Observational tests of an inhomogeneous cosmology

by Christoph Saulder

In collaboration with Steffen Mieske & Werner W. Zeilinger

European Southern Observatory

www.eso.org

institut für astronomie

UNIVERSITÄTSSTERNWARTE WIEN

Collaborators and more

Nezihe Uzun

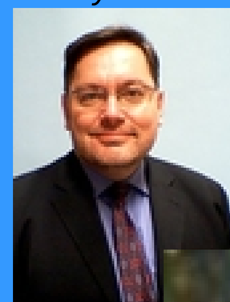
University of Canterbury

David L. Wiltshire

University of Canterbury

Werner W. Zeilinger

University of Vienna



Steffen Mieske

ESO Chile

Christoph Saulder

ESO Chile

Igor Chilingarian

Harvard Smithsonian CfA

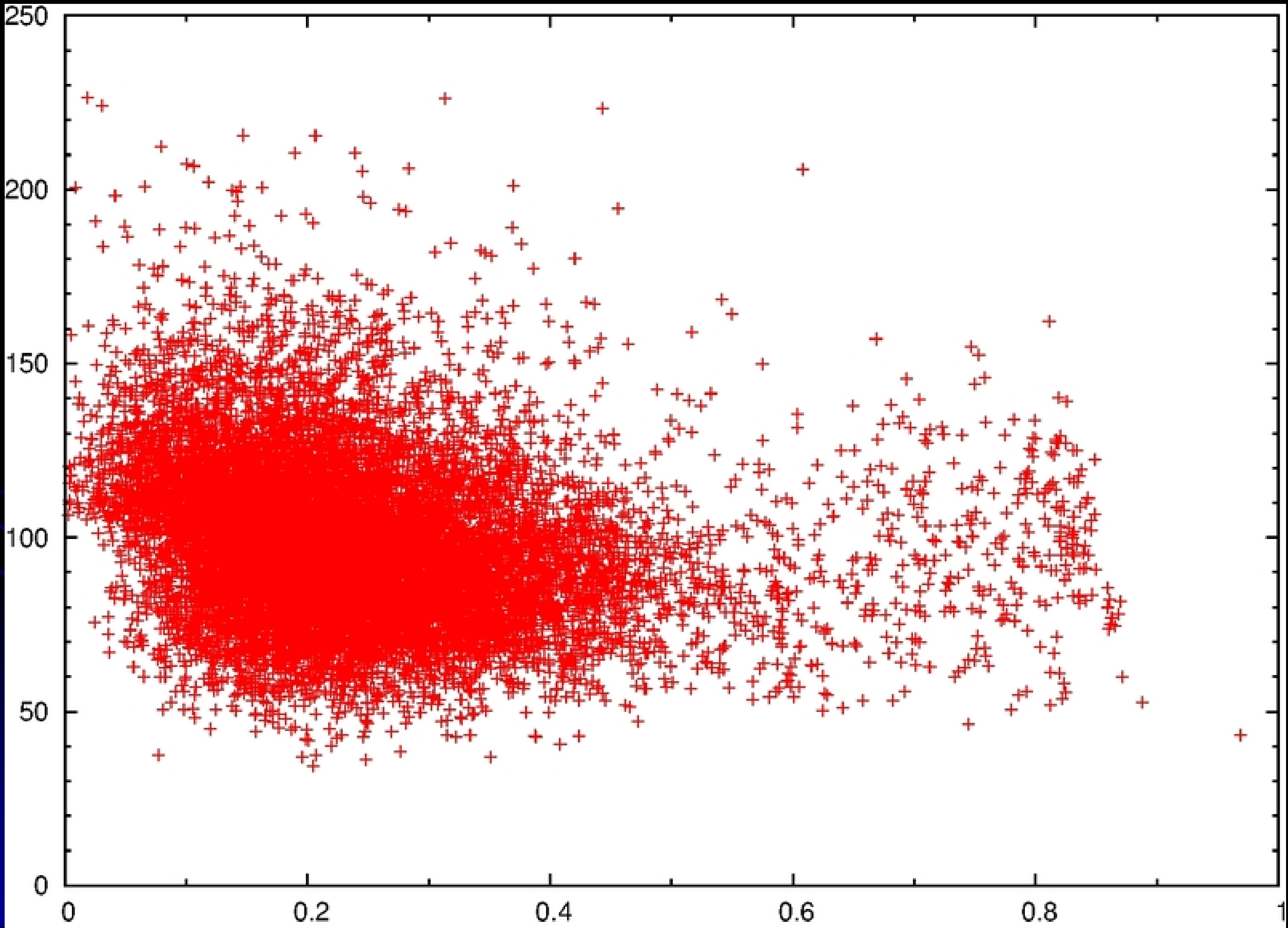
Syksy Räsänen

University of Helsinki

Thomas Buchert

Université Lyon 1

What is the meaning of this plot?



outline of this talk

- A review of basic (standard) cosmology
- Timescape cosmology
- Observational features
- Data sources
- Performing the test
  - Recalibrating the fundamental plane
  - Modeling the foreground
  - Quantifying biases
  - Measuring individual Hubble parameters
  - Testing timescape cosmology
- First results and conclusions

A review of basic cosmology

- Cosmology ➔ applied General Relativity

- Einstein's field equation

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Cosmological principle:

  homogeneity and isotropy

- Friedmann-Lemaître-Robertson-Walker metric

$$ds^2 = c^2 dt^2 - a(t)^2 \left[dr^2 + f(r) \left[d\theta^2 + \sin(\theta) d\varphi^2 \right] \right]$$

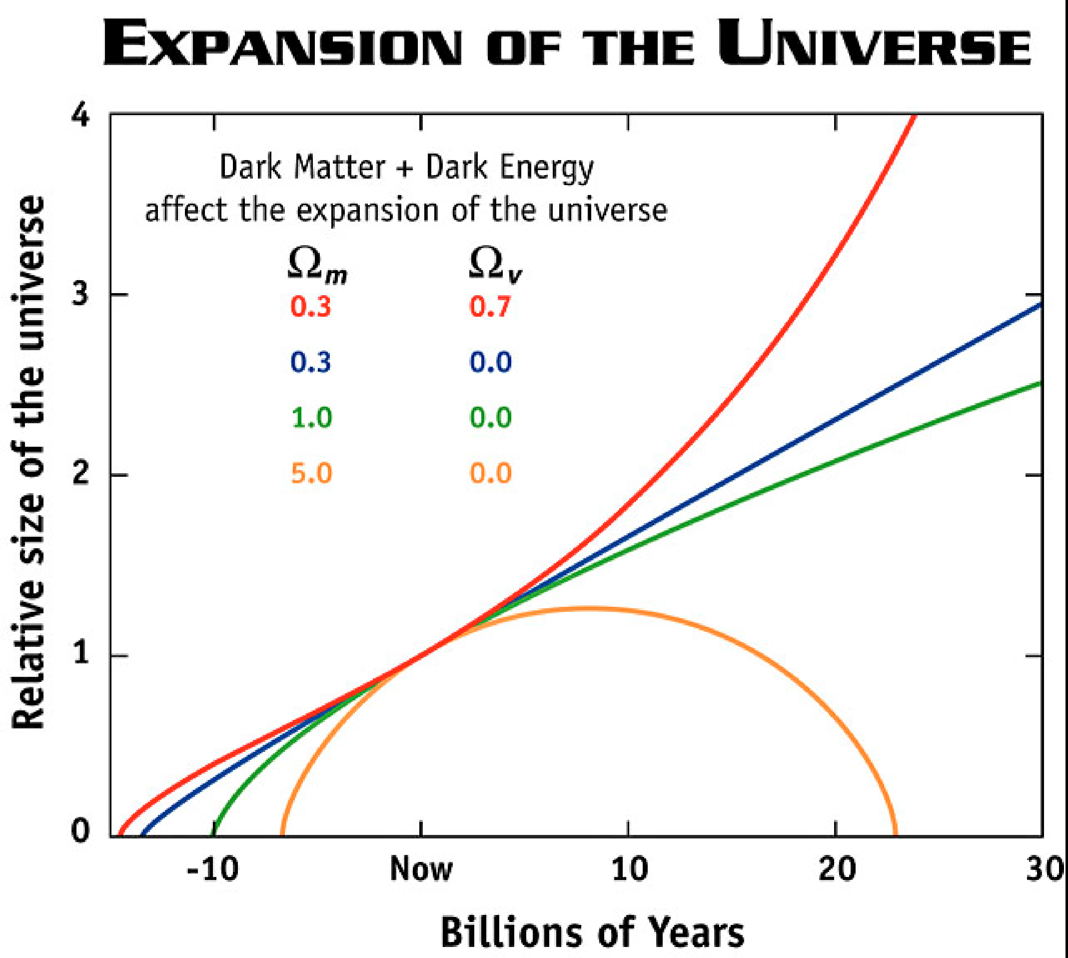
- Friedmann equations:

