Title: Nonlinear Structure Formation and Apparent Acceleration: An Investigation

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Abstract:

Nonlinear Structures and Apparent Acceleration: An Investigation

Alessio Notari [1]

McGill University, Montréal

May 2007 / Talk @ "Origins of Dark Energy"

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[1] Talk based on:
Tirthabir Biswas (McGill U.), Reza Mansouri (McGill U. & Sharif U., Iran), A. N. astro-ph/0606703 (*Onion*)
Tirthabir Biswas (McGill U. & Penn State U.), A. N. astro-ph/0702555 (*Swiss Cheese*)

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Outline

Inhomogeneity and acceleration

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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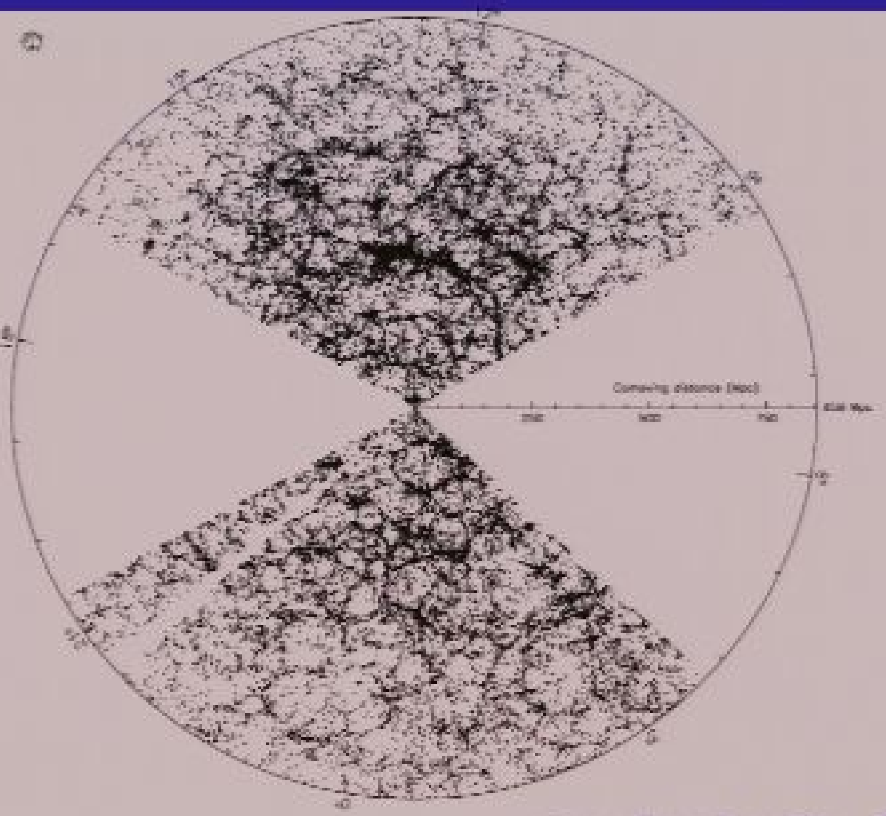
- It is a good approximation

- ..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)

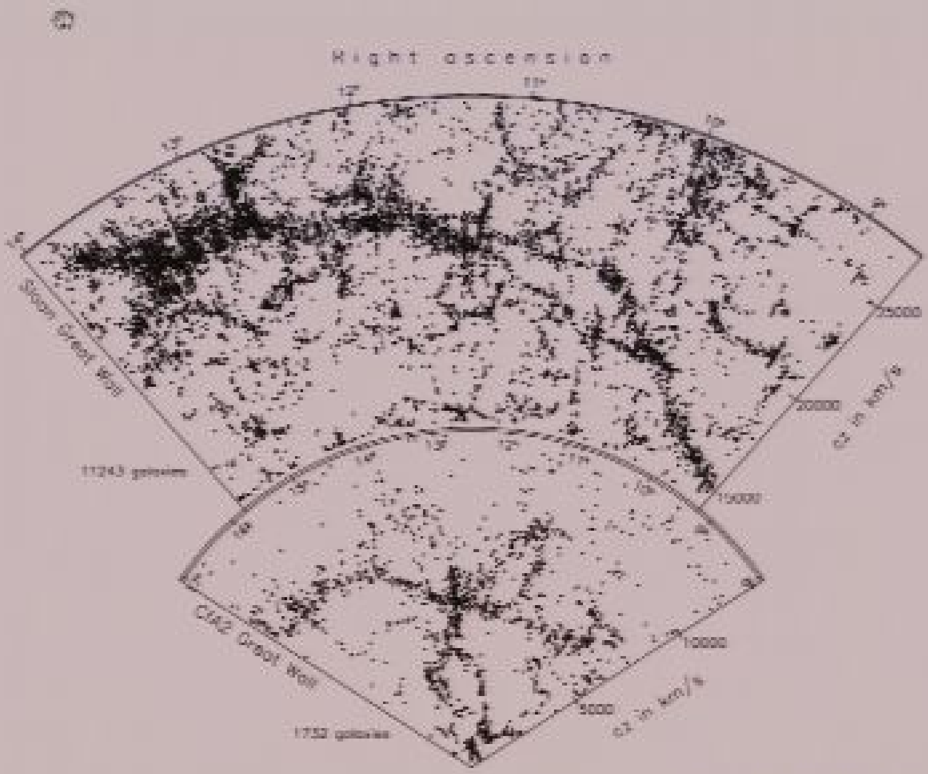
- Superclusters upto few hundreds of Mpc (10% of Hubble radius), nonlinear objects

- Network with sponge-like structure: pancakes surrounding voids. Typical lenght $100 - 150\mathrm{Mpc}/h$.

