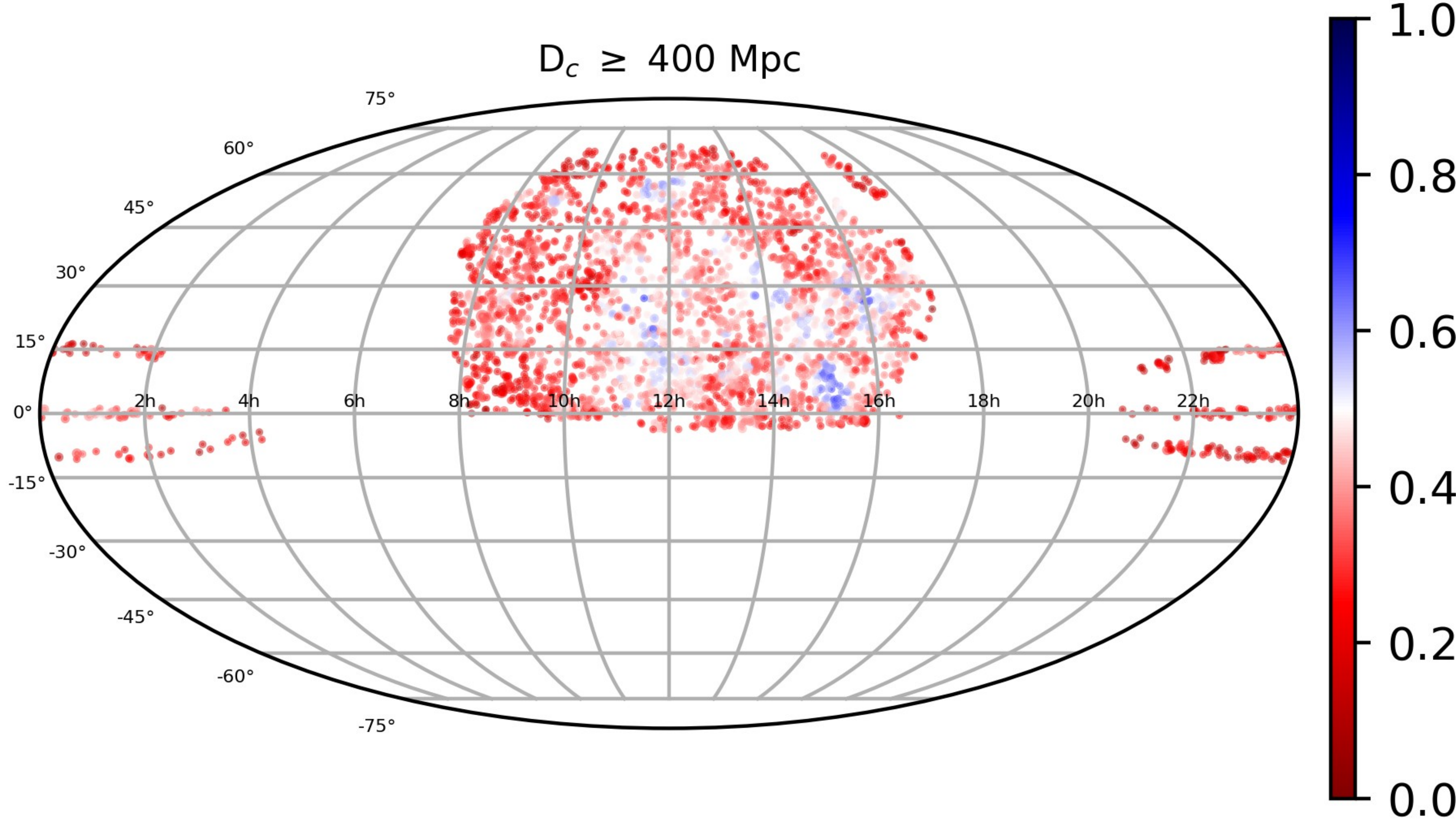


100 Mpc ≤ D$_c$ < 200 Mpc
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h
1.0
0.8
0.6
0.4
0.2
0.0

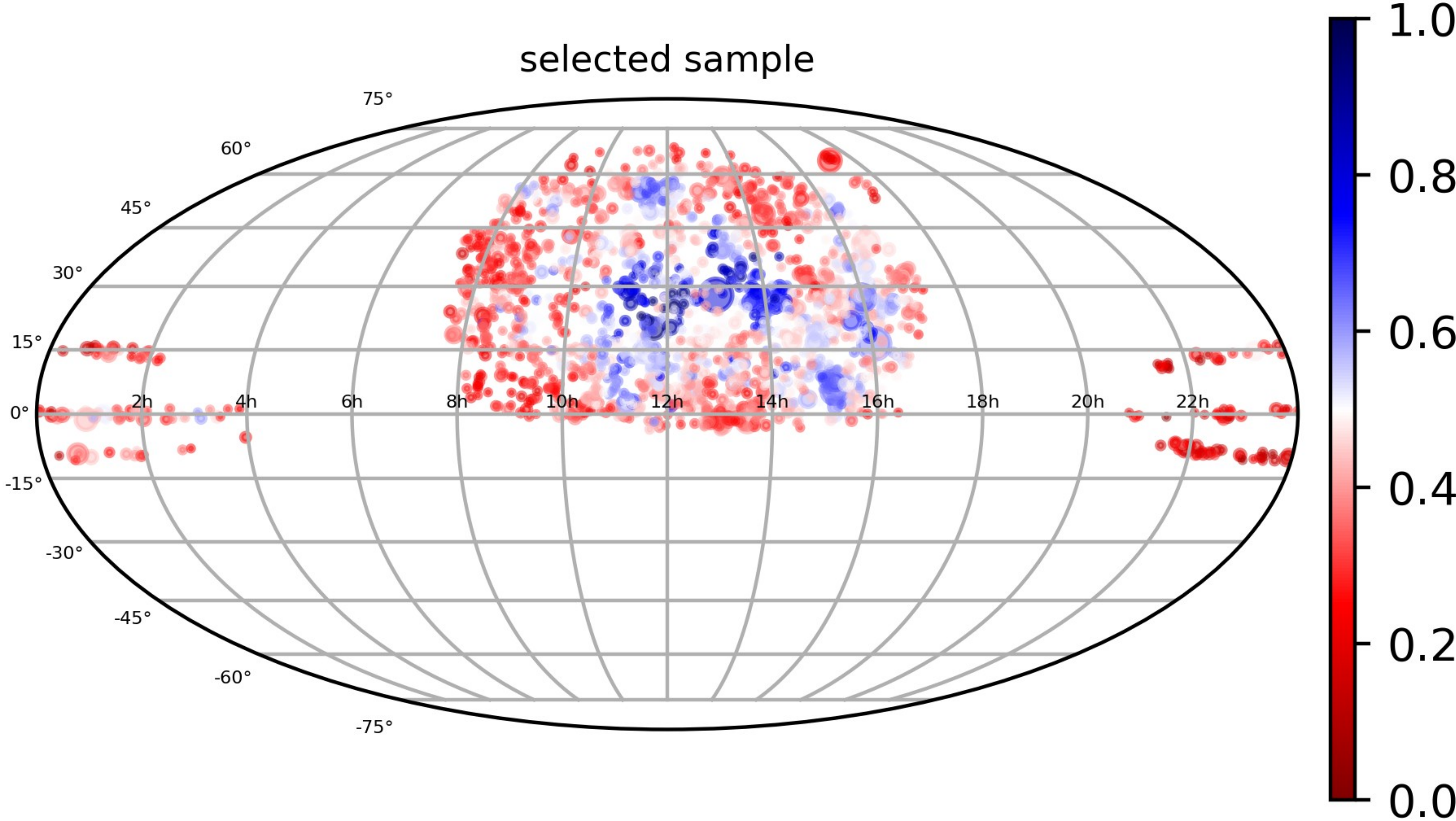
200 Mpc $\leq$ D_c < 300 Mpc




300 Mpc ≤ D$_c$ < 400 Mpc
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h
1.0
0.8
0.6
0.4
0.2
0.0



D$_c$ ≥ 400 Mpc
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h
1.0
0.8
0.6
0.4
0.2
0.0



selected sample
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h
1.0
0.8
0.6
0.4
0.2
0.0

Conclusions

- A meaningful test for timescape cosmology against Λ-CDM cosmology with **public survey data** and **simulated data** only **(Saulder+ 2018)**

- Good agreement of observational data with certain Λ-CDM mock catalogues, while in conflict with our approximated timescape cosmology model.

