# Observational tests of an inhomogeneous cosmology

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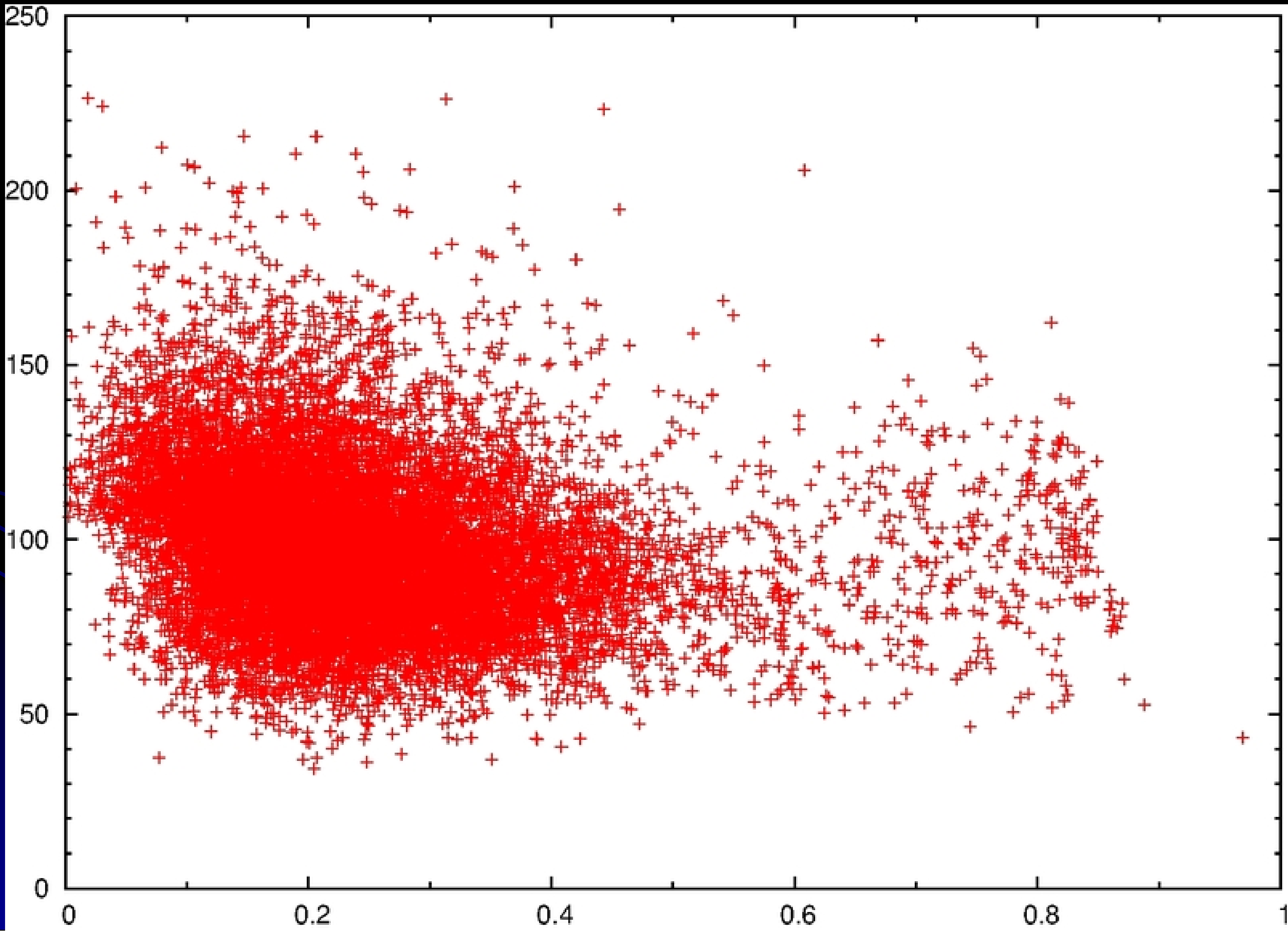
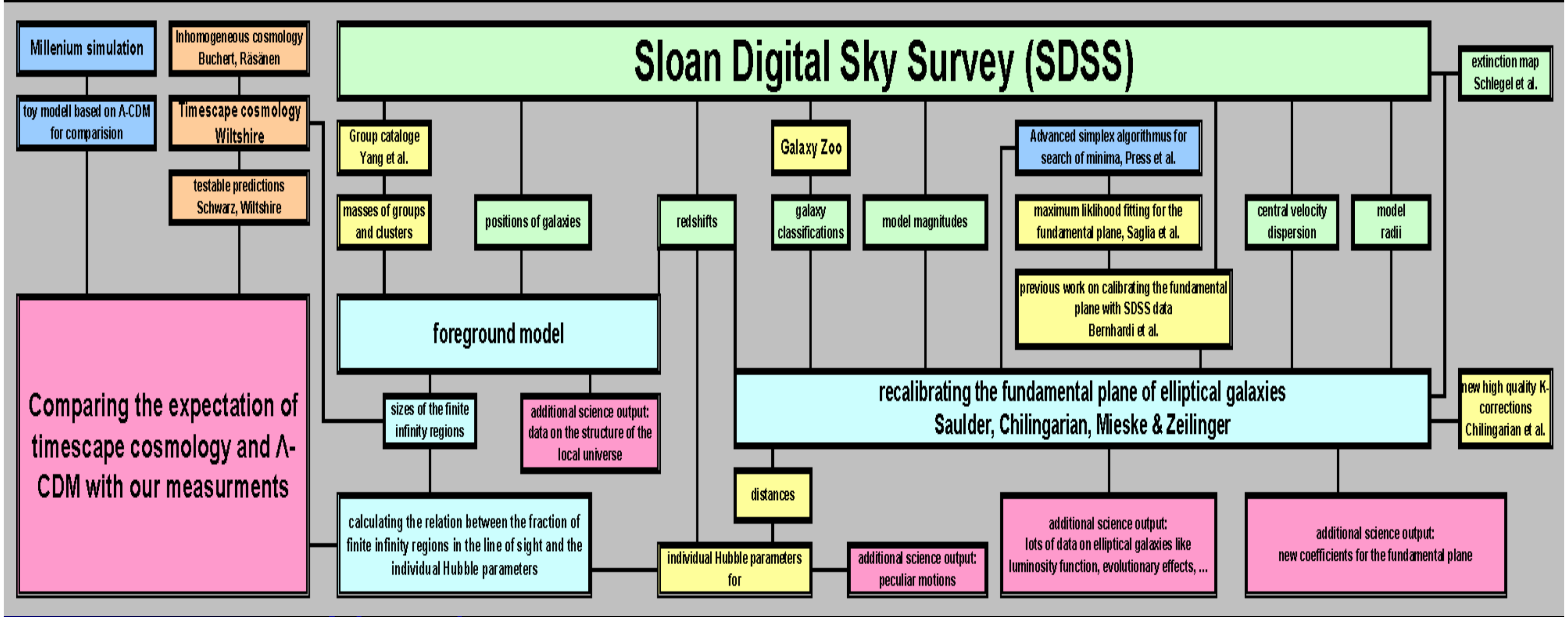
# What is the meaning of this plot?