SDSS data

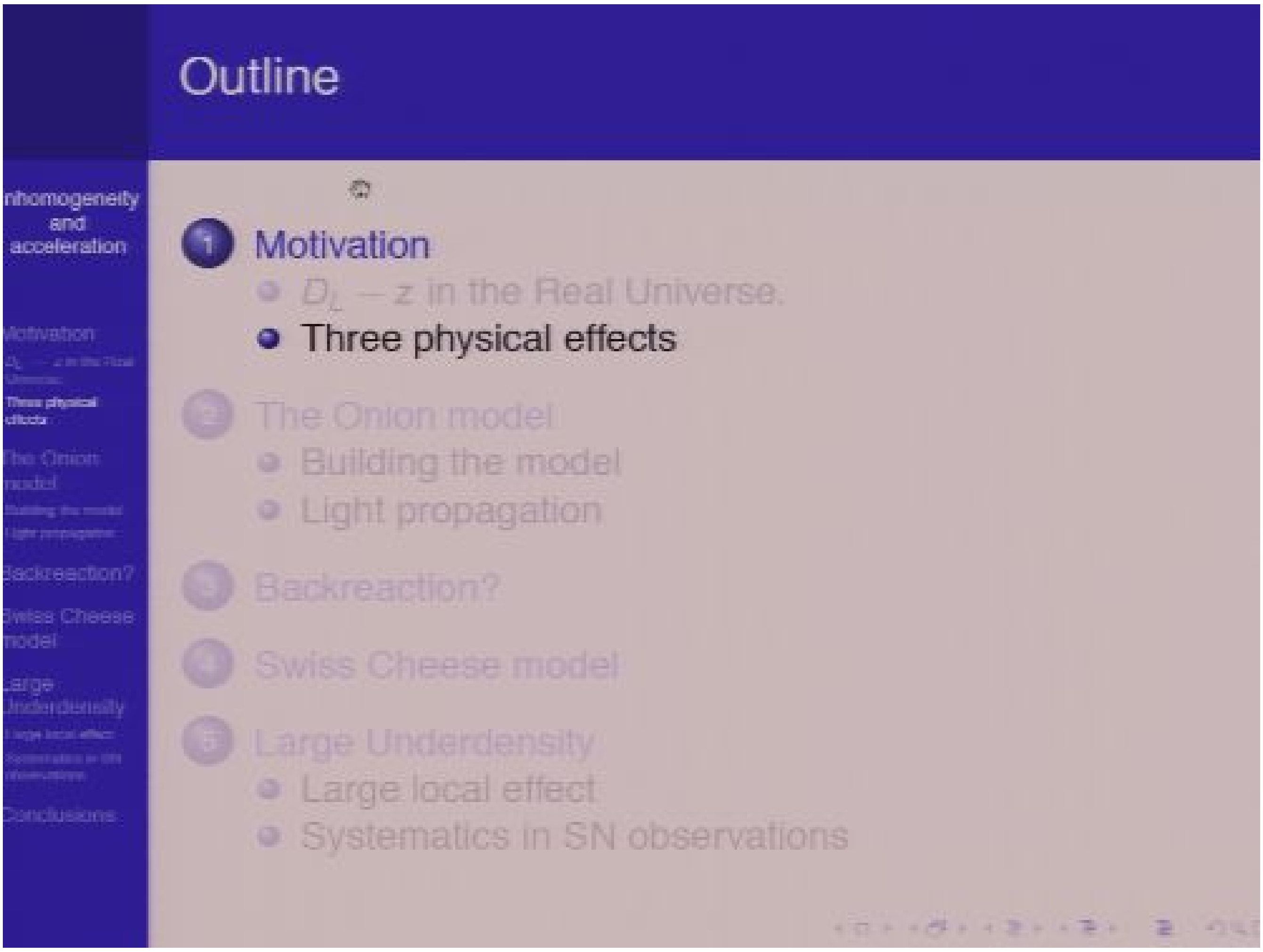


Great walls


Right ascension
Sloan Great Wall
11243 galaxies
25000
20000
15000
cz in km/s
CfA2 Great Wall
1732 galaxies
10000
5000
cz in km/s

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



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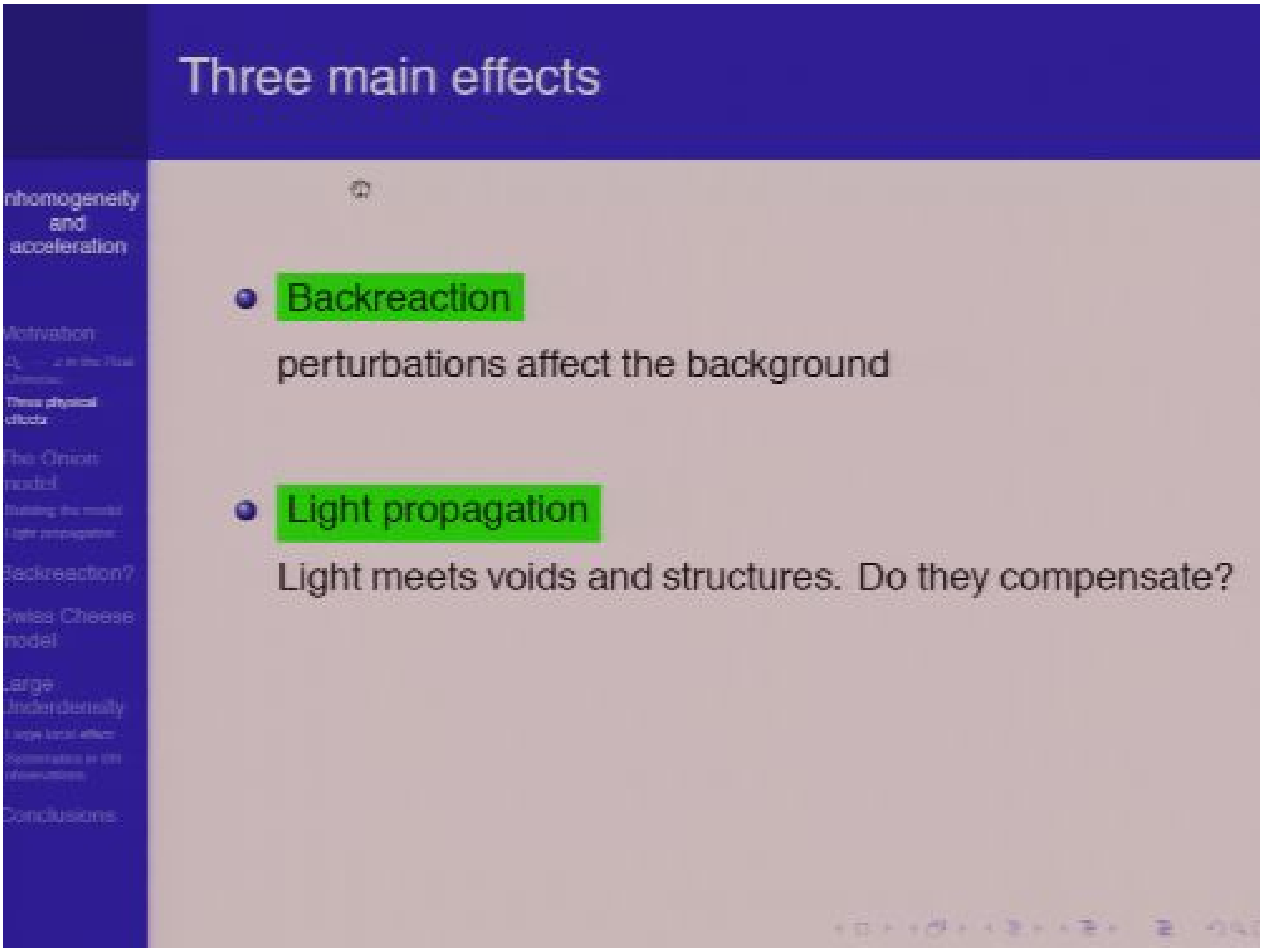
Three main effects

- **Backreaction**

  perturbations affect the background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Light meets voids and structures. Do they compensate?

Three main effects

- **Backreaction**

  perturbations affect the background

- **Light propagation**

  Light meets voids and structures. Do they compensate?

- **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 $\frac{d}{dt}\langle \rho(t, x) \rangle_D = -3 \frac{\dot{a}_D(t)}{a_D(t)} \langle \rho(t, x) \rangle_D$
- Features:

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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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  - 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 al. '05, Mansouri '06,...

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- ⇒ low z observations may be very different from average.
- Since acceleration is inferred comparing low z with high z...
- Can this mimick acceleration [2]?