- **Inhomogeneities** can**not** explain the accelerated expansion of the universe

without dark energy

Comment & Reply

- David Wiltshire commented on our claims in Wiltshire 2018
- Approximation of timescape cosmology or not?
- Our model is based on Wiltshire 2007 approach … two phase model … no gradients in voids, because there is no description of them
- Differential expansion is a feature of even more general inhomogenous cosmological model

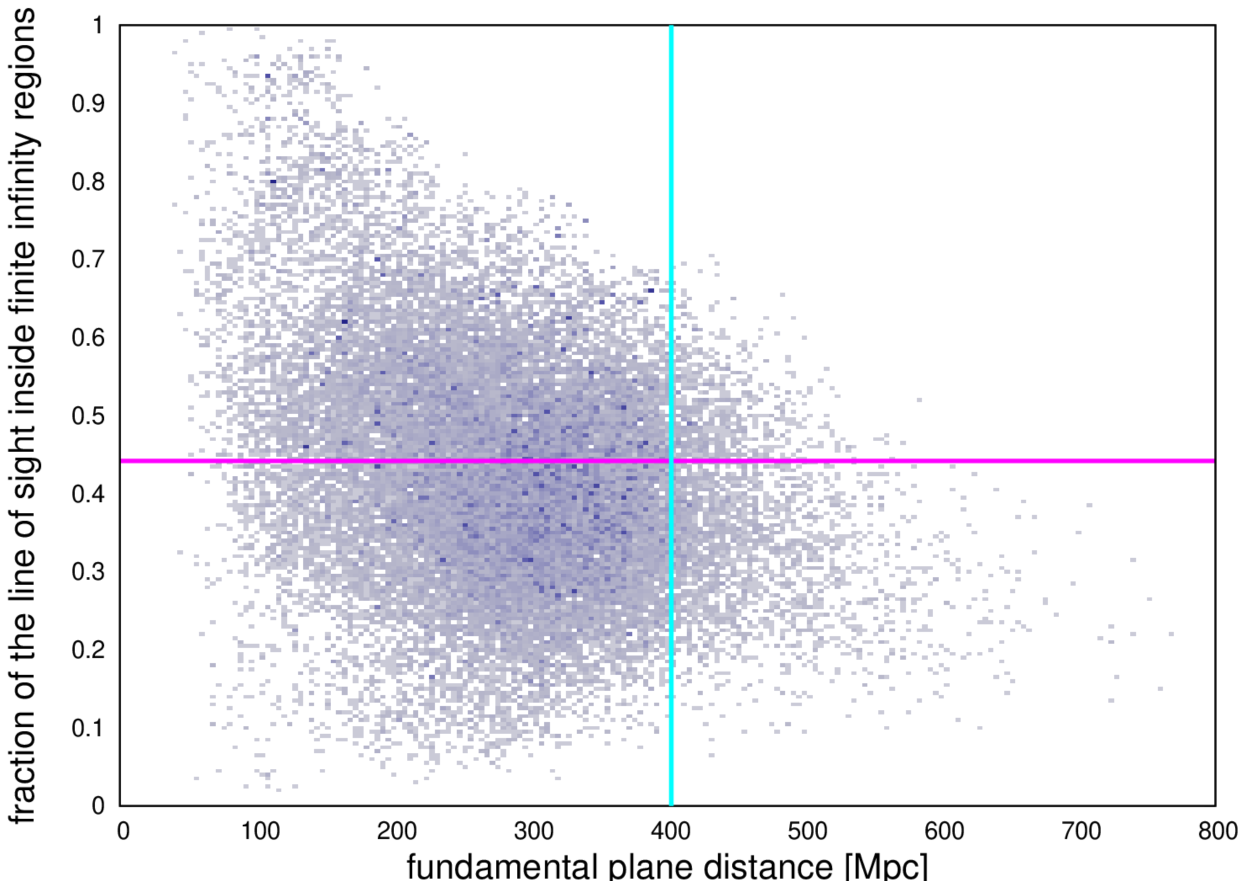
- (approximated timescape) mock catalogues are based on Newtonian dynamics (plus “deformation”)
- Kaiser effect might different in timescape cosmology
- No suitable simulations for timescape available → mocks should be a rough estimate of the effect
- Volumes of voids are different in timescape cosmology … accounted for via a bias factor

