Title: Nonlinear Structure Formation and Apparent Acceleration: An Investigation

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Abstract: We present analytically solvable nonlinear models of structure formation in a Universe with only dust, using LTB solutions. We show that the luminosity distance-redshift relation has significant corrections at low redshift (Doppler effect). We discuss different possibilities that could further enhance this effect and mimick Dark Energy. We find negligible integrated effect, suppressed by $(L/R_{H})^3$ (where L is the size of the structure, and R_{H} is the Hubble radius) and we make contact with cosmological perturbation theory.

Nonlinear Structures and Apparent Acceleration: An Investigation

Alessio Notari [1]

McGill University, Montréal

May 2007 / Talk @ "Origins of Dark Energy"

[1] Talk based on:
Tirthabir Biswas (McGill U.) , Reza Mansouri (McGill U. & Sharif U., Iran) , A. N. astro-ph/0606703 (*Onion*)

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Outline

1. Motivation
   - $D_L - z$ in the Real Universe.
   - Three physical effects
2. The Onion model
   - Building the model
   - Light propagation
3. Backreaction?
4. Swiss Cheese model
5. Large Underdensity
   - Large local effect
   - Systematics in SN observations

$D_L - z$ relation in the Real Universe.

- In Standard Cosmology we use the Friedmann-Lemaître-Robertson-Walker model.
- We compute D_L (or D_A) and z
- To fit the data we need a $p < 0$ term.
- To what extent is justified to use a *homogeneous* model?

A good approximation?

- At $z \gg 1$ (CMB epoch, for example) tiny density fluctuations on all observed scales.
- It is a good approximation

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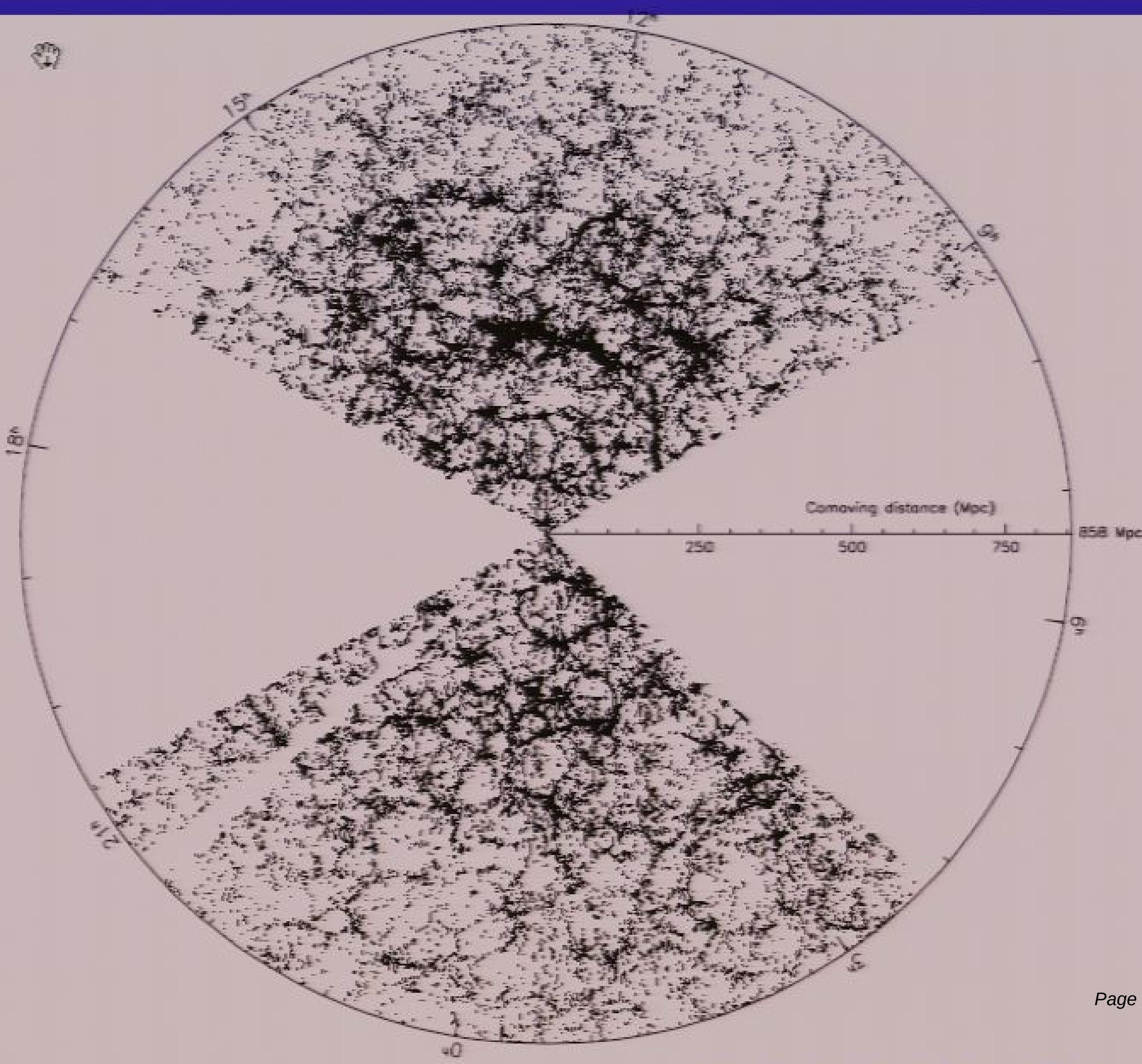
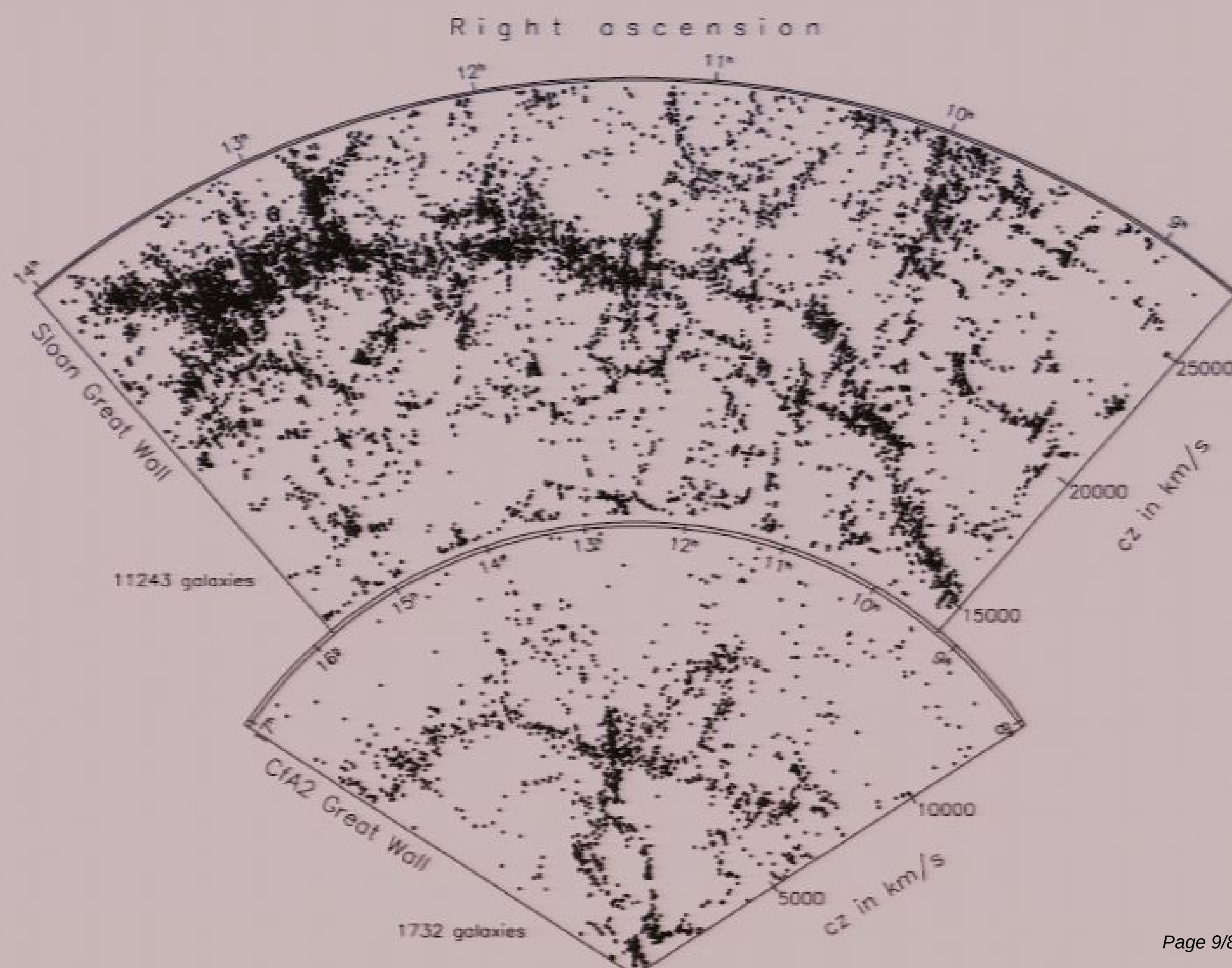
- At $z \gg 1$ (CMB epoch, for example) tiny density fluctuations on all observed scales.
- It is a good approximation
- ..but at late times $\delta \equiv \frac{\delta\rho}{\rho} > 1$ for all scales $L \lesssim \mathcal{O}(10)/h\mathrm{Mpc}$ (1% of Hubble radius)
- Superclusters upto few hundreds of Mpc (10% of Hubble radius), nonlinear objects
- Network with sponge-like structure: pancakes surrounding voids. Typical lenght $100 - 150\mathrm{Mpc}/h$.