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- $\Rightarrow$ low z observations may be very different from average.
- 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

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

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

$$R = \frac{GM(r)}{2|k(r)|r^2}[\cos h(u) - 1], \quad (2.1)$$

$$t - t_b(r) = \frac{GM(r)}{[2|k(r)|r^2]^{3/2}}[\sin h(u) - u].$$

- $k(r) = 0$,

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

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 $\delta(r, t_{now}) \gg 1$) [3]

[3] Warning: several previous papers make use of decaying modes!

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- We play with $k(r)$ to describe $\delta(r, t_I)$.
- $k = 0$ 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.

[3] Warning: several previous papers make use of decaying modes!

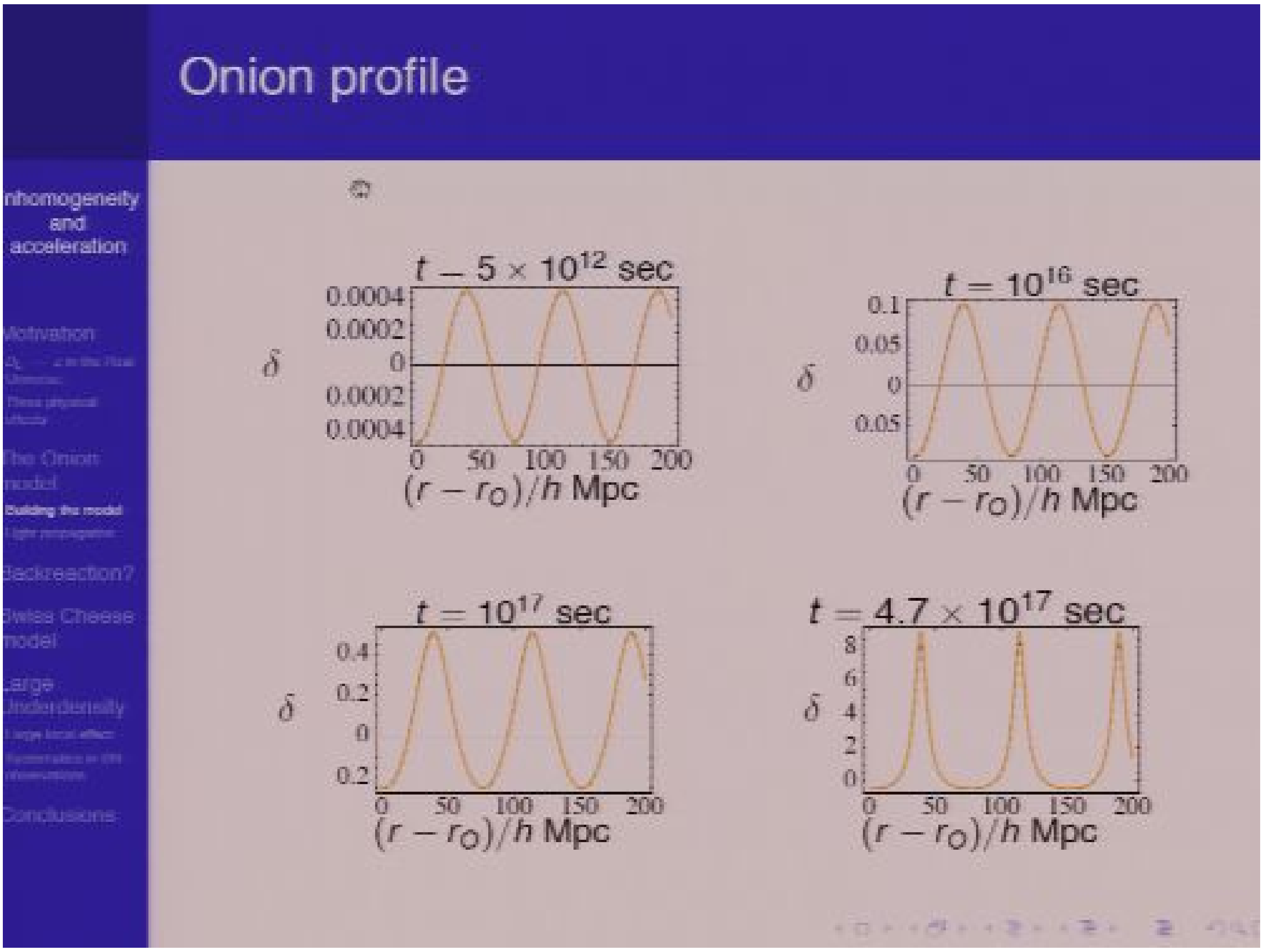
Choosing $A(r)$

- 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
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$t = 5 \times 10^{12}$ sec
$t = 10^{16}$ sec
$t = 10^{17}$ sec
$t = 4.7 \times 10^{17}$ sec
δ
$(r - r_O)/h$ Mpc

Outline

Redshift

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

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

Redshift

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

- 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

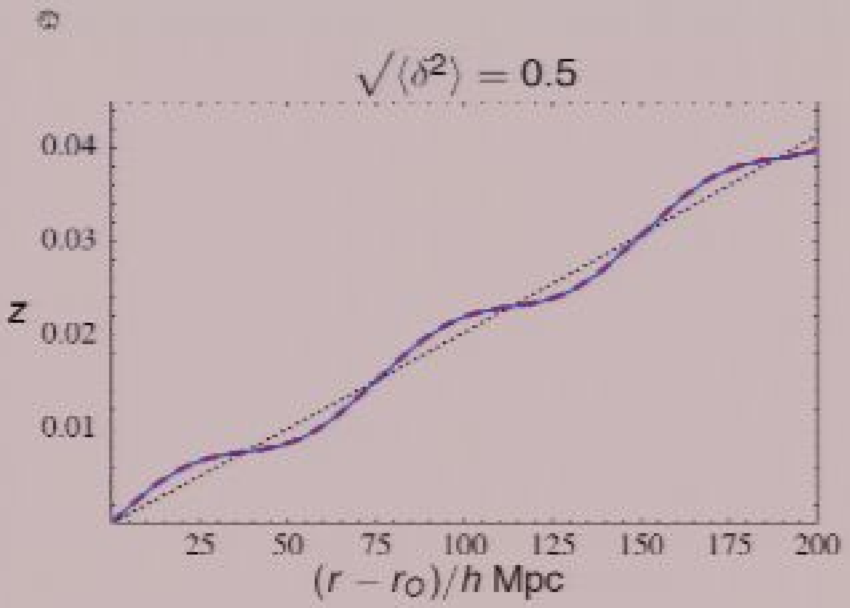

Figure: Redshift (z) along the geodesic of a photon arriving at $r = r_O$ at time $t = t_O$. In this plot $r_O = 36.5L$, $t_O = 3.3 \times 10^{17}$sec.