- **Observations agree with Λ-CDM** …

so either timescape cosmology does not work or is indistinguishable from Λ-CDM with our test

Outlook

- Deeper surveys will not improve the test



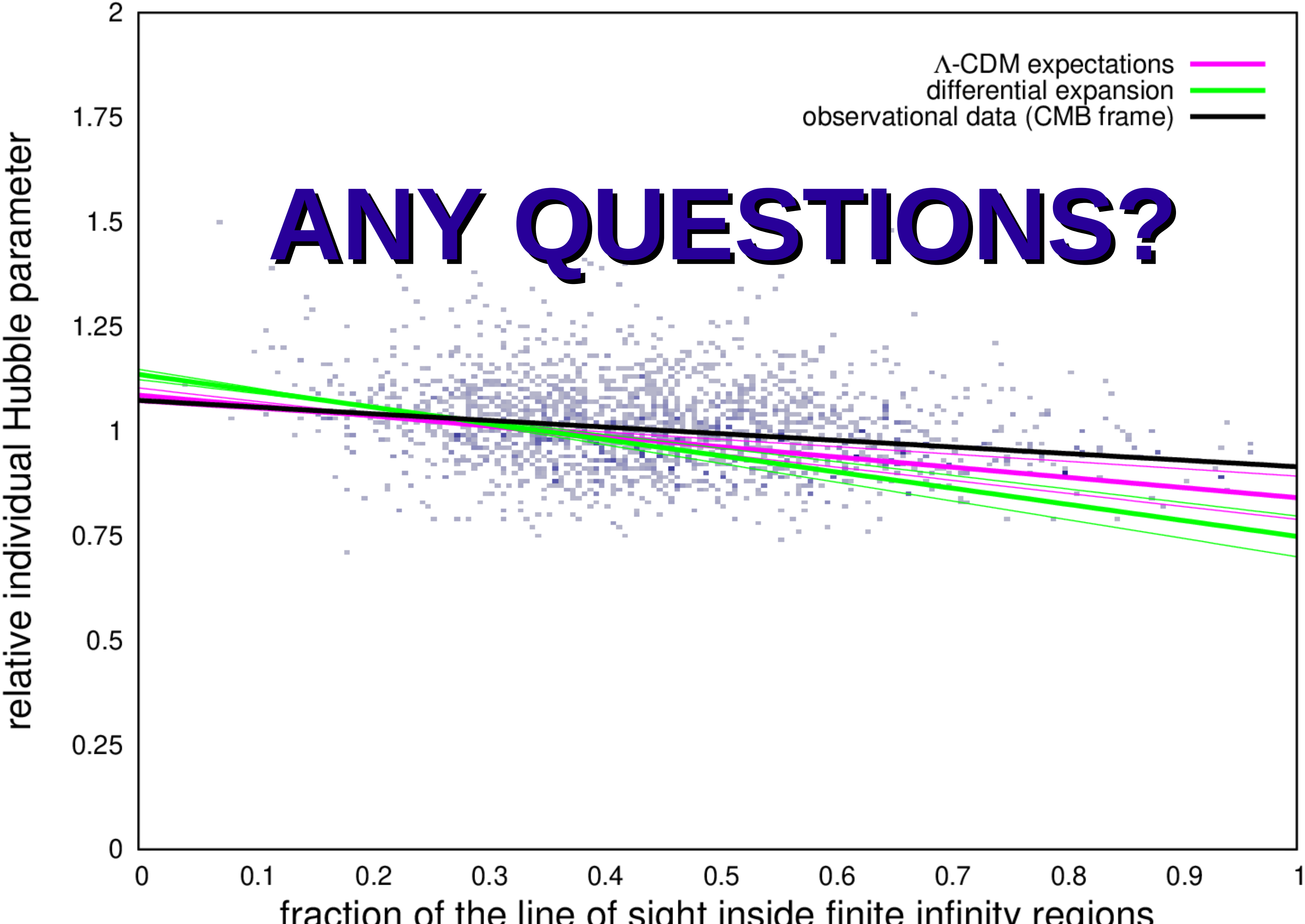
- However, a **larger sky coverage** could improve it: 6dFGS, Taipan, SDSS-V, … (but beware of systematics)

- **Other distances indicator** (Tully-Fischer relation, supernovae Typ Ia, …) → CosmicFlows-3 (Tully+ 2016)
- **Better numerical simulations!**

Why bother to further improve?

