Can an Inhomogeneous Universe mimic Dark Energy?

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CERN

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[1] In collaboration with:
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Outline

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- Problem: We do not understand
  - the amount (why of the same amount as Matter today)?
  - its nature (is it vacuum energy?)

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- Other observations (BAO and LSS...) fit consistently

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- What happens to observations when we have departure from a *homogeneous* model?
- Can we accomodate for *all* this evidence if we relax (to some degree) homogeneity?

Homogenous Universe: a good approximation?

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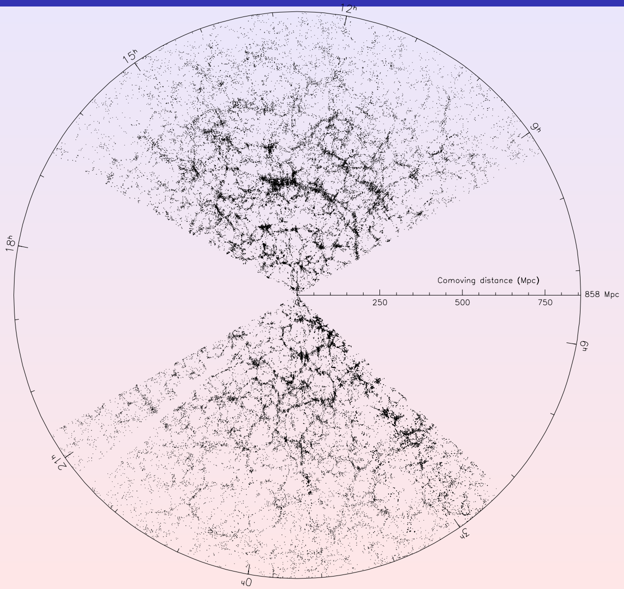
- Superclusters upto few hundreds of Mpc (10% of Hubble radius), nonlinear objects ("cosmic web")

SDSS data ("The cosmic web")



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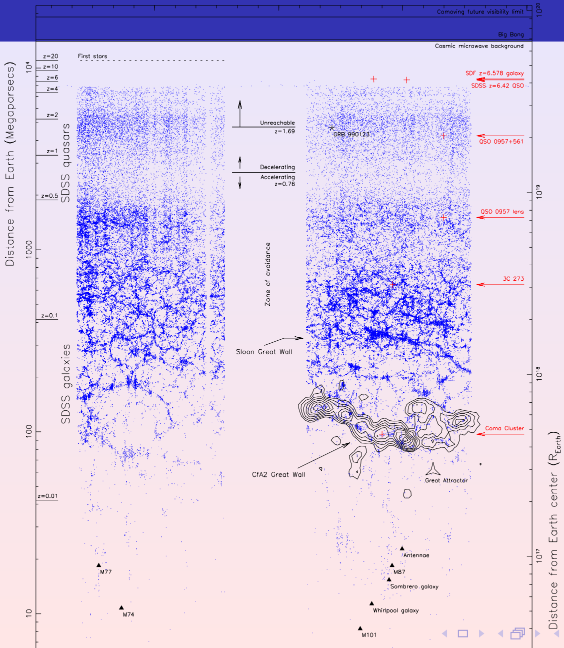
Comoving future visibility limit
Big Bang
Cosmic microwave background
First stars
z=20
z=10
z=6
z=4
z=2
z=1
z=0.5
z=0.1
z=0.01
Distance from Earth (Megaparsecs)
SDSS quasars
SDSS galaxies
Unreachable z=1.69
Decelerating
Accelerating z=0.76
Zone of avoidance
Sloan Great Wall
CfA2 Great Wall
Great Attractor
GRB 990123
SDF z=6.578 galaxy
SDSS z=6.42 QSO
QSO 0957+561
QSO 0957 lens
3C 273
Coma Cluster
Antennae
M87
Sombrero galaxy
Whirlpool galaxy
M101
M77
M74
Distance from Earth center (R_{Earth})