# outline of this talk

- (Standard) cosmology
- Timescape cosmology
- Observational features
- Data sources
- Performing the test
  - Recalibrating the fundamental plane
  - Modeling the foreground
  - Measuring individual Hubble parameters
  - Testing timescape cosmology
- First results and conclusions

# It is a huge project:



# (Standard) Cosmology

- 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**

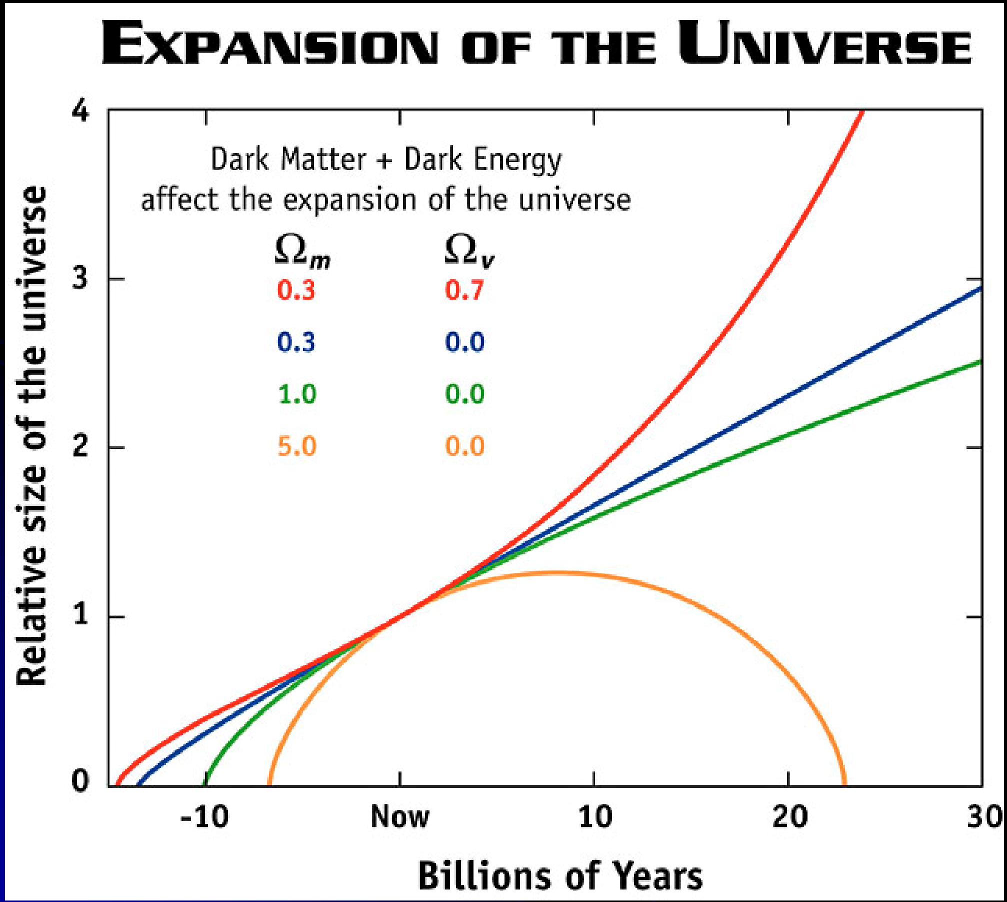
- Friedmann-Lemaître-Robertson-Walker metric

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

Friedmann equations:

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

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



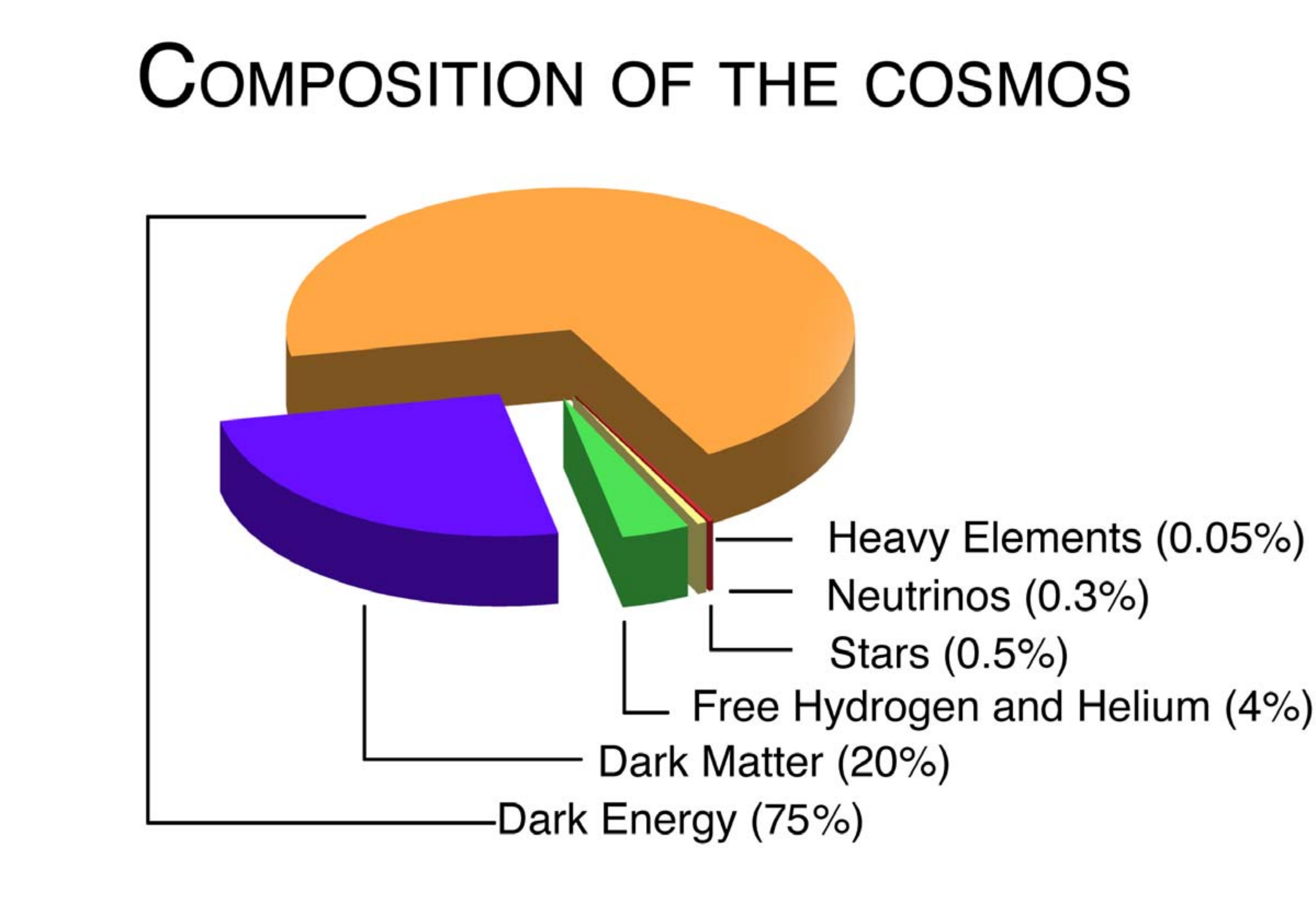

by NASA

Written using energy densities:

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

Observed accelerated expansion due to **Dark Energy?**

# Standard-model: Λ-CDM




by Leibinger, 2009

# Remark

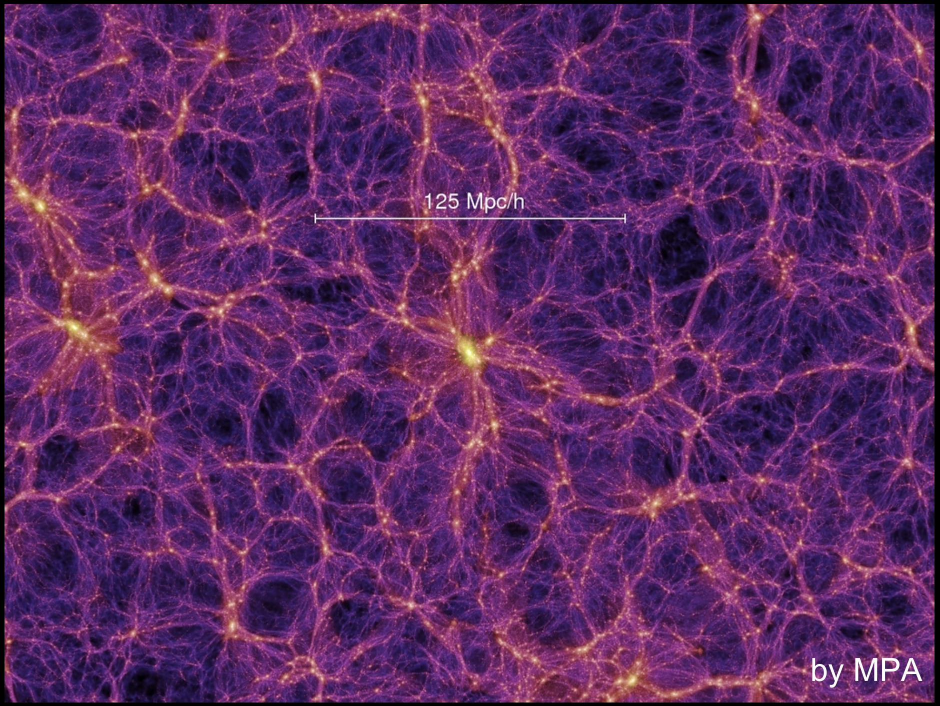
- There are many inhomogeneous cosmological models.