- Other models of inhomogeneous cosmology (Clarkson+ 2012/14, Umeh+ 2014a,b)
- Potential (smaller) impact on cosmological parameters (observational upper limit needed)
- Magnitude still disputed (Kaiser&Peacock 2015)

ANY QUESTIONS?



Additional slides

Comparison of parameters

Timescape cosmology

- H_0 = ~61.7 (void) /

  ~48.2 (wall) km/s/Mpc
- age = ~ 14.7 Gyr (wall)
- f_V = 0.76
- Ω_b/Ω_M = ~3.1

- from Leith+ 2007

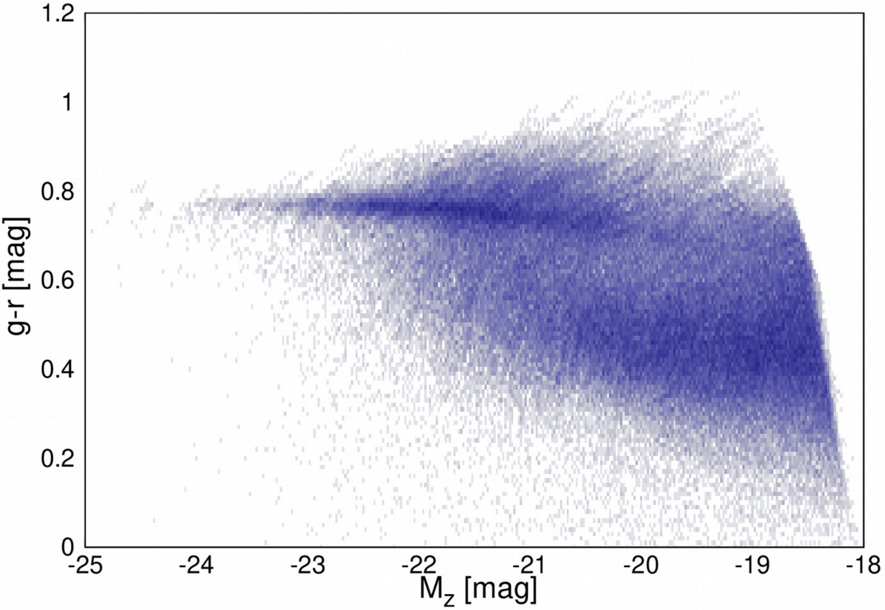
Λ-CDM cosmology

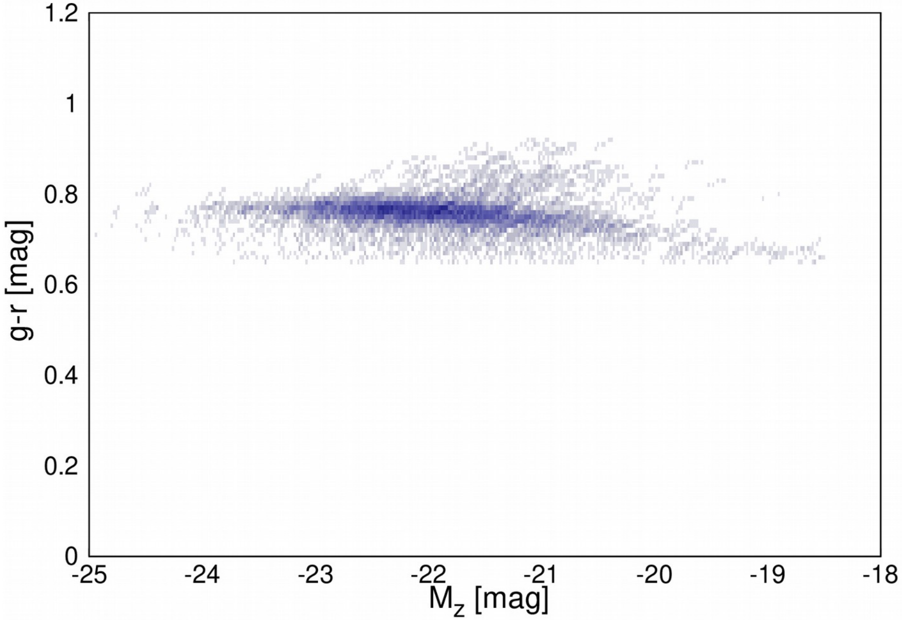
- H_0 = ~67.8 km/s/Mpc

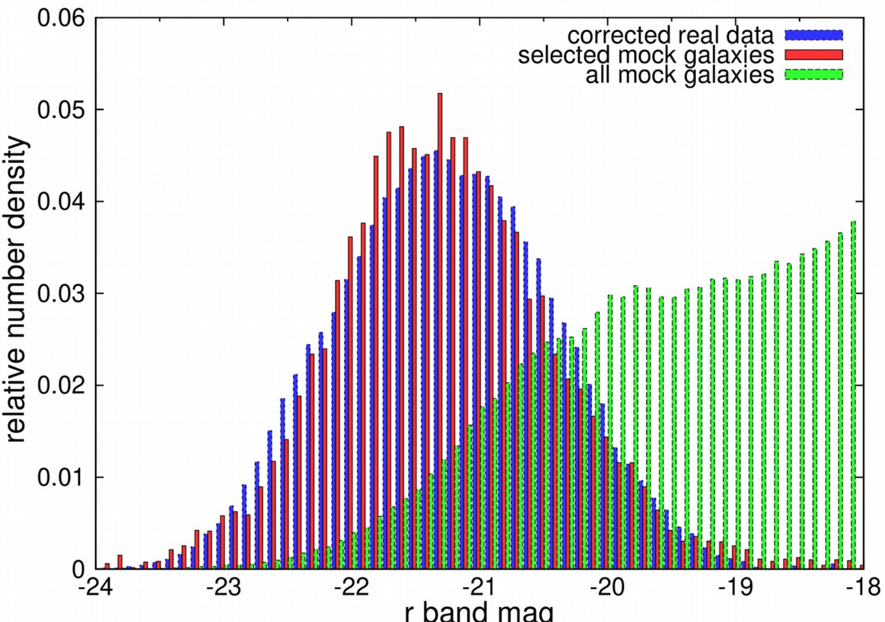
- age = ~13.8 Gyr
- Ω_Λ = 0.69
- Ω_b/Ω_M = ~5.4