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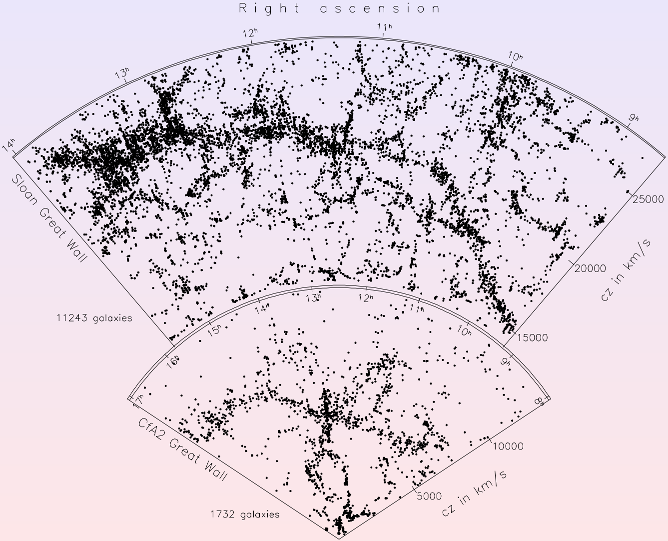

Right ascension
12h
11h
10h
13h
9h
14h
Sloan Great Wall
25000
20000
cz in km/s
11243 galaxies
15000
13h
12h
14h
11h
15h
10h
16h
9h
8h
7h
CfA2 Great Wall
10000
5000
cz in km/s
1732 galaxies

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  What if we live in a local void?

A few words on backreaction

- Averaging of Einstein's Equations
  Nonlinearity $\Rightarrow$ extra terms in Friedmann equations[3]

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$$V_D = \int_D \sqrt{h}\, d^3x, \qquad a_D(t) \equiv \left(\frac{V_D}{V_{D_0}}\right)^{1/3};$$

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$$\frac{\ddot{a}_D}{a_D} = -\frac{4\pi G}{3}\left(\rho_{\rm eff} + 3P_{\rm eff}\right),$$

$$\left(\frac{\dot{a}_D}{a_D}\right)^2 = \frac{8\pi G}{3}\rho_{\rm eff},$$

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The extra terms

- Where

$$\begin{aligned} \rho_{\rm eff} &= \langle \rho \rangle_D - \frac{Q_D}{16\pi G} - \frac{\langle R \rangle_D}{16\pi G} \\ P_{\rm eff} &= -\frac{Q_D}{16\pi G} + \frac{\langle R \rangle_D}{48\pi G}, \end{aligned}$$

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$$P_{\text{eff}} = -\frac{Q_D}{16\pi G} + \frac{\langle R \rangle_D}{48\pi G},$$

- The *real* question: how large is it?

Perturbatively: 2^{nd} order

- On a large Domain the dominant term has the form[4] :

$$\overline{\frac{H_D - H}{H}} = \frac{25}{54}\frac{1}{a^2H^2}\overline{\langle\varphi\nabla^2\varphi\rangle}$$

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$$= A^2 \frac{a}{a_0} \left(\frac{h \, \Gamma \mathrm{Mpc}^{-1}}{H_0} \right)^2 \int_0^\infty dq \, q \, T^2(q)$$

where $A \sim 10^{-5}$, $\Gamma = \Omega_M h e^{-\Omega_B - \sqrt{2h}\Omega_B / \Omega_M}$.

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where roughly

$$\epsilon \equiv \frac{A}{1+z}\left(\frac{h\Gamma \mathrm{Mpc}^{-1}}{H_0}\right)^2 \times Int$$

with

$$Int = \int dq T^2(q) \approx 0.02$$

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- Note: $\epsilon \ll 1$ at high z

$\epsilon(z)$

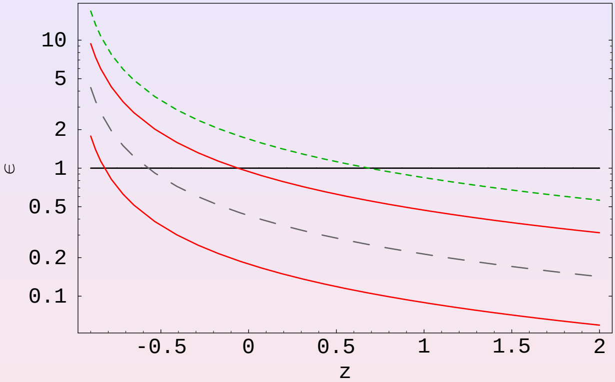

Figure: *Grey dashed line: central value,*
Red solid lines: 2σ ranges
(We used the growth factor as in matter domination. For comparison, green dotted line: $\Omega_M = 1$).