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3c^2} \rho - \frac{Kc^2}{a^2}$$

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2} (\rho + 3p)$$

- Expressed using relative energy densities:

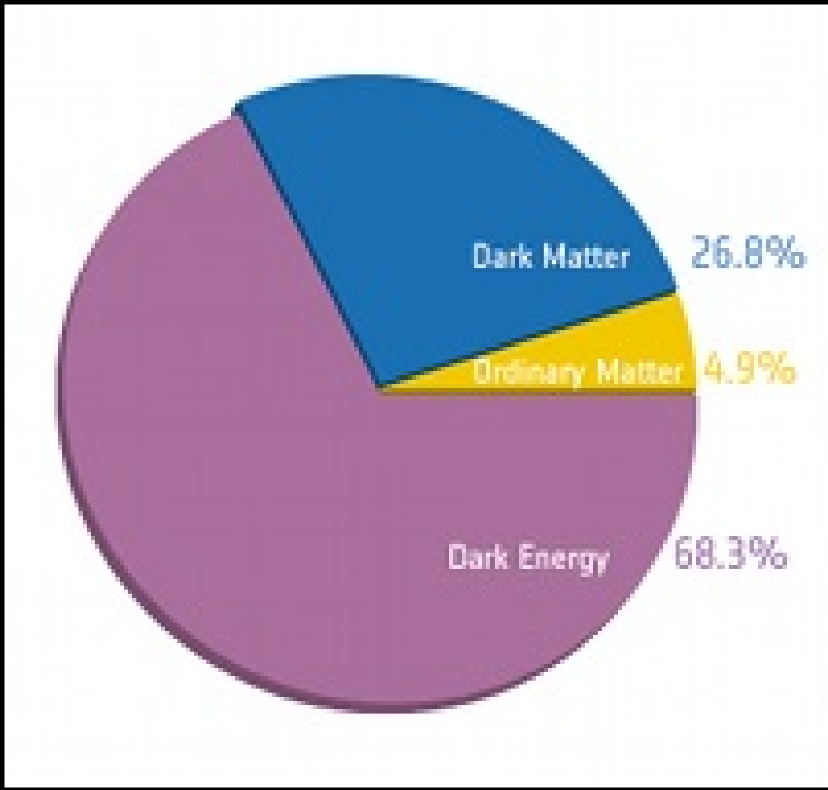
$$\frac{H^2}{H_0^2} = \Omega_\gamma a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$



by NASA

Best fit: Λ-CDM

by ESA



Observed accelerated expansion due to **D a r k E n e r g y ?**

Remark

- There are many inhomogeneous cosmological models.

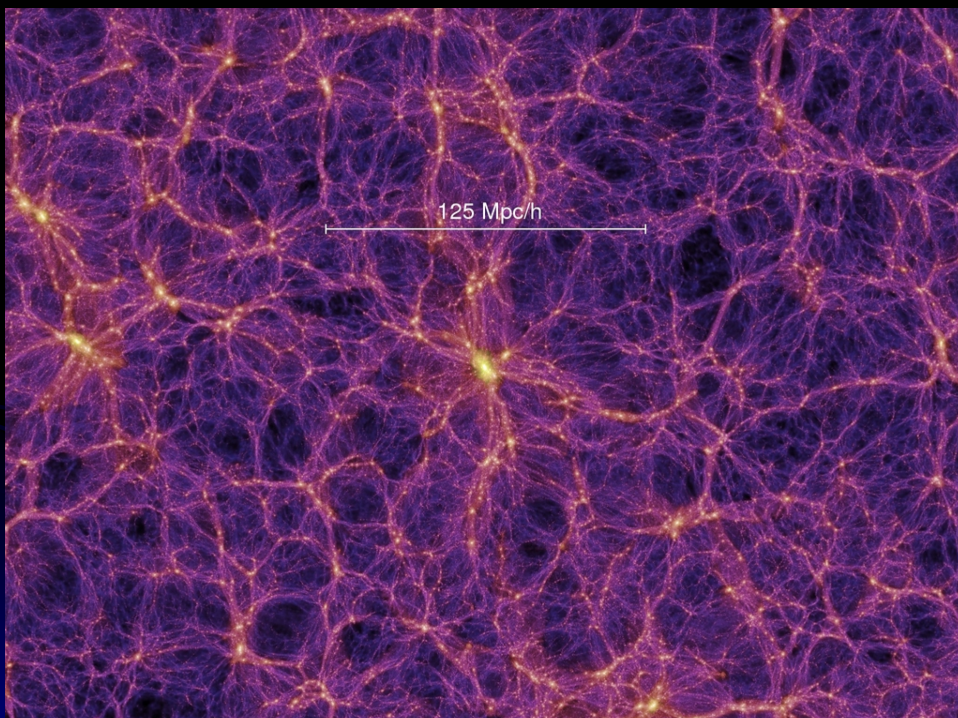
- I will **NOT** talk about:
  - Super-horizon inhomogeneities
  - The local universe is underdense compared to the rest of the universe.
  - Tilted universe theories

- I will just talk about inhomogeneities (cluster and voids) which are really observed.

