Observational tests of an inhomogeneous cosmology

PhD defence

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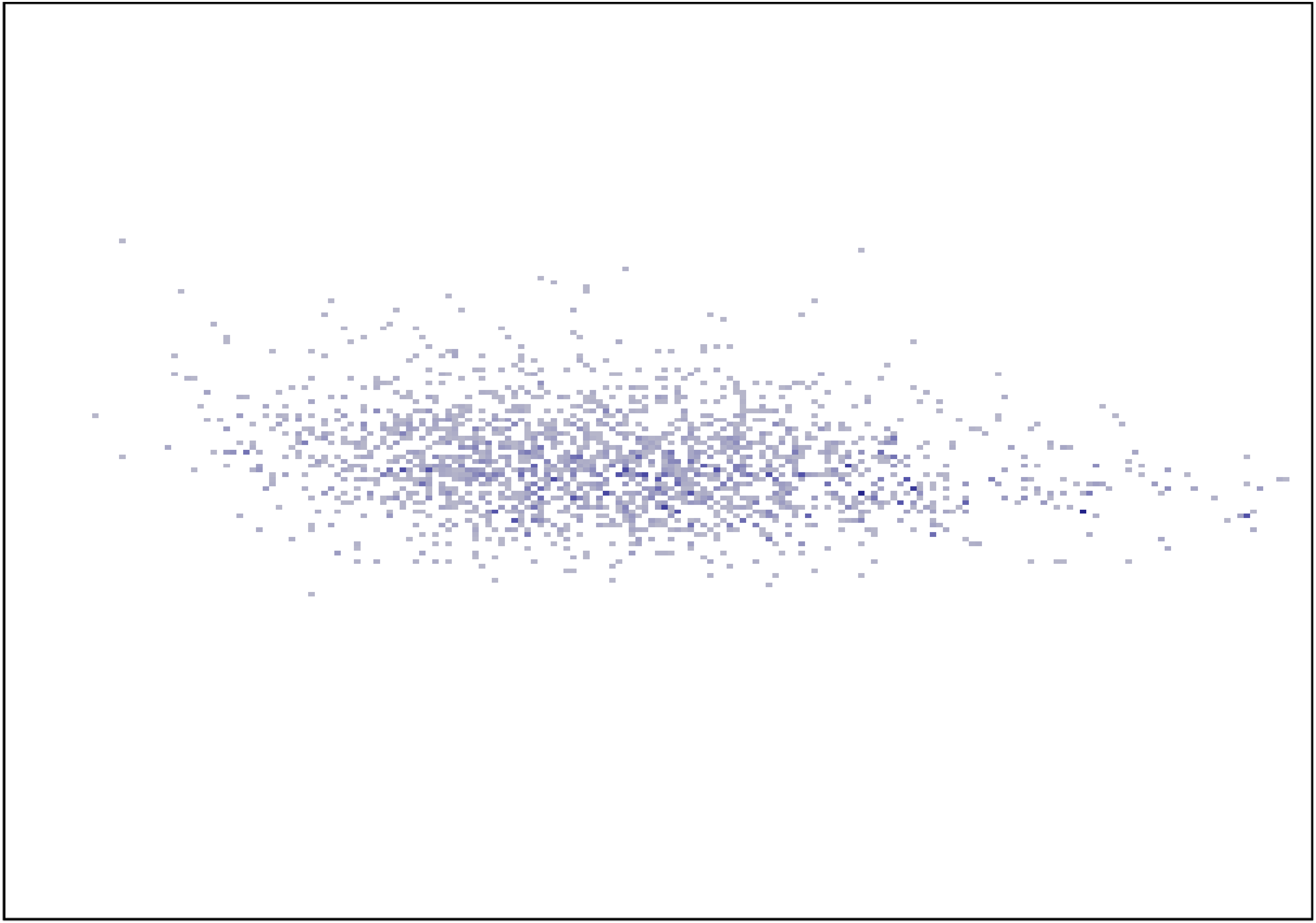

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Λ-CDM cosmology

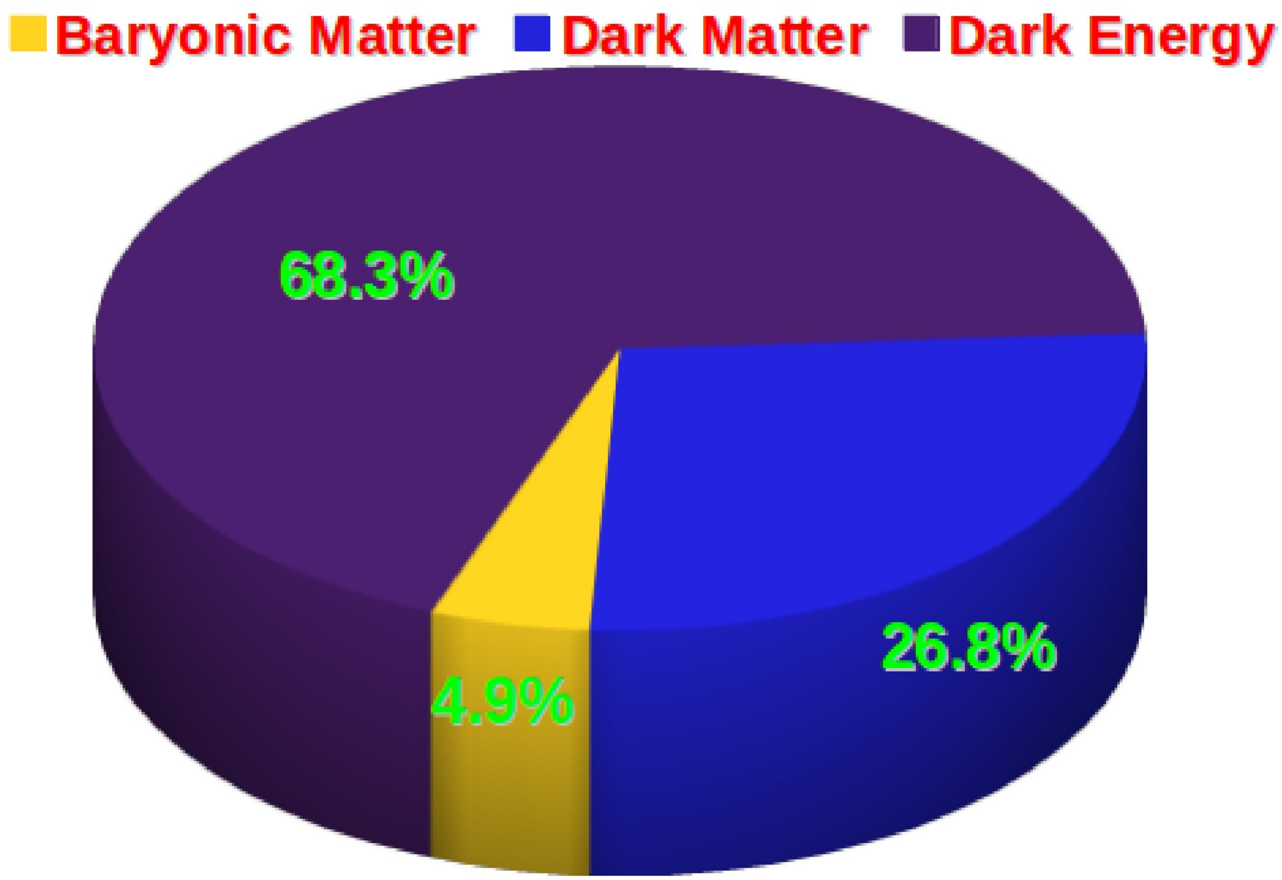
- Based on the following assumptions:
  - General Relativity (including a cosmological constant)
  - Homogenity
  - Isotropy

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)

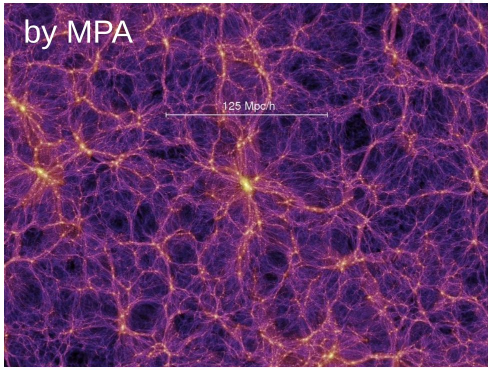


- The present-day universe is dominated by **Dark Energy**

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)



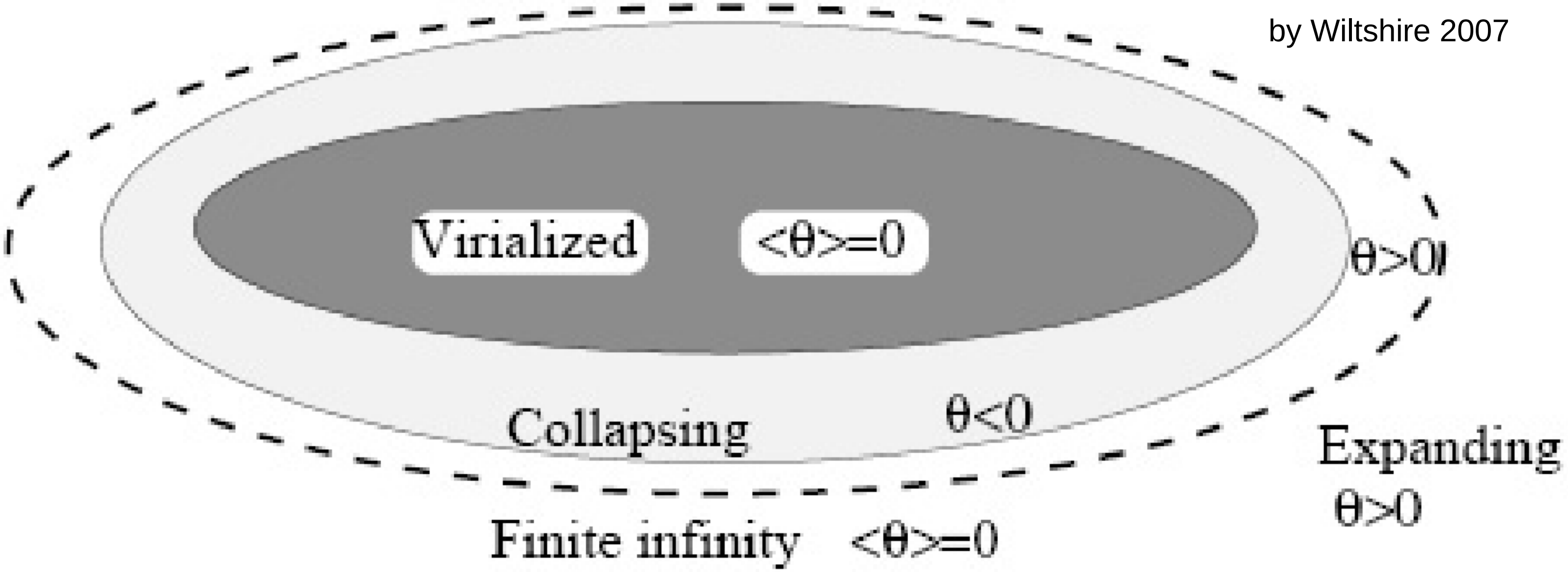
- Two-phase models:
  - **Voids**: empty, locally open geometry
  - **Walls**: on average renormalized critical density, locally flat geometry

$$\left(\frac{\dot{\bar a}}{\bar a}\right)^2+\frac{\dot f_V^{\,2}}{9 f_V(1-f_V)}-\frac{\alpha^2 f_V^{1/3}(1-f_V)}{\bar a^2}=\frac{8\pi G}{3}\bar\rho_0\frac{\bar a_0^{\,3}}{\bar a^3}$$

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

- 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**

Apparent accelerated expansion

without

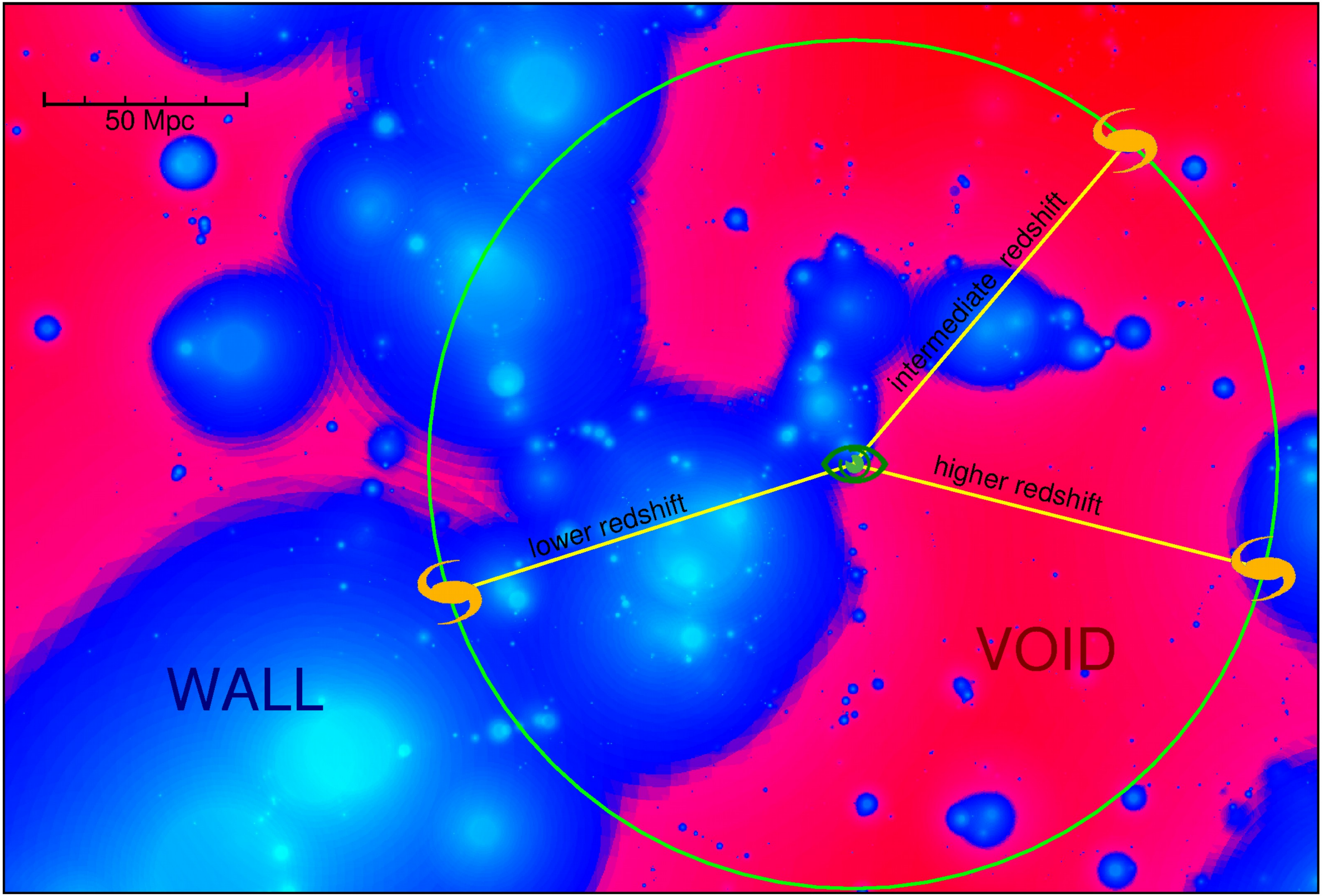
Dark Energy

- Nice theory, isn't it?