SDSS data


12h
15h
9h
18h
6h
21h
3h
0h
Comoving distance (Mpc)
250
500
750
858 Mpc

Great walls


Right ascension
12h
11h
10h
13h
9h
14h
Sloan Great Wall
25000
20000
cz in km/s
11243 galaxies
13h
12h
14h
11h
15h
10h
15000
16h
9h
CfA2 Great Wall
10000
5000
cz in km/s
1732 galaxies

Beyond FLRW

- So, consider $p = 0$ inhomogenous models.
- Two motivations:
  - Can one mimick acceleration (with $p = 0$)?
  - In any case can we quantify deviations from FLRW?
- Difficult but well-defined questions

Inhomogeneity and acceleration

Outline

Three main effects

- Backreaction

  perturbations affect the background

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  Light meets voids and structures. Do they compensate?

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- **Large local fluctuation**

  What if we live in a local void?

Backreaction

- Typically one looks at the average $\langle \rho(t,x) \rangle_D$ at fixed comoving time t
- And defines $\frac{d}{dt}\langle \rho(t,x) \rangle_D = -3\frac{\dot{a}_D(t)}{a_D(t)}\langle \rho(t,x) \rangle_D$
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- Features:
  - $a_D(t)$ does *not* evolve as in FLRW (Buchert '97 and '00): gravity is nonlinear + local effects
  - It can accelerate in principle (Nambu and Tanimoto '05, Chuang, Gu, Hwang '05, A. N. '05, Kolb Matarrese Riotto '05)

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  - It can accelerate in principle (Nambu and Tanimoto '05, Chuang, Gu, Hwang '05, A. N. '05, Kolb Matarrese Riotto '05)
  - How large is the effect in real world?
  - (Hui & Seljak '95, Rasanen '04, Kolb Matarrese Notari Riotto '05) : 10^{-5} at second order in PT
  - (Rasanen '04): suggests large effect at nonlinear order. (A. N. '05, Kolb Matarrese Riotto '05): corrections become all of the same order at $z \approx 1$.
  - (Fry & Siegel '05): suggest 10^{-5} with Newtonian arguments.

Problems with backreaction approach

- If there is a sizable effect, it is nonlinear
- PT is not able to calculate it
- Not completely clear how to connect $a_D(t)$ to observable quantities

Light propagation

- The observable is not $a_D(t)$, but $D_L - z$.
- A cone of light is focused close to structures, defocused far from them (D_L is different).
- Each photon is redshifted differently in empty space and close to structures (z is different).
- Do they compensate to give $D_L - z$ FLRW?
- Take into account that nonlinear voids occupy more volume than structures.

Local fluctuations

- Suppose that we live in a peculiar local region (example: *local void*)
- $\Rightarrow$ low z observations may be very different from average.

---

[2] Tomita '98, Tomita '00, Celerier '01, Wiltshire '05, Moffat '05, Alnes et

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- Since acceleration is inferred comparing low z with high z...
- Can this mimick acceleration [2]?

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- Since acceleration is inferred comparing low z with high z...
- Can this mimick acceleration [2]?
- How much contrast δ and how large L is needed?

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Lemaître-Tolman-Bondi metrics

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$$ds^2 = -dt^2 + \frac{R'^2(r,t)}{1+2k(r)r^2}dr^2 + R^2(r,t)(d\theta^2 + \sin^2\theta d\varphi^2)$$

with comoving coordinates (r, θ, φ) and proper time t.

- Spherically symmetric (but one can also put Observer far from Center).
- Einstein equations:

$$\frac{1}{2}\frac{\dot{R}^2(r,t)}{R^2(r,t)} - \frac{GM(r)}{R^3(r,t)} = \frac{k(r)r^2}{R^2(r,t)},$$

$$4\pi\rho(r,t) = \frac{M'(r)}{R'(r,t)R^2(r,t)},$$

LTB metrics

$$ds^2 = -dt^2 + \frac{R'^2(r,t)}{1+2k(r)r^2}dr^2 + R^2(r,t)(d\theta^2 + \sin^2\theta d\varphi^2)$$

It has the solutions:

- For $k(r) > 0$ ($k(r) < 0$),

$$\begin{aligned} R &= \frac{GM(r)}{2|k(r)|r^2}[\cos h(u) - 1], \\ t - t_b(r) &= \frac{GM(r)}{[2|k(r)|r^2]^{3/2}}[\sin h(u) - u]. \end{aligned} \tag{2.1}$$

- $k(r) = 0$,

$$R(r,t) = \left[\frac{9GM(r)}{2}\right]^{1/3}[t - t_b(r)]^{\frac{2}{3}}.$$

Choosing the functions

- "Gauge" choice: $M(r) = \frac{4\pi}{3} M_0^4 r^3$
- The idea is to describe structure formation
  (start with $\delta(r, t_I) \ll 1$ and end up with $\delta(r, t_{\text{now}}) \gg 1$) [3]

[3] Warning: several previous papers make use of deceiving model

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- $k = 0$ flat FLRW, $k = \pm 1$ open/closed FLRW, with $R(r, t) = r\, a(t)$.

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$$k(r) \propto \frac{1}{r} k_0 \sin^2\left(\frac{\pi r}{L}\right)$$

- Two parameters, L and k_0.

Choosing $A(r)$

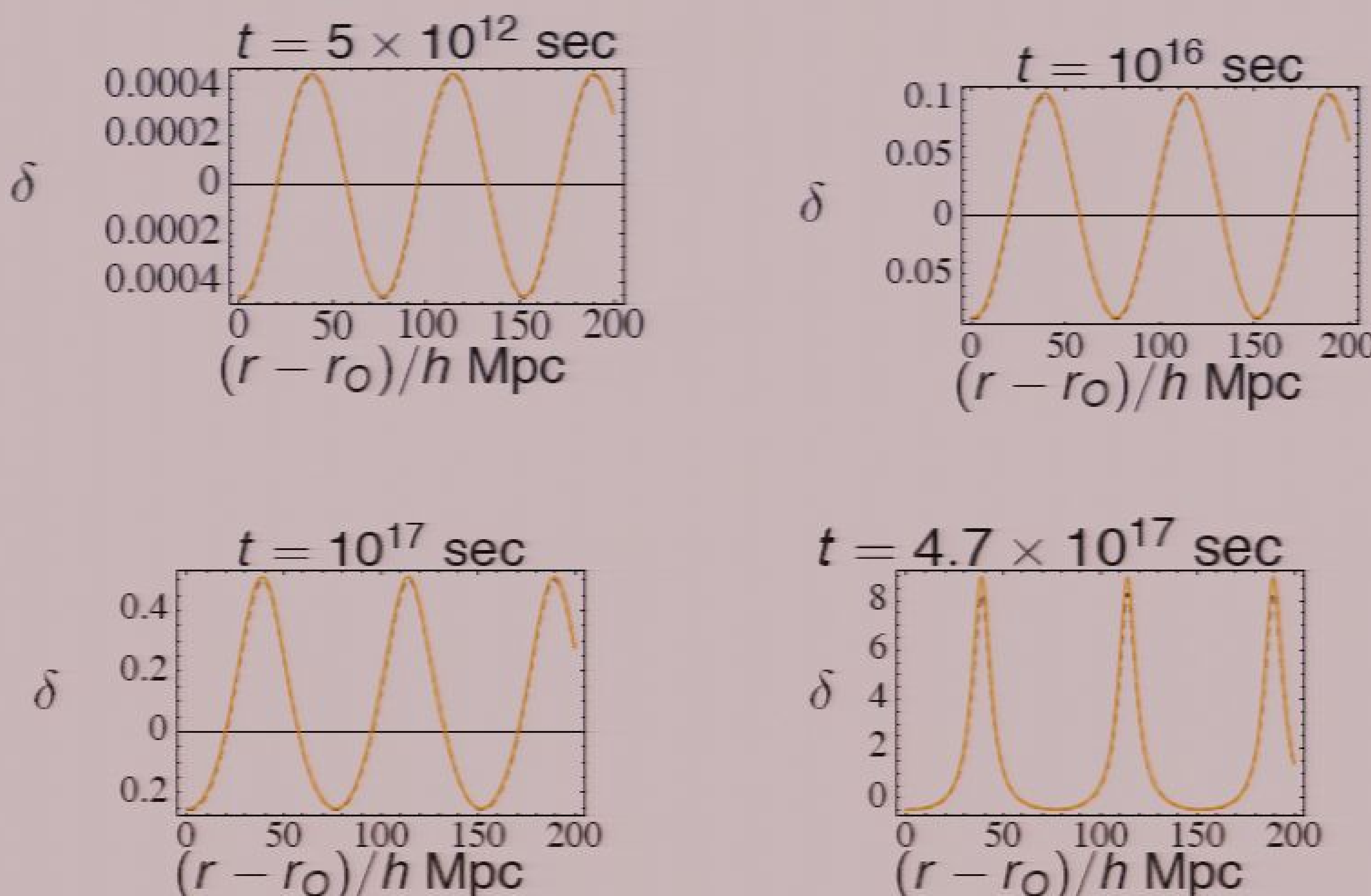
- Roughly:

$$\rho(r,t) = \frac{M_0^4}{6\pi(\tilde{M}t)^2\left[1+\epsilon_0(t)\sin\left(\frac{2\pi r}{L}\right)\right]}\ ,\ \epsilon_0(t) \propto k_0 t^{\frac{2}{3}}$$

$$\delta = \frac{\epsilon}{1+\epsilon} = \frac{\epsilon_0(t)\sin\left(\frac{2\pi r}{L}\right)}{1+\epsilon_0(t)\sin\left(\frac{2\pi r}{L}\right)}$$

- $\epsilon \ll 1$ linear growth
- ϵ not small: δ grows rapidly (as in Zel'dovich approx)
- We work before collapse (in real world there is virialization).