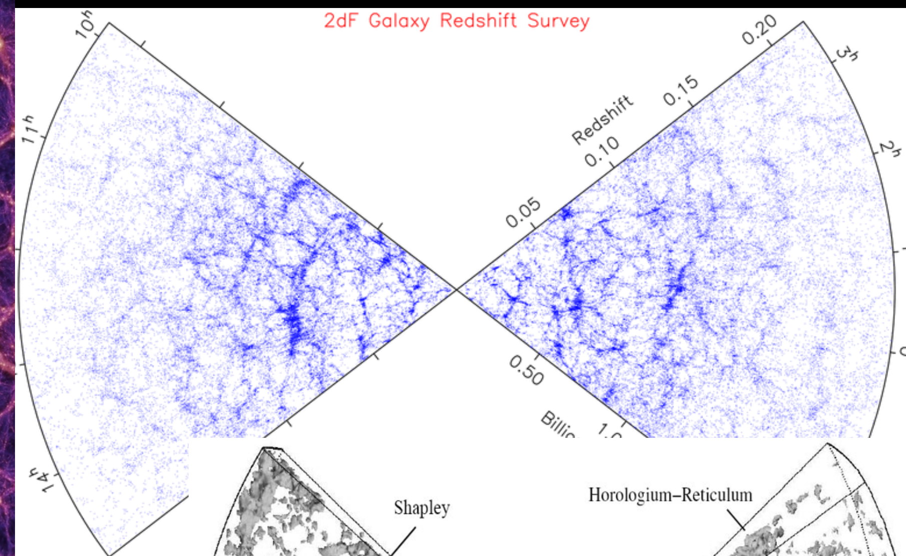
Timescape cosmology

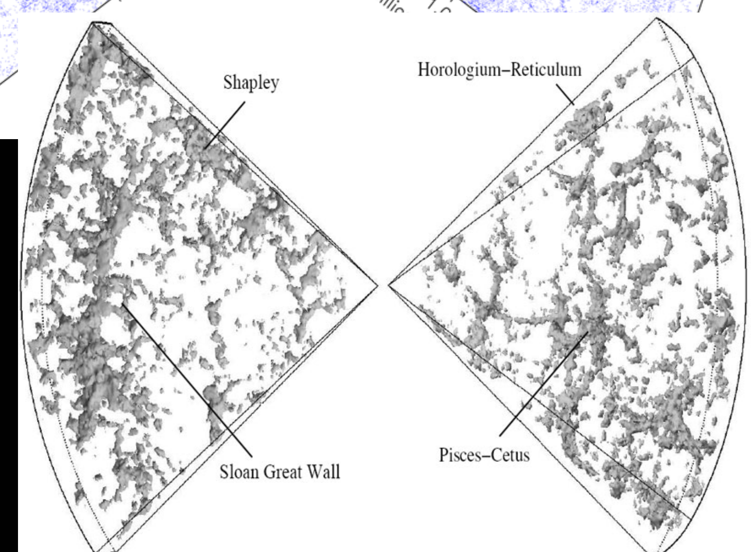
- The universe is **NOT** homogeneous
  ➔voids and clusters

By 2dFGRS



by MPA





By 2dFGRS

- We live in an inhomogeneous universe.
- General relativity is a non-linear theory.
- The averaging over inhomogeneities on large scales has to be modified.
- Back reaction from inhomogeneities expected.
- Life is not as simple as in an FLRW-universe, but how is it different?

- Perturbative approach (Buchert, 2000):

$$3\left(\frac{\dot{\bar{a}}}{\bar{a}}\right)^2 = 8\pi G\langle\rho\rangle - \frac{1}{2}\langle R\rangle - \frac{1}{2}Q \qquad 3\frac{\ddot{\bar{a}}}{\bar{a}} = -4\pi G\langle\rho\rangle + Q$$

$$\partial_t\langle\rho\rangle + 3\frac{\dot{\bar{a}}}{\bar{a}}\langle\rho\rangle = 0 \qquad Q = \frac{2}{3}\left\langle\left(\theta - \langle\theta\rangle\right)^2\right\rangle - 2\langle\sigma\rangle^2$$

- Pure perturbation theory alone isn't sufficient. (Räsänen, 2006)

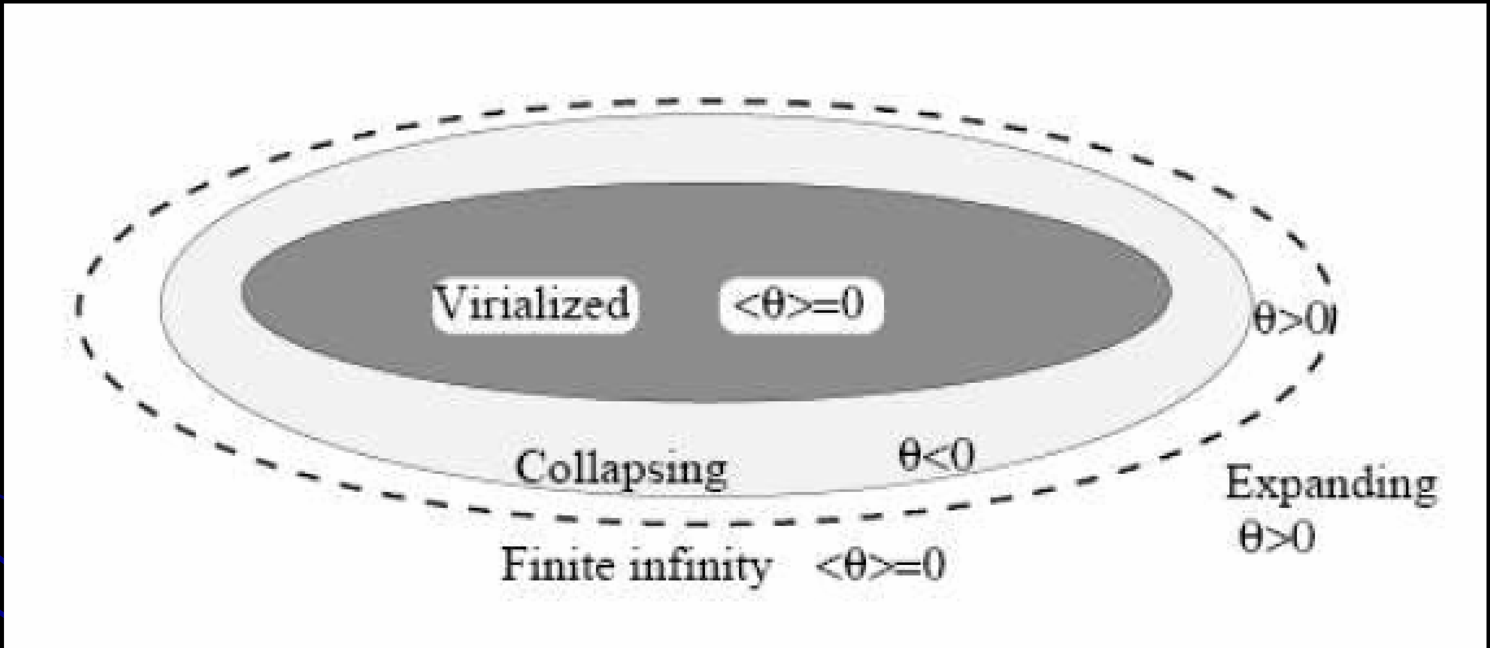
- Dropping the concept of a universal time parameter – increasing the importance of the local metric (Wiltshire, 2007)

- The timescape cosmology model by Wiltshire:
  - Two phase model – walls and voids
    → Swiss-cheese or Fractal Bubble model

by NZZ

  - Voids are empty → locally open geometry
  - Walls have a renormalized critical density on average → locally flat geometry

- Different clock rates in voids and walls.
- The two phases are separated by a finite infinity boundary.



by Wiltshire, 2007

- Lapse function on transition demands a reinterpretation of the features in the CMB.