  BUT

- Are these back-reactions 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)

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)

- Sample with large sky-coverage, sufficient depth and redshift data: **SDSS**
- Redshift-independent distance indicator: **fundamental plane** of elliptical galaxies
- Model of the matter distribution in the local universe: **SDSS** supplemented by **2MRS**
- Numerical simulations for mock catalogues: **Millennium simulation**

Calibrating the fundamental plane

- Empirical relation for elliptical galaxies

$$\log_{10}(R_0) = a \cdot \log_{10}(\sigma_0) + b \cdot \log_{10}(I_0) + c$$

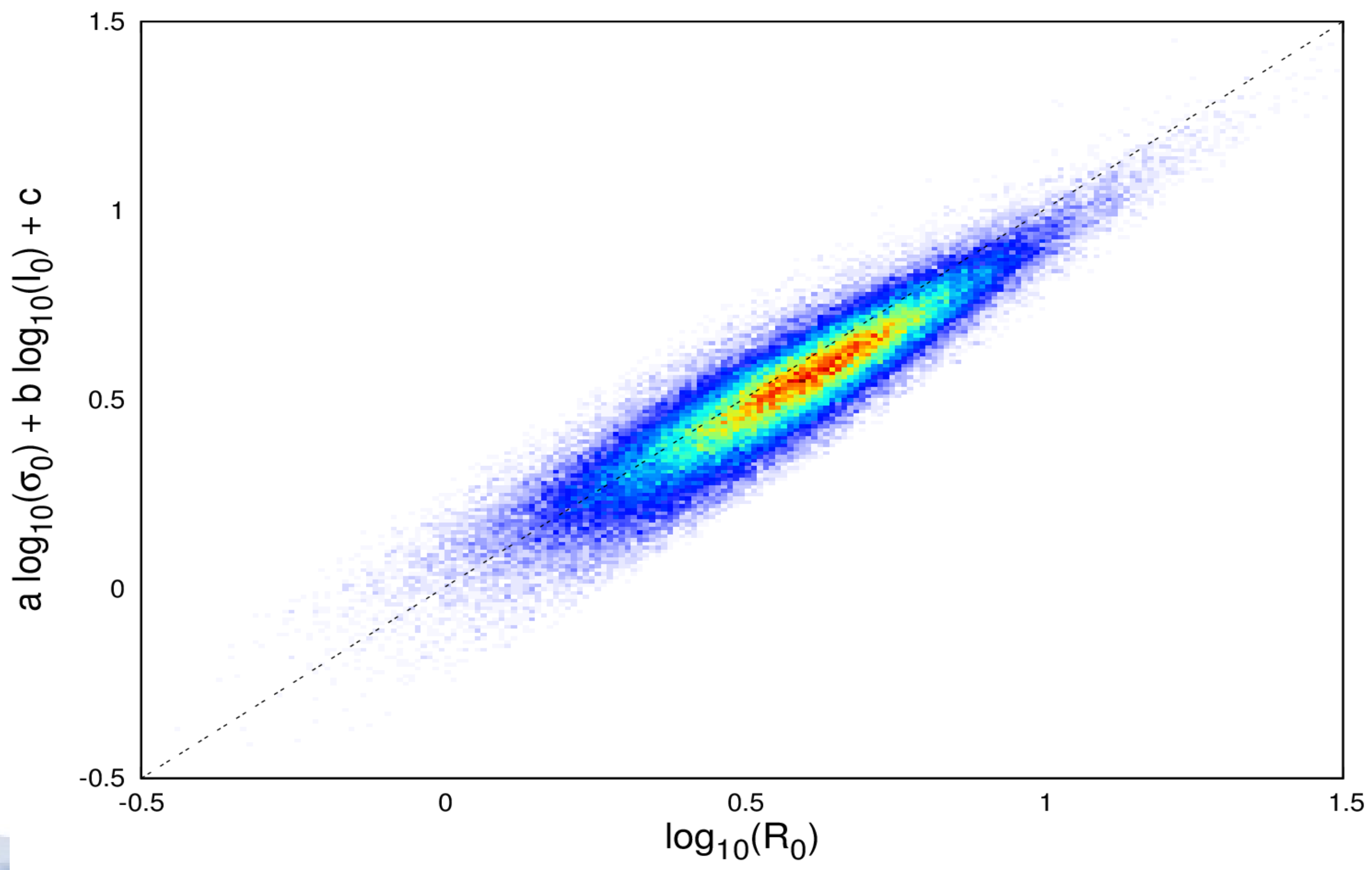
- 3 parameters: **scale radius** R_0, **central velocity dispersion** σ_0 (redshift independent), and the **surface brightness** (redshift independent) $\mu_0 = -2.5 \cdot \log_{10}(I_0)$

- 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

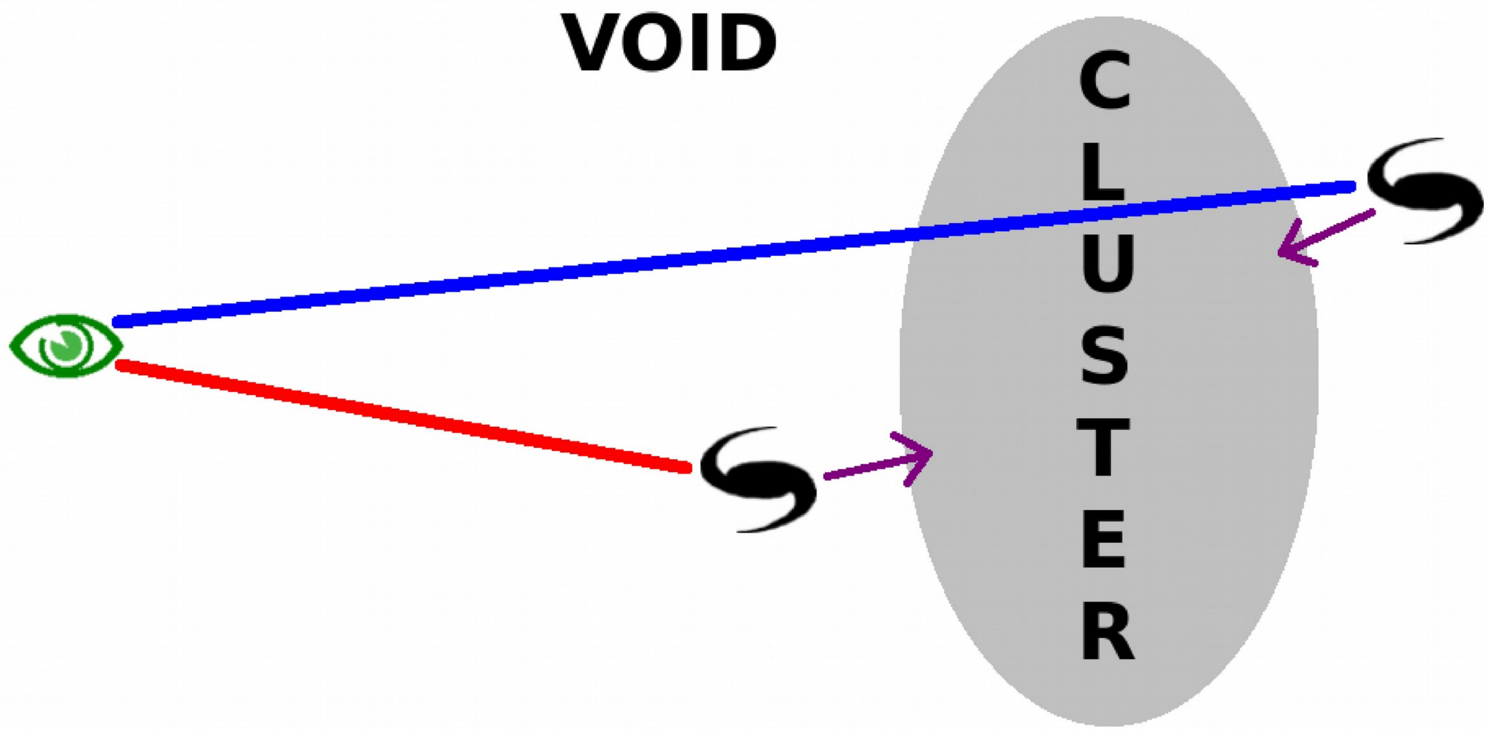
- Four catalogues published in Saulder+ 2015b:
  - SDSS group catalogue
  - 2MRS group catalogue
  - SDSS based **fundamental plane distance group catalogue** (using the SDSS group catalogue and the fundamental plane data from Saulder+ 2015a)
  - **Catalogue of finite infinity regions** derived from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

Mock catalogues

- Consider potential biases, such as coherent infall



- Millennium simulation
- Baseline for comparison to observational data

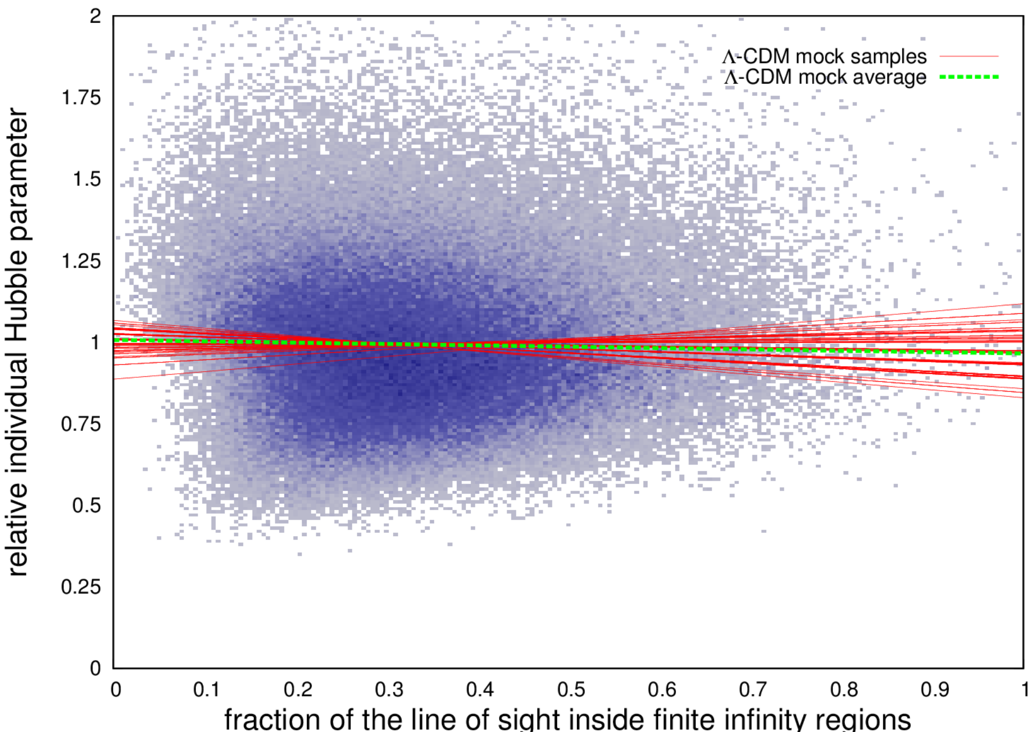
- For both models (Λ-CDM and timescape):
  - For groups and finite infinite regions: same mock catalogues as for the group finder calibration
  - Identifying early-type galaxies in the simulated data and introducing scatter of the fundamental plane
- For timescape cosmology only:
  - Using the complete (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

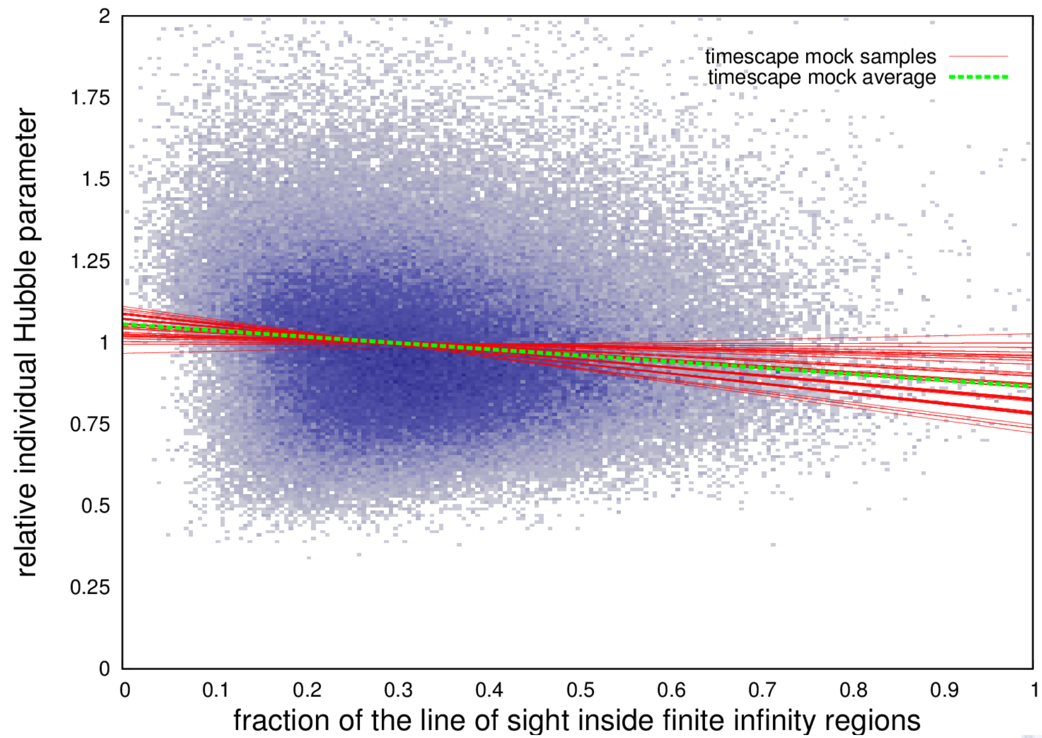
Performing the test

- 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) $\rightarrow$ ¼ sky coverage

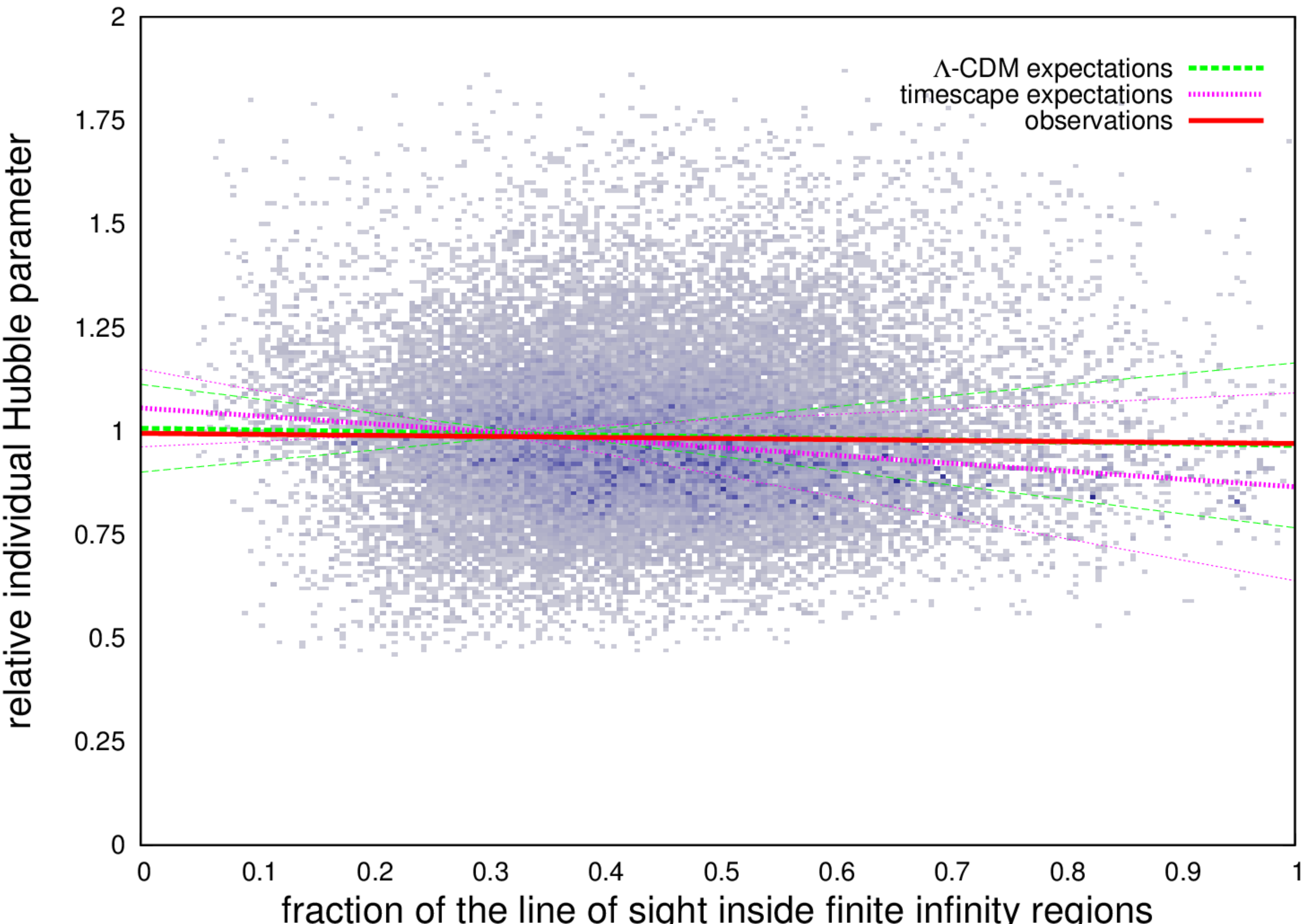


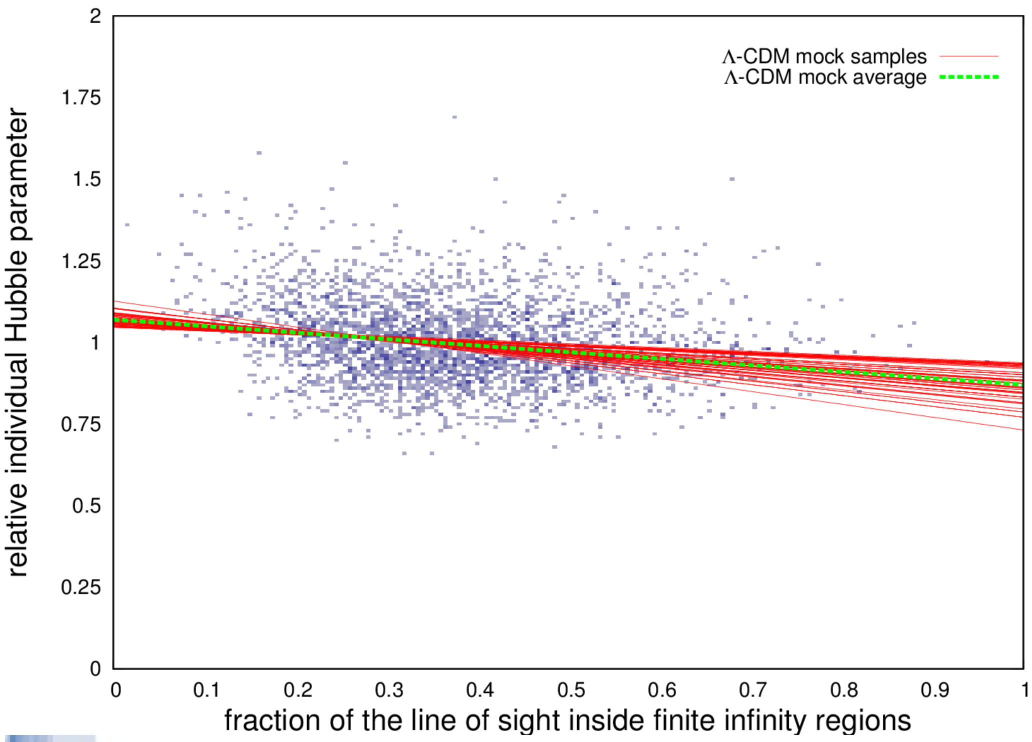


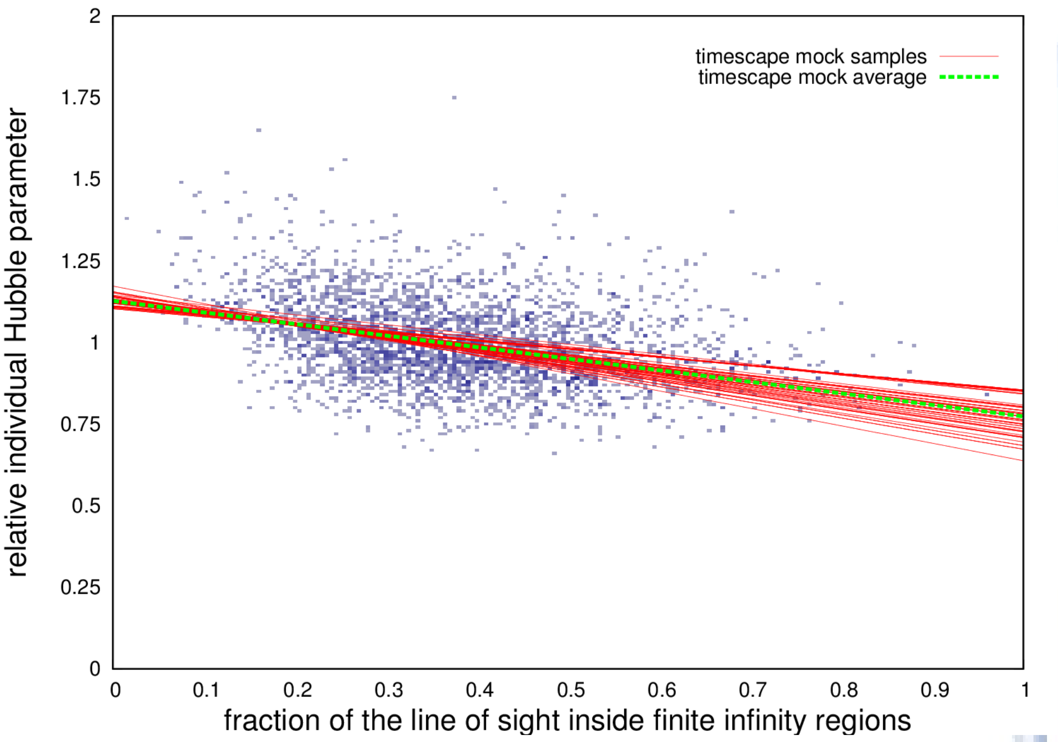
- **High variability** between the combined mock catalogues of the same cosmology (σ_k = 0.10/0.11 vs. ($k_{\Lambda\text{-CDM}}$-k_{ts}) = 0.15)
- Large scatter in the relative individual Hubble parameters