Onion profile



Outline

Redshift

$$\frac{dz}{dr} = \frac{(1+z)\dot{R}'}{\sqrt{1+2E}}.$$

- Analytical (small $k(r)$ but large δ) and numerical

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- Analytical (small $k(r)$ but large δ) and numerical
- The result:

$$1 + z(r) \simeq (1 + z_{\rm FLRW}(r)) exp\left[-\frac{2\epsilon_0(t)}{\pi}\left(\frac{L}{r_{\rm hor}}\right)\cos\left(\frac{2\pi r}{L}\right)\right] ,$$

for observer at minimum or maximum of density

- For small z the correction is quite large:

$$z \simeq z_{\rm FLRW}\left[1 - \frac{\epsilon}{\pi}\frac{L}{\delta r}\cos\left(\frac{2\pi r}{L}\right)\right] ,$$

where we have defined $\delta r \equiv r - r_O$.

- It's a peculiar velocity correction , radial correlated

Analytical and numerical results for z

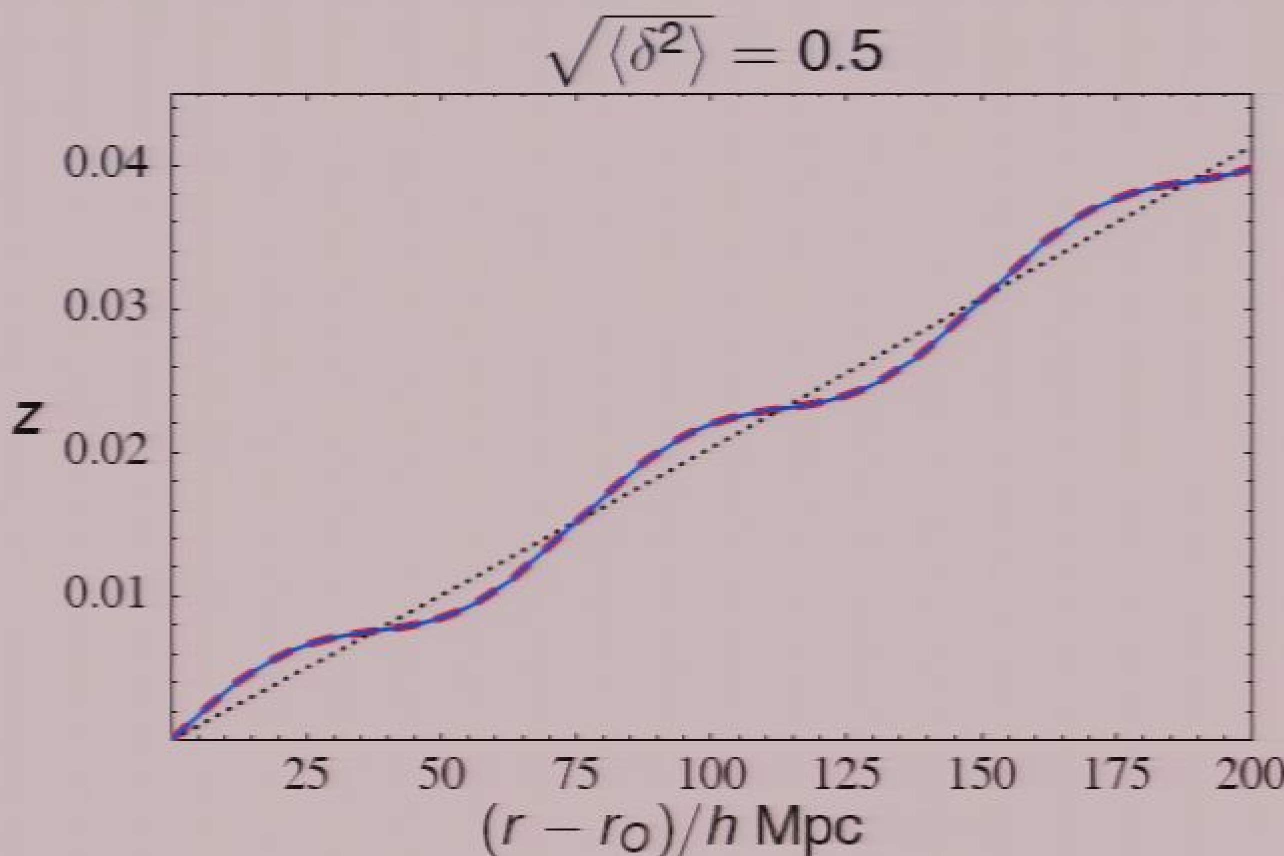

Figure: Redshift (z) along the geodesic of a photon arriving at $r = r_O$ at time $t = t_O$. In this plot $r_O = 36.5L$, $t_O = 3.3 \times 10^{17}$sec.

Numerical and analytical D_L

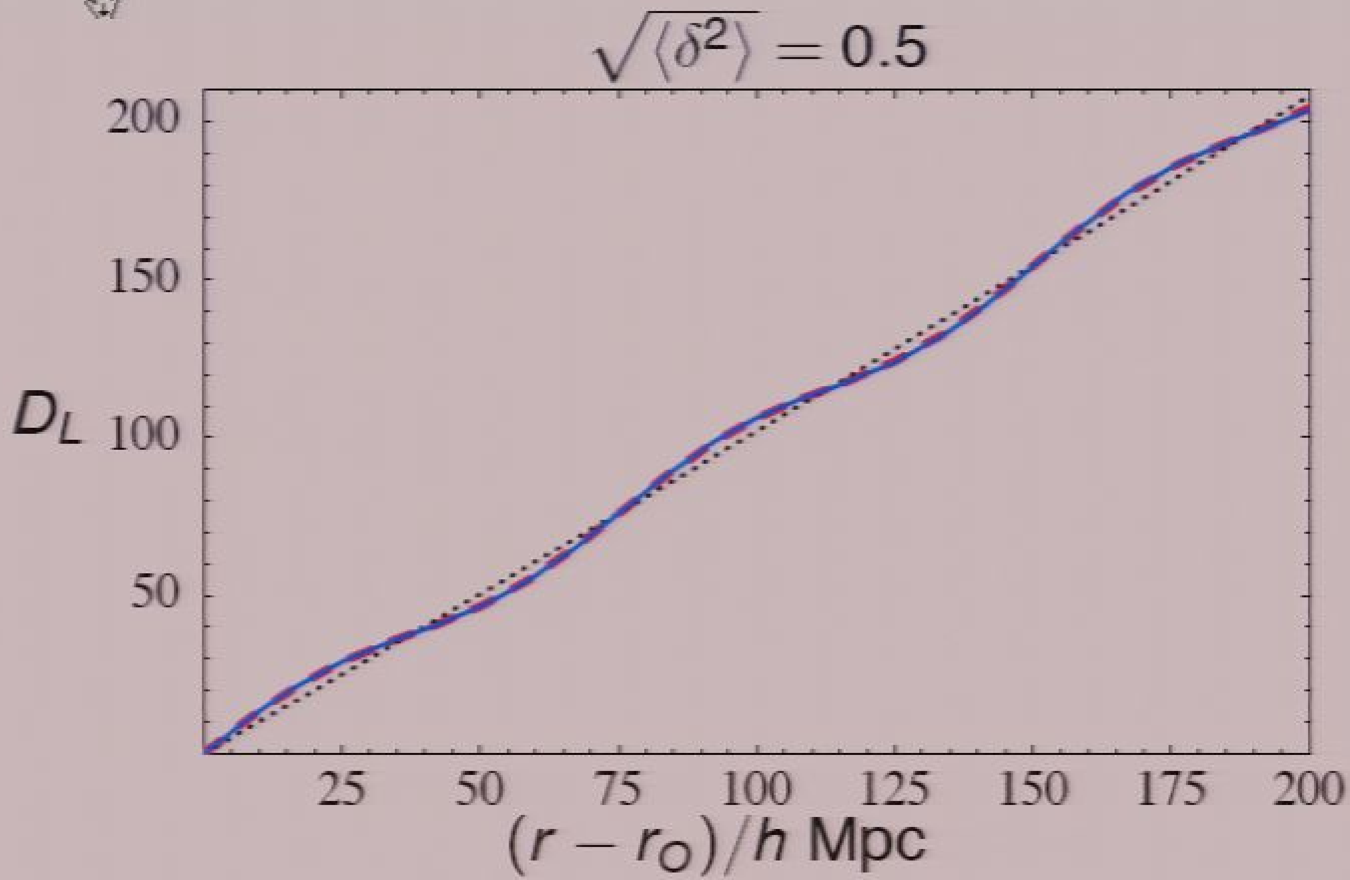

Figure: Luminosity distance (D_L) along the geodesic of a photon arriving at $r = r_O$ at time $t = t_O$. In this plot $r_O = 36.5L$, $t_O = 3.3 \times 10^{17}$sec.

Is there backreaction?