- Consequence: time flows differently in voids and walls.

  ➔ the centers of the voids are older than the cores of cluster

- Consequence: voids expand faster than walls due to local geometry.

- At last scattering the universe was close to homogeneity.

- Structure formation made it inhomogeneous

- Nowadays the universe has a void dominated fractal bubble structure.

- Fraction of voids f_v in a comoving volume increases by time due to different expansion rates in voids and walls.

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

$$\ddot{f}_v + \frac{\dot{f}_v^{\,2}\left(2 f_v - 1\right)}{2 f_v \left(1 - f_v\right)} + 3\frac{\dot{\bar{a}}}{\bar{a}}\dot{f}_v - \frac{3\alpha^2 f_v^{1/3}\left(1 - f_v\right)}{2\bar{a}^2} = 0$$

Wiltshire, 2007

- The average expansion is approaching the void expansion rate.

One naturally gets an

accelerated expansion

without the need of

Dark Energy!

- Nice theory, isn‘t it?

BUT

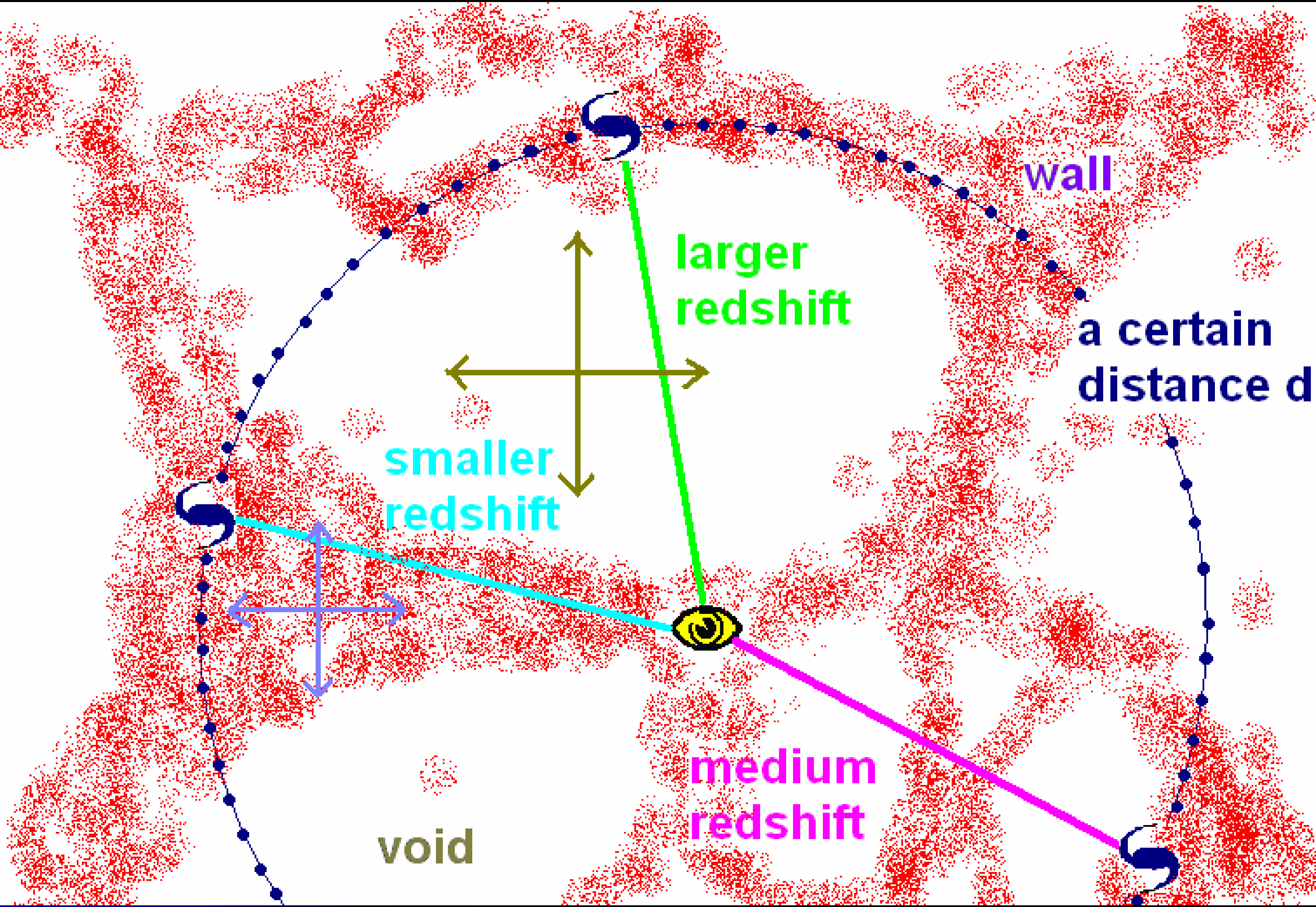
- Are these back reactions really strong enough to explain the cosmic acceleration.
- Proper calculations are hard to make due to the complexity of General relativity.
- Estimates are ranging from negligible to extremely important (Marra et al. 2010, Mattsson et al. 2010, Kwan et al. 2009, Clarkson et al. 2009, Paranjape 2009, van den Hoogen 2010)

- **Only tests can provide an answer!**

Observational features

- CMB-power spectrum, cosmic rays, …
- different Hubble parameters depending on the environment:

  void regions expand about 17-22%
  faster than wall regions
- observed Hubble parameter should depend on the foreground (fraction of wall regions in the line of sight) (Schwarz 2010)
- effect averages out at the scale of homogeneity


wall
larger
redshift
a certain
distance d
smaller
redshift
medium
redshift
void

- optimal distance between 50 and 200 Mpc
- requires redshift and another independent distance indicator, like the fundamental plane
- lots of data required
- homogenous sample on a large area of the sky: e.g. elliptical galaxies from SDSS
- one also has to model the foreground

Data sources

- Observational data: SDSS DR8
  GalaxyZoo (SDSS based)
  Yang et al. 2007 (SDSS based)
  NED (NASA Extragalactic database)