- 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 isn't homogeneous




- General relativity is a non-linear theory

- Averaging on large scales has to be modified
  ➔ back reaction from inhomogeneities expected

- Pertubative approach (Buchert, 2000):

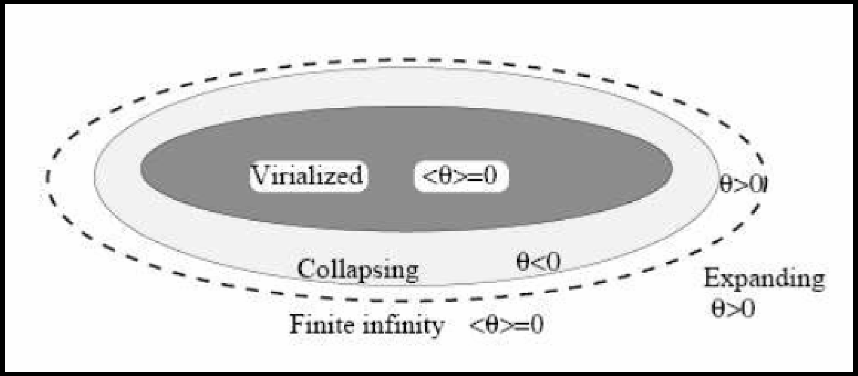
$$3\left(\frac{\dot{\bar{a}}}{\bar{a}}\right)^2 = 8\pi G\langle\rho\rangle - \frac{1}{2}\langle R\rangle - \frac{1}{2}Q \qquad 3\frac{\ddot{\bar{a}}}{\bar{a}} = -4\pi G\langle\rho\rangle + Q$$

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

- Pure pertubation 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
  - 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.

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

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

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

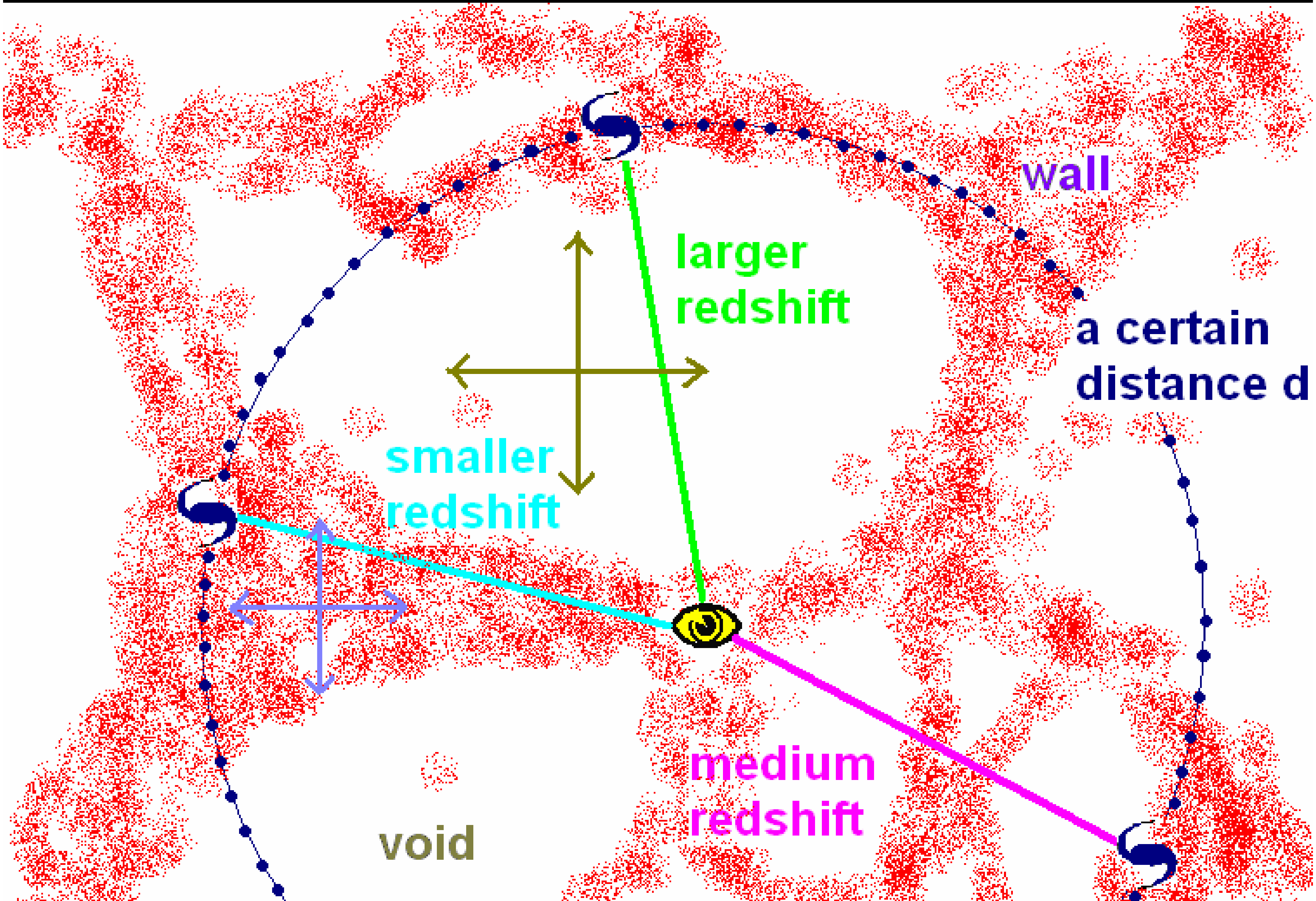
- Are these back reactions really strong enough to explain the cosmic acceleration.
- Proper calculations are hard to make due to the complexity of General relativity.
- Estimates are ranging from negligible to extremely important (Marra et al. 2010, Mattsson et al. 2010, Kwan et al. 2009, Clarkson et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