Numerical and analytical D_L

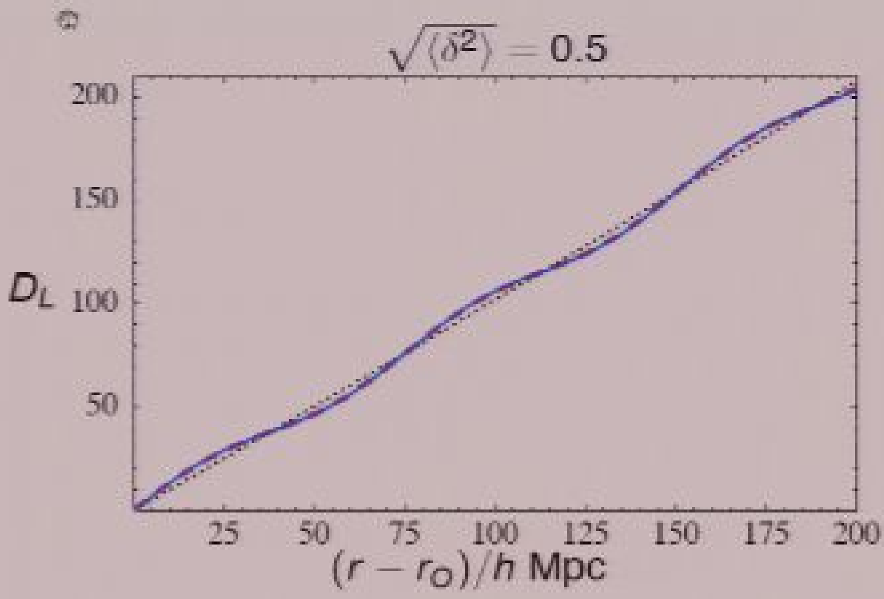

Figure: Luminosity distance (D_L) along the geodesic of a photon arriving at $r = r_O$ at time $t = t_O$. In this plot $r_O = 36.5L$, $t_O = 3.3 \times 10^{17}$sec.

Is there backreaction?

No sizeable "overall" effect

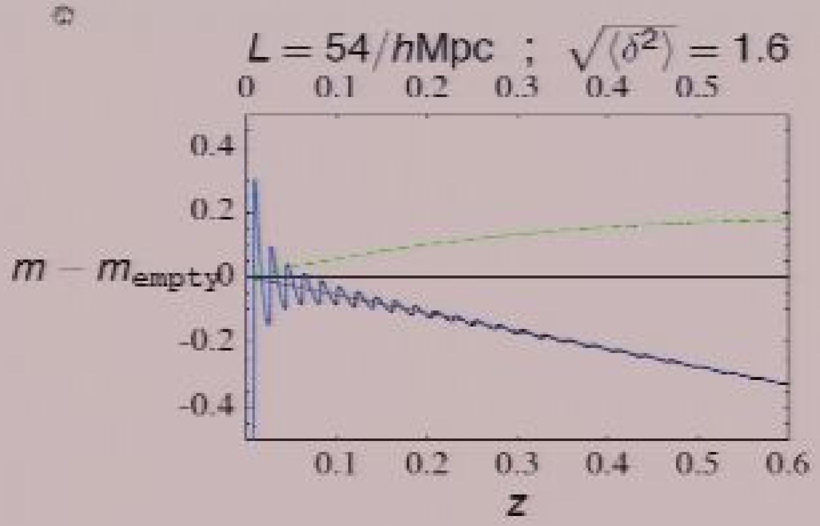

Figure: $m - Log_{10}(D_L)$

No sizeable "overall" effect

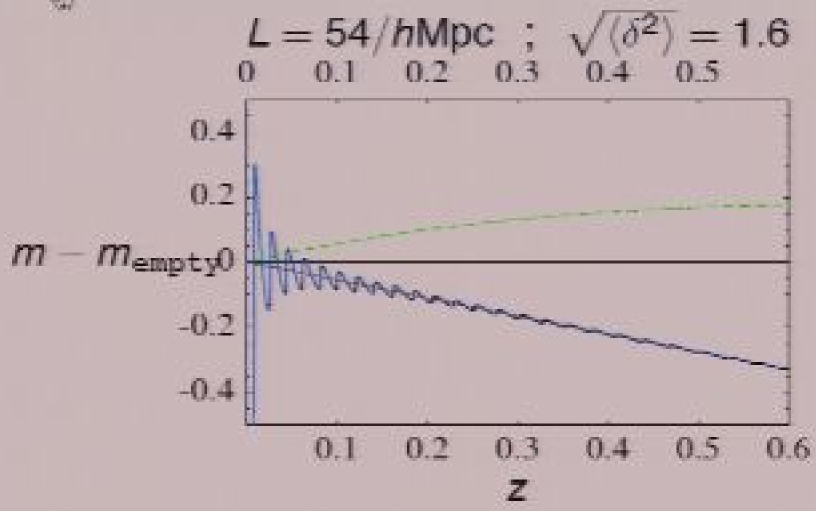

Figure: $m - Log_{10}(D_L)$

- 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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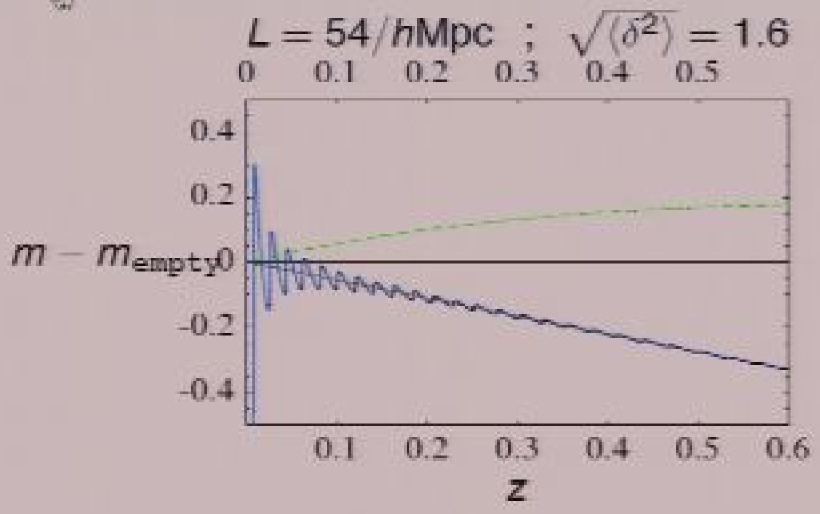

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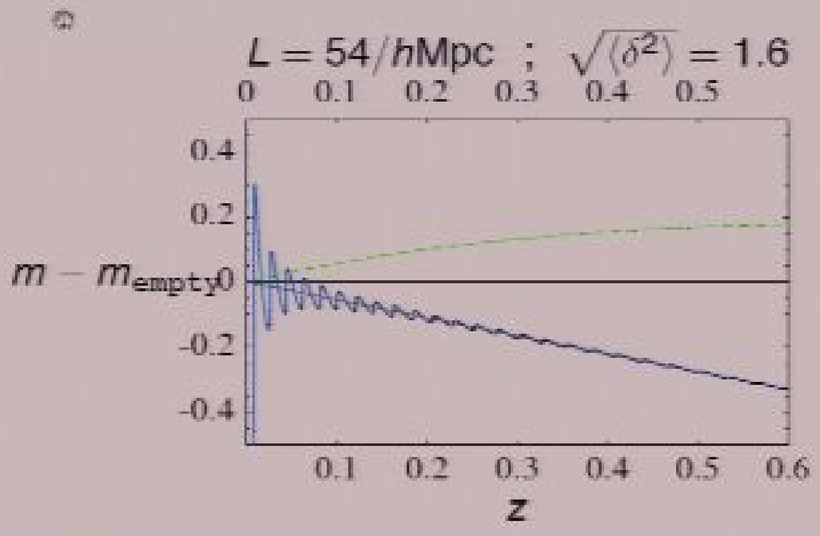

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  - Example $k(r) = k_0 \left[\left(\frac{r}{L}\right)^2 - 1 \right]$
- Void at the center, structure at the boundary
- Consider also nonlinear k
- Is there any large net effect for a photon travelling through a patch?
- Both Observer and Source in 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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- And...there is no backreaction on the outside FLRW region by construction due to spherical symmetry (Birkhoff's theorem)
- 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
- It goes like L/r_H

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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- Our philosophy: Try to make contact with realistic cosmology
- What's the smallest L and δ that can possibly work?