→ uncertainty in fundamental plane distances

- Observational data → close to Λ-CDM



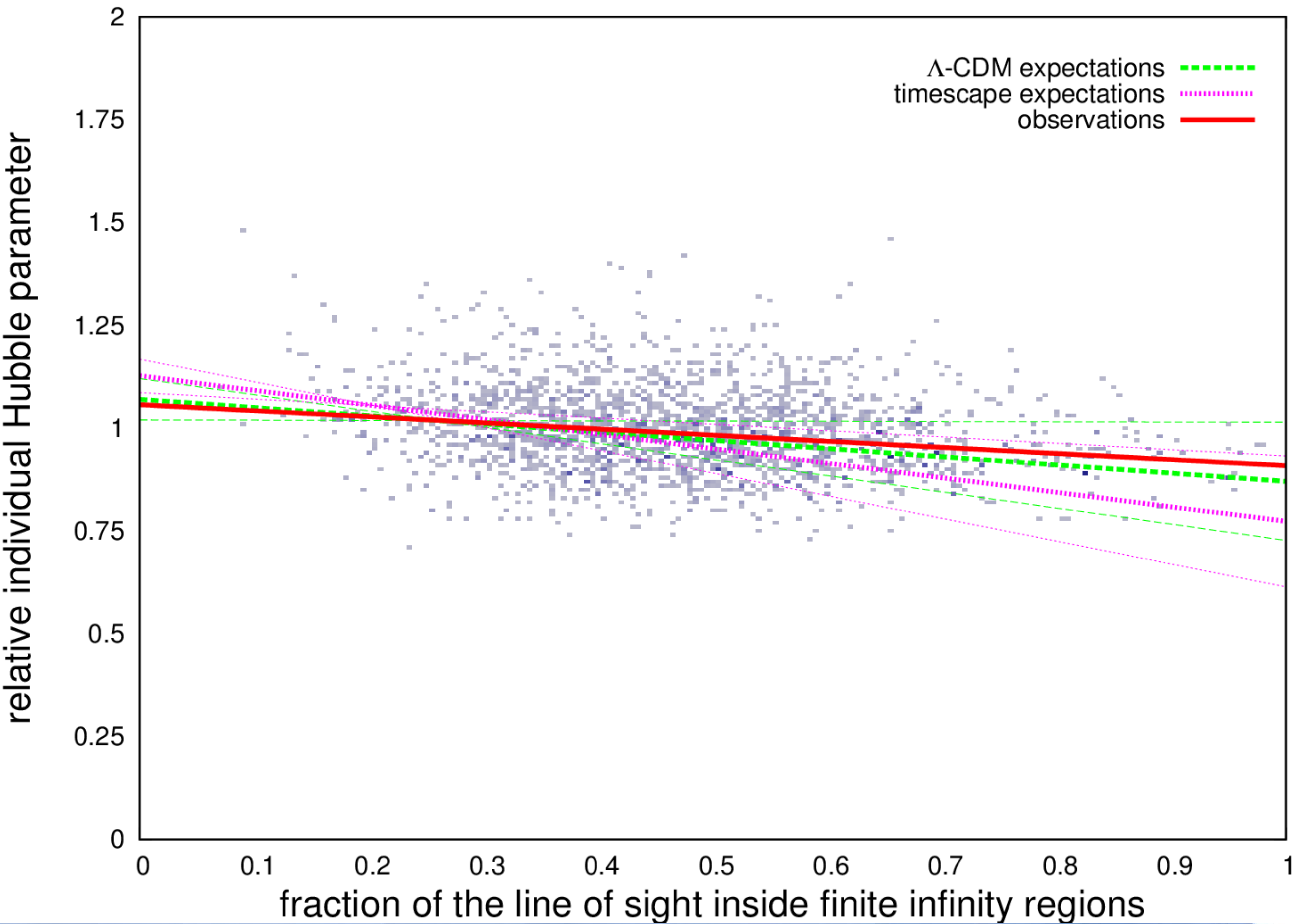




- Introduce additional selection criteria:
  - Distance limit: ~326 Mpc/h (≙ redshift 0.1)
  - **At least 3 early-type galaxies per group**

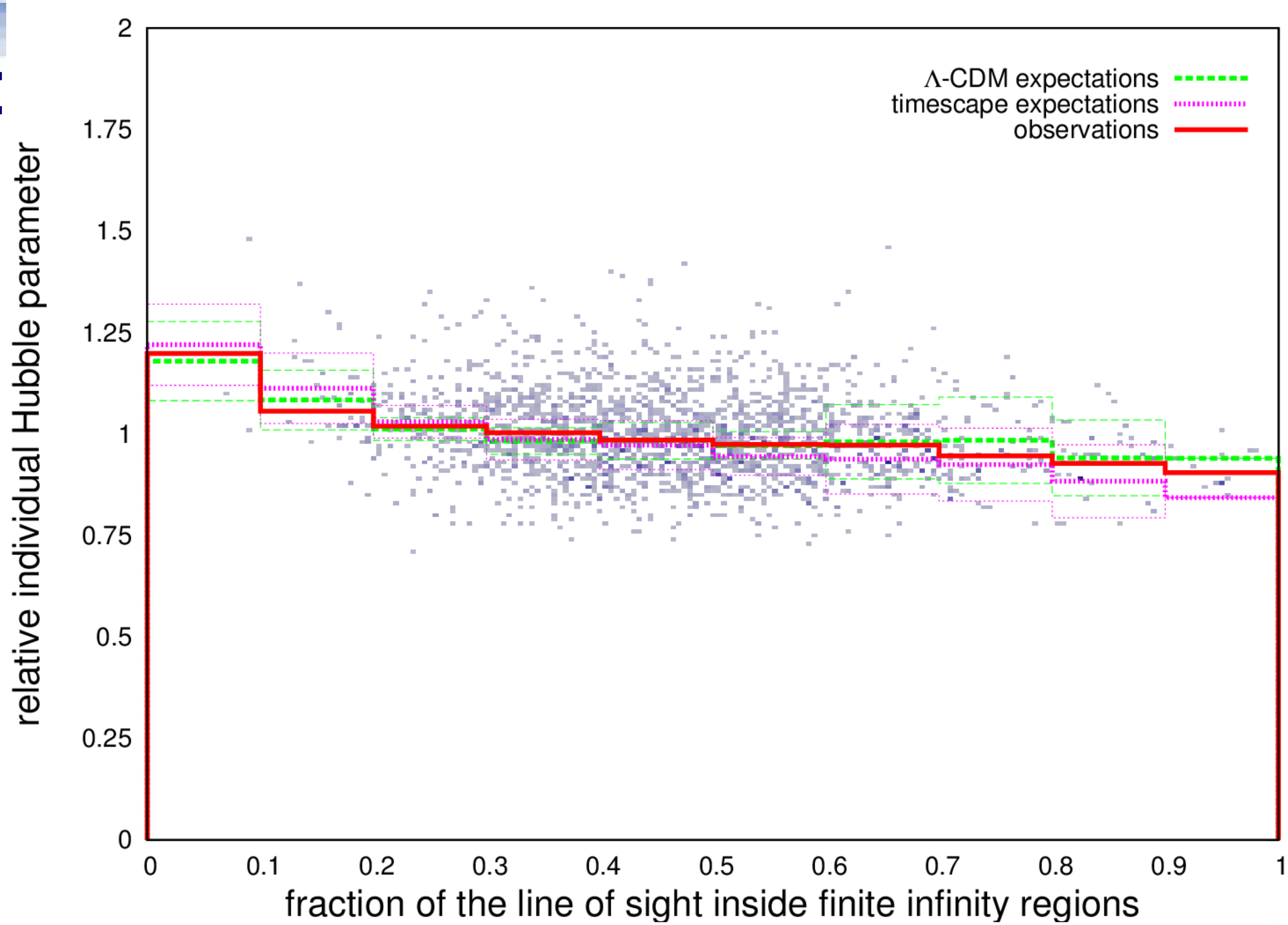
- Scatter reduced (σ_k = 0.06/0.07), but also number of groups

- Observational data → timescape is 3-σ outlier



- Binned analysis:

  less clear, but preferences for Λ-CDM over timescape



- Fits on binned data yield similar results as direct fits

- Kolmogorov-Smirnov test: p-values are very low, but are higher for Λ-CDM than timescape cosmology

Open issues

- **Dearth of rich groups** in the Millennium simulation
- Cosmological parameters of the Millennium simulation are slightly dated
- **No** fully self-consistent numerical **simulation** using **timescape cosmology**
- Finite infinity regions are only approximated
- Possible **systematic effects** from using the **fundamental plane** (Joachimi+ 2015, Saulder+ 2015b)

Conclusions

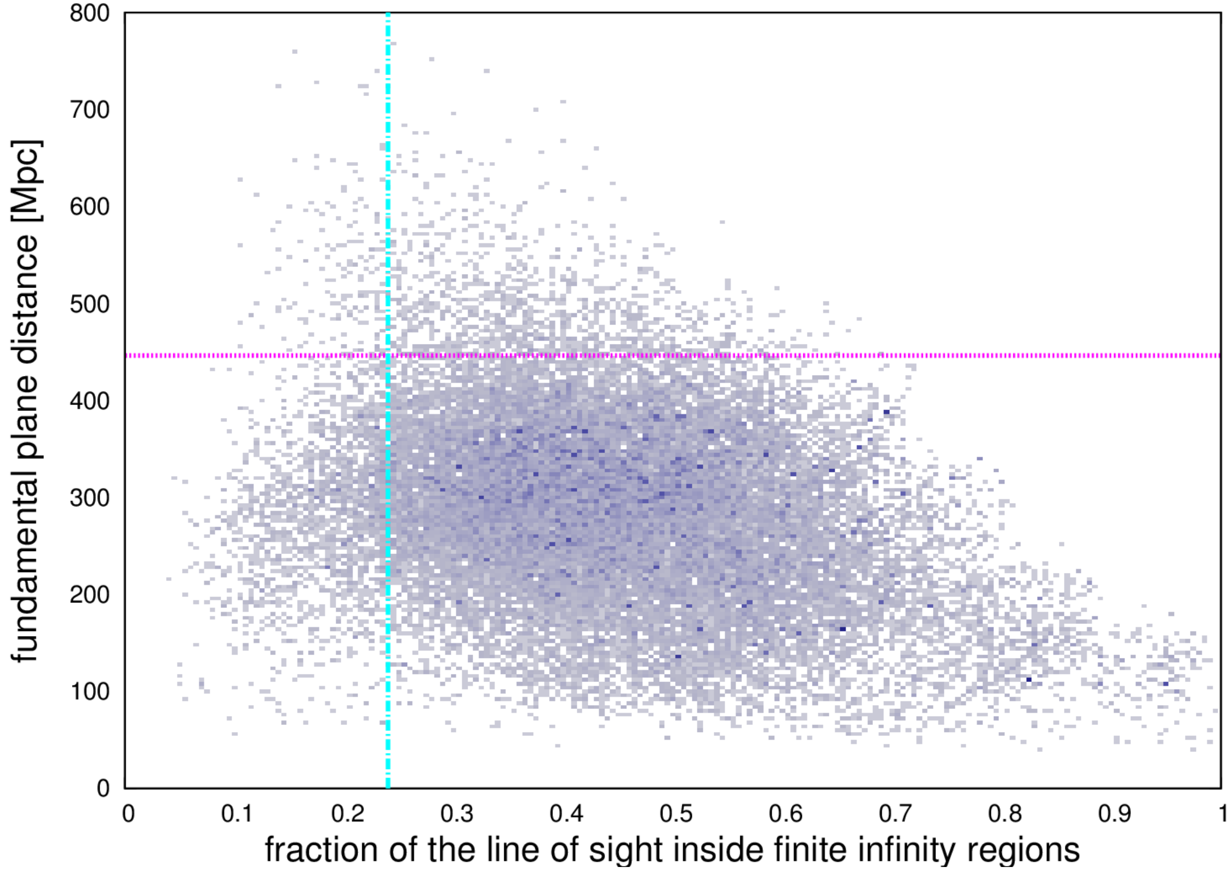
- A meaningful test for timescape cosmology against Λ-CDM cosmology with **public survey data** and **simulated data** only (Saulder+ in prep.)

- Many useful products along the way
  - Fundamental plane calibrations (Saulder+ 2013)
  - List of compact high velocity dispersion early-type galaxies (Saulder+ 2015a)
  - SDSS and 2MRS group catalogues (Saulder+ 2015b)
  - Future work on peculiar motions is planned

- Good agreement of observational data with Λ-CDM simulated data
- Observations significantly deviate from our models based on timescape cosmology
- **All statistical tests clearly favour Λ-CDM cosmology (P_{linreg}=0.430) over timescape cosmology (P_{linreg}=0.002)**
- **Inhomogeneities** can**not** explain the accelerated expansion of the universe **without dark energy**

Outlook

- Deeper surveys will not improve the test



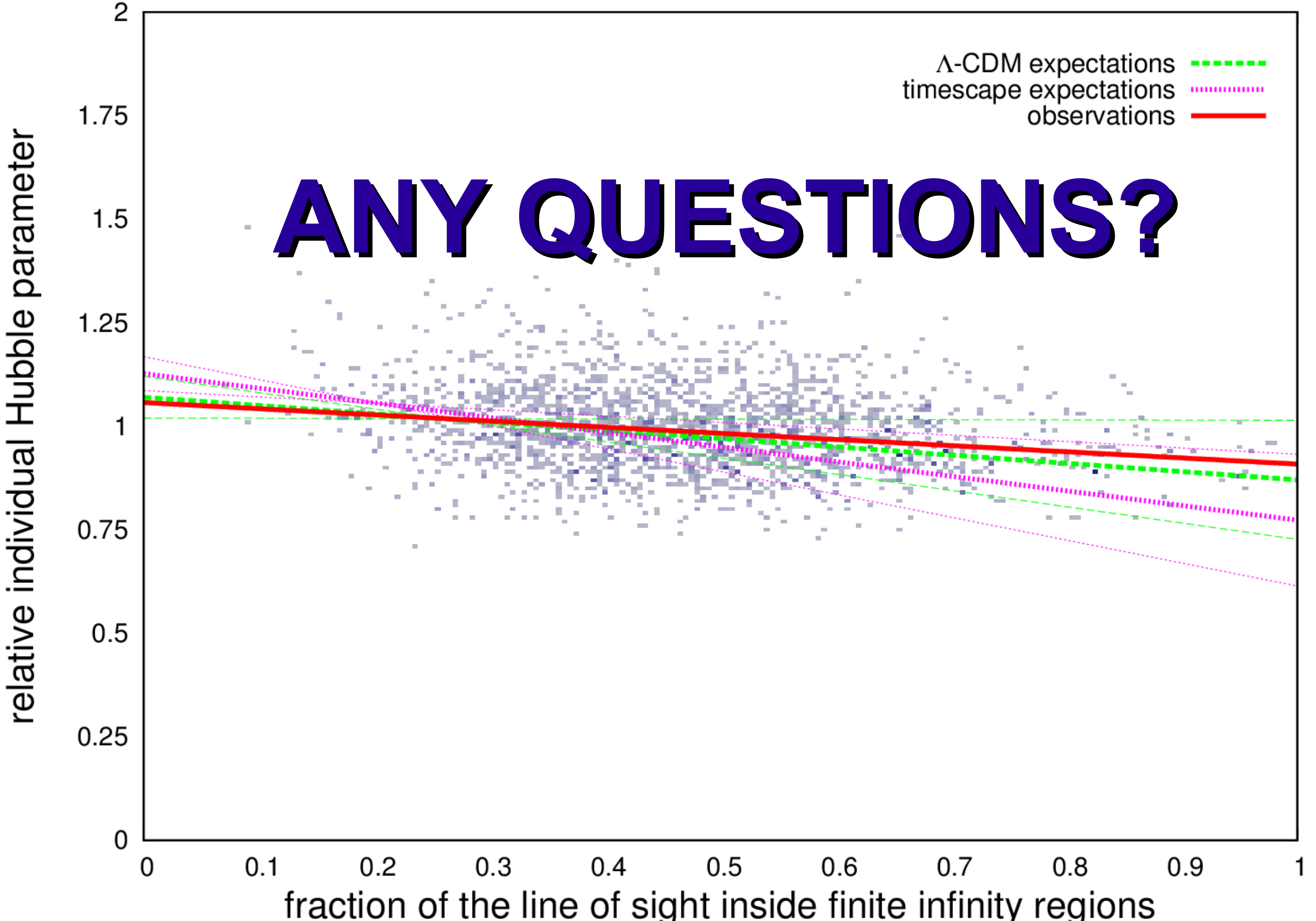
- However, a **larger sky coverage** could improve it: 6dFGS, ATLAS, ...