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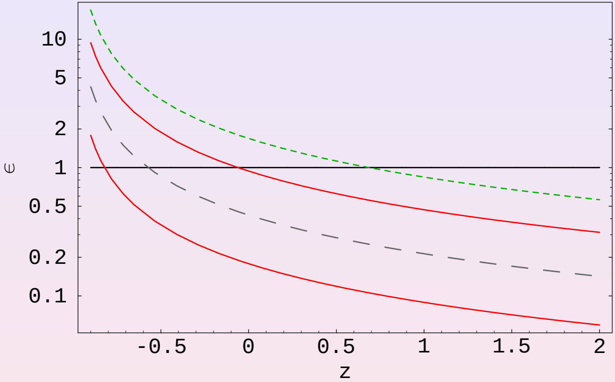

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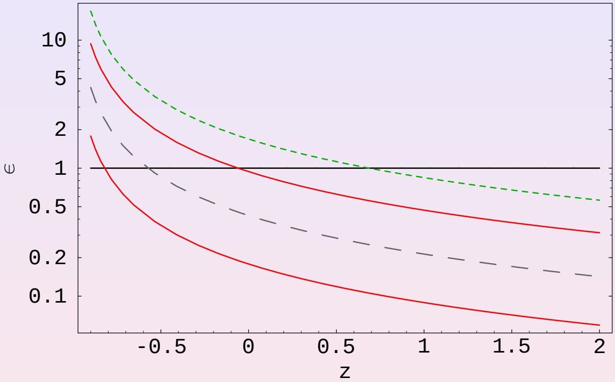
Void vs Dark Energy

Motivations
Backreaction
Light propagation
Results
Local Void
Minimal Void
Building the model
Light propagation
Fitting the data
SNIa Hubble diagram
WMAP
Putting things together
Other cosmological observations
Conclusions



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- Cannot disentangle this from backreaction
- Compute $\frac{\Delta z}{1+z}$ and $\frac{\Delta D}{D}$ in the presence of structures

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- We study null geodesic in this metric

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[6] T. Biswas-A. N. '06-'07

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A local fluctuation?

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- How much contrast δ and how large L is needed?

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- Let's review some literature and observations on Voids

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- It could be detected via lensing (S. Das and D. Spergel '08) and via non-gaussian coupling Rees-Sciama effect - lensing (I.Masina and A.N., in preparation)

Observational Status

- Some observational evidence for a local large underdense region ($\sim$ 25% less dense, $r \sim 200\,\mathrm{Mpc}/h$) from number counts of galaxies (2MASS) (Frith et al. Mon. Not. Roy. Astron. Soc. **345**, 1049 (2003))
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- It would represent a 4σ fluctuation, at odds with ΛCDM.
- Many Large Voids identified via ISW effect in the SDSS LRG catalog (about $100\,\mathrm{Mpc}/h$ radius) (Granett et al. '08)
- Also in contradiction with ΛCDM: $P < 10^{-8}$ (Sarkar & Hunt '08)

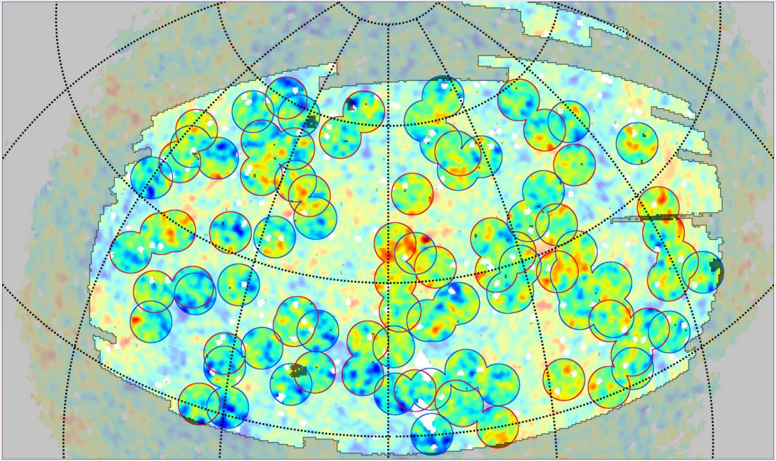

Figure: Granett, Neyrinck & Szapudi ’08

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- Watkins, Feldman & Hudson '08: use peculiar velocities of various (4500) objects in a $100 Mpc/h$ radius. Find $400 km/sec$ (expected $100 km/sec$)

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- Need for a Large Void also for BAO: a better fit is obtained with at least ($1\,\mathrm{Gpc}$) (Garcia-Bellido & Haugboelle).