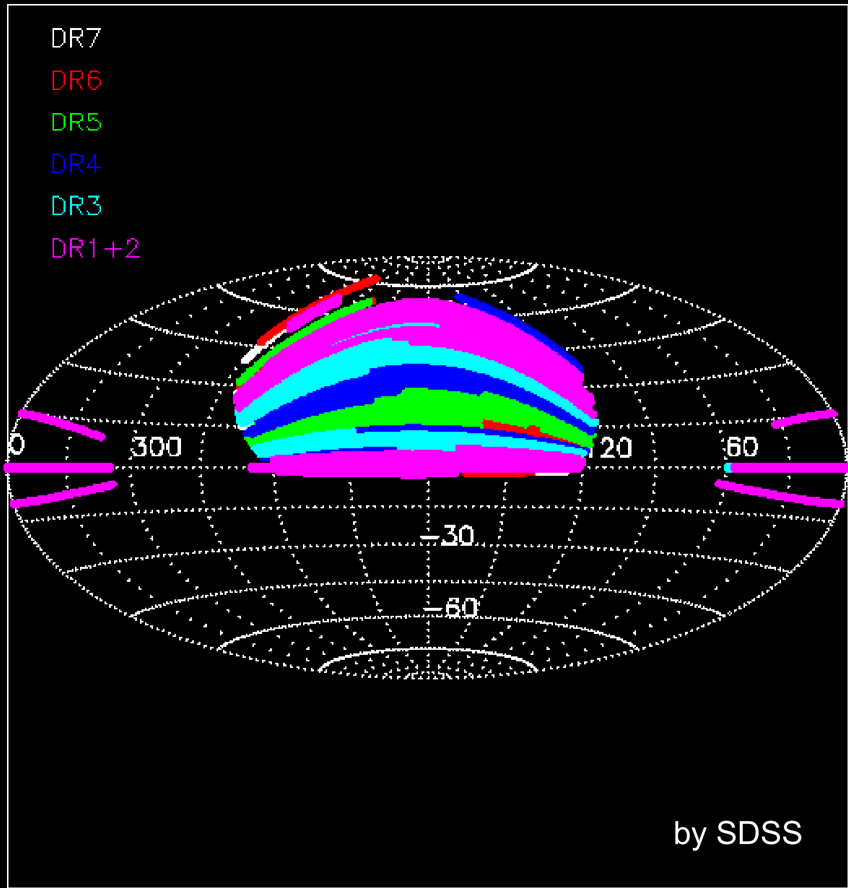
- Simulated data for $\Lambda$CDM:
  Millenium Simulation

- 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.
- Only DR4 – smaller sky coverage
- We will extend it by ourselves for DR8.

# Millenium Simulation

- First results published in 2005 a working group of the MPIA.
- Numerical simulation with Dark Matter & $\Lambda$-type Dark Energy (based on $\Lambda$-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
- Contains merger trees too

# Performing the test

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

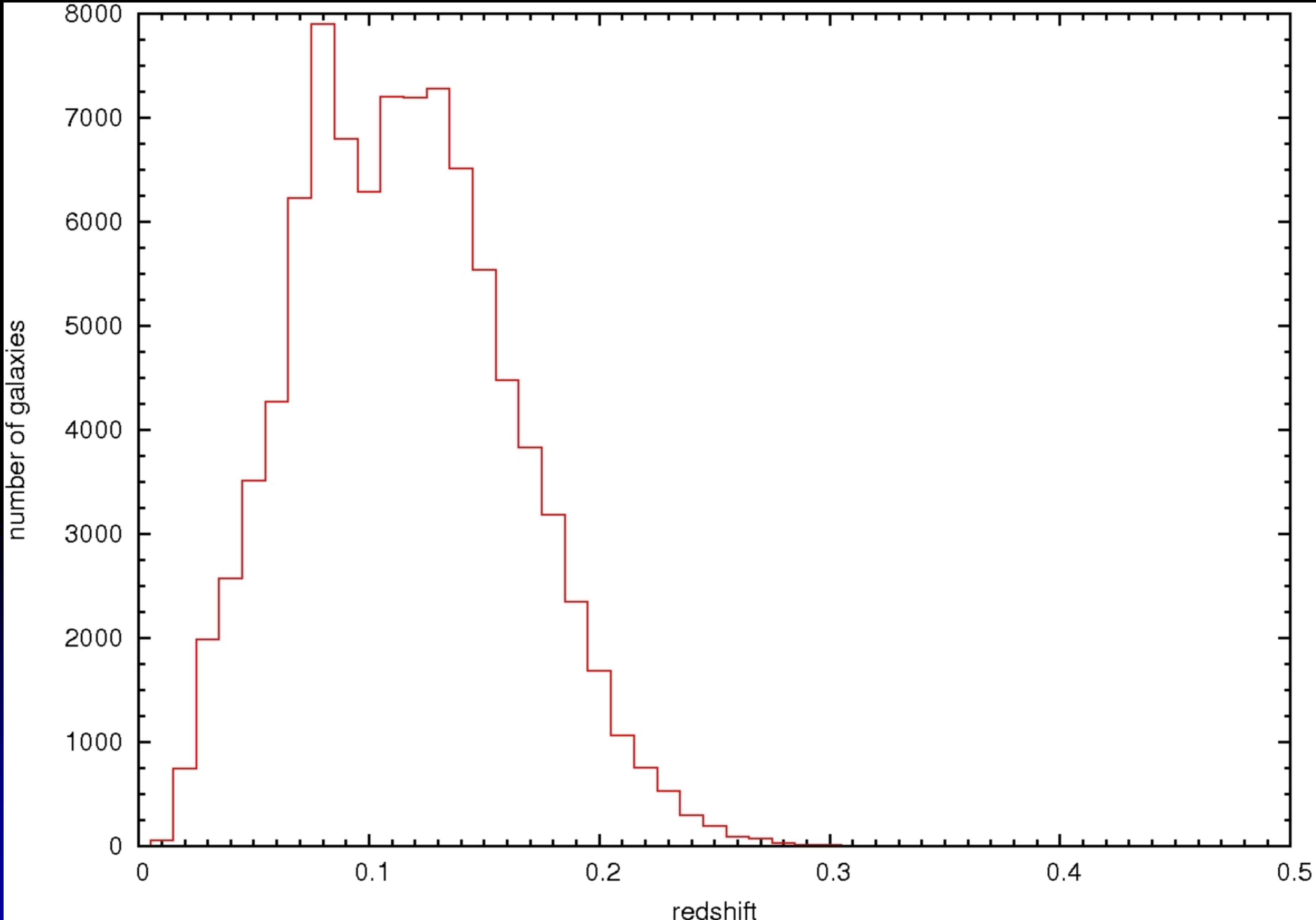
# Recalibrating the fundamental plane

- Distance indicator for elliptical galaxies
- Relation between the effective radius, the central velocity dispersion and the mean surface brightness