- **Other distances indicator** (Tully-Fischer relation, supernovae Typ Ia, …)
- 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

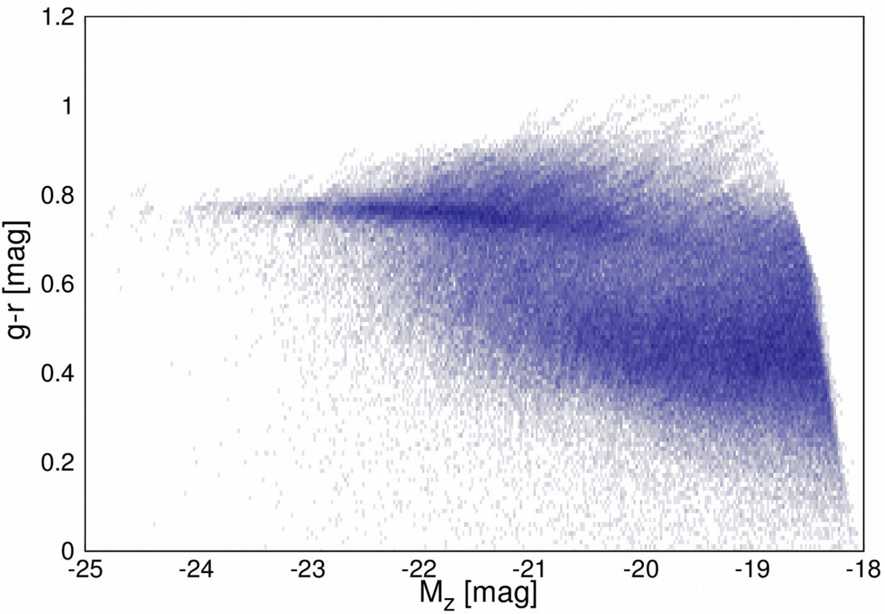
Timescape cosmology

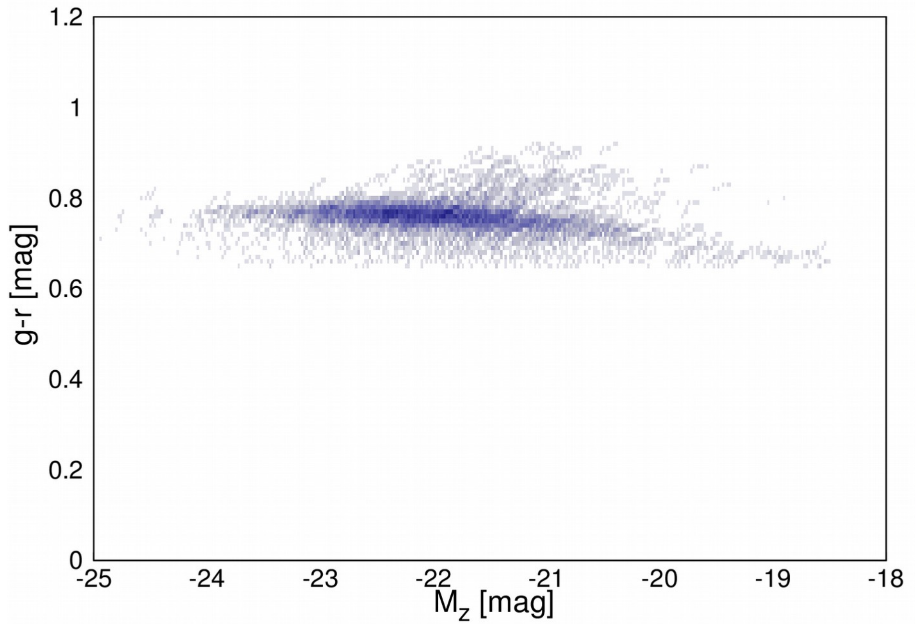
- H_0 = ~61.7 (void) / ~48.2 (wall) km/s/Mpc
- age = ~ 14.7 Gyr (wall)
- f_V = 0.76
- Ω_b/Ω_M = ~3.1
- from Leith+ 2007

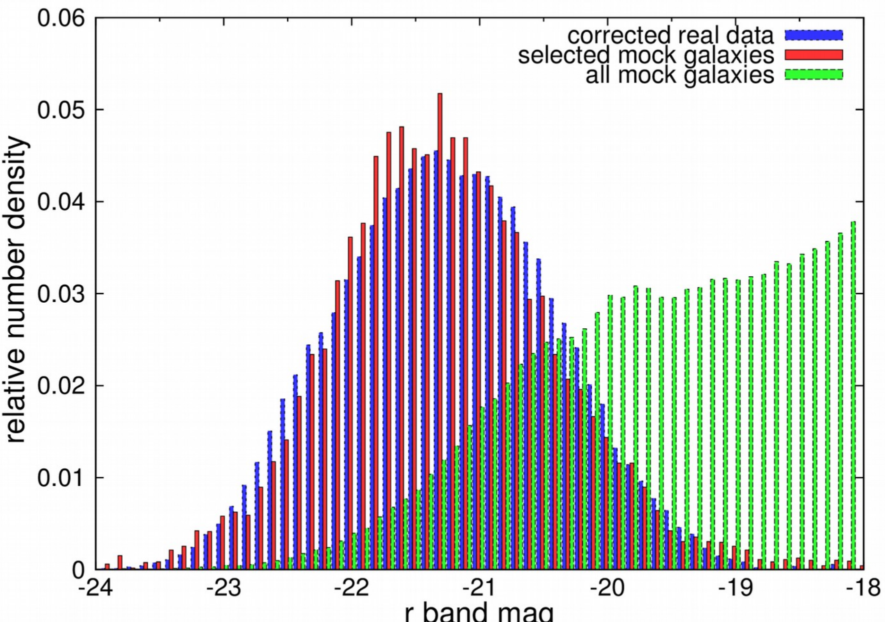
Λ-CDM cosmology

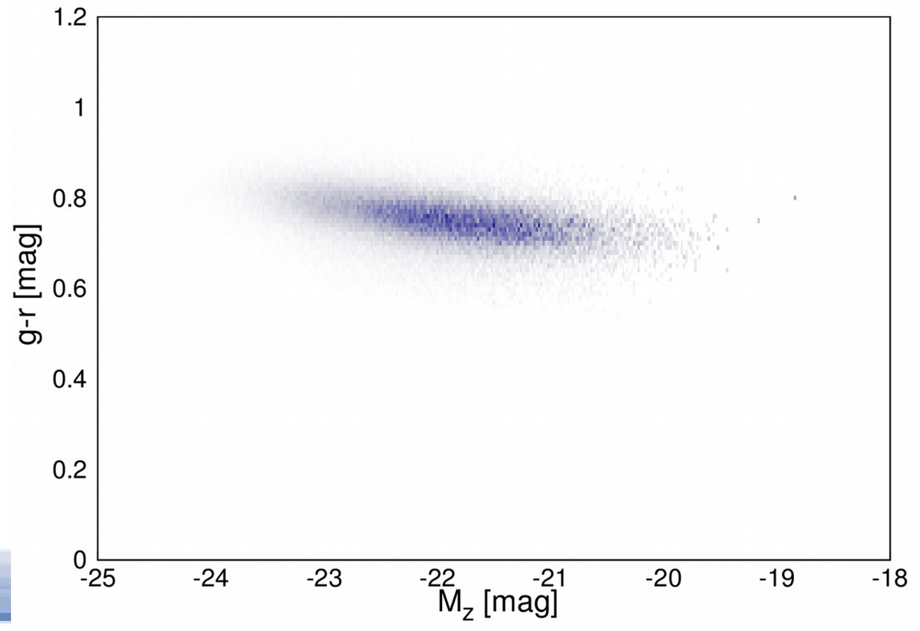
- H_0 = ~67.8 km/s/Mpc
- age = ~13.8 Gyr
- Ω_Λ = 0.69
- Ω_b/Ω_M = ~5.4
- from Planck XIII 2015