Outline

Lemaître-Tolman-Bondi metrics

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

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

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- Spherically symmetric.
- Einstein equations:

$$\begin{aligned} \frac{1}{2}\frac{\dot{R}^2(r,t)}{R^2(r,t)} - \frac{GM(r)}{R^3(r,t)} &= \frac{r^2k(r)}{R^2(r,t)}, \\ 4\pi\rho(r,t) &= \frac{M'(r)}{R'(r,t)R^2(r,t)}, \end{aligned}$$

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It has the solutions:

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

$$\begin{aligned} R &= \frac{GM(r)}{2r^2|k(r)|}[\cos h(u) - 1], \\ t - t_b(r) &= \frac{GM(r)}{[2r^2|k(r)|]^{3/2}}[\sin h(u) - u]. \end{aligned} \tag{4.1}$$

- $k(r) = 0$,

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

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

LTB merged to FLRW

- Matching of an LTB sphere (of radius L) to FLRW:

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- Two parameters, L and k_{max}.

The density

- Roughly:

$$\rho(r,t) \simeq \frac{\langle\rho\rangle(t)}{1+(t/t_0)^{2/3}\epsilon(r)},$$

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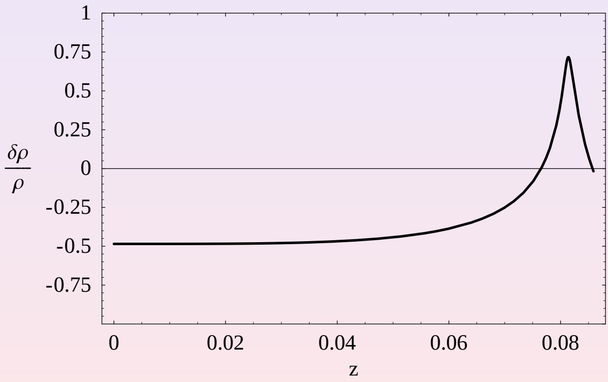
- We work at most with $\delta \sim \mathcal{O}(1)$.

The density profile



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Luminosity (Angular) Distance

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- For generic observer (but radial trajectory):

$$D_A = R_S \left(R_O \int_{r_O}^{r_S} \frac{R'(r,t(r))}{(1+2E(r))(1+z(r))R(r,t(r))^2} dr \right) \,,$$

Analytical approximation

$$f \equiv \frac{\sqrt[3]{2}(\cosh(u)-1)}{3^{2/3}(\sinh(u)-u)^{2/3}} - 1 \quad (4.2)$$

$$u_0 = 6^{1/3}(\sinh(u)-u)^{1/3}\,. \quad (4.3)$$

Then, one can use this function in the following equations:

$$\tau(r) = \tau_0 - \frac{\pi}{9}\gamma^2\bar{M}r[1+f(\gamma^2\tau_0^2k(r))]\,, \quad (4.4)$$

$$1+z(r) = \left(\frac{\tau_0}{\tau(r)}\right)^2 \exp\left[\frac{4\pi\gamma^2\bar{M}r}{9}f(\gamma^2\tau_0^2k(r))\right] \quad (4.5)$$

$$D_L(r) = \frac{\pi}{3}\gamma^2 r\tau(r)^2[1+f(\gamma^2\tau_0^2k(r))][1+z(r)]^2 \quad (4.6)$$

$$\tau_0 = \left(\frac{2\bar{M}}{3H_0}\right)^{1/3} \quad (4.7)$$

$$\gamma = \left(\frac{9\sqrt{2}}{\pi}\right)^{1/3} \quad (4.8)$$

Outline

High and low z

- Evidence for acceleration comes from mismatch between:
  - measurements at low redshift ($0.03 \lesssim z \lesssim 0.08$)
  - high-z SN (roughly $0.4 \lesssim z \lesssim 1$)

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- We choose large $r_{\texttt{Void}}$ (at $z \approx 0.08 - 0.09$)
- $\Rightarrow$ The Local Bubble is different from the average.