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

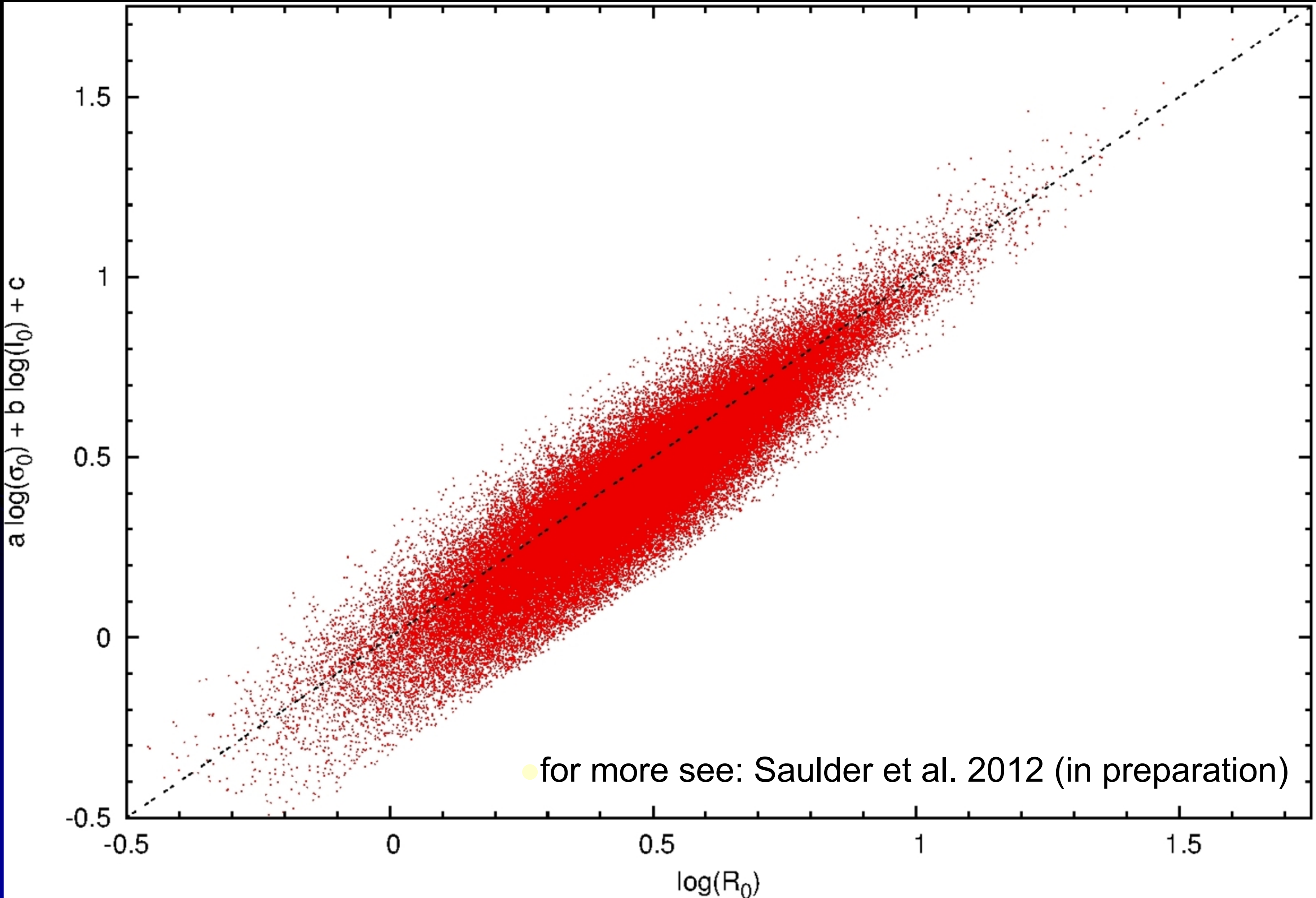
- We have the largest data set and new high quality K-correction (Chiligarian et al. 2010).
- We use similar methods as Bernhardi et al. 2003.

The elliptical sample from SDSS/GalaxyZoo: >90000 galaxies, I will use ~70000 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. Get surface brightness
6. Correct for cosmological dimming
7. Correct redshifts for motion relative to the CMB
8. estimate distance based on redshift
9. Calculate effective radius of galaxy
10. Fit the fundamental plane