Identification of early-type galaxies in the Millennium simulation

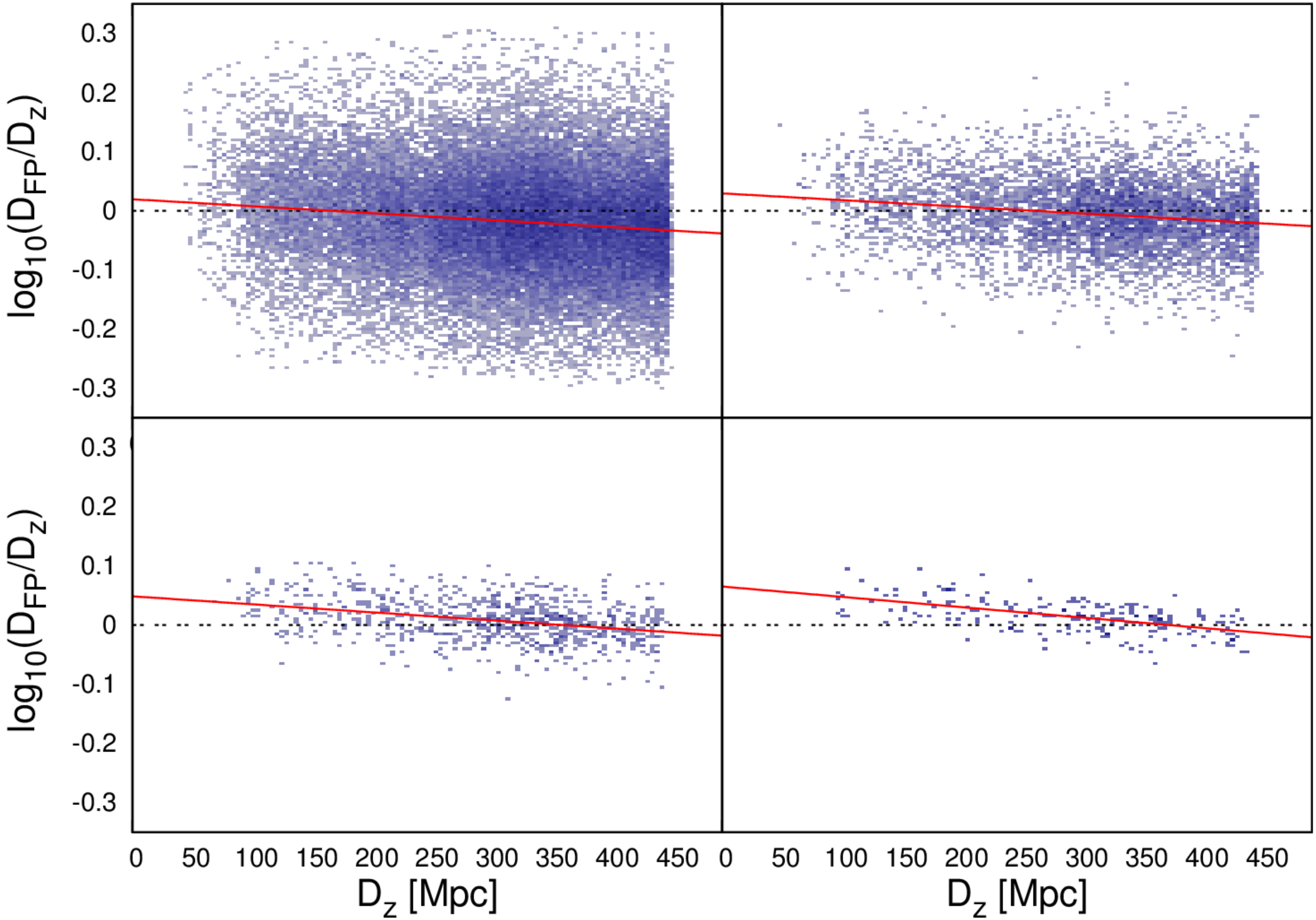


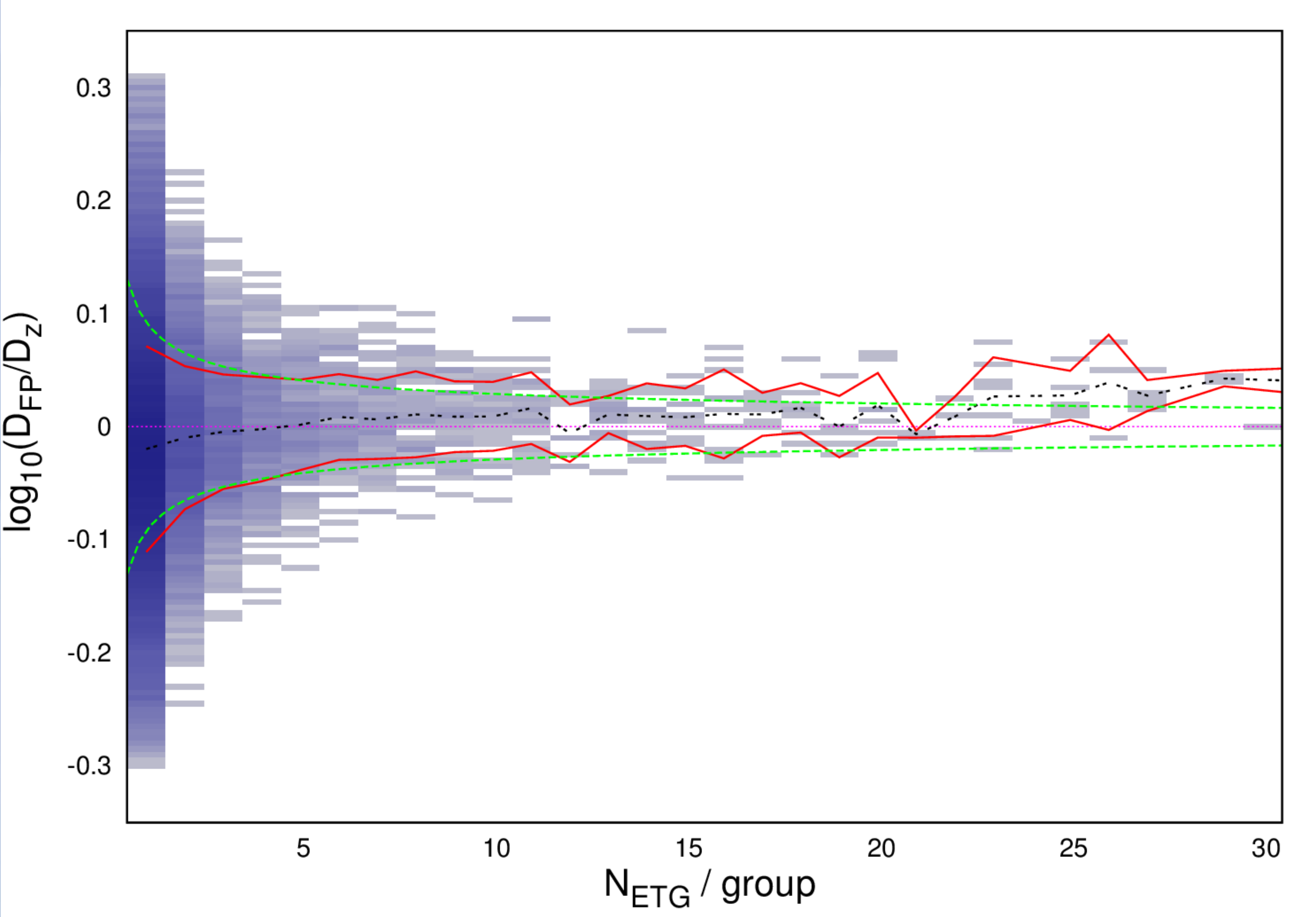






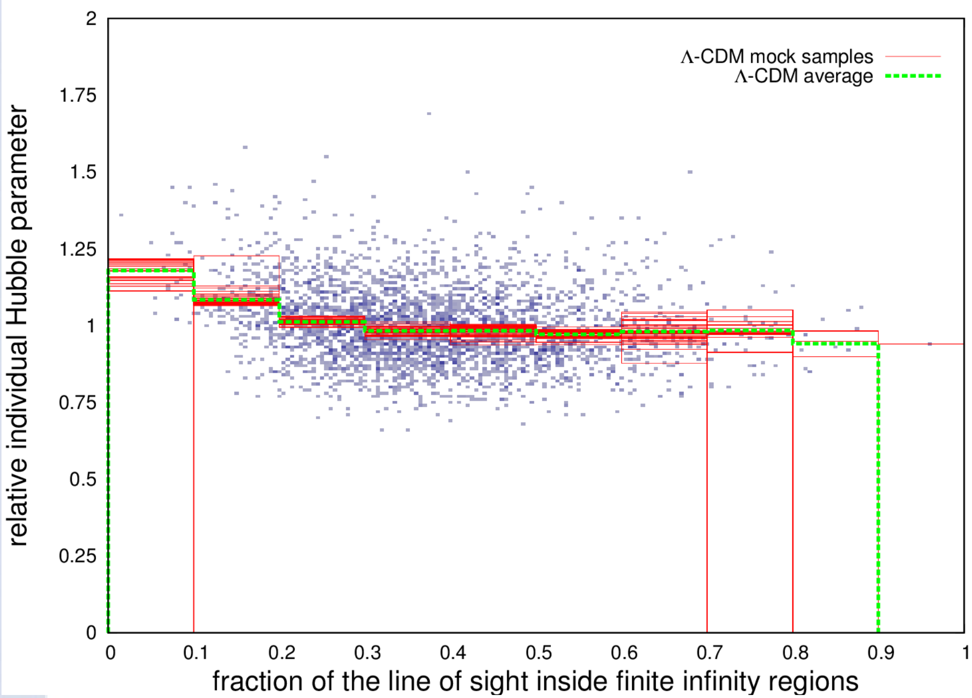
Fundamental plane biases

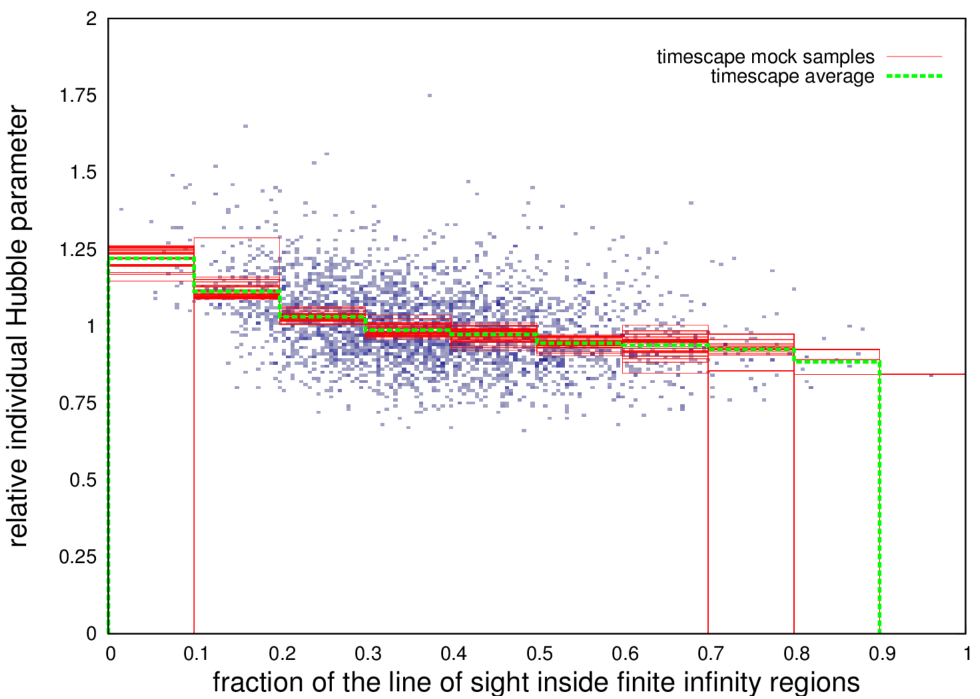




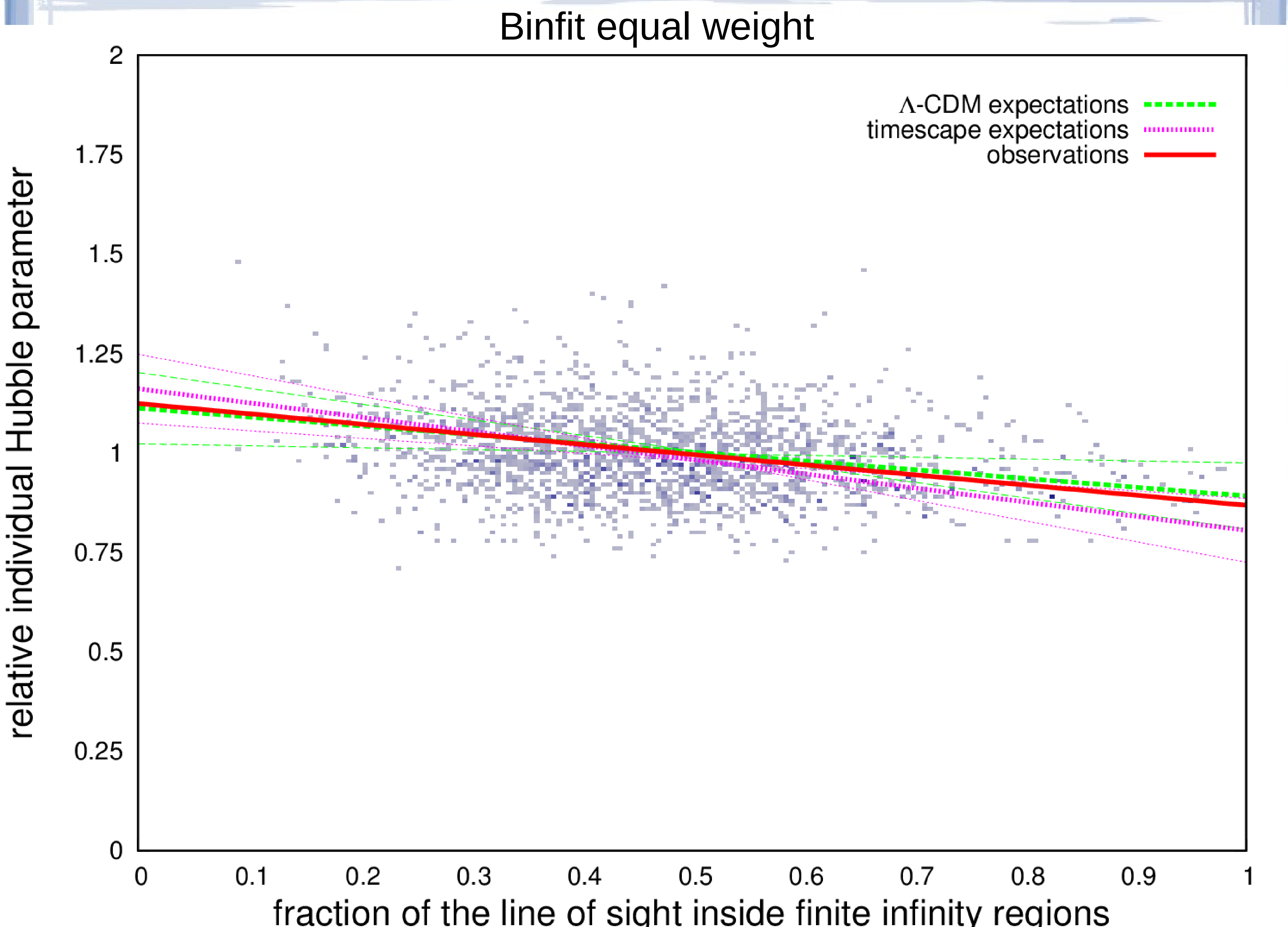
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
log10(DFP/Dz)
5
10
15
20
25
30
NETG / group

Binned analysis

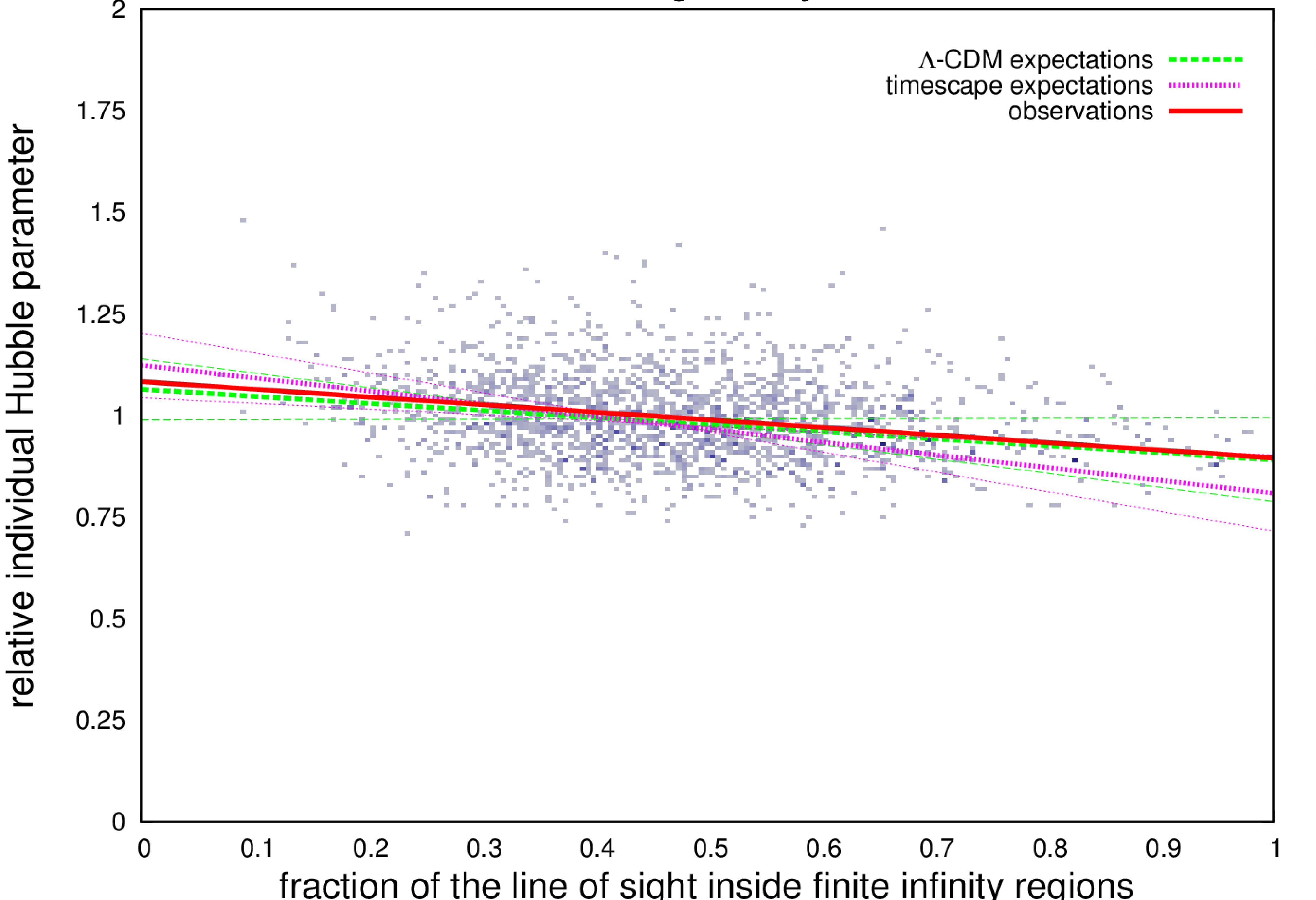




- Sensitive to normalization
- Larger scatter in outer bins

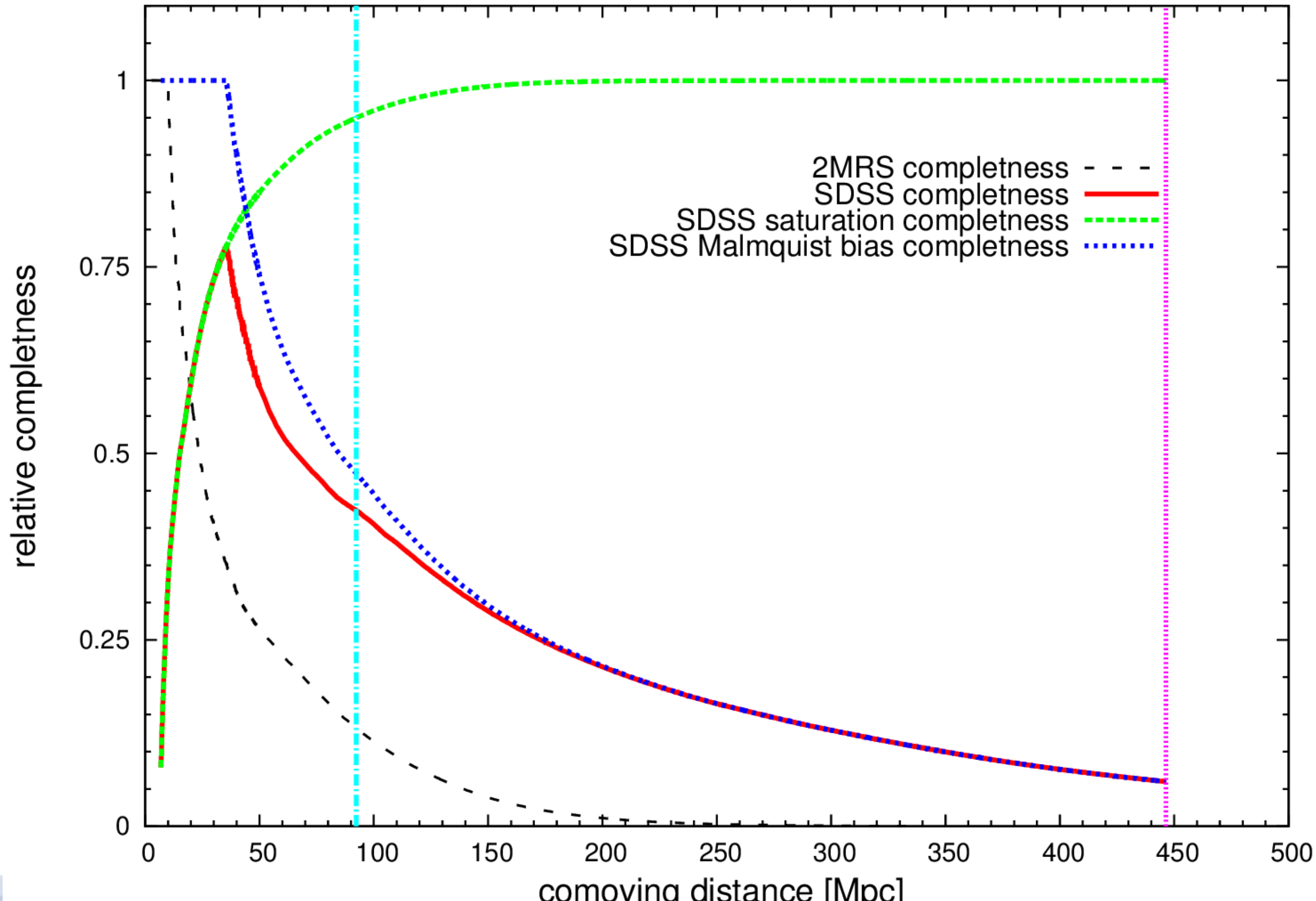

Binfit equal weight
Λ-CDM expectations
timescape expectations
observations
relative individual Hubble parameter
fraction of the line of sight inside finite infinity regions
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Binfit weighted by scatter