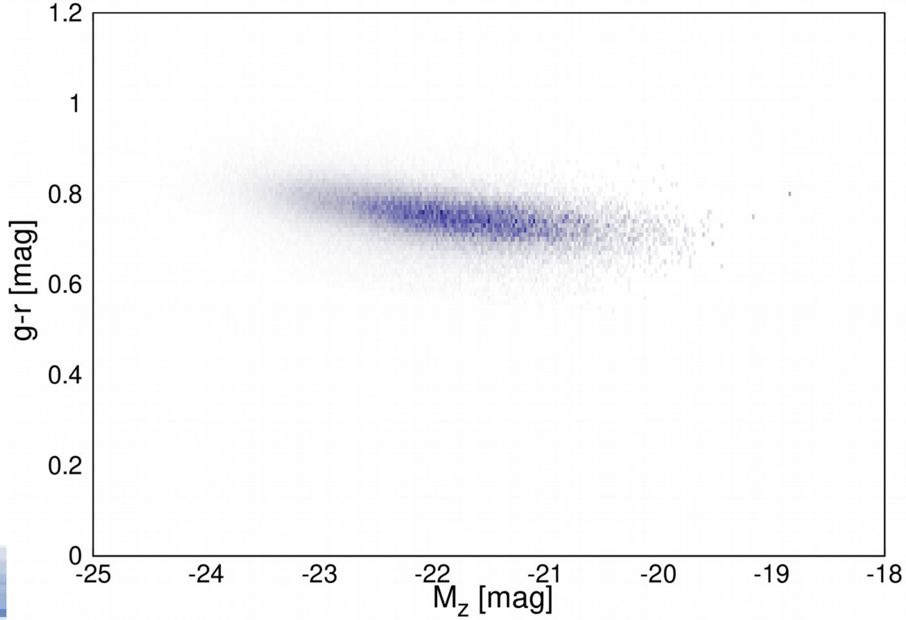
- from Planck XIII 2015

Identification of early-type galaxies in the Millennium simulation

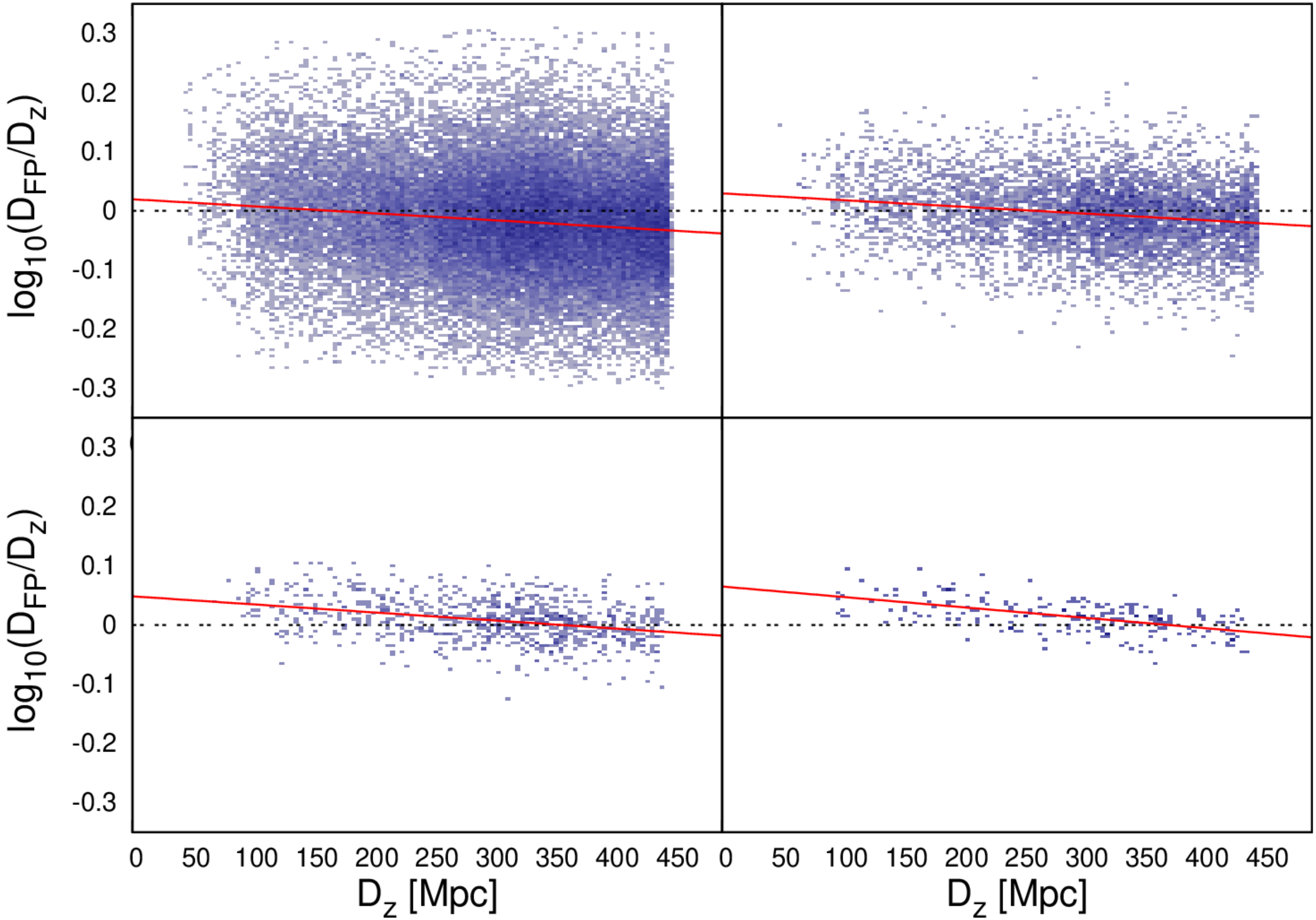