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- What's the smallest L and $\bar{\delta}$ 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 ($z \gtrsim 0.3$):

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

Low z

- We use $h_{\rm OUT} \approx 0.5$.
- 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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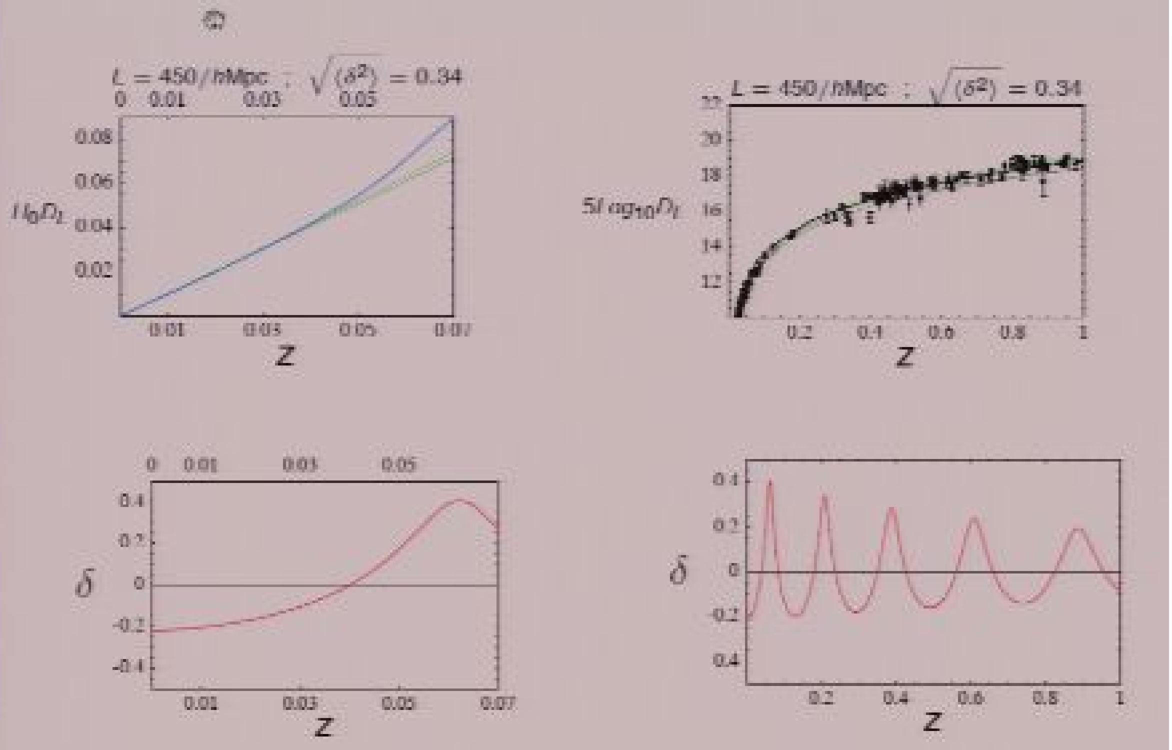
- We need a local patch, that at least extends up to $z \approx 0.07$ to have a linear Hubble diagram in $0.03 \leq z \leq 0.07$.
- Therefore: $L \gtrsim 400/h$ Mpc (diameter)
- Put Observer in a void

Hubble Diagrams



SDSS data

Inhomogeneity and acceleration

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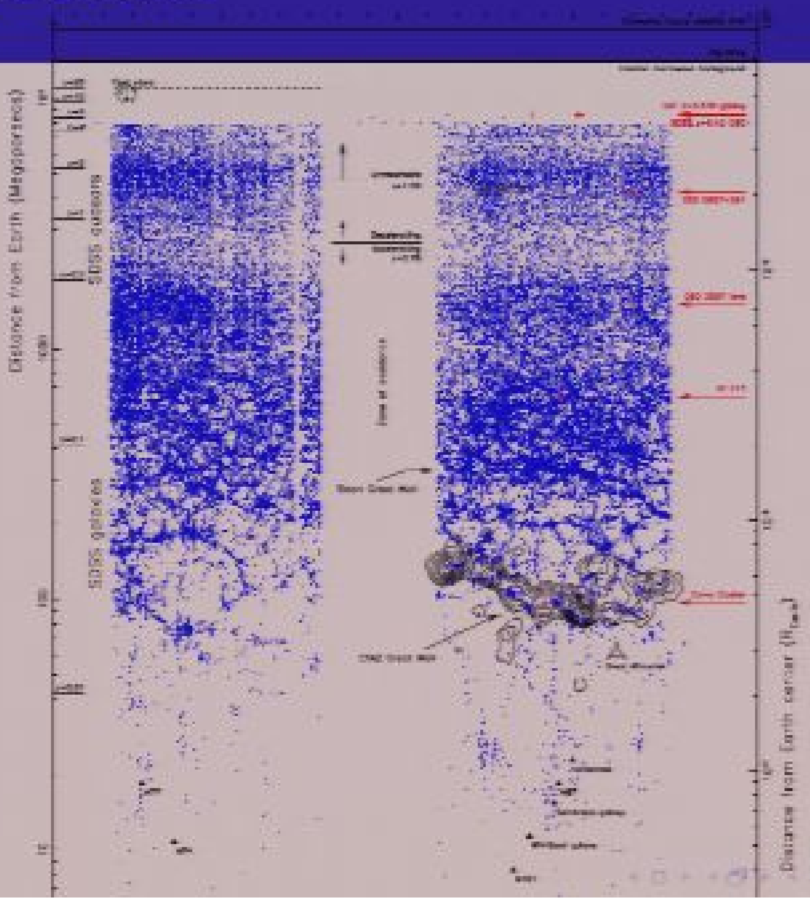
  - Large local effect
- Conclusions