Outside just matter dominated (even if there are other Bubbles, their effect is small)

Roughly

- At high z ($z \gtrsim 0.1$), just matter dominated Universe:

$$D_{\rm EdS}(z) \approx \frac{2}{H_{\rm out}}\left(1 + z - \sqrt{1+z}\right).$$

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- Two (reduced) Hubble parameters: h and h_{out}
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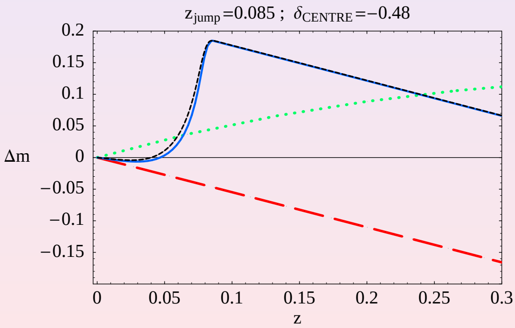
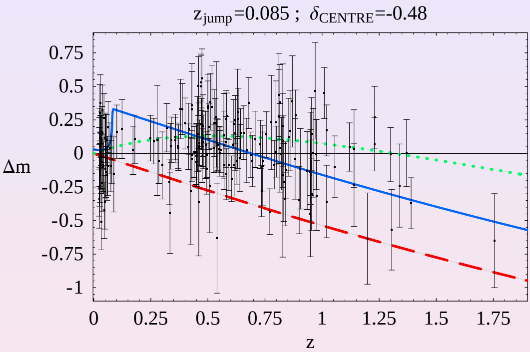
- h corresponds to what is measured

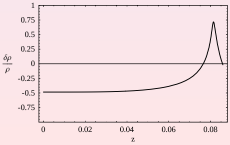
Δm for different models

- Magnitude is $m \equiv 5Log_{10}D(z)$
- The open “empty” Universe is subtracted ($\Omega_K = -1$)



$m - z$ diagram: Riess data





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- We vary $\mathcal{J}$ and compute the χ^2.

Fitting SNIa with a Jump

Void vs Dark Energy

Riess et al. dataset, astro-ph/0611576 (182 SNIa)

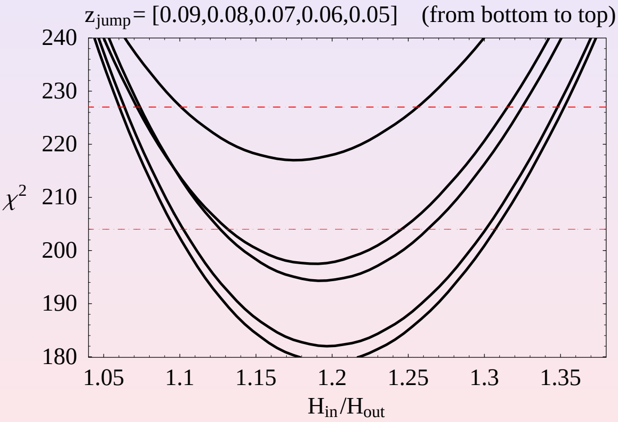

Figure: The red dashed lines are 10% and 1% goodness-of-fit (182 data points)

LTB Void fit

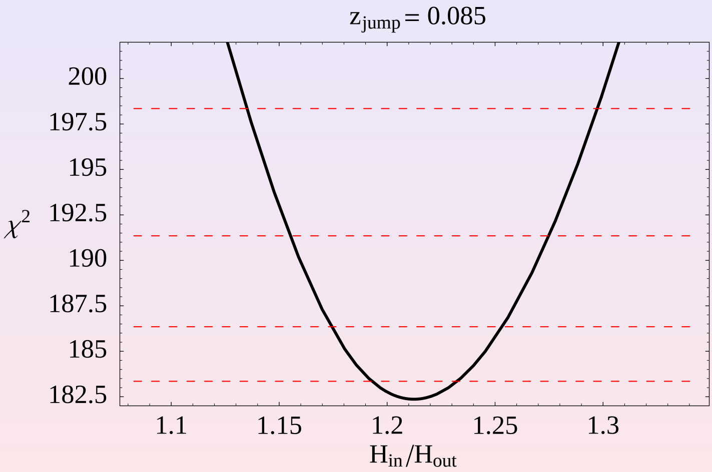

Figure: Here we use the full LTB model. We show 1σ, 2σ, 3σ and 4σ intervals (using likelihood $\propto e^{-\chi^2/2}$).