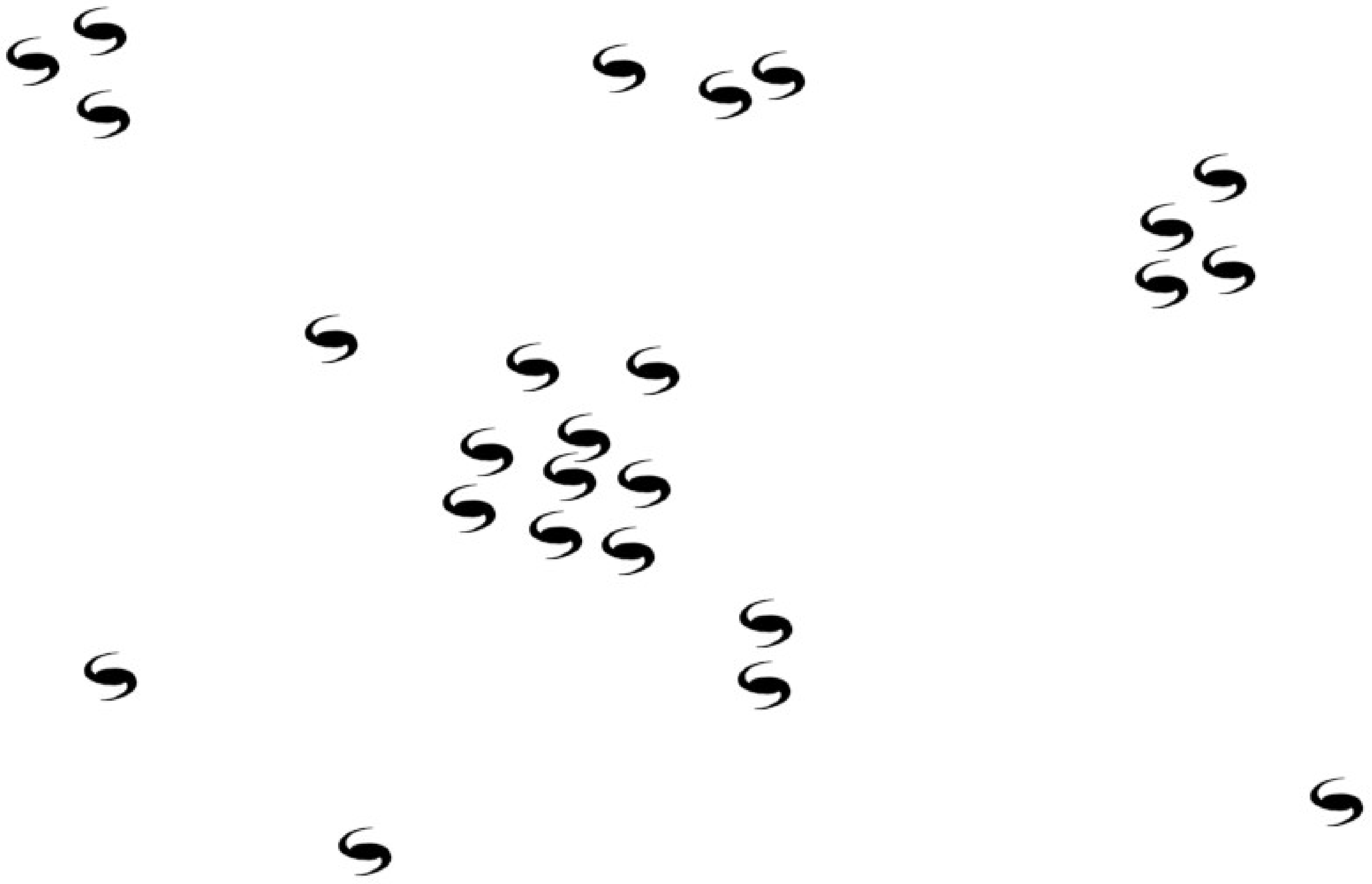
Merging of SDSS and 2MRS

- Weighting parameters of merged groups by the completeness function

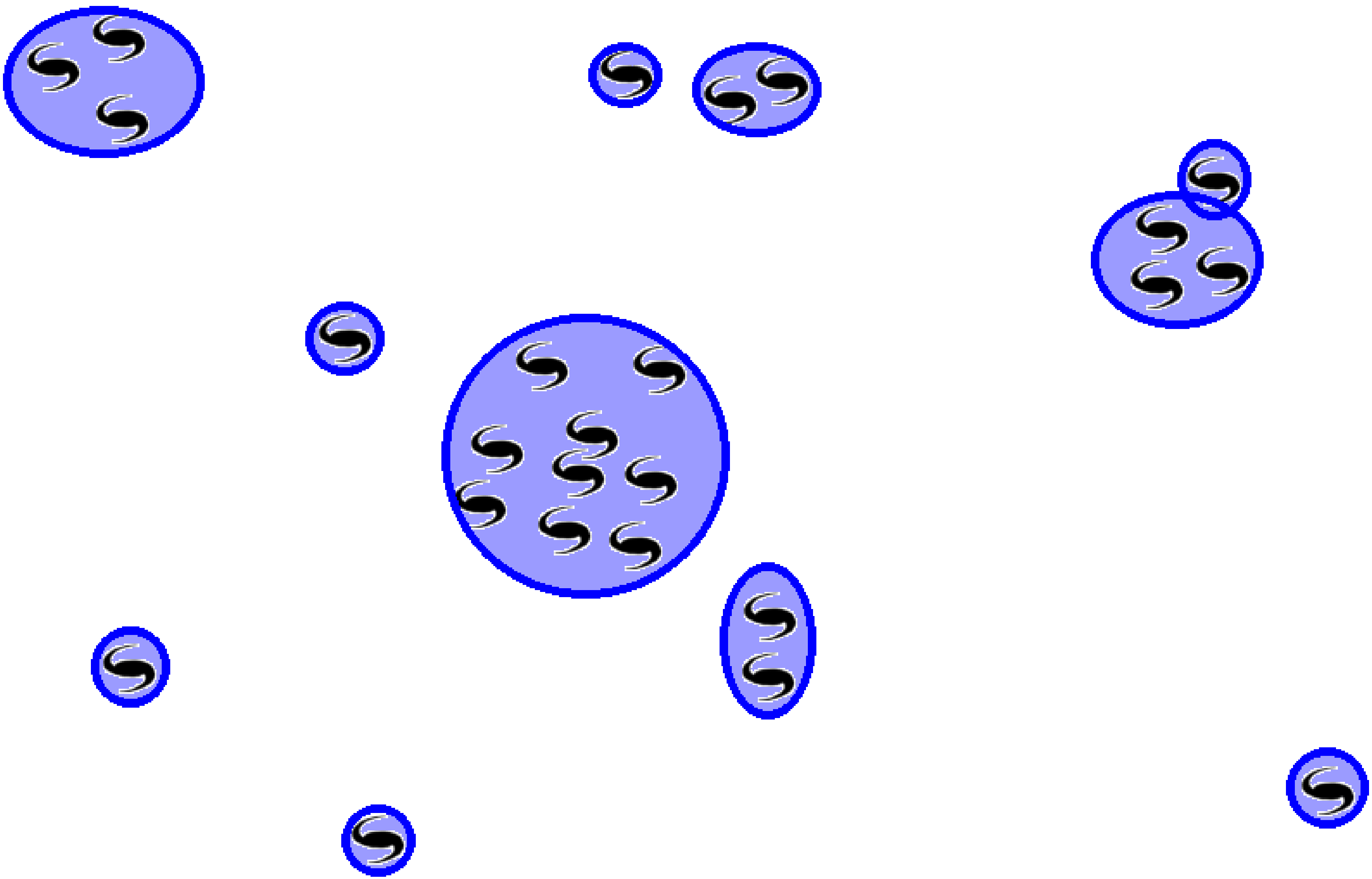


Algorithm to derive finite infinity regions

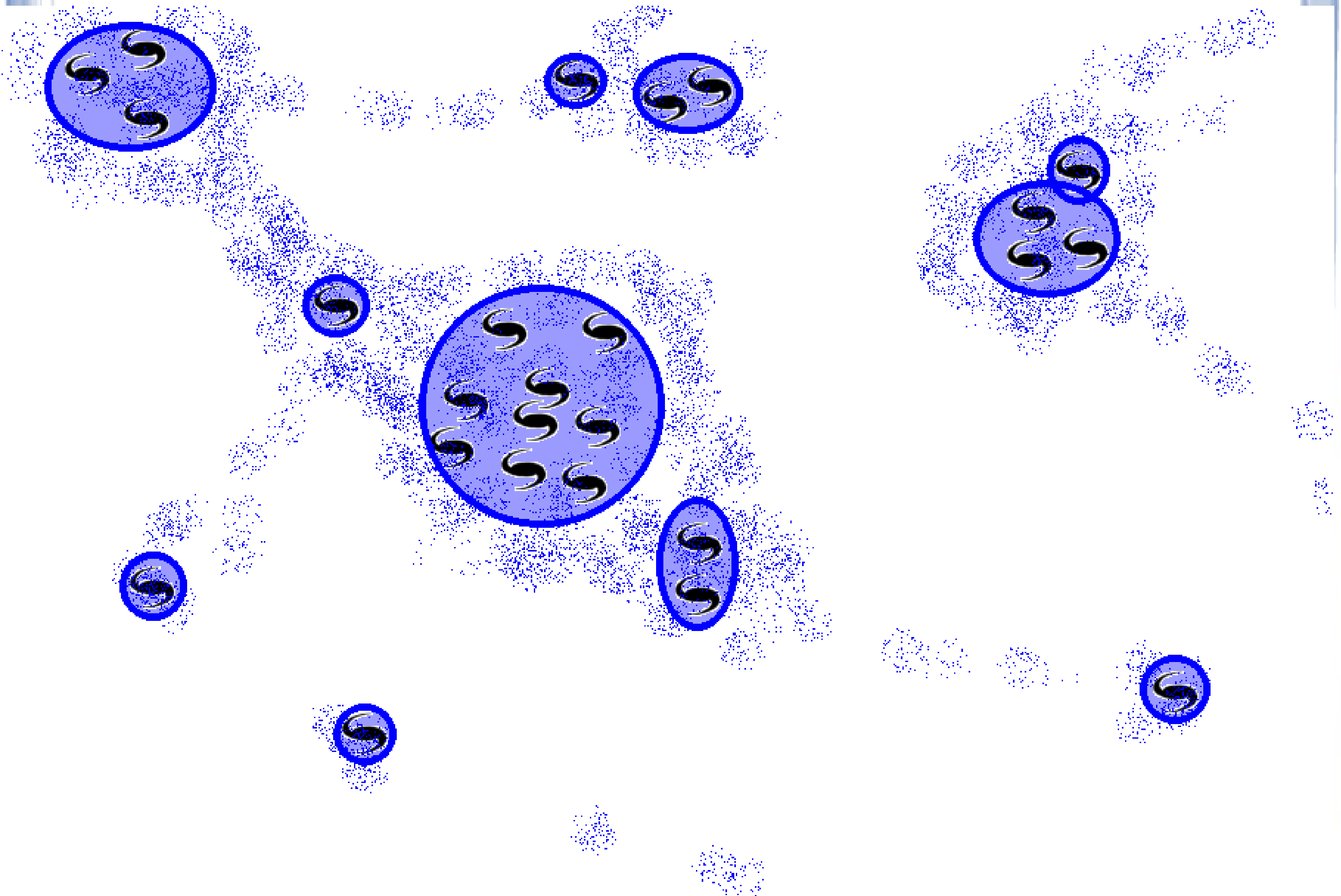
Observed/simulated distribution of galaxies



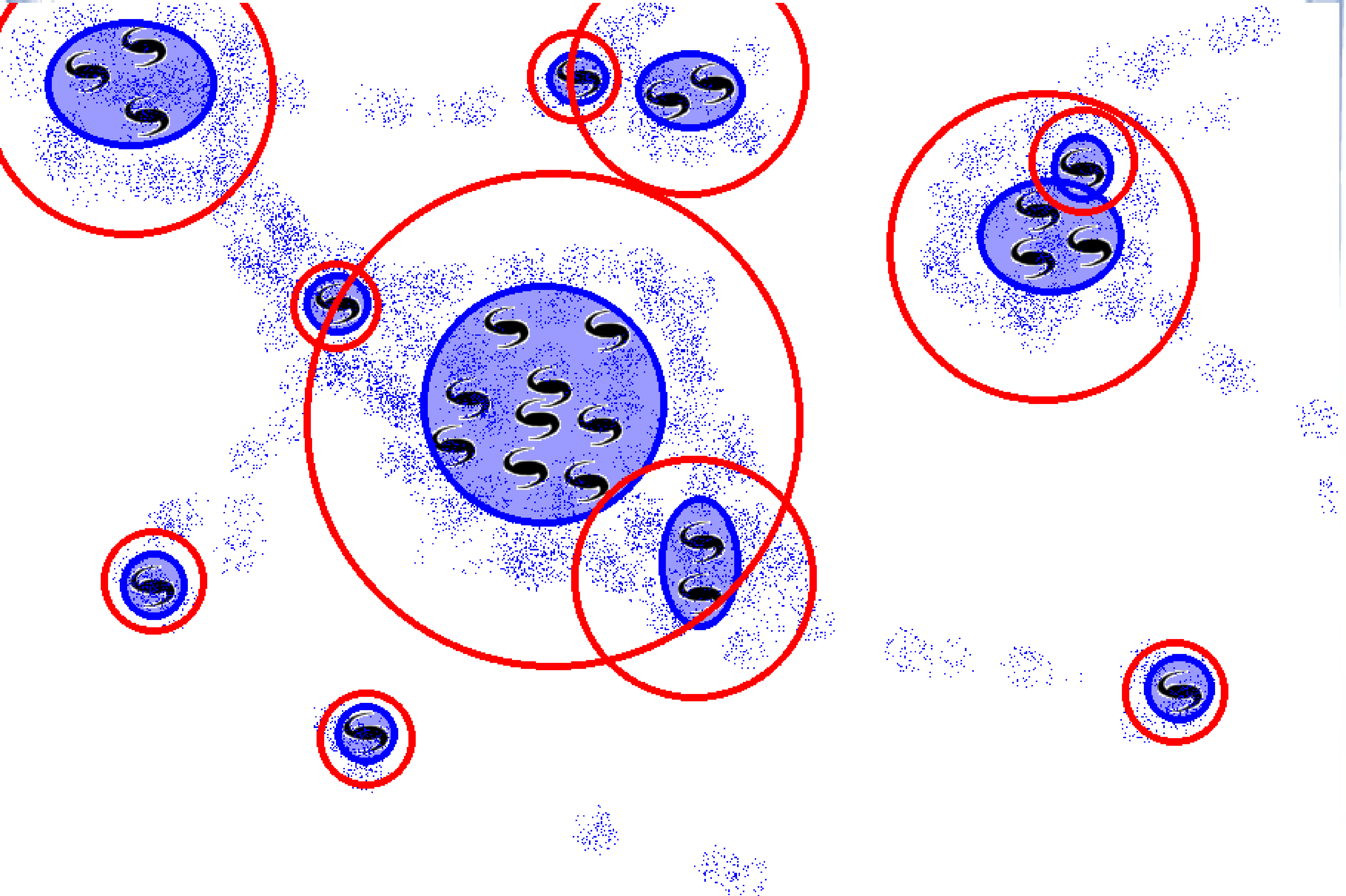
Calculate/use dark matter halos (FoF groups)



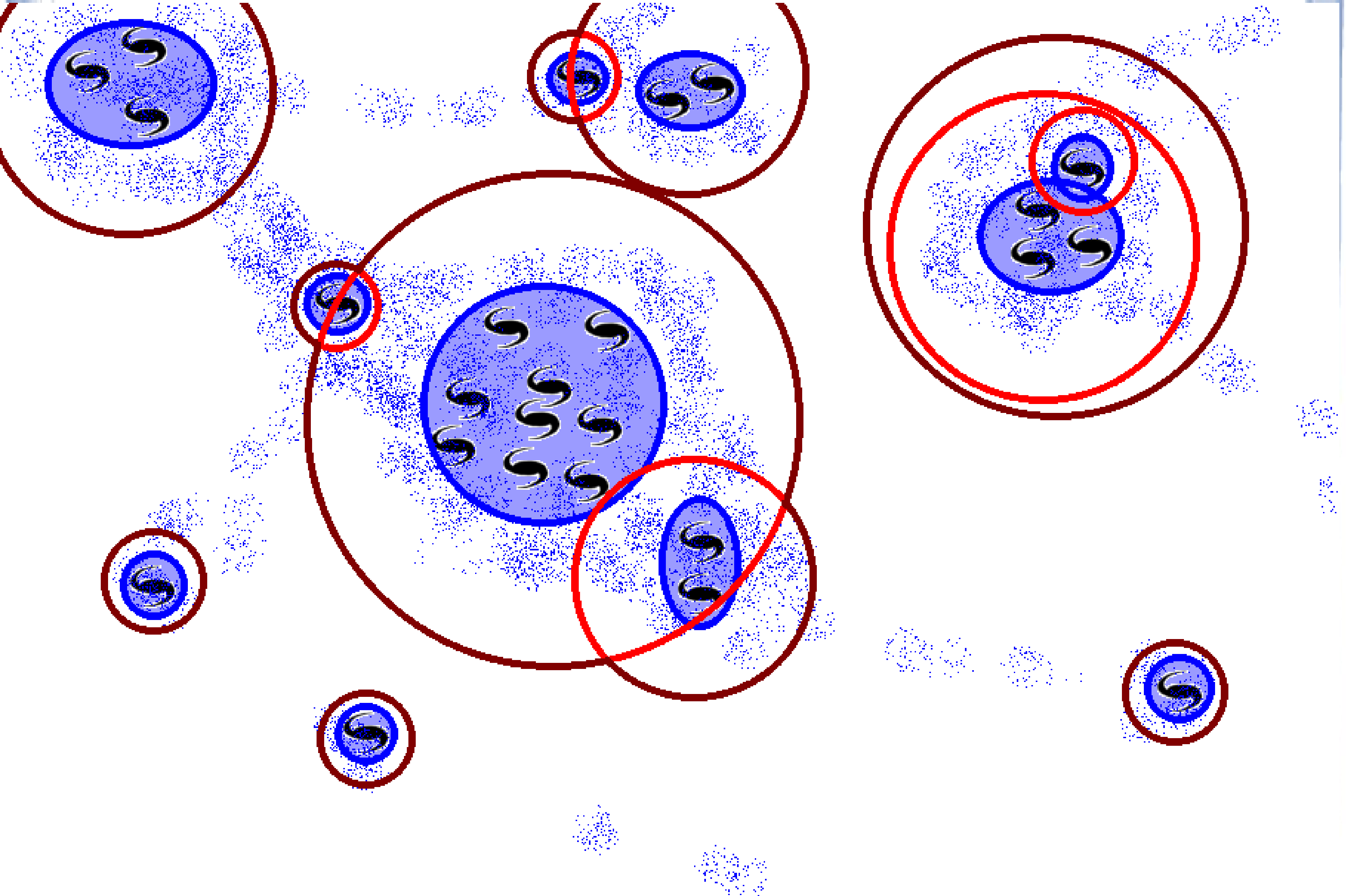
There is also dark matter outside the halos and unbound in the halos.