No sizeable "overall" effect

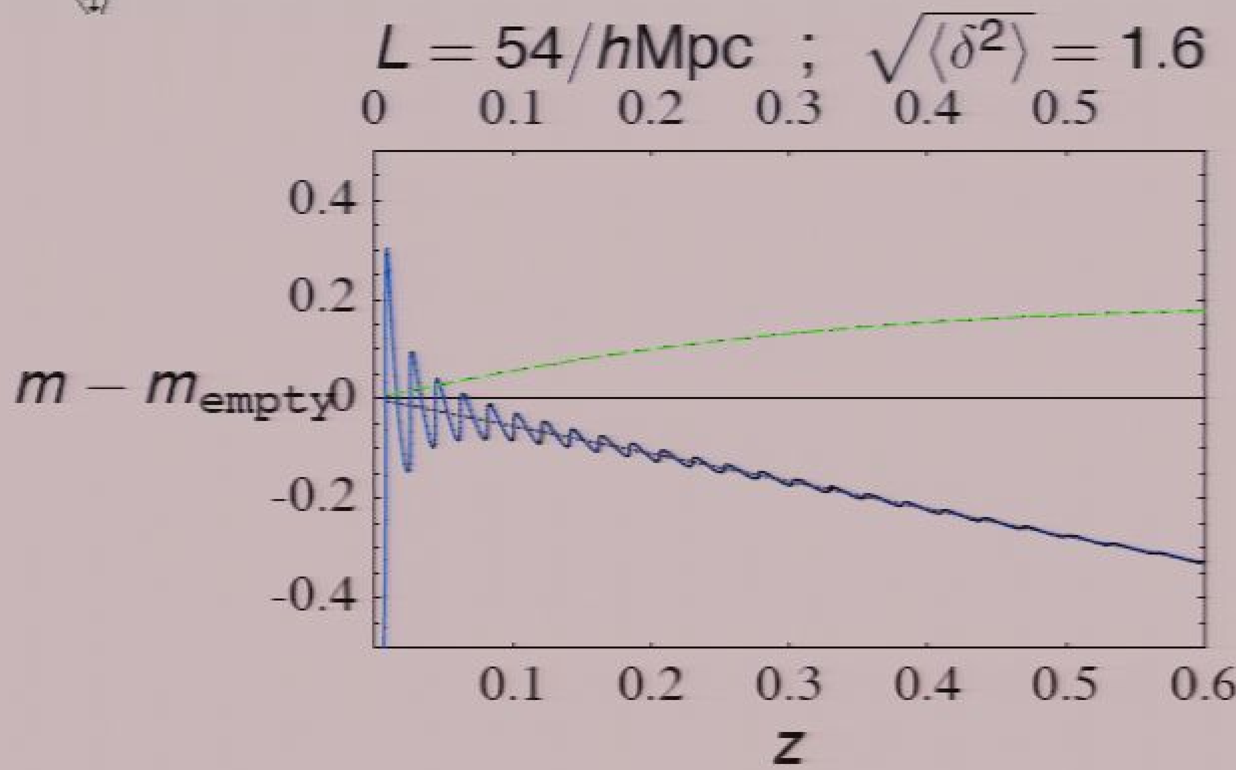

Figure: $m \equiv Log_{10}(D_L)$

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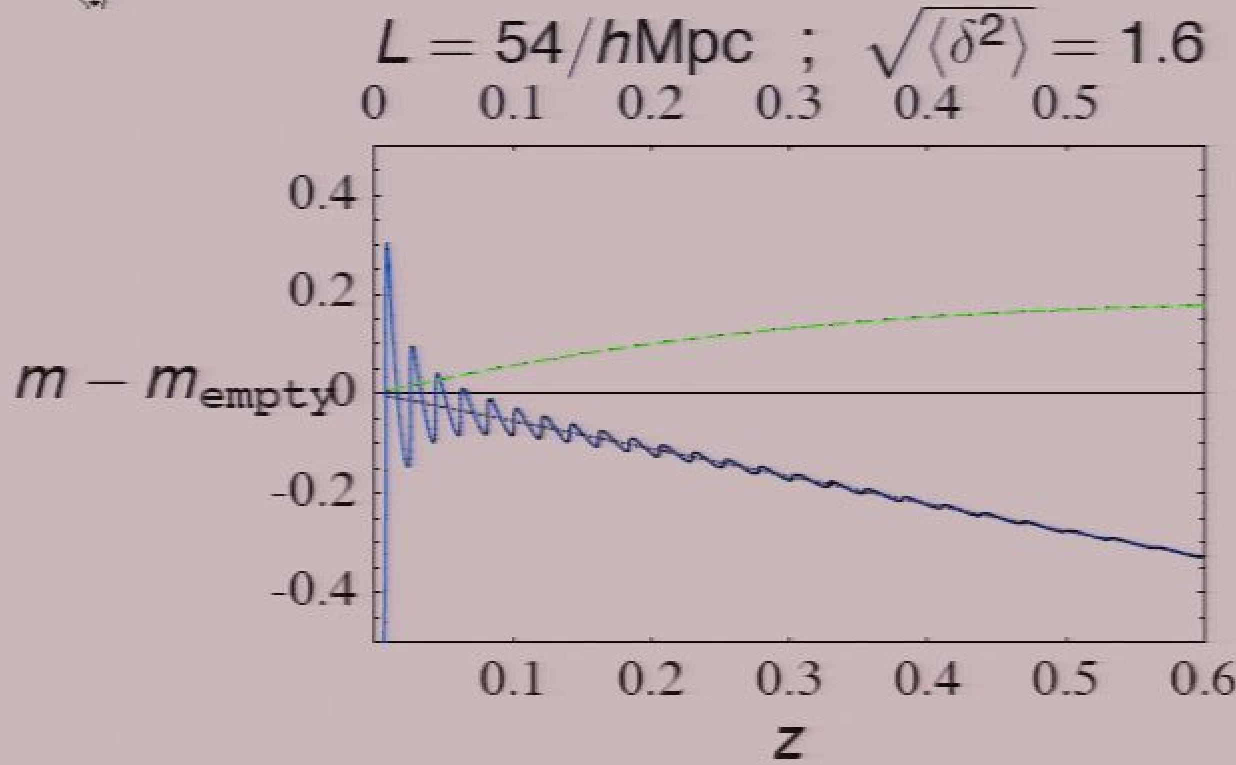

Figure: $m \equiv Log_{10}(D_L)$

- Is it because of the specific profile?
- Is it because of small "curvature" $k(r)$?

Swiss-Cheese model

- Carve a spherical patch from FLRW
- Replace it with LTB
- We can try also with large curvature $k(r)$ inside
  - Use $k'(0) = 0$ (No cusp in ρ at the center)
  - $k'(L) = k(L) = 0$ (matching conditions with FLRW)
  - Example $k(r) = k_0 \left[\left(\frac{r}{L}\right)^2 - 1 \right]$
- Void at the center, structure at the boundary

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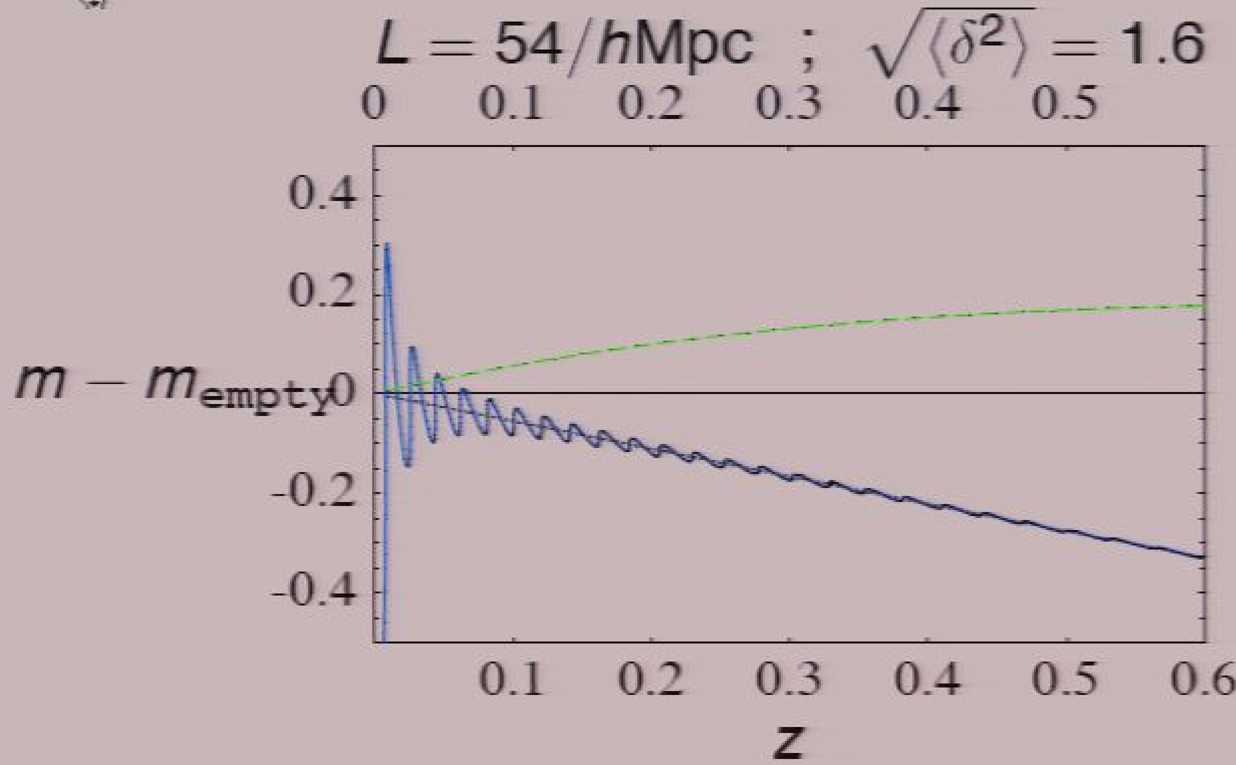