χ^2: Riess data

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

Model	χ^2 (181 d.o.f.)
ΛCDM (with $\Omega_M = 0.27, \Omega_\Lambda = 0.73$)	160
EdS (with $\Omega_M = 1, \Omega_\Lambda = 0$)	274
Void ($\sqrt{\langle\delta^2\rangle} \approx 0.4$ on $L = 250/h\mathrm{Mpc}$)	182

Remarks:

- With instrumental error only: no smooth curve can give a good fit
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Remarks:

- With instrumental error only: no smooth curve can give a good fit
- Estimated error from intrinsic variability added in quadrature
- Not as good as ΛCDM
- Becomes better including curvature Ω_k *outside*

χ^2: UNION data

Table: Comparison with data (Union data)

Model	χ^2 (307 d.o.f.)
ΛCDM (with $\Omega_M = 0.27, \Omega_\Lambda = 0.73$)	304
Void ($\sqrt{\langle\delta^2\rangle} \approx 0.4$ on $L = 500/h\mathrm{Mpc}$)	340
Void ($\sqrt{\langle\delta^2\rangle} \approx 0.7$ on $L = 2000/h\mathrm{Mpc}$)	304

Remarks:

- It seems necessary to consider a larger Void (*Gpc* scale)
- Or add curvature? (work in progress)

UNION fit with 2Gpc

Void vs Dark Energy

Motivations
Backreaction
Light propagation
Results
Local Void
Minimal Void
Building the model
Light propagation
Fitting the data
SNIa Hubble diagram
WMAP
Putting things together
Other cosmological observations
Conclusions

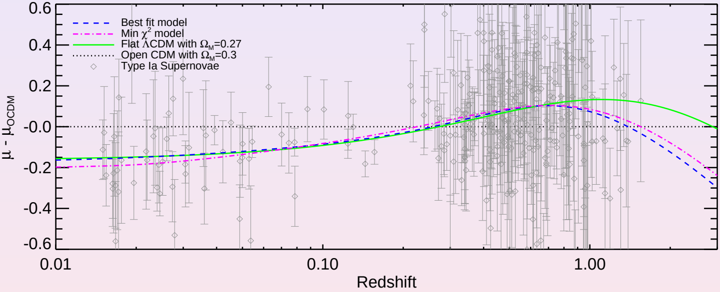

Figure: Taken from Garcia-Bellido & Haugboelle ’08 (similar fits also in Zibin et al. ’08)

Outline

The ΛCDM fit

- We try to fit the WMAP 3-yr data

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- We try to fit the WMAP 3-yr data
- We look at TT and TE correlations, using CosmoMC

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  - Flat spectrum plus bump (as in P. Hunt and S. Sarkar, arXiv:0706.2443 [astro-ph]; A. Blanchard, M. Douspis, M. Rowan-Robinson and S. Sarkar, Astron. Astrophys. **412**, 35 (2003) [arXiv:astro-ph/0304237].)

Priors (ΛCDM)

The usual prior set is:

- Allow for nonzero Ω_Λ.
- Power-law spectrum with index n_s.
- (eventually with running α_s)
- $P(k) \propto k^{n_s(k_0)+\frac{1}{2}ln(k/k_0)\alpha_s}$

Priors: without Λ

A different prior set, that we use:

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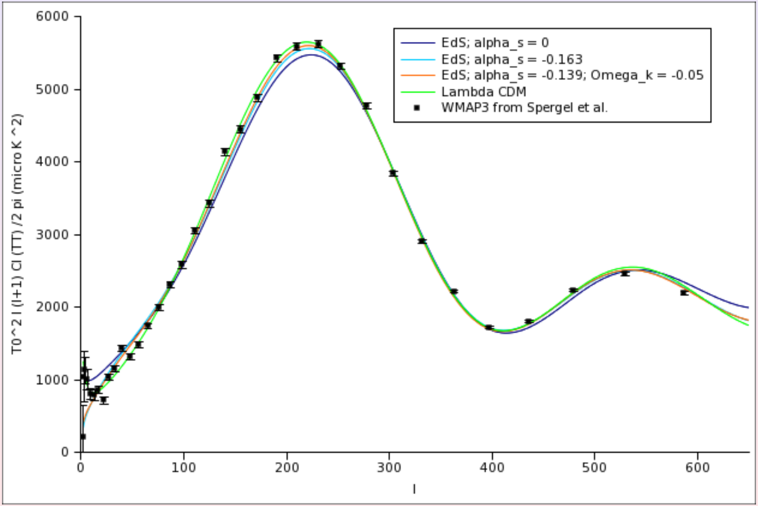
- (we also may allow for some curvature)

Fit to WMAP3


6000
5000
4000
3000
2000
1000
0
0
100
200
300
400
500
600
l
T0^2 l (l+1) Cl (TT) /2 pi (micro K ^2)
EdS; alpha_s = 0
EdS; alpha_s = -0.163
EdS; alpha_s = -0.139; Omega_k = -0.05
Lambda CDM
WMAP3 from Spergel et al.