Assign finite infinity regions using the calibrations from Millimil

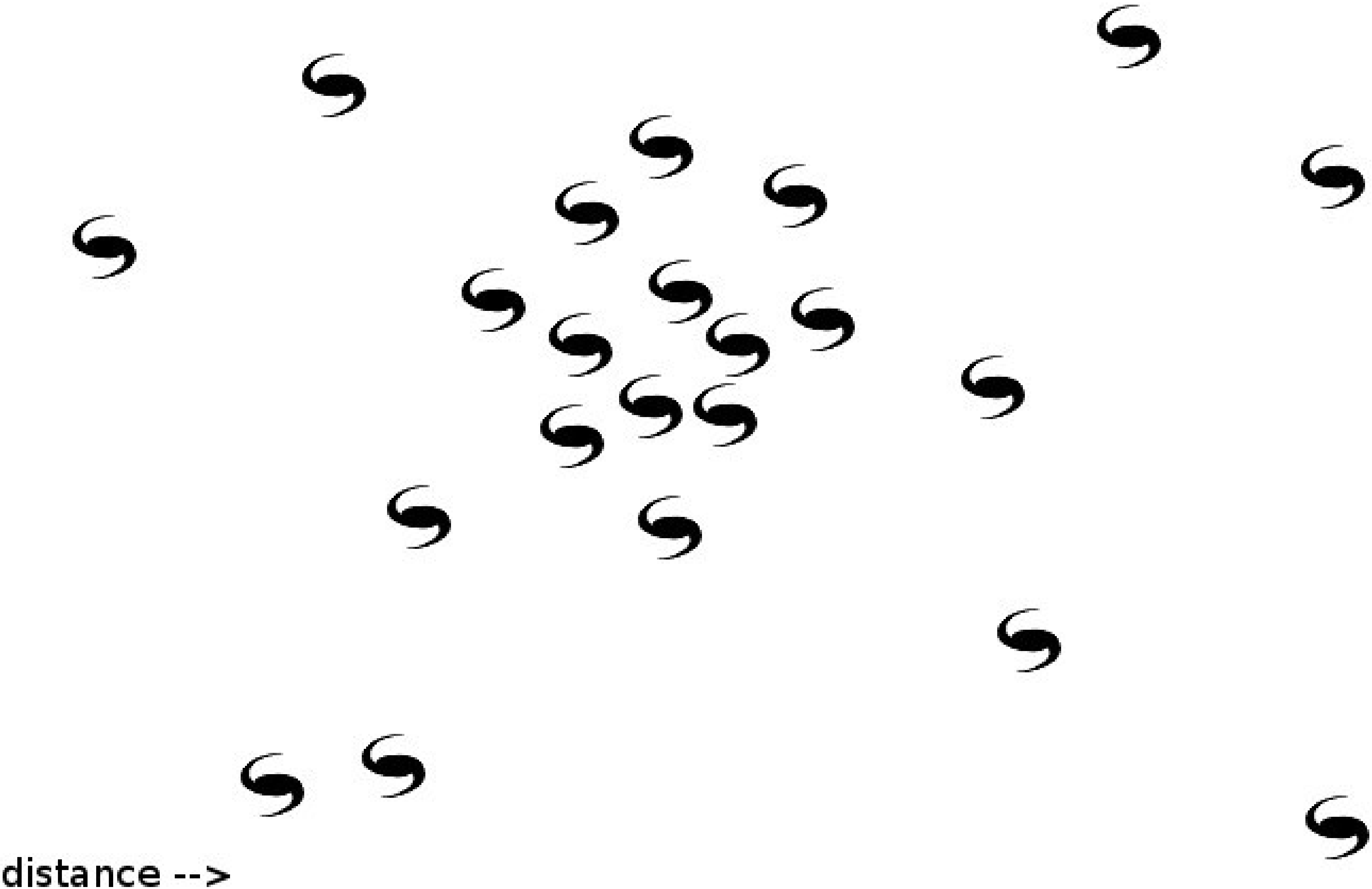


Iteratively merging enclosed finite infinity regions

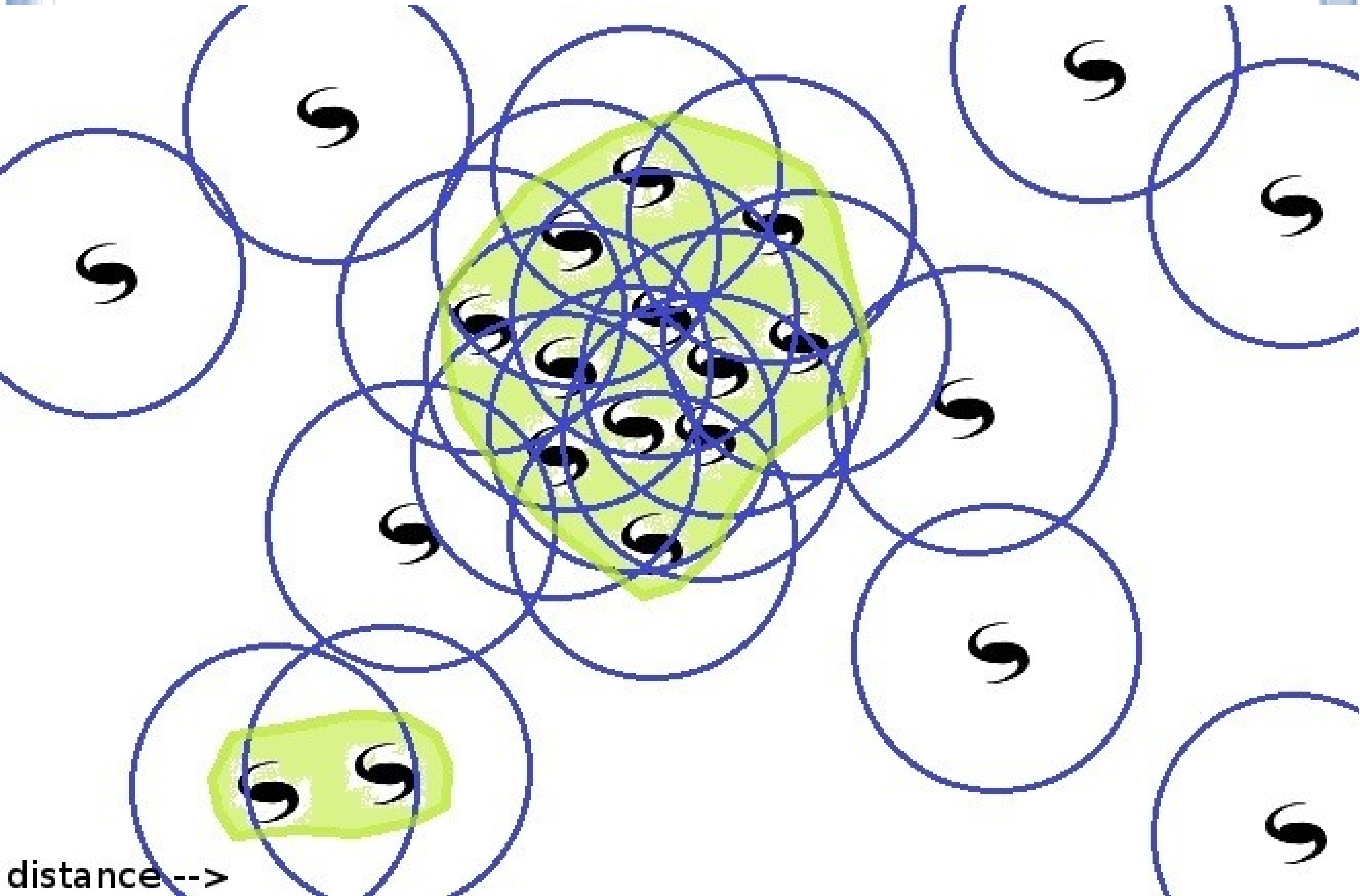


FoF group finder

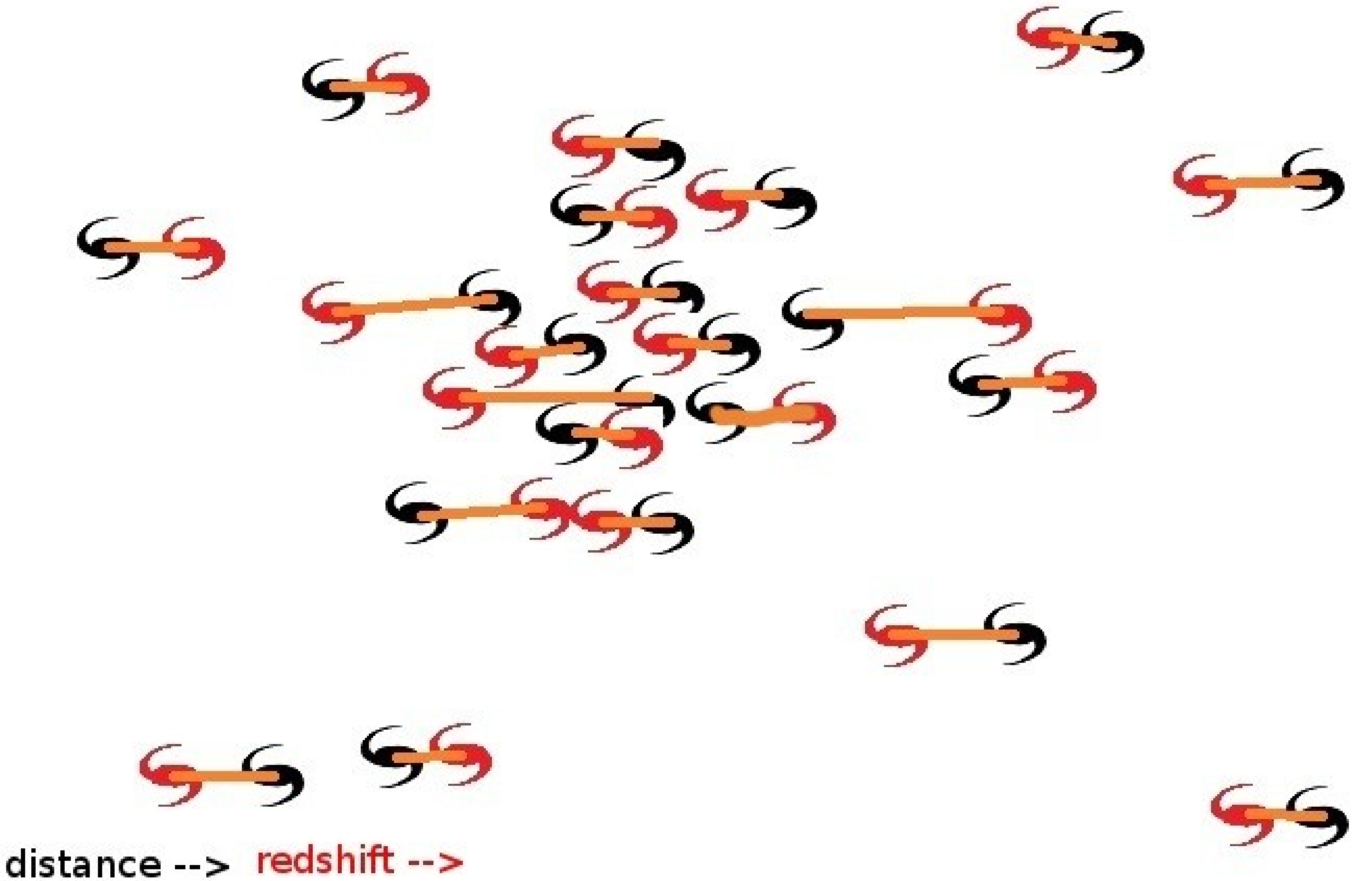
“real” galaxy distribution (e.g. from Mock catalogues)