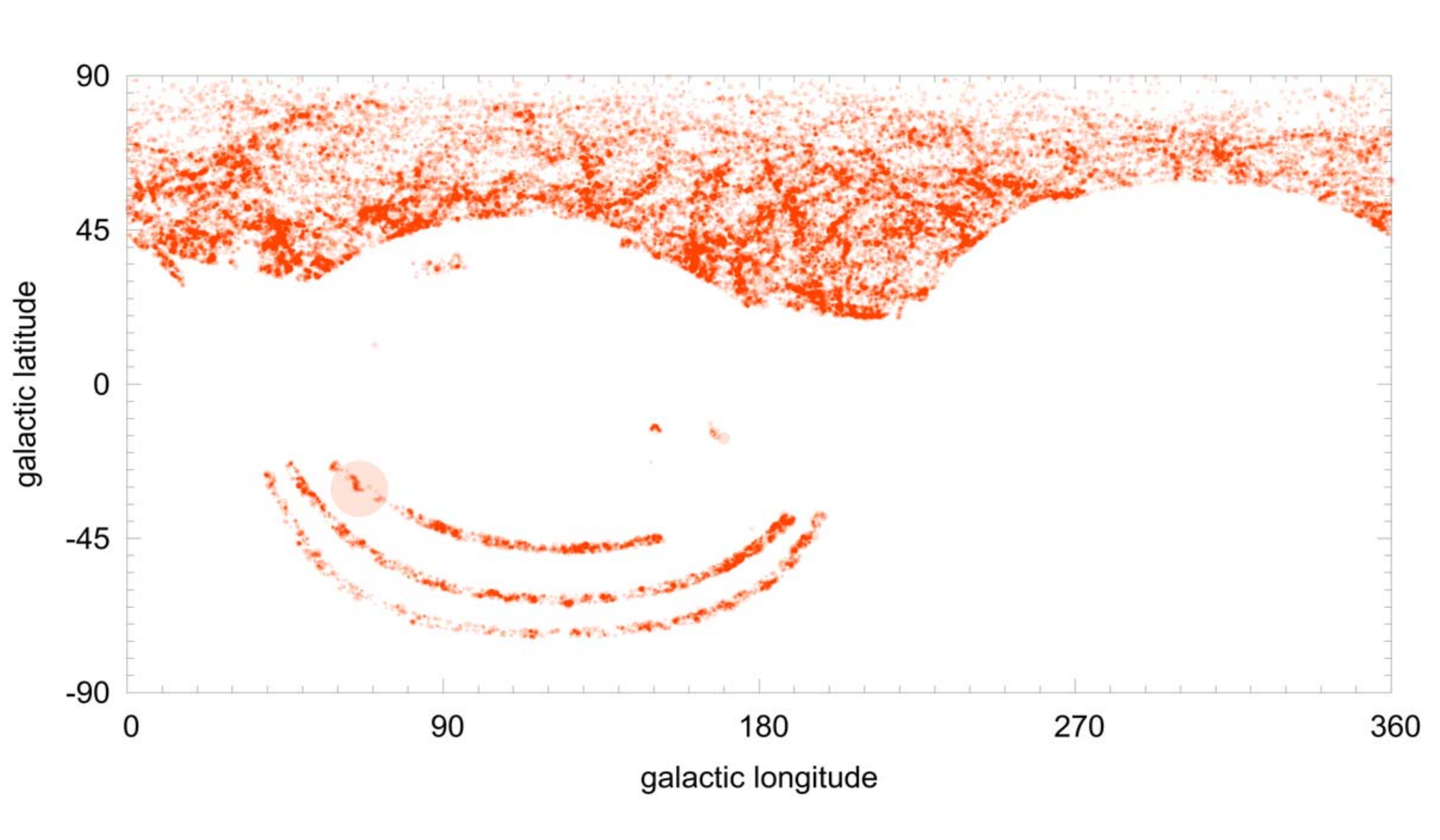
- RMS in r-band ~10%



# The foreground model

- Getting positions, redshift based distances of more than 350 000 galaxies from SDSS
- Masses from Yang et al. 2007, if available.
- Else Masses from an assumed mass/light ratio
- This will be improved in the future!

- Homogenous spheres with renormalized critical density around galaxies and clusters




A part of the foreground model between 100 and 150 $h^{-1}$ Mpc

# Measuring individual Hubble parameters

- Definition: “individual Hubble parameter” = the Hubble parameter measures for one individual galaxy