$m - z$ plot

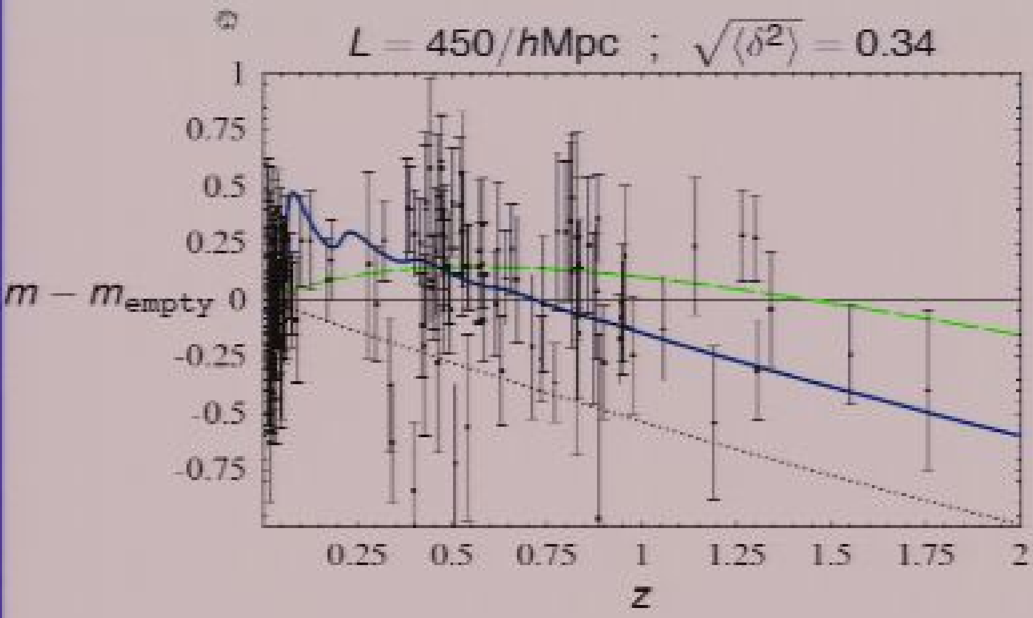


Figure: The blue solid line is our numerical solution, the black dotted line is the CDM model ($\Omega_m = 1$), and the green long-dashed line is the ΛCDM result (with $\Omega_\Lambda = 0.73$). We have superimposed SN gold data set *Riess et al.*

Individual contributions to χ^2

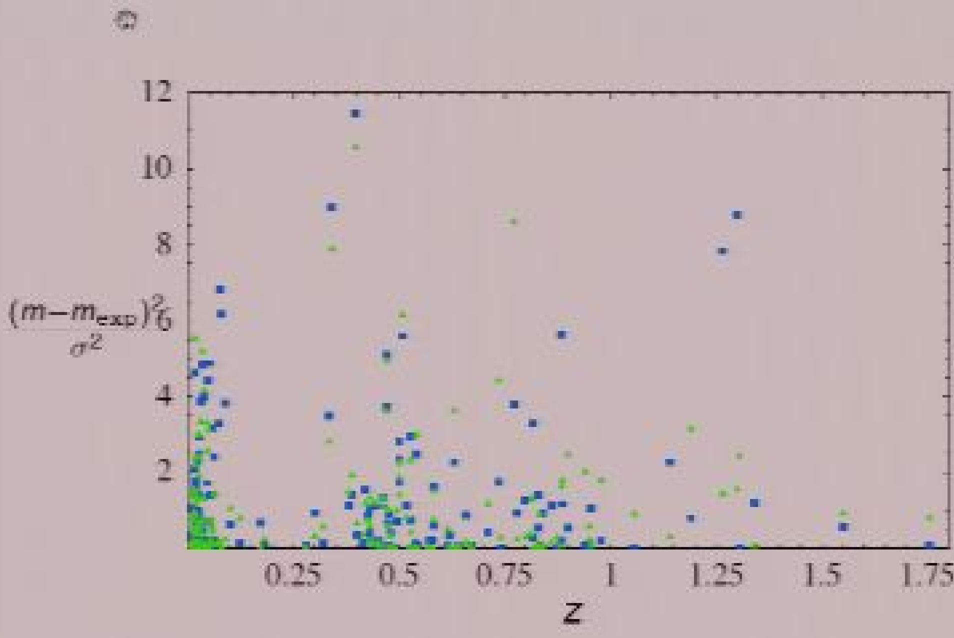


Figure: We show here the contribution to the χ^2 for each data point (gold data set of *Riess et al.*) Our model (blue boxes) is compared with ΛCDM with $\Omega_\Lambda = 0.73$ (green triangles).

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,
$\Omega_{b,\mathrm{OUT}}/\Omega_{m,\mathrm{OUT}} = 0.13$,

Assessment of the "Local Void" scenario

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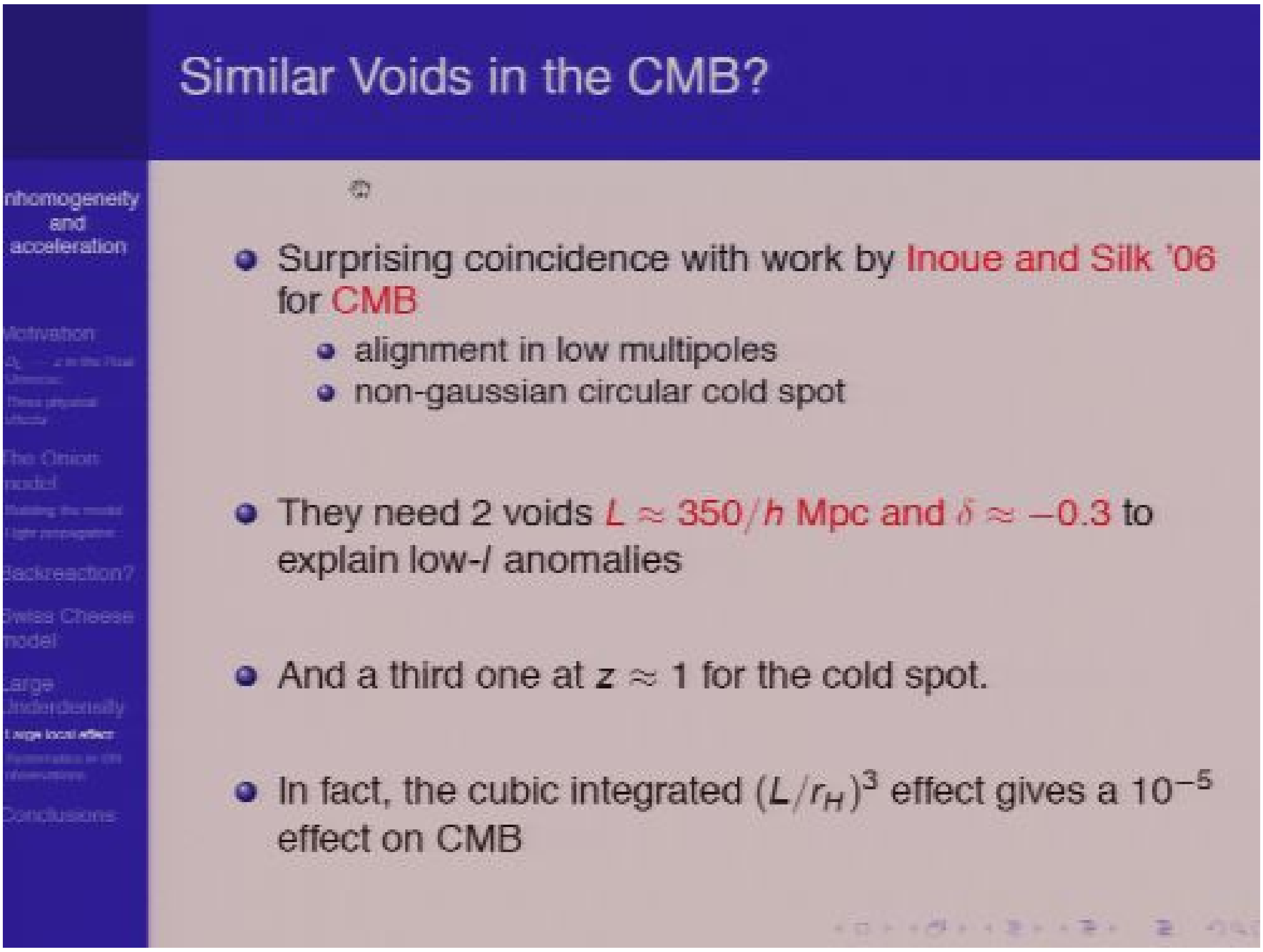
- Full CMB spectrum?