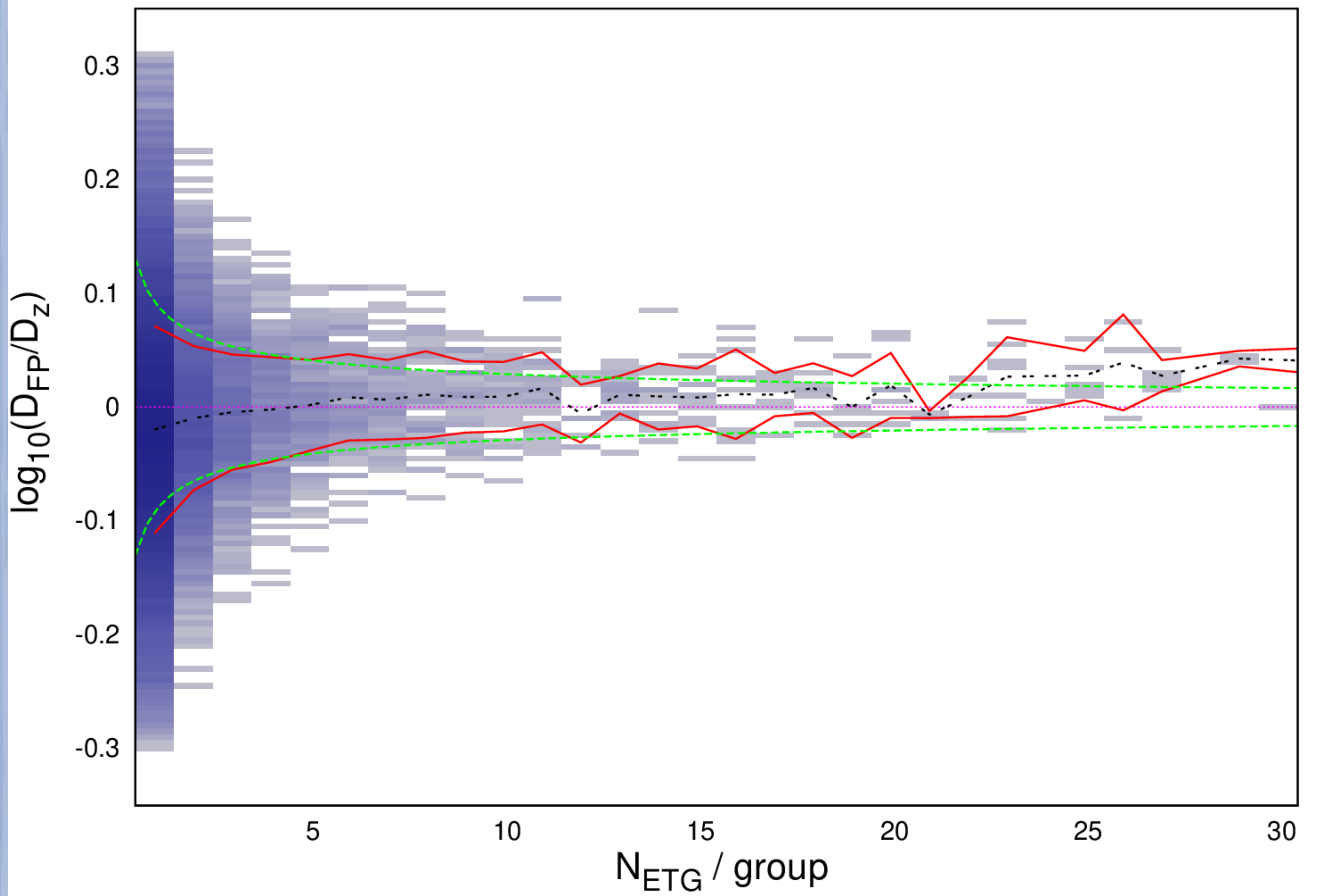






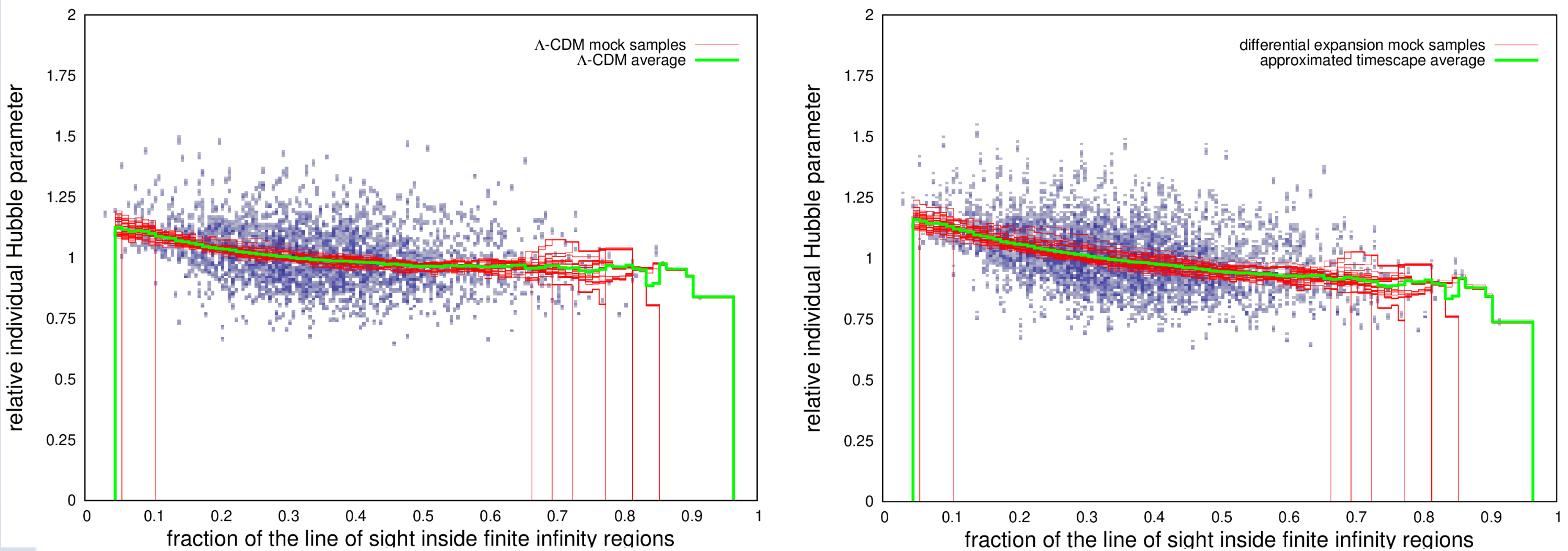
Fundamental plane biases





0.3
0.2
0.1
0
-0.1
-0.2
-0.3
$\log_{10}(D_{FP}/D_z)$
5
10
15
20
25
30
N_{ETG} / group