FOF groups

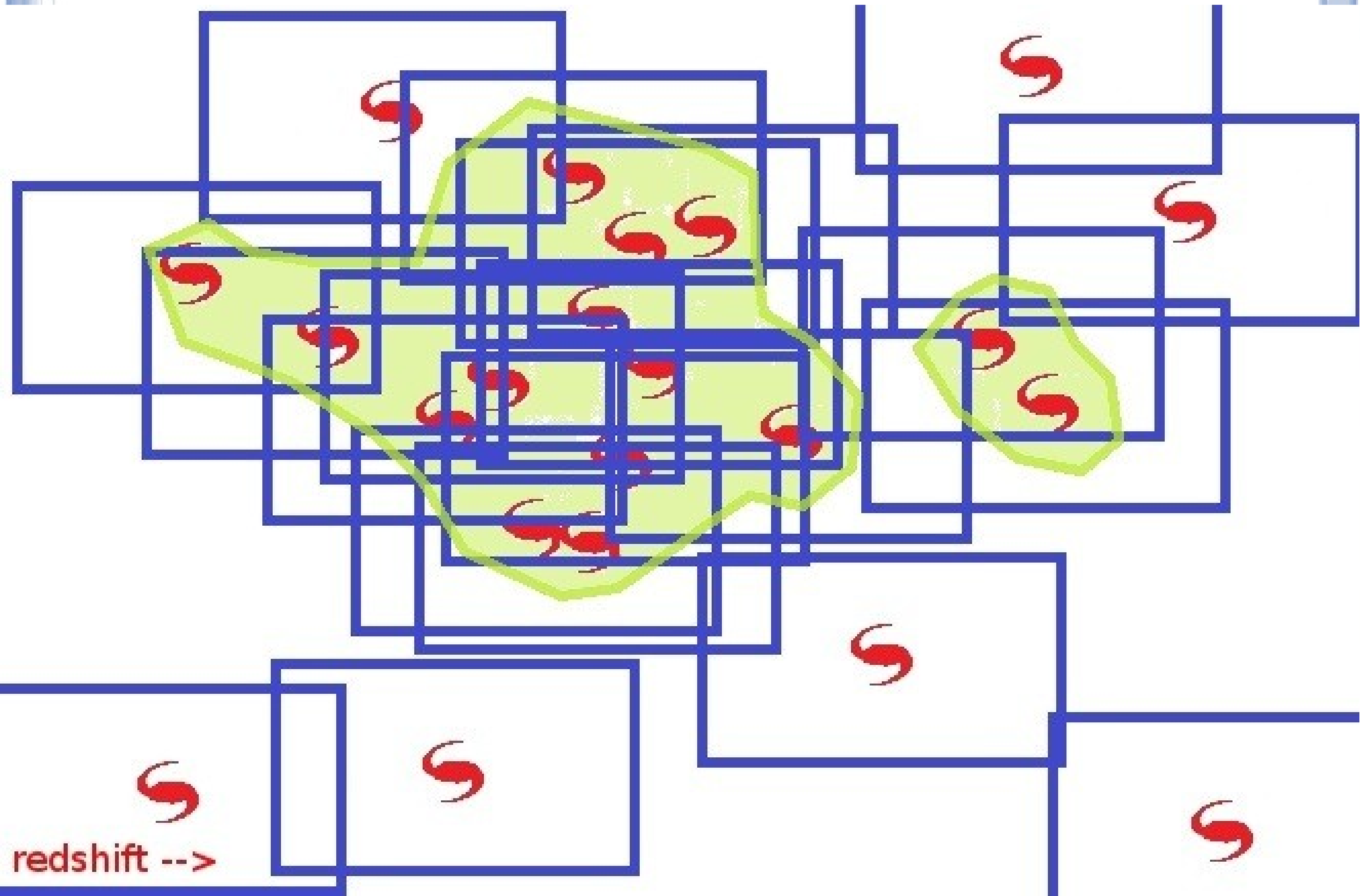


move to redshift space – peculiar motions

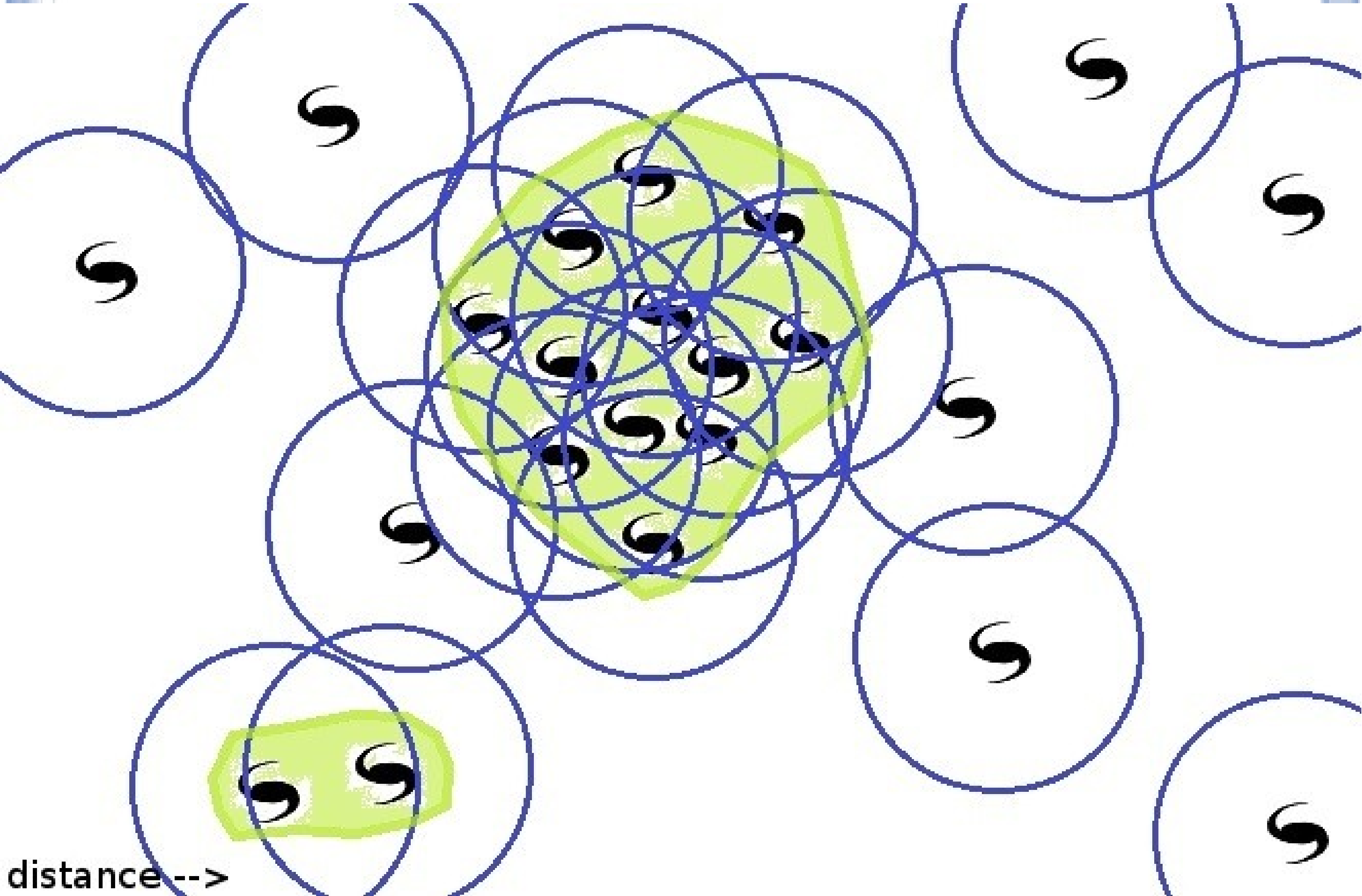


redshift space – observed distribution

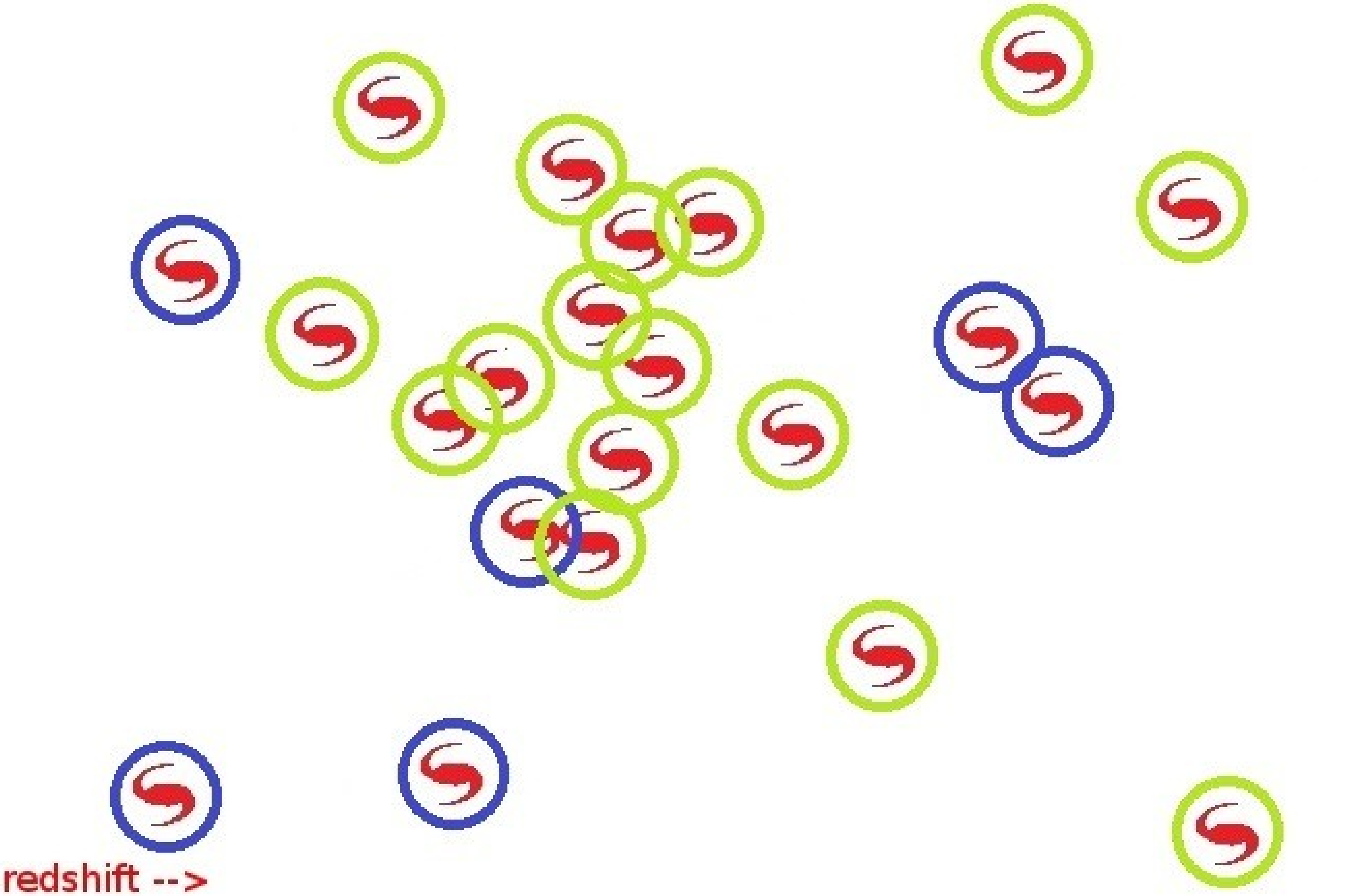
group finder



Comparison with “real” distribution

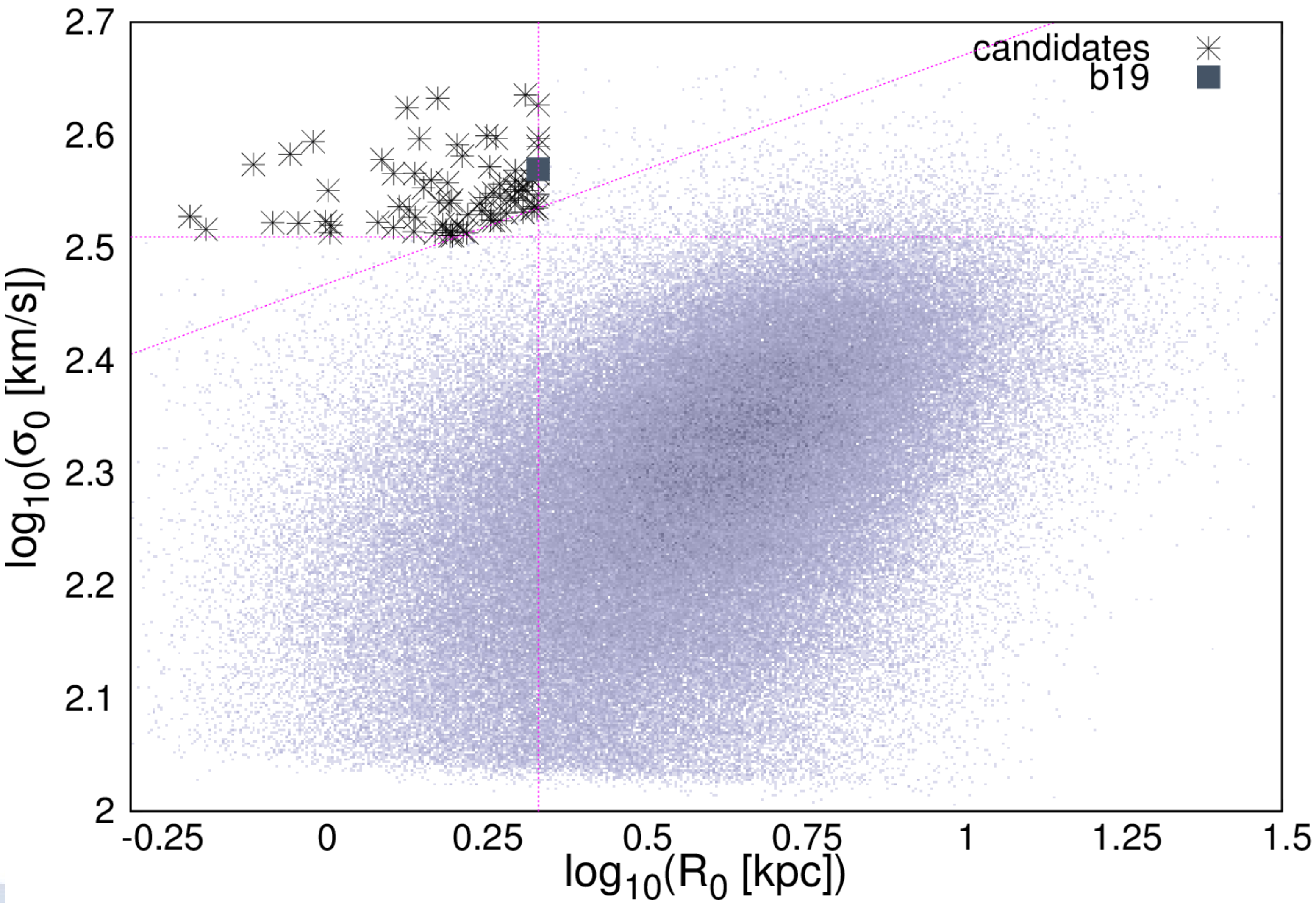


Quality analysis – false positive / false negative

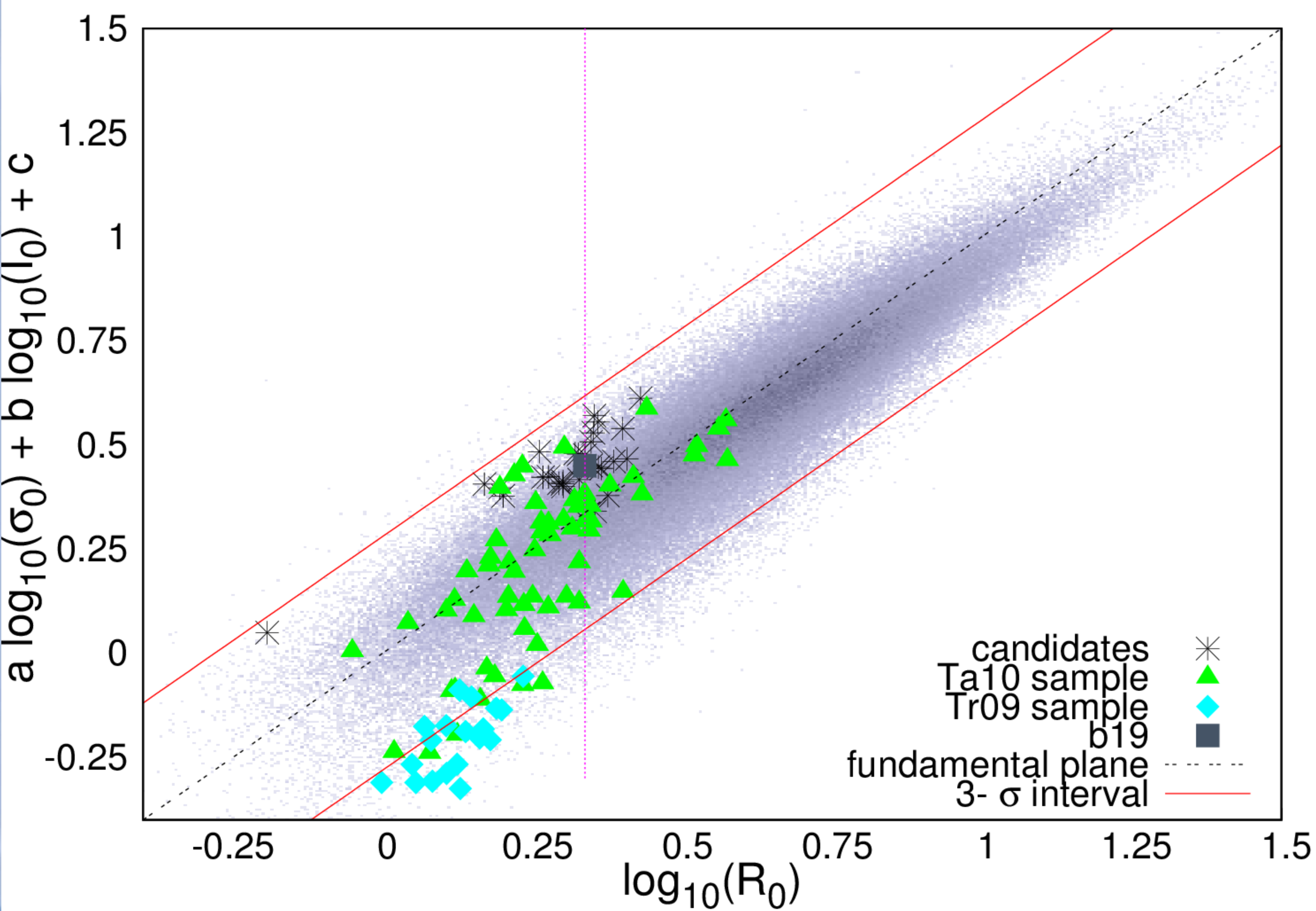


Compact massive ETG

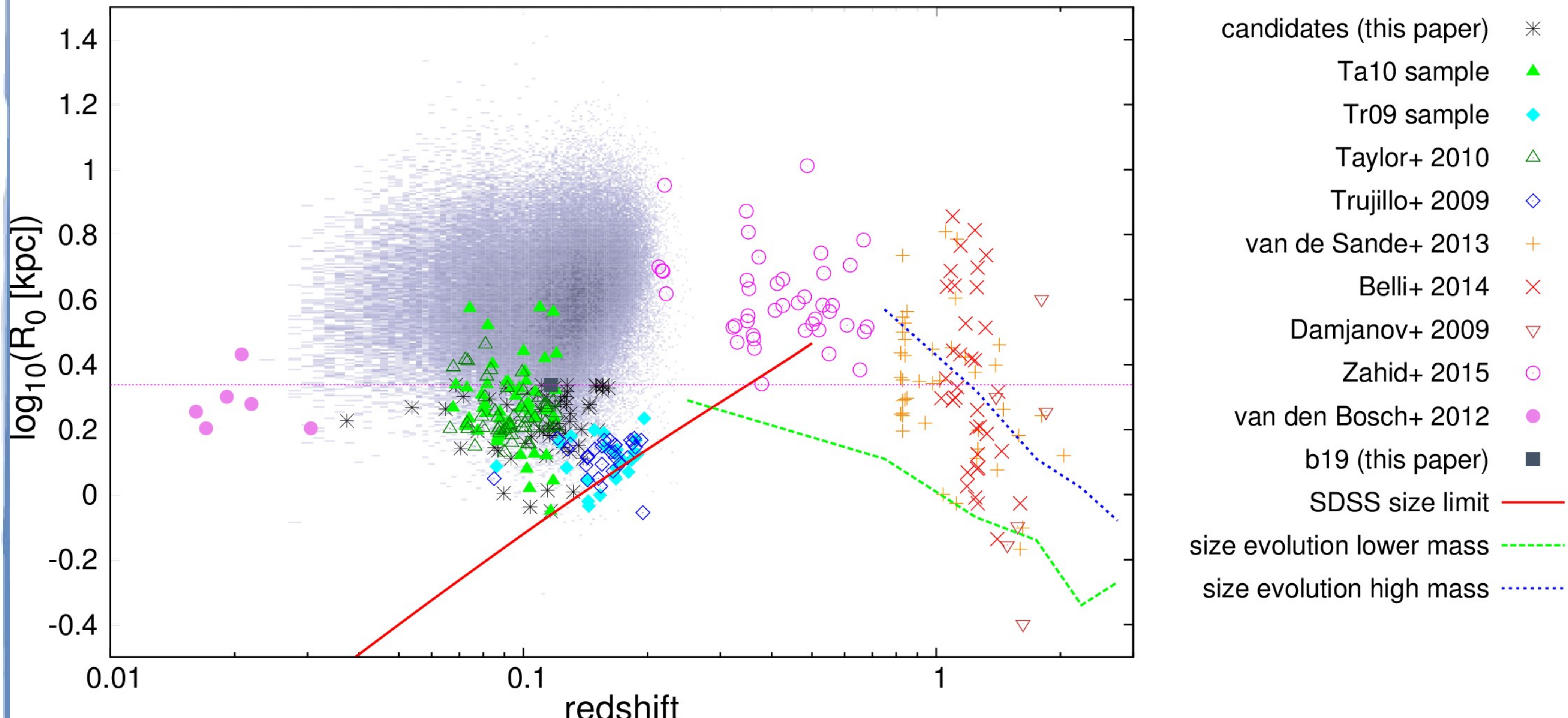
- High σ_0 and small R_0 galaxies similar to b19

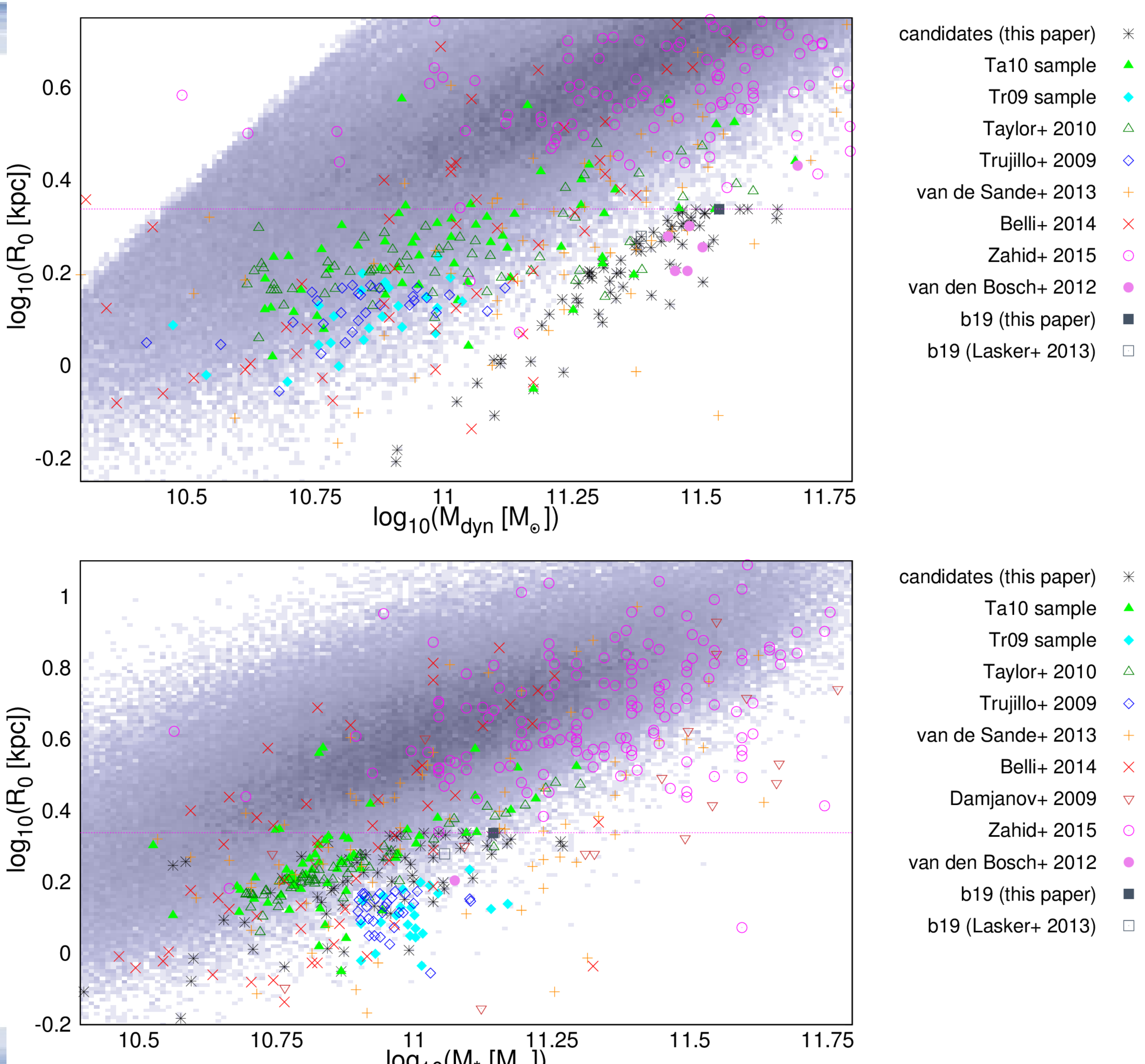


* b19 is not a fundamental plane outlier



- Evolved from red nuggets from the early universe





log10(R0 [kpc])
log10(Mdyn [M☉])
candidates (this paper)
Ta10 sample
Tr09 sample
Taylor+ 2010
Trujillo+ 2009
van de Sande+ 2013
Belli+ 2014
Zahid+ 2015
van den Bosch+ 2012
b19 (this paper)
b19 (Lasker+ 2013)
log10(R0 [kpc])
log10(M* [M☉])
candidates (this paper)
Ta10 sample
Tr09 sample
Taylor+ 2010
Trujillo+ 2009
van de Sande+ 2013
Belli+ 2014
Damjanov+ 2009
Zahid+ 2015
van den Bosch+ 2012
b19 (this paper)
b19 (Lasker+ 2013)

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

N/A

Sorry,

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