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.


Similar Voids in the CMB?
Inhomogeneity and acceleration
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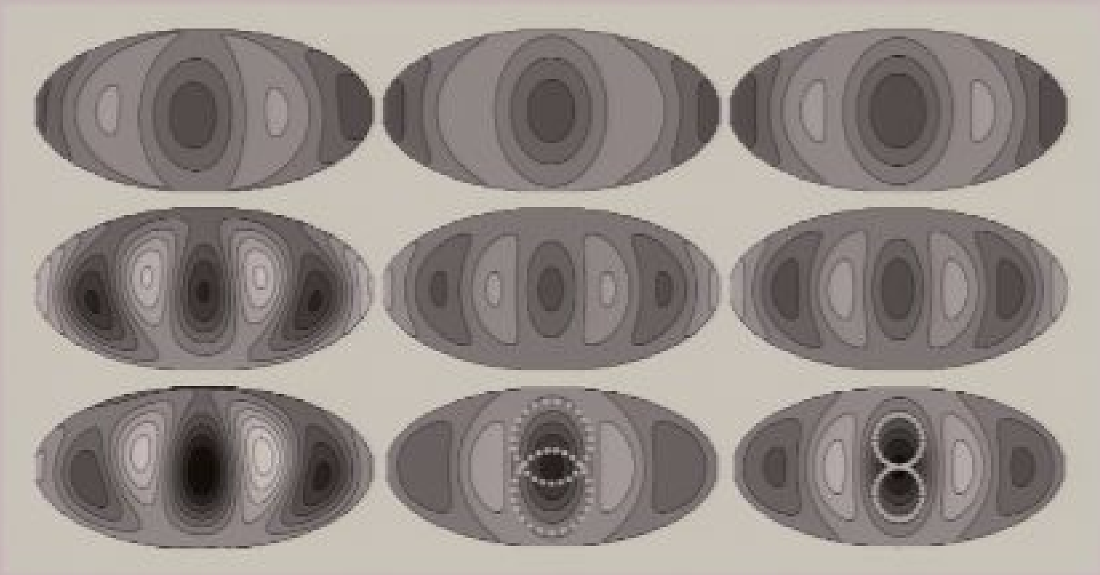
They need 2 voids $L \approx 350/h$ Mpc and $\delta \approx -0.3$ to explain low-l anomalies
And a third one at $z \approx 1$ for the cold spot.
In fact, the cubic integrated $(L/r_H)^3$ effect gives a 10^{-5} effect on CMB

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?

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[4] William J. Frith, N. Metcalfe, T. Shanks (Durham U.) 2005 MNRAS, astro-ph/0509875. William J. Frith, G.S. Busswell, R. Fong, N. Metcalfe, T. Shanks (Durham U.) 2003. MNRAS. astro-ph/0302331