Goodness-of-fit

	C_l^{TT}		$C_l^{TT} + C_l^{TE}$		**Total**	
Model	χ^2_{eff}	G.F.	χ^2_{eff}	G.F.	χ^2_{eff}	G.F.
Concordant ΛCDM	1038.9	4.7%	1455.2	11.3%	3538.6	41%
EdS $\alpha_s = 0$	1124.6	0%	1711.9	0%	3652.3	6%
EdS $\alpha_s \neq 0$	1057.8	1.9 %	1475.5	5.7%	3577.4	24.6%
EdS $\alpha_s,\ \Omega_k = -0.050$	1048.7	2.9%	1466	7.9%	3560.9	31.1%

Table:
1^{st} *column*: high-l TT ($31 \leq l \leq 1000$)
2^{nd} *column*: high-l TT ($31 \leq l \leq 1000$) and TE ($24 \leq l \leq 450$)
3^{rd} *column*: total of TT ($2 \leq l \leq 1000$) and TE ($2 \leq l \leq 450$)

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- larger value of Ω_M/Ω_b (around 10 instead of 6)
- $\Omega_b h^2_{\mathtt{out}}$ ($\sim 0.018^{+0.001}_{-0.002}$) consistent with BBN constraint (which is $0.017 \leq \Omega_b h^2_{\mathtt{out}} \leq 0.024$, at 95% C.L.)

Parameter values

	ΛCDM	EdS, $\alpha_s = 0$	Eds, $\alpha_s \neq 0$	Eds, $\alpha_s, \Omega_k \neq 0$
$\Omega_b h^2_{\mathtt{out}}$	$0.022^{+0.002}_{-0.002}$	$0.022^{+0.001}_{-0.001}$	$0.018^{+0.001}_{-0.002}$	$0.019^{+0.002}_{-0.001}$
$\Omega_m h^2_{\mathtt{out}}$	$0.106^{+0.021}_{-0.013}$	$0.198^{+0.008}_{-0.011}$	$0.186^{+0.011}_{-0.009}$	$0.167^{+0.009}_{-0.007}$
Ω_Λ	$0.759^{+0.041}_{-0.103}$	0	0	0
z_{re}	$11.734^{+4.993}_{-7.619}$	$8.697^{+4.351}_{-6.694}$	$13.754^{+2.246}_{-5.752}$	$13.342^{+2.55}_{-5.011}$
Ω_k	0	0	0	-0.05
n_s	$0.96^{+0.04}_{-0.04}$	$0.94^{+0.021}_{-0.038}$	$0.732^{+0.07}_{-0.071}$	$0.761^{+0.069}_{-0.069}$
α_s	0	0	$-0.161^{+0.044}_{-0.044}$	$-0.13^{+0.037}_{-0.048}$
$10^{10} A_s$	$20.841^{+3.116}_{-3.442}$	$25.459^{+2.135}_{-2.766}$	$25.302^{+2.182}_{-2.968}$	$23.975^{+2.198}_{-2.448}$
Ω_m / Ω_b	$4.73^{+0.999}_{-0.485}$	$9.119^{+0.341}_{-0.357}$	$10.094^{+0.645}_{-0.489}$	$8.929^{+0.512}_{-0.541}$
h_{out}	$.72857^{+.05137}_{-.07393}$	$.46857^{+.00888}_{-.01307}$	$.4523^{+.01291}_{-.01129}$	$.42069^{+.01107}_{-.00919}$
Age/GYr	$13.733^{+0.389}_{-0.369}$	$13.908^{+0.399}_{-0.258}$	$14.408^{+0.369}_{-0.4}$	$15.338^{+0.342}_{-0.393}$
σ_8	$0.77^{+0.121}_{-0.109}$	$1.012^{+0.056}_{-0.081}$	$0.919^{+0.07}_{-0.075}$	$0.862^{+0.06}_{-0.063}$
τ	$0.095^{+0.072}_{-0.074}$	$0.047^{+0.037}_{-0.041}$	$0.079^{+0.023}_{-0.044}$	$0.081^{+0.024}_{-0.041}$