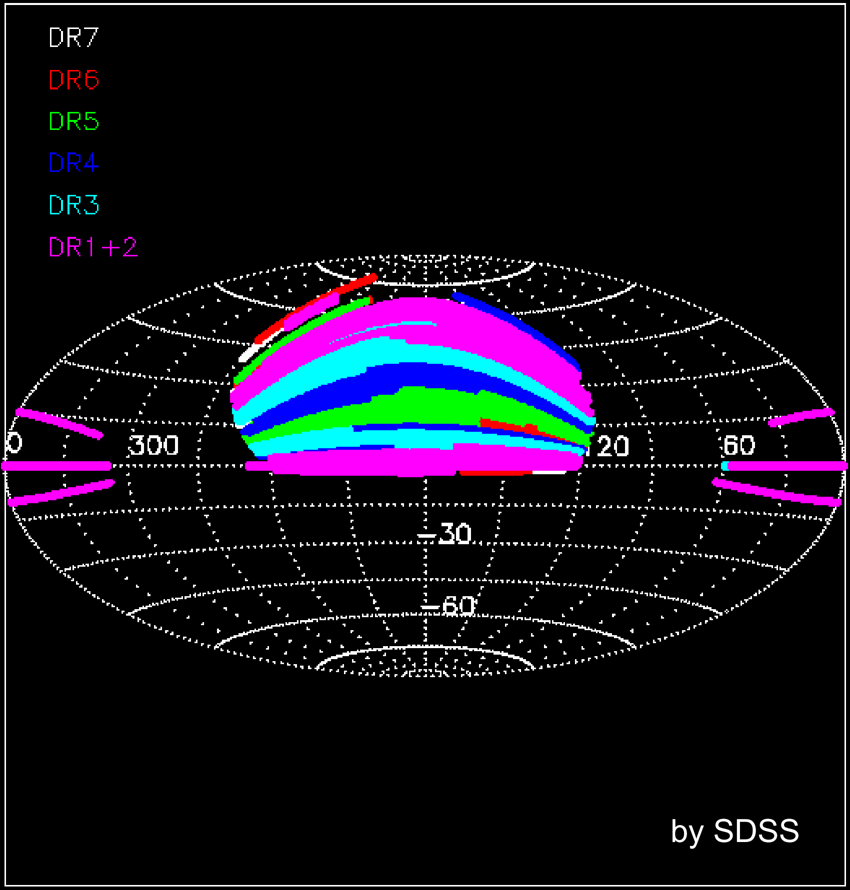
- Simulated data for ΛCDM:
  Millennium Simulation

- Maybe also other data sources in the future.

- All data is already there
  → **no new observations required!**

SDSS DR8

- Sloan Digital Sky Survey (www.sdss.org)
- imagining data of
  357 million objects
- spectra of about
  930 000 galaxies
- covers almost 12 000 deg²
- only northern hemisphere



- Different model fits for all galaxies (magnitudes and effective radii)
- Extinction map based on Schlegel et al, 1998
- 5 filters: u g r i z
- Spectroscopic measurements of central velocity dispersion and redshift
- Classification done by GalaxyZoo and additional conditions

GalaxyZoo

- SDSS data is classified using a large community of volunteer amateurs
- the first results are included in SDSS DR8
- Difference between elliptical and spirals
- Likelihood based on the number of votes

Group catalog by Yang et al.

- SDSS based catalog on galaxy groups and clusters.
- Contains masses from velocity dispersion.
- The latest version is based on DR7 (same spectroscopic sky coverage as DR8)
- Incomplete for $z<0.01$ ➔ we will have to fill this gap with **NED data**

Millenium Simulation

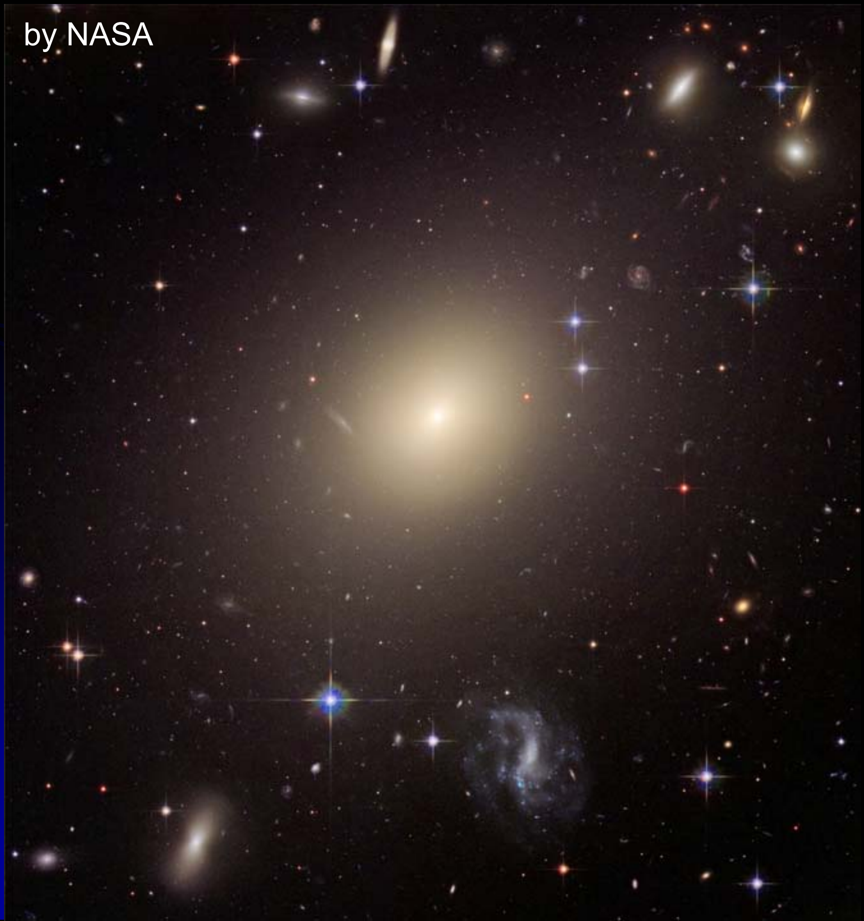
- First results published in 2005 a working group of the MPIA.
- Numerical simulation with Dark Matter & Λ-type Dark Energy (based on Λ-CMD cosmology).
- 10^{10} particles
- a cube of $500h^{-1}$Mpc length
- Resolution of $5h^{-1}$kpc
- with 10^{7} galaxies more luminous than the SMC
- It contains semi-analytic galaxy models too.

Performing the test

- Recalibrating the fundamental plane
- Modeling the foreground
- Measuring individual Hubble parameters
- Quantifying biases
- Testing timescape cosmology

Recalibration the fundamental plane

- Distance indicator for giant elliptical galaxies



- Relatively simple stellar systems

  de Vaucouleurs profile: $I(r) = I_0 \cdot \exp\left(-7.67\left(\frac{r}{r_e}\right)^{\frac{1}{4}}\right)$