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?
- 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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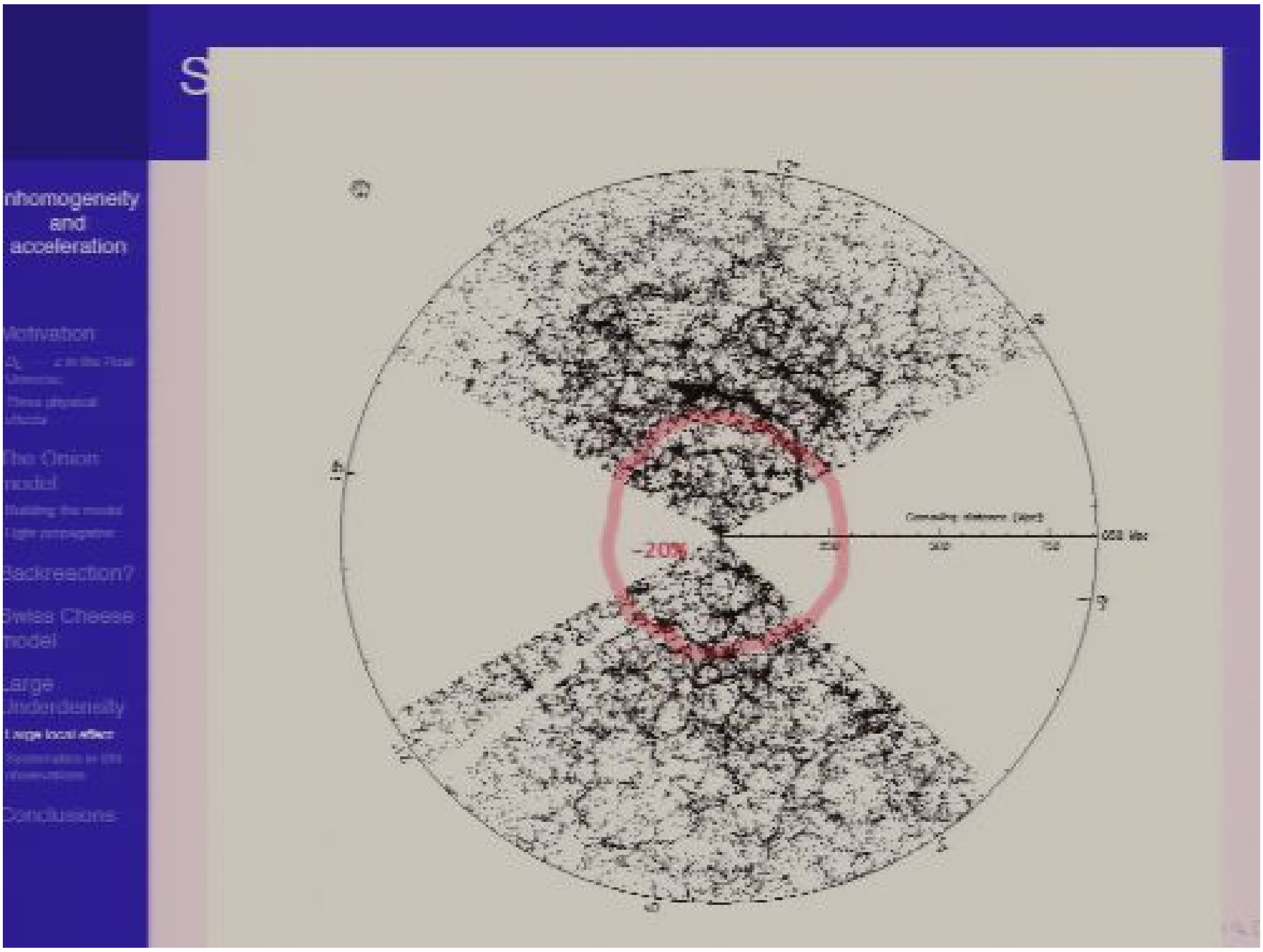
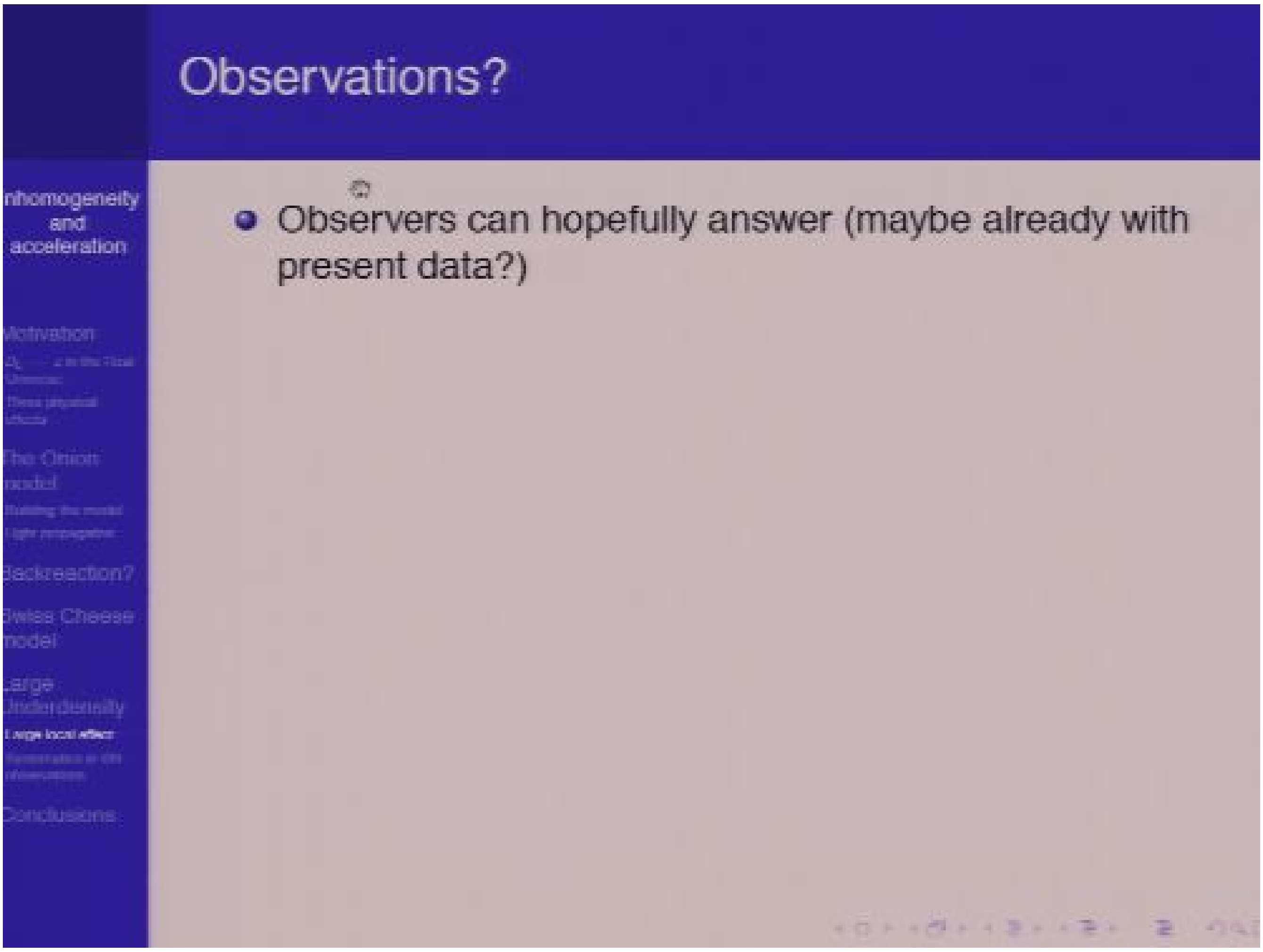

Inhomogeneity and acceleration
Motivation
The Onion model
Backreaction?
Swiss Cheese model
Large Underdensity
Large local effect
Conclusions
-20%


Observations?
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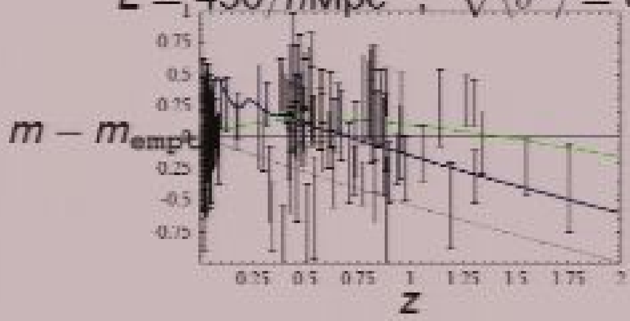

- SDSS II is definitely going to discriminate this hypothesis ($L = 400/h$ and $\delta = -0.3$): lots of data at intermediate redshift (40 SN)...very soon.

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

Inhomogeneity and acceleration

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

With lower value of δ

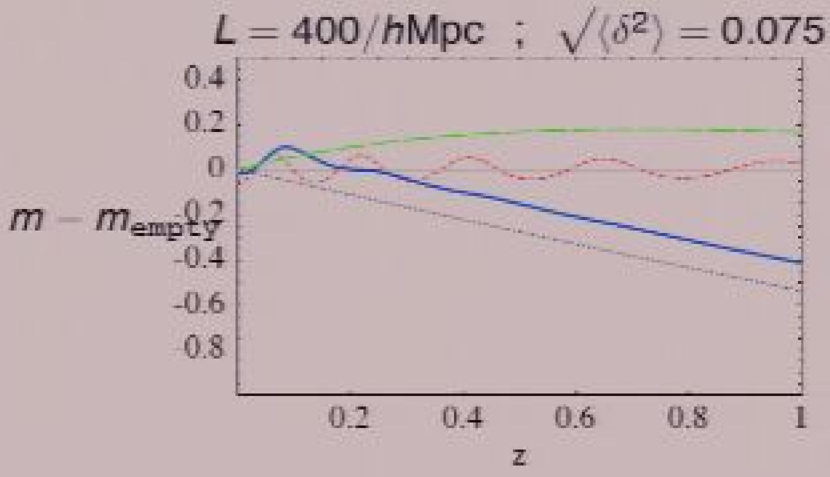

Figure: Magnitude residual from empty FLRW (Δm) vs. redshift (z). We have superimposed the red thin dashed line (density contrast seen by the photon).

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 $\Delta m \sim 0.05$ (and a similar anisotropy).