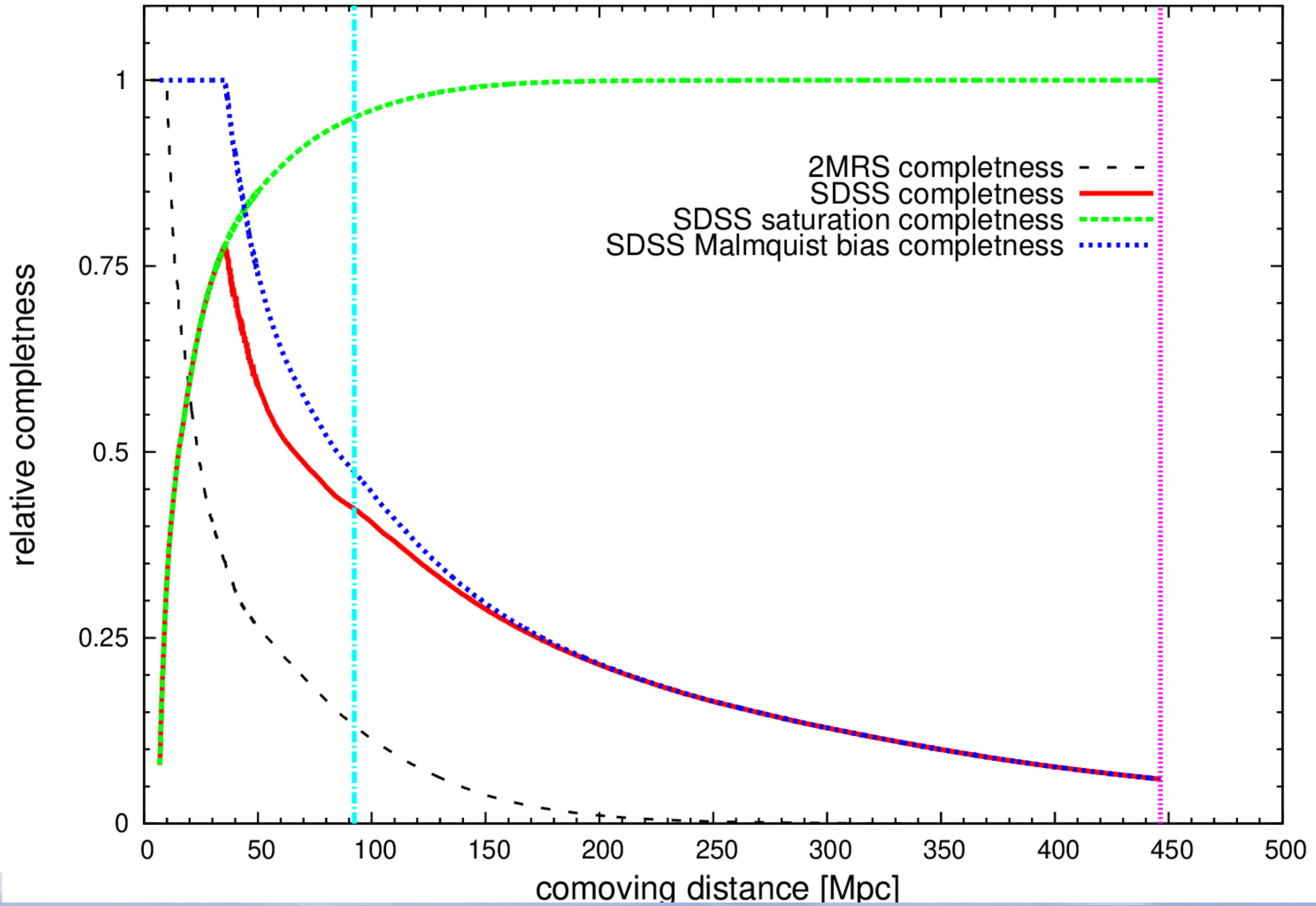
Binned analysis



- Sensitive to normalization
- Larger scatter in outer bins

Merging of SDSS and 2MRS

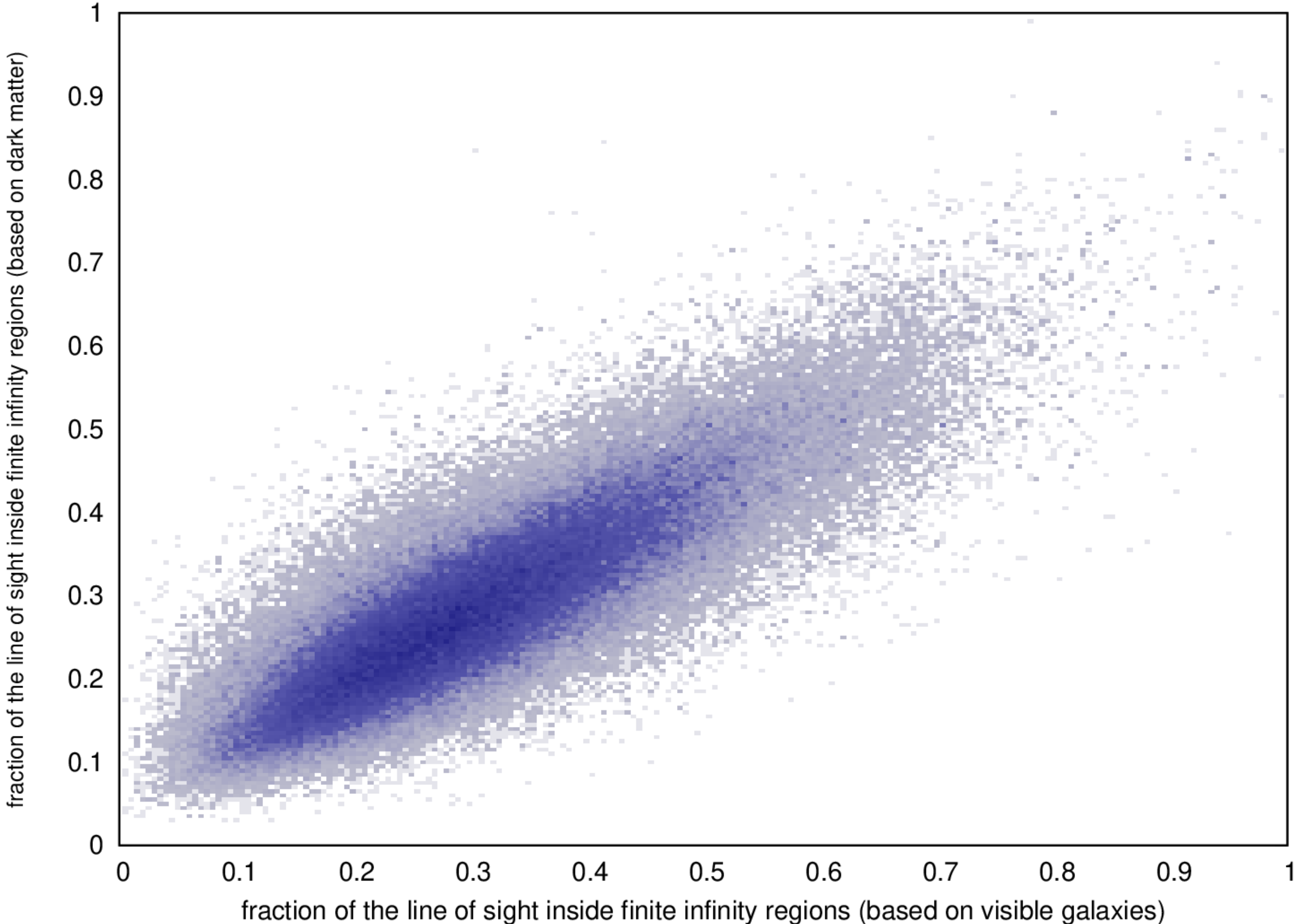
- Weighting parameters of merged groups by the completeness function



Other tests for timescape cosmology

- H(z) measure
- Om(z) dependence
- Alcock–Paczynski test (proper length and BAO)
- Inhomogeneity test based on H(z) and D(z)
- Time drift in Lyman-α forest
- Effective ω Equation of state

Incompleteness bias for finite infinity regions



N/A

Sorry,

but I haven't prepared a slide for this question.