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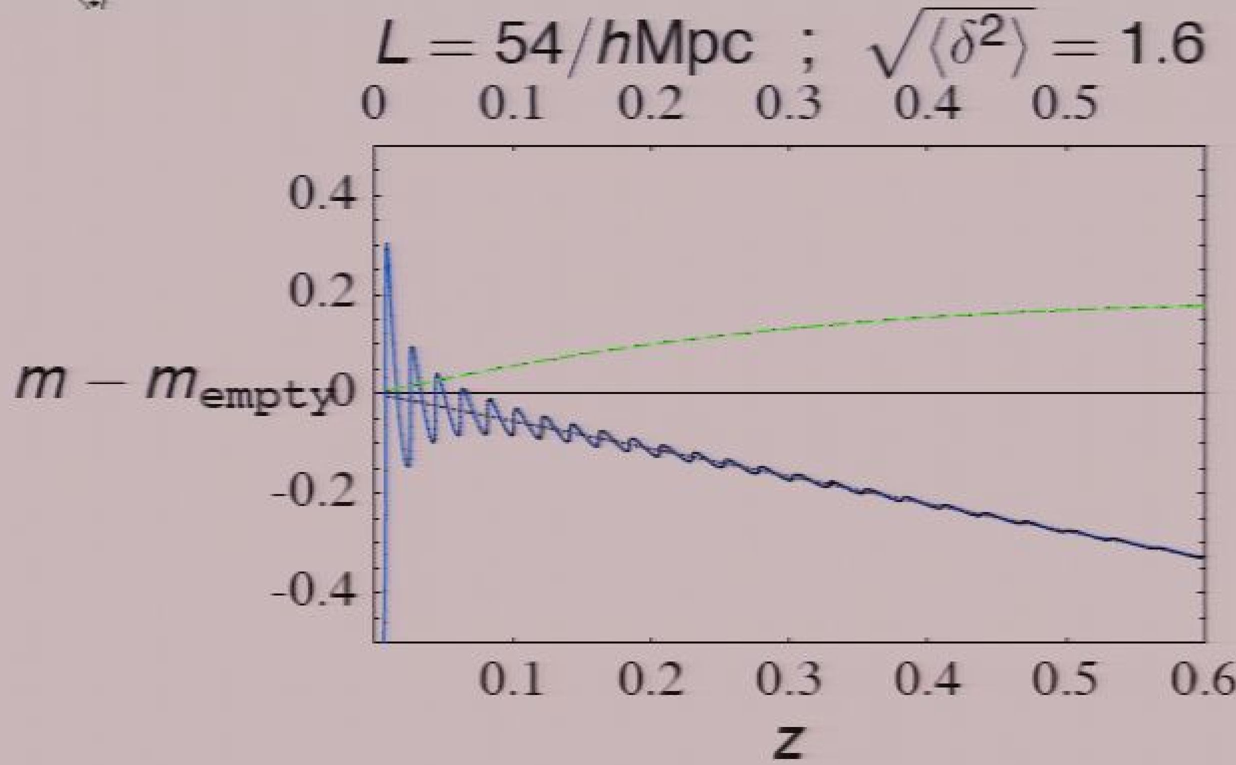

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  - Example $k(r) = k_0 \left[\left(\frac{r}{L}\right)^2 - 1 \right]$
- Void at the center, structure at the boundary
- Consider also nonlinear k
- Is there any large net effect for a photon travelling through a patch?
- Both Observer and Source in the FLRW region

Net effect? Backreaction?

- We disentangled different effects making contact with usual Perturbation Theory (for small k) in Newtonian gauge

$$\Phi \propto \int dr\, r\, k(r) \propto k_0 \left(\frac{L}{r_H}\right)^2$$

- Integrated effect is usual Rees-Sciama effect: always $(L/r_H)^3$ also for large k (analytical and numerical)

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- So, LTB does not seem to give sizeable backreaction... maybe go to nonspherical models?

Swiss-Cheese model: Doppler effect

- Doppler effect (motion of sources) Large effect at small z
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Swiss-Cheese model: Doppler effect

- Doppler effect (motion of sources) Large effect at small z
- It goes like L/r_H
- Basic picture: sources attracted towards the outer dense shells.
- Inside the Void: collective radial velocity adds to expansion

Large void?

Are spherical models still interesting (at least for speculations..)?

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- That's how LTB can mimick Acceleration!

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- What's the smallest L and δ that can possibly work?

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- What's the smallest L and δ that can possibly work?
- Also: estimate the typical systematic correction to SN observations (See also Ali Vanderveld's talk)

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High and low z

- Evidence for acceleration comes from mismatch between:
  - measurements at low redshift ($0.03 \lesssim z \lesssim 0.07$)
  - high-z SN (roughly $0.4 \lesssim z \lesssim 1$)
- We choose large L (up to $z \approx 0.07$)
- $\Rightarrow$ The local Bubble is different from the average ("Hubble Bubble").
- In the region ($z \gtrsim 0.3$):

$$D_{FLRW} \approx \frac{2}{H_{\mathrm{OUT}}}(1 + z - \sqrt{1+z})\,.$$

Low z

- We use $h_{\mathrm{OUT}} \approx 0.5$.
- We need larger local H_{IN} due to inhomogeneities
- We need a local patch, that at least extends up to $z \approx 0.07$ to have a linear Hubble diagram in $0.03 \leq z \leq 0.07$.

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- We need a local patch, that at least extends up to $z \approx 0.07$ to have a linear Hubble diagram in $0.03 \leq z \leq 0.07$.
- Therefore: $L \gtrsim 400/h$ Mpc (diameter)
- Put Observer in a void