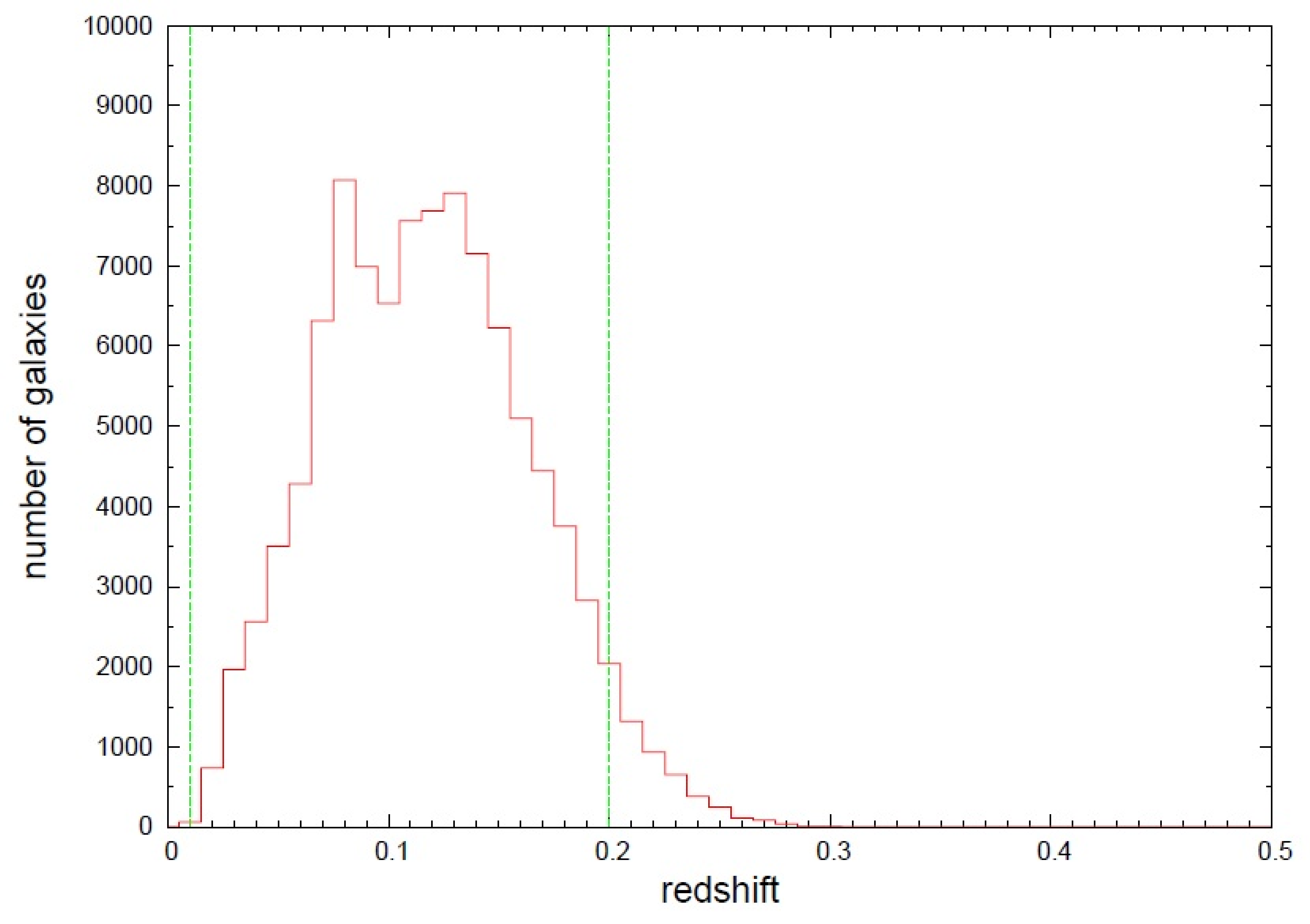
- Relation between the effective radius, the central velocity dispersion and the mean surface brightness

$$\log(R_0) = a \cdot \log(\sigma_0) + b \cdot \log(I_0) + c$$

- We have the largest data set and new high quality K-correction (Chiligarian et al. 2010).

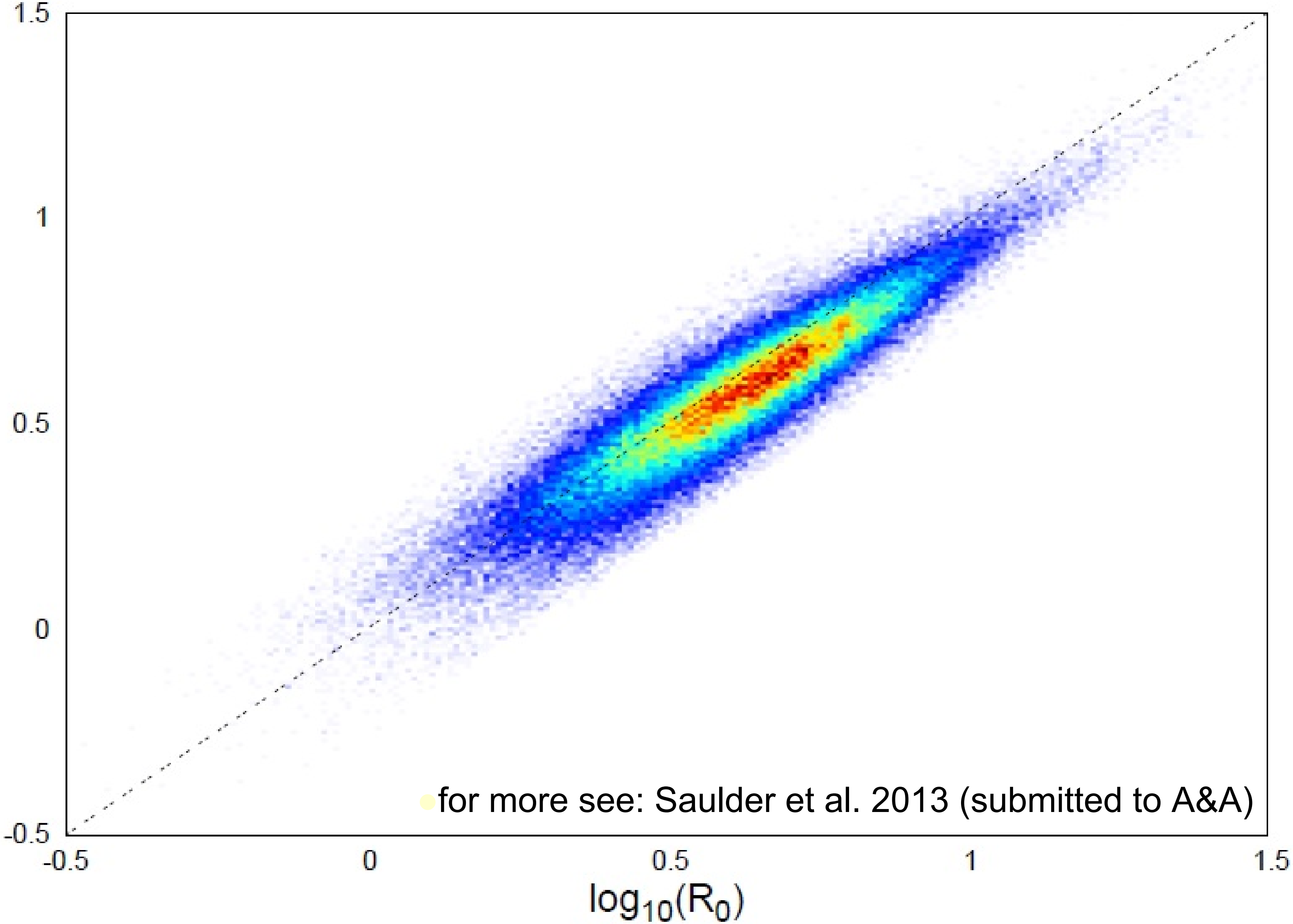
- We use similar methods as Bernhardi et al. 2003.

The elliptical sample from SDSS/GalaxyZoo: >100000. We use ~93000 of them.



1. correct for extinction
2. K-correction (Chiligarian et al. 2010)
3. Correct effective radius for ellipticity
4. Correct for fixed aperture of SDSS fiber
5. Correct redshifts for motion relative to the CMB
6. Correct for passive evolution
7. Get surface brightness
8. Correct for cosmological dimming
9. Estimate distance based on redshift
10. Calculate effective radius of galaxy
11. Fit the fundamental plane
    (with Malmquist bias corrected least squares)

- Average distance error <15% in the i and z-band



- for more see: Saulder et al. 2013 (submitted to A&A)

The foreground model

- Getting positions, redshift based distances and masses of almost 640 000 galaxies, groups and clusters from Yang et al. 2007 (latest version).