- 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 with fundamental plane

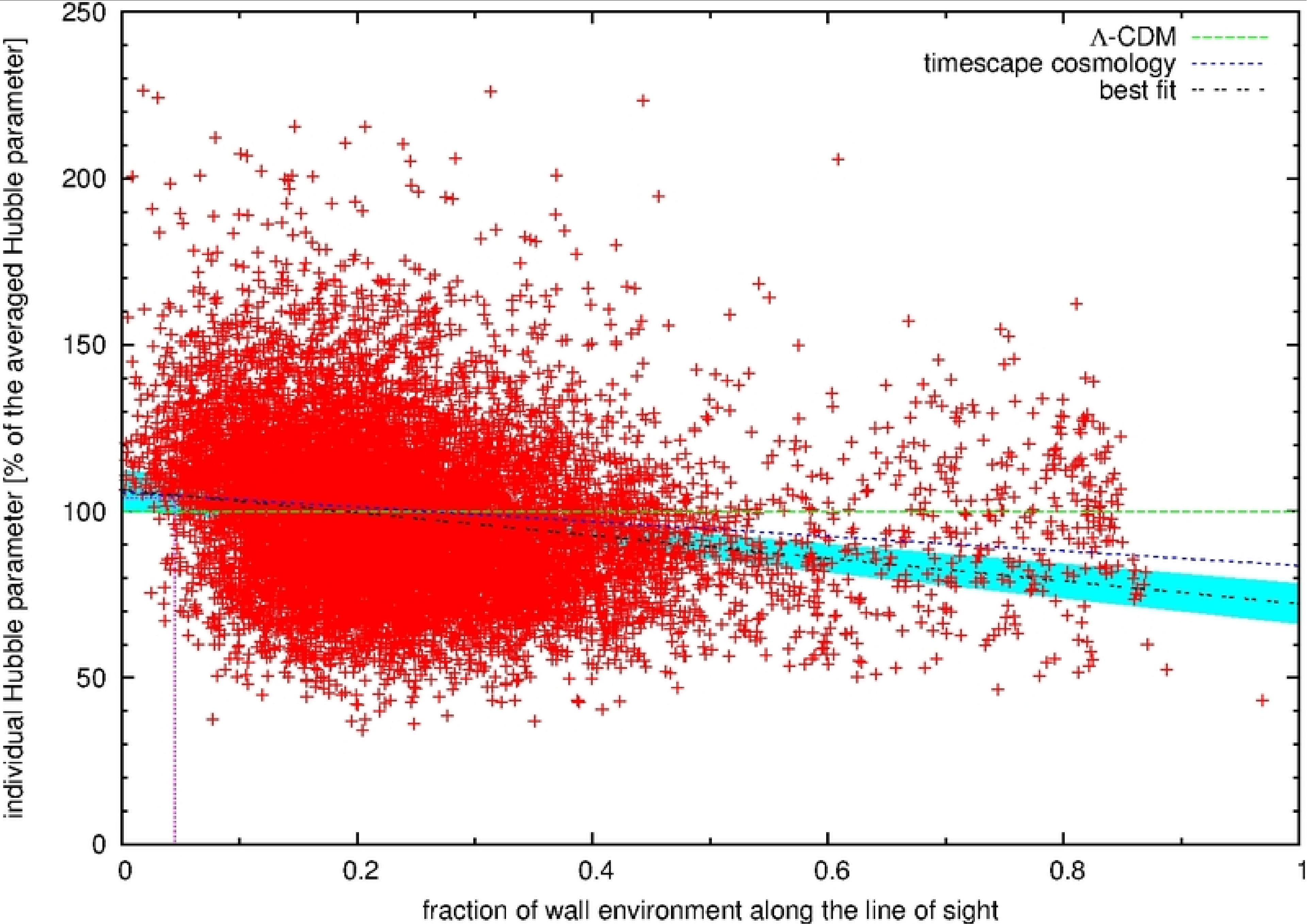
# First results and conclusions

- Calculate fraction of the line of sight to those galaxies, which is inside infinity regions by intersecting it with the foreground model.
- Basic high school mathematics: strait lines intersecting with spheres and do some interval nesting afterwards.
- But 10 000 X 350 000 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 with 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

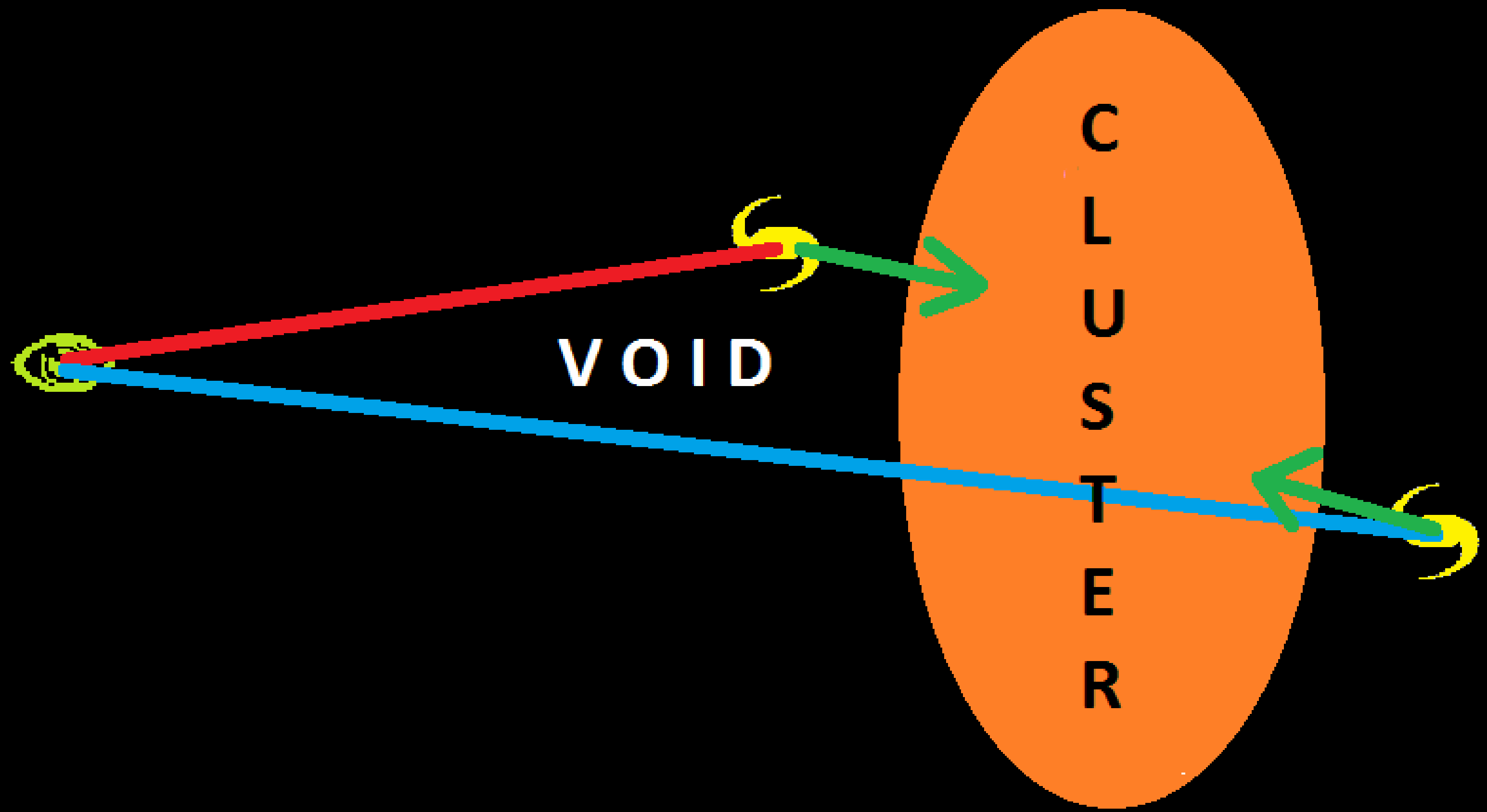
- The fitted lines for such a data set strongly depend on the fitting technique.

- The total lack of galaxies with almost 100% void foreground and low individual Hubble parameters is significant.

- Our models are still rather simple.

- The assumption of a horizontal line for the $\Lambda$-CDM expectation is too naïve.

- Coherent infall into clusters has to be considered.




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

- 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 $\Lambda$-CDM.

**CAST LIGHT ON DARK ENERGY**

# ANY QUESTIONS?