Hubble Diagrams

Inhomogeneity and acceleration

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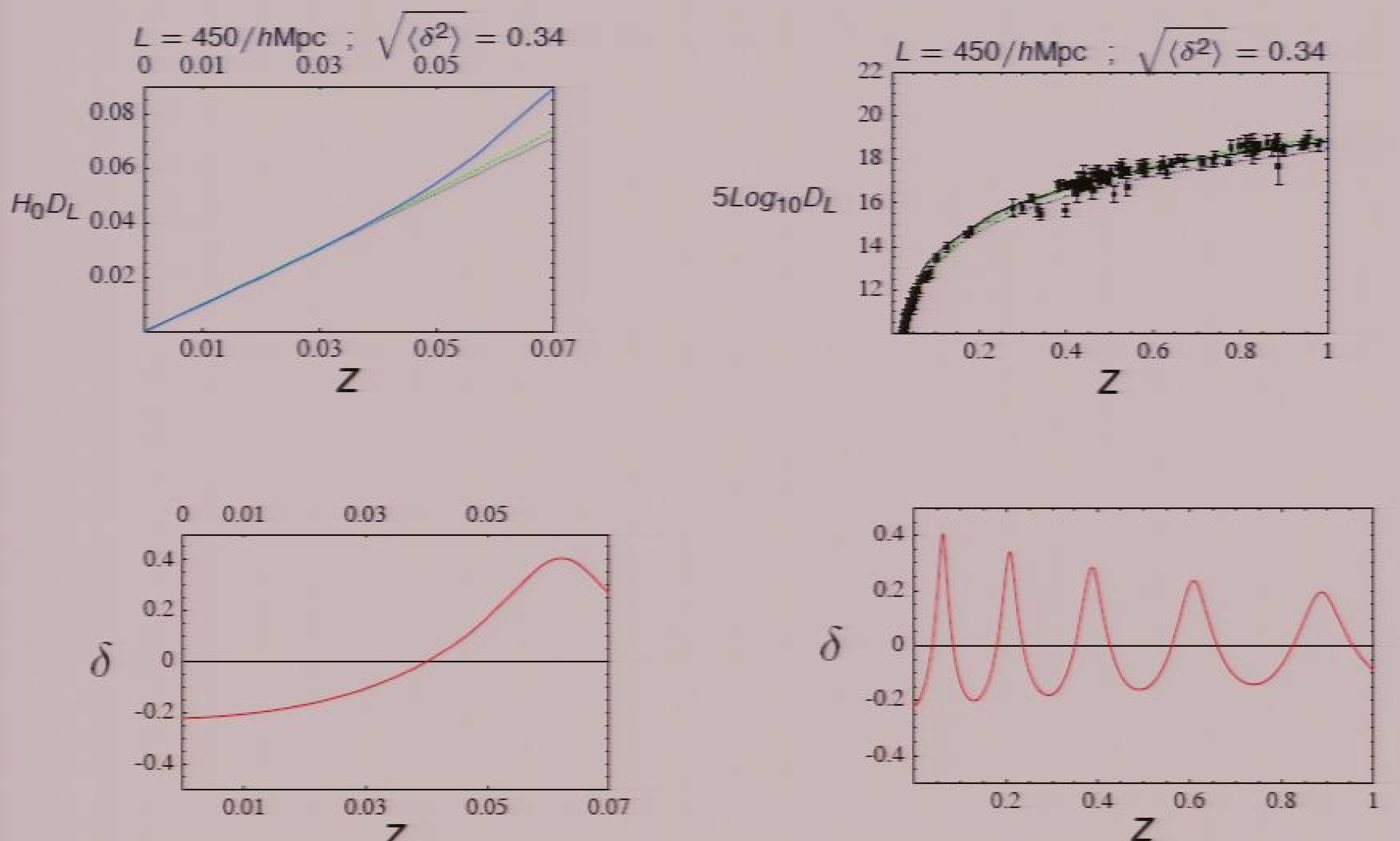
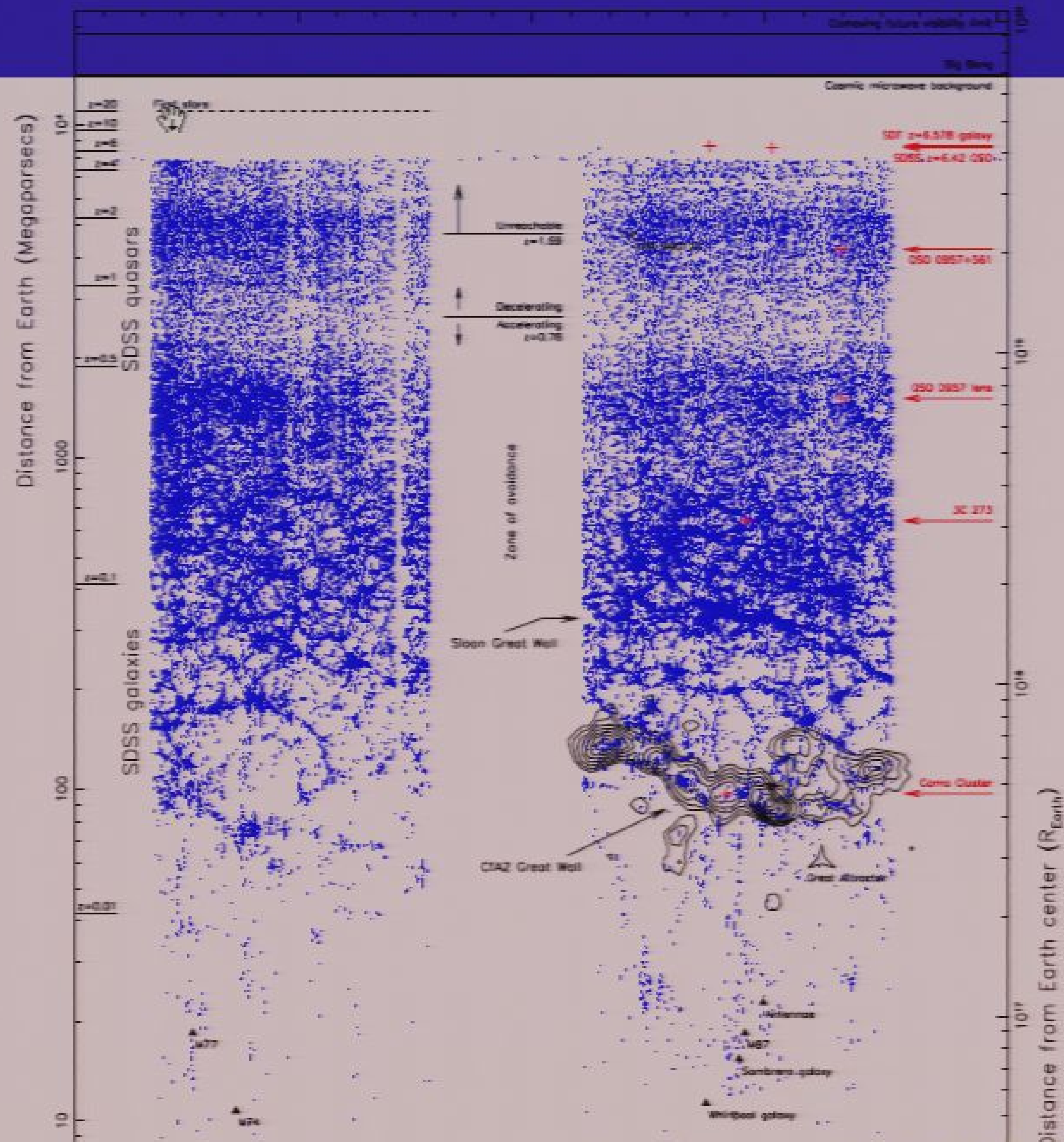


SDSS data



Comoving future visibility limit
Big Bang
Cosmic microwave background
First stars
SDF z=6.578 galaxy
SDSS z=6.42 QSO
Unreachable
Decelerating
Accelerating
QSO 0957+561
QSO 0957 lens
3C 273
Zone of avoidance
Sloan Great Wall
Coma Cluster
CfA2 Great Wall
Great Attractor
M87
Sombrero galaxy
Whirlpool galaxy
SDSS quasars
SDSS galaxies
Distance from Earth (Megaparsecs)
Distance from Earth center (R_{Earth})

$m - z$ plot

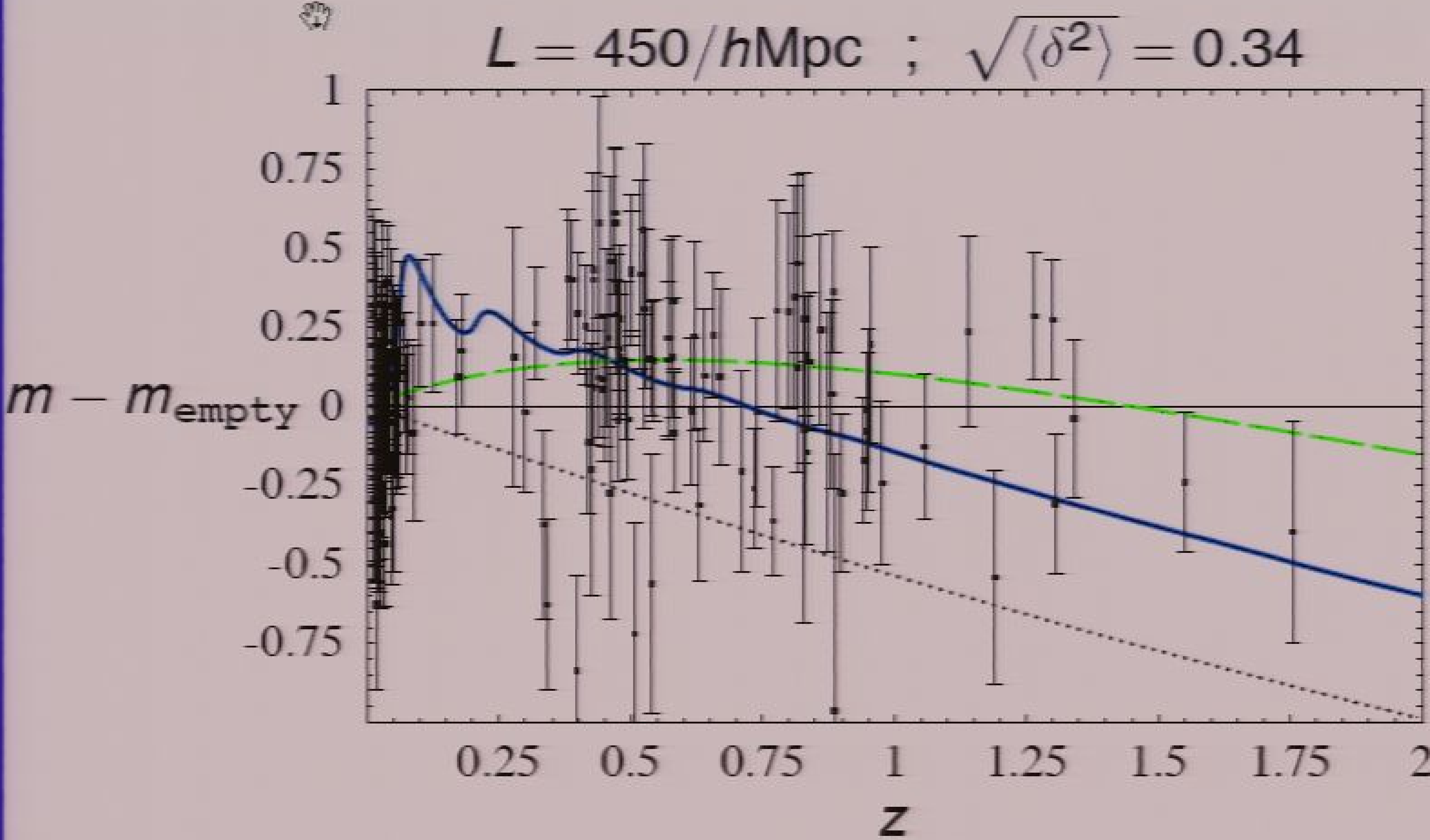


Figure: The blue solid line is our numerical solution, the black dotted line is the CDM model ($\Omega_m = 1$), and the green long-dashed line is the ΛCDM result (with $\Omega_\Lambda = 0.73$). We have