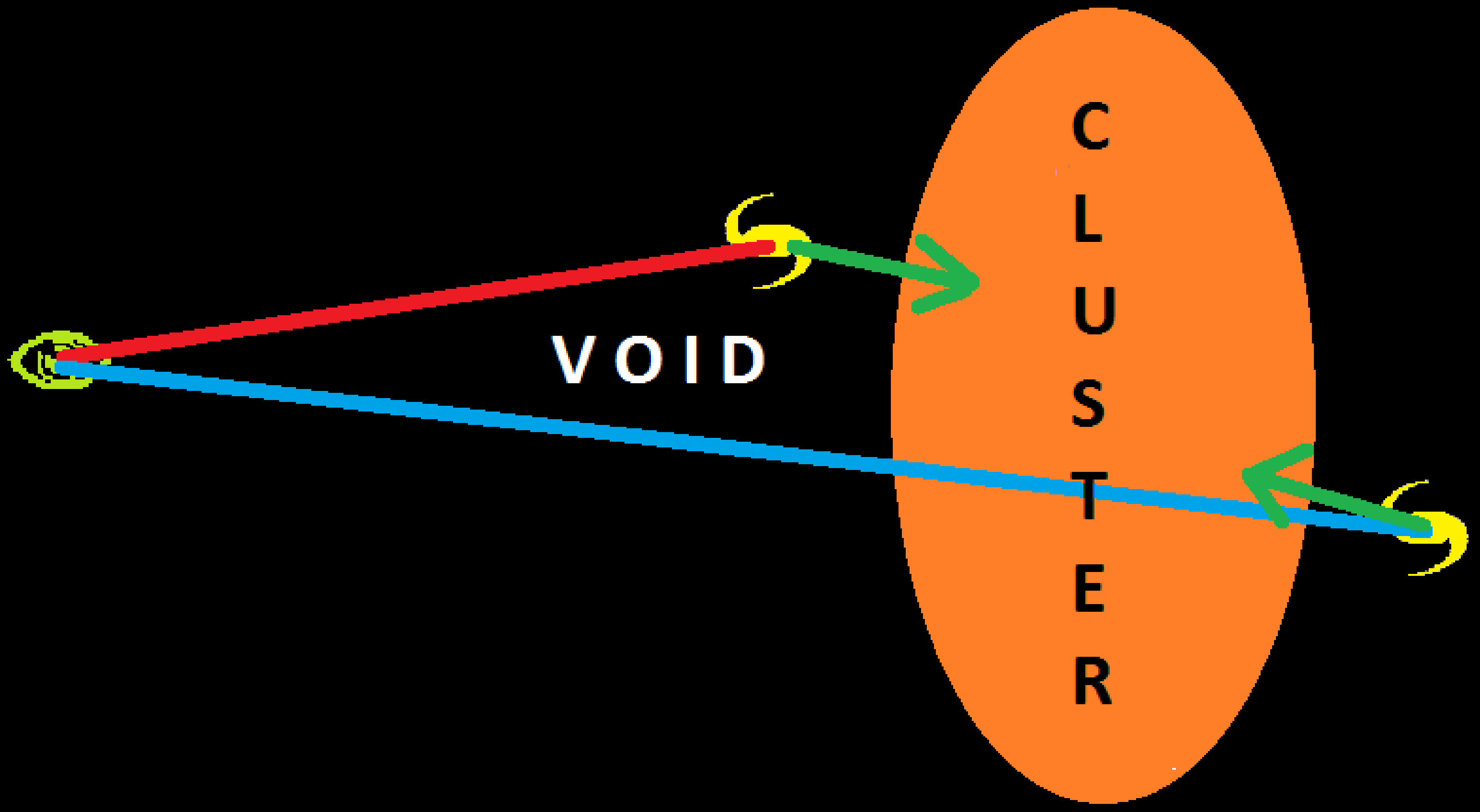
- Yang et al. 2007 does not cover z<0.01

- We fill the gap with data from NED (almost 20000 galaxies in the SDSS area)

- Using the masses to assign a finite infinity region around every object.

Quantifying biases

- Uncertainties in the distance measurement
  → clusters and statistics
- Incompleteness of the foreground model
  → missing objects are small and mainly bound to larger objects within the sample
- Peculiar motions causes a scatter
  → basically random → statistics
- Coherent infall into clusters has to be considered and quantified.



- A mock catalogue from the Millennium Simulation is required to estimate the Λ-CDM signal in our data.

Measuring individual Hubble parameters

- Definition: “individual Hubble parameter” = the Hubble parameter measures for one individual galaxy (or cluster)

- Quality selected sample of more than 10000 elliptical galaxies from SDSS with $z<0.1$