Individual contributions to χ^2

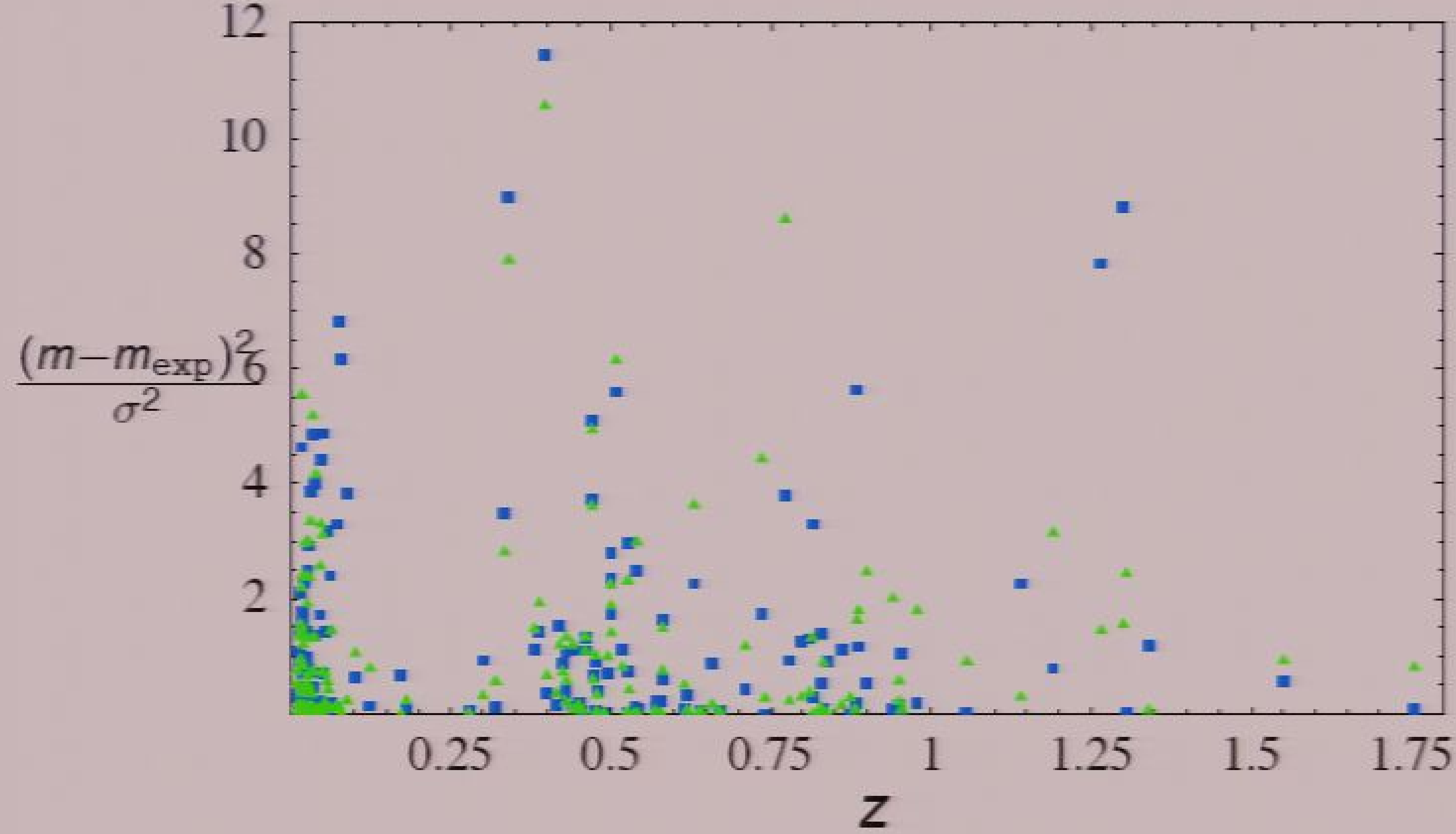


Figure: We show here the contribution to the χ^2 for each data point (gold data set of *Riess et al.*) Our model (blue boxes) is compared with ΛCDM with $\Omega_\Lambda = 0.73$ (green triangles).

χ^2 comparison

Table: Comparison with data (gold data set of *Riess et al.*)

Model	χ^2 (157 d.o.f.)
ΛCDM (with $\Omega_M = 0.27, \Omega_\Lambda = 0.73$)	178
EdS (with $\Omega_M = 1.00, \Omega_\Lambda = 0.00$)	325
Onion ($\sqrt{\langle\delta^2\rangle} = 0.34$ on $L = 450/h\mathrm{Mpc}$)	212

Table: Comparison with data (full data set of Riess et al.)

Model	χ^2 (186 d.o.f.)
ΛCDM (with $\Omega_M = 0.27, \Omega_\Lambda = 0.73$)	233
EdS (with $\Omega_M = 1.00, \Omega_\Lambda = 0.00$)	403
Onion ($\sqrt{\langle\delta^2\rangle} = 0.34$ on $L = 450/h\mathrm{Mpc}$)	273

First acoustic peak in CMB

- We do not introduce curvature. But global H is low.
- Our model reduces to EdS model, already by $z \sim 0.2$
- For instance:

$$\Omega_{m,\mathrm{OUT}} = 0.9\ ,\ h_{\mathrm{OUT}} = 0.58\ ,$$

$+$ standard baryon-to-matter ratio,
$\Omega_{b,\mathrm{OUT}}/\Omega_{m,\mathrm{OUT}} = 0.13$,

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- Full CMB spectrum?

Similar Voids in the CMB?

- Surprising coincidence with work by Inoue and Silk '06 for CMB
  - alignment in low multipoles
  - non-gaussian circular cold spot
- They need 2 voids $L \approx 350/h$ Mpc and $\delta \approx -0.3$ to explain low-l anomalies
- And a third one at $z \approx 1$ for the cold spot.

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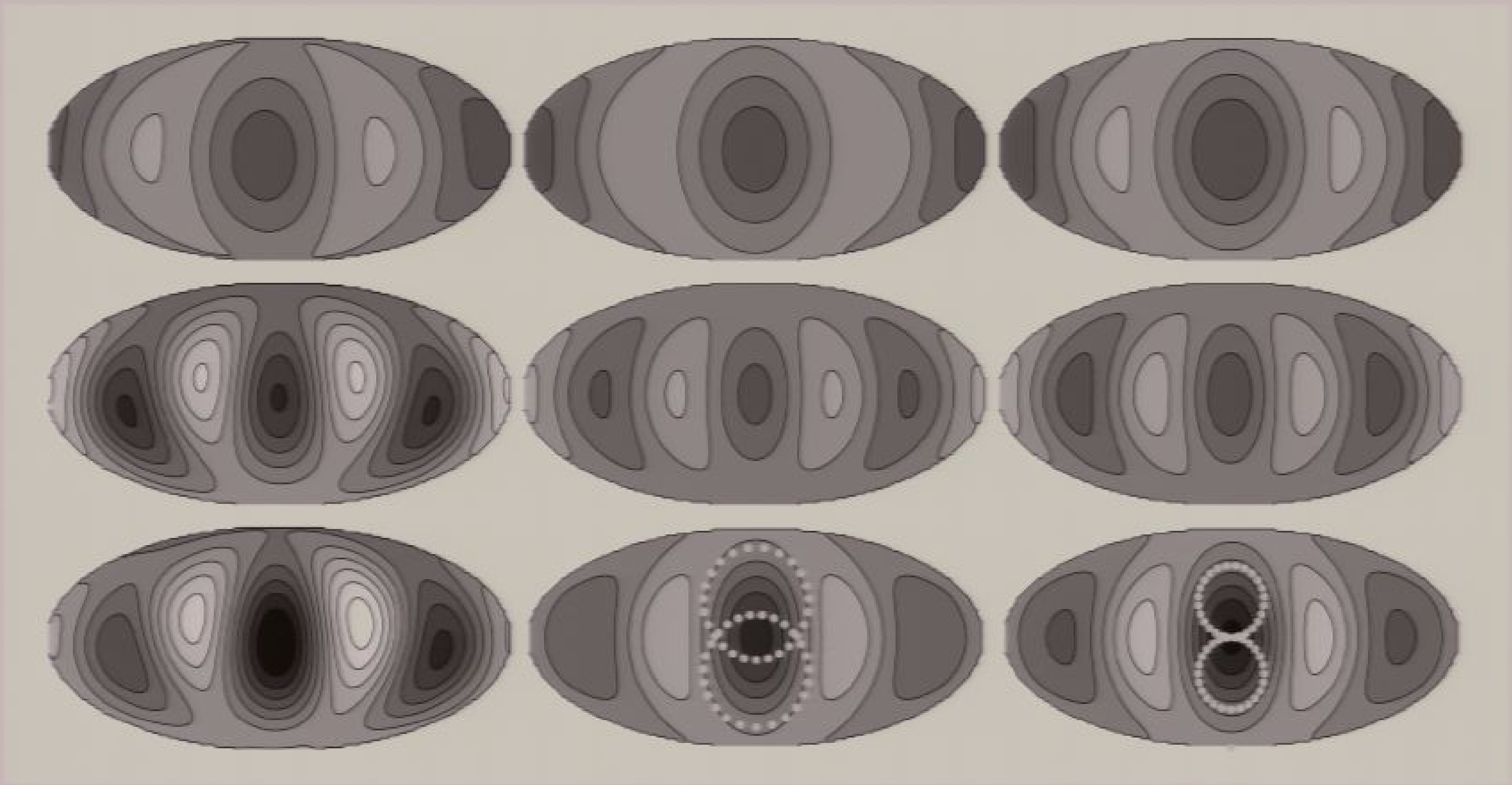
- In fact, the cubic integrated $(L/r_H)^3$ effect gives a 10^{-5} effect on CMB

Voids in the CMB?



(Inoue and Silk '05)

Can such voids exist??

- The real question: How unlikely is the existence of such Voids? Nonlinear percolation of small voids (Inoue and Silk)?
- Does it require non-standard Structure Formation or non-standard Primordial features or nongaussianity?

[4] William J. Frith, N. Metcalfe, T. Shanks (Durham U.) 2005.MNRAS, astro-ph/0509875. William J. Frith,

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- Simulations agree with real data?
- J. Einasto '06 claims fraction of superclusters in real data (SDSS and 2dFGRS) 5 times larger than simulations (Millennium Run)
- L=150 Mpc/h, 25% local underdensity in the Southern Galactic Cap (2MASS) ?[4]

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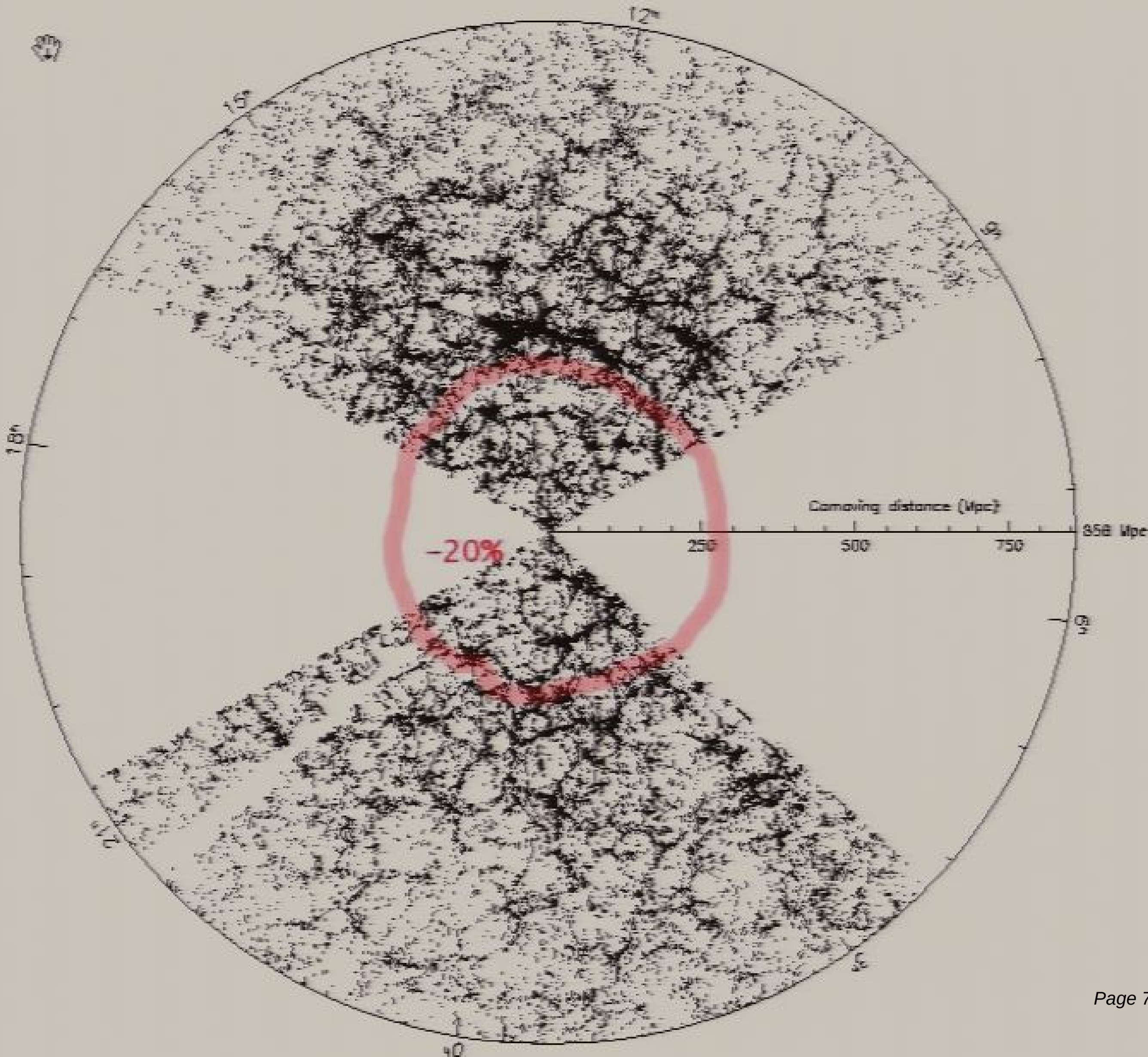
S

nhomogeneity and acceleration



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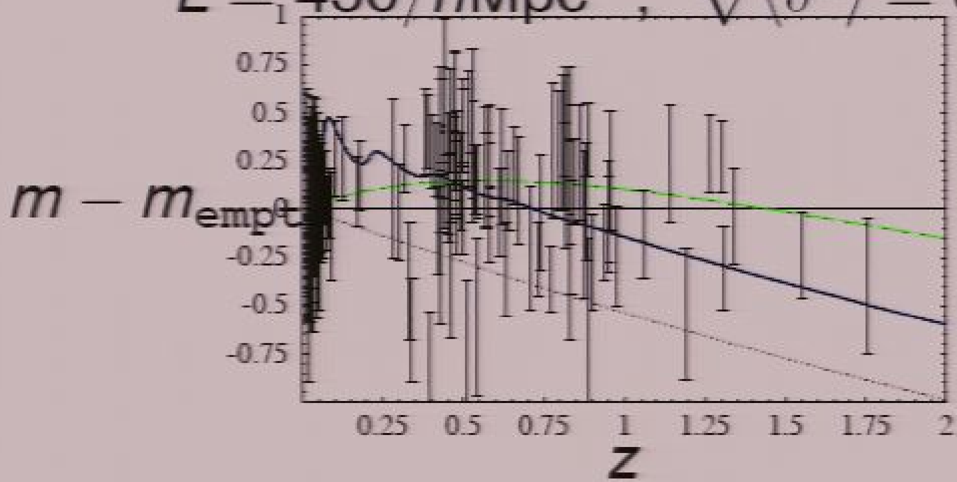
$L = 450/h\text{Mpc} \;\; ; \;\; \sqrt{\langle\delta^2\rangle} = 0.34$



- SDSS II is definitely going to discriminate this hypothesis ($L = 400/h$ and $\delta = -0.3$): lots of data at intermediate redshift (40 SN)...very soon.

Observations?

- How unlikely is that we live near the Center of such a Void?
- We need to be at most at $10\,Mpc$ from the center (CMB dipole)
- Anisotropy in Hubble rate[5]?
- ISW? Maybe it is due to large Voids?

[5] M.L. McClure, C.C. Dyer, astro-ph/0703556

Outline

With lower value of δ

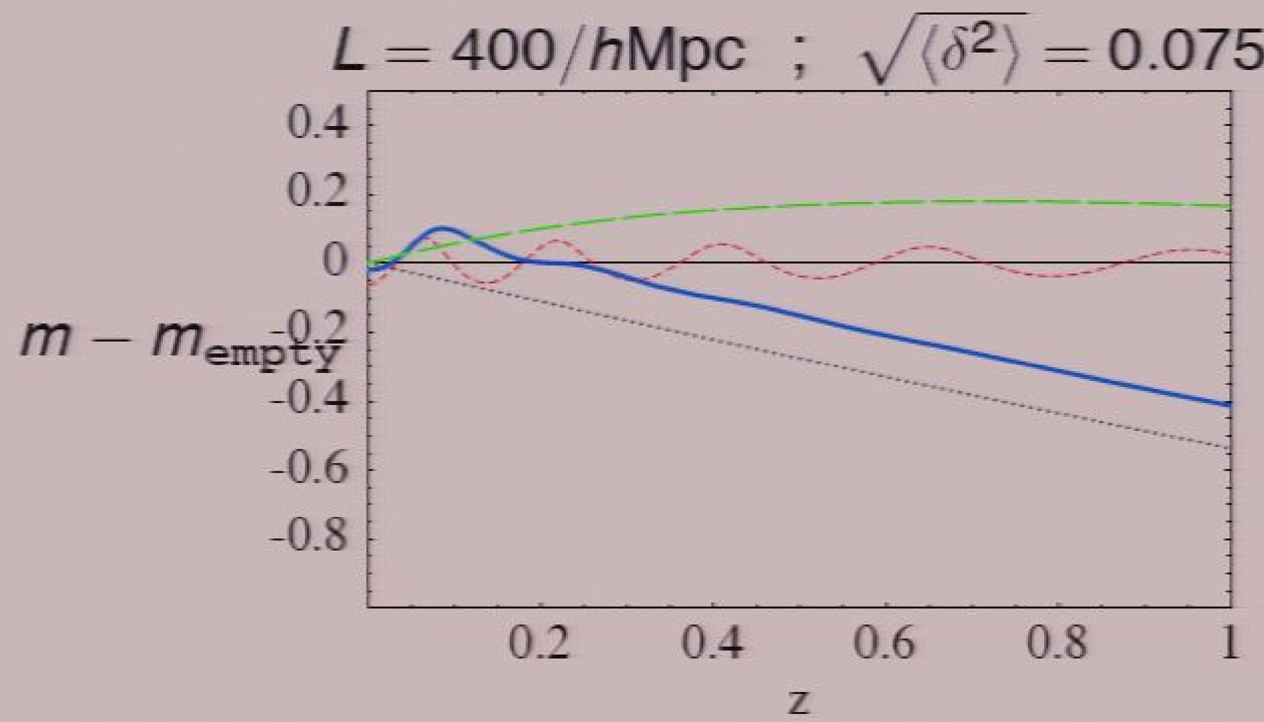


Figure: Magnitude residual from empty FLRW (Δm) vs. redshift (z). We have superimposed the red thin dashed line (density contrast seen by the photon).

Typical systematics $\delta \approx 0.025 \Rightarrow \Delta m \approx 0.05$

Conclusions

- We constructed nonlinear examples of structure formation (Onion and LTB Swiss-Cheese), and computed light propagation (D_L and z).
- Integrated effect/ backreaction negligible for acceleration. Spherical symmetry?
- We have shown how a Large Local Fluctuation can roughly mimick acceleration (Radius $\approx 200/hMpc$, $\delta = 0.3$)
- In any case we have found a typical systematic of $\Delta m \simeq 0.05$ (and a similar anisotropy).