- Simple Hubble's law: $$H = \frac{c \cdot z}{D}$$

D obtained by the fundamental plane

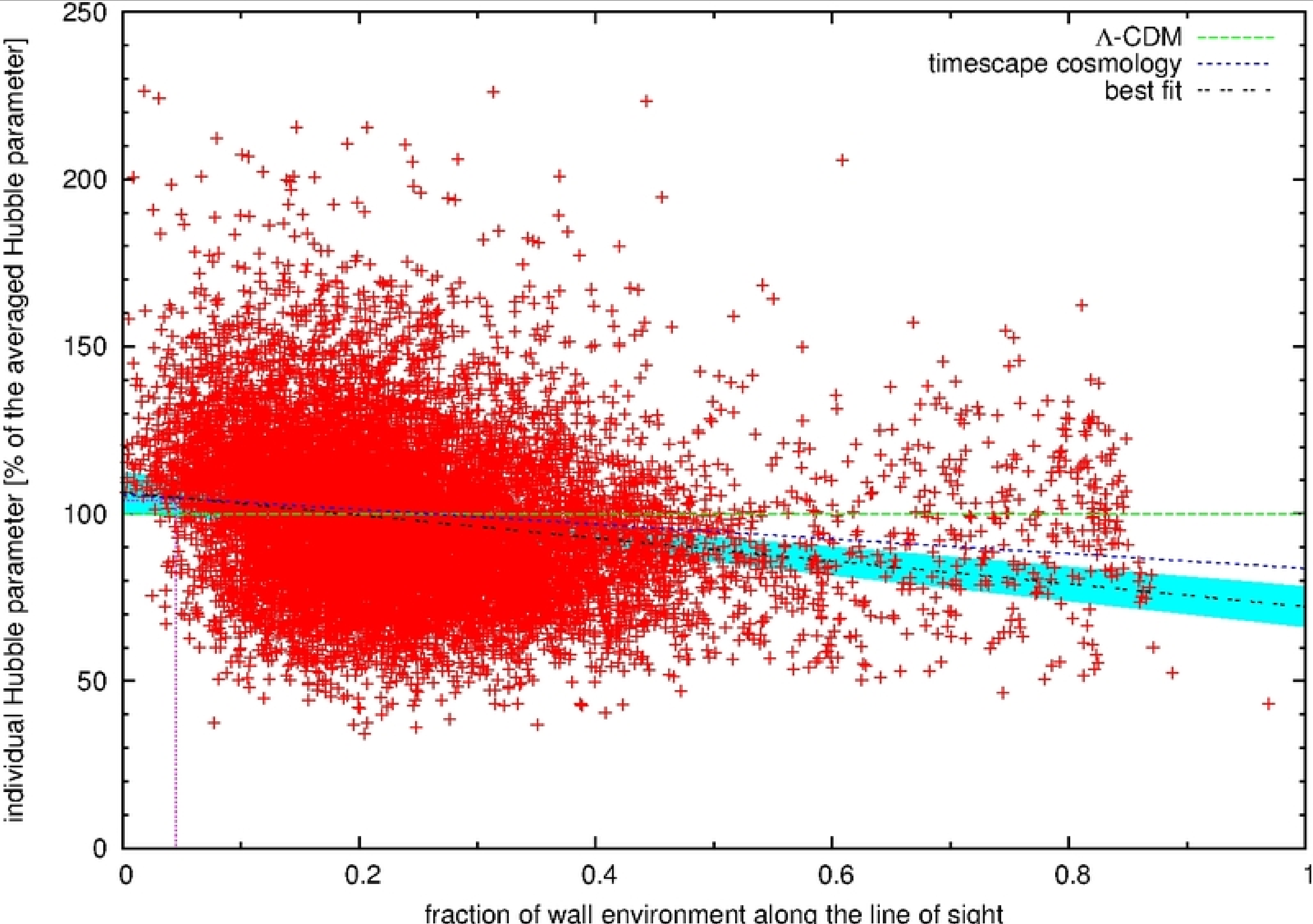
First results and conclusions

- For every galaxy, we calculate the fraction of the line of sight, which is inside finite infinity regions, by intersecting it with the foreground model.
- Basic high school mathematics: intersecting straight lines with spheres + some interval nesting
- But 10 000 X 500 000 times ➔ requires a lot of computation power ➔ parallelized code on the Astro-Cluster in Vienna.

- Compare the fraction of the wall environment (=inside finite infinity) in the line of sight to the individual Hubble parameter for every galaxy in the sample.

- Note: Individual Hubble parameter is just relative value → normalized to the mean Hubble parameter of the sample

MAKE A PLOT



Λ-CDM
timescape cosmology
best fit
individual Hubble parameter [% of the averaged Hubble parameter]
fraction of wall environment along the line of sight
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1

- The fitted lines for such a data set strongly depend on the fitting technique.
- The total lack of galaxies with almost 100% void foreground and low individual Hubble parameters is significant.
- Our models are still rather simple, but improving.
- The assumption of a horizontal line for the Λ-CDM expectation is too naïve ➔ comparison with the Millennium simulation

- Using the fundamental plane to calculate distances

  ➔ additional output: new coefficients for the fundamental plane of elliptical galaxies

- Comparing distances and redshifts

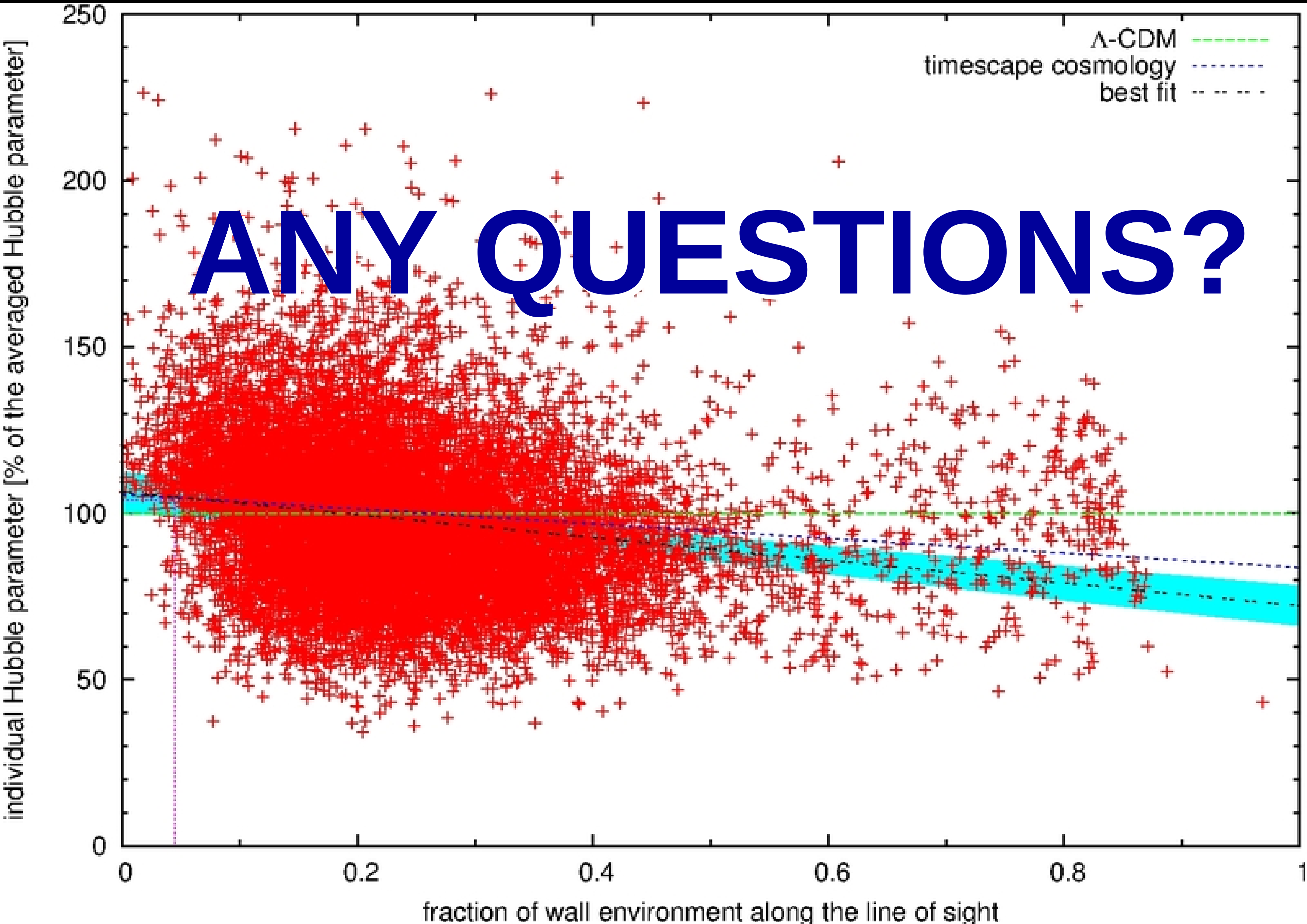
  ➔ additional output: peculiar motions

- The foreground model

  ➔ additional output: masses of clusters and galaxies + peculiar motions

- Testing timescape cosmology
- First results look promising, but there are still several open problems in our models.
- Positive results would be a major discovery.
- Intermediate results would favor Dark Energy theories with a Chameleon effect such as f(R) modified gravity.
- Negative results would support the Λ-CDM.

CAST LIGHT ON DARK ENERGY


ANY QUESTIONS?
Λ-CDM
timescape cosmology
best fit
individual Hubble parameter [% of the averaged Hubble parameter]
fraction of wall environment along the line of sight
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1