Table: Most likely parameter values with 1 σ errors for the various COSMOMC Runs

Parameter likelihood

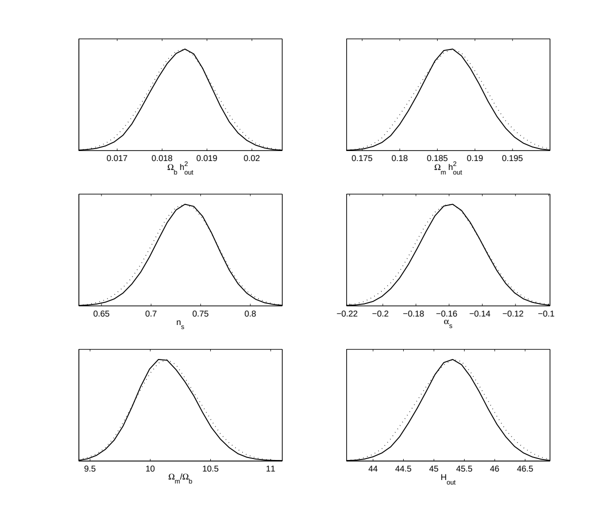

Figure: likelihoods to WMAP 3-yr for the run “EdS with α_s”

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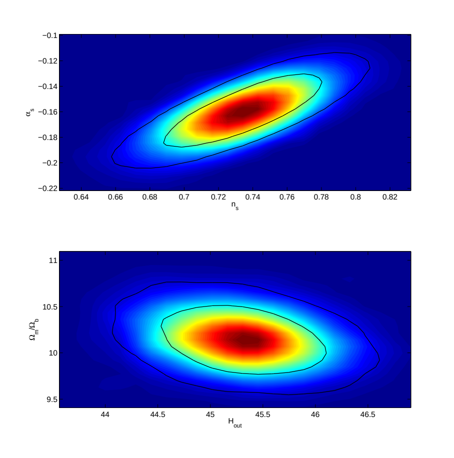

Figure: Contour likelihood plots to WMAP 3-yr for the run “EdS with α_s”

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  - $h = 0.72 \pm 0.08$ from HST (W. L. Freedman *et al.*, Astrophys. J. **553**, 47 (2001))
  - $h = 0.62 \pm 0.01 \pm 0.05$ from HST with corrected Cepheids (A. Sandage *et al.*, Astrophys. J. **653**, 843 (2006))
  - $h = 0.59 \pm 0.04$ from Supernovae (Parodi, Saha, Sandage and Tammann, arXiv:astro-ph/0004063.)
  - $h = 0.54^{-.03}_{+.04}$ SZ effect ($z \approx 1$) (E. D. Reese *et al.* Astrophys. J. **581**, 53 (2002))

Parameter Contours

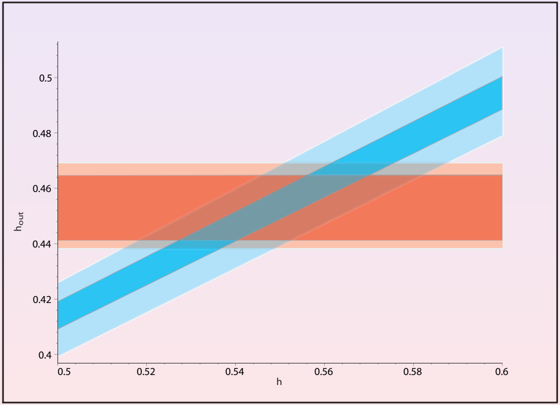

Figure: 1-σ and 2-σ Contour plots for h vs. h_{out}.

Summarizing the constraints

At 95% C.L. we have (for $L \approx 250/h$ Mpc) :

- $1.17 \leq \mathcal{J} \leq 1.25 \Rightarrow 0.42 \leq |\delta_0| \leq 0.58$

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  (but note that the average $\sqrt{\langle \delta^2 \rangle}$ is smaller)

- $0.44 \leq h_{\mathtt{out}} \leq 0.47$
- $0.51 \leq h \leq 0.59$

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  $\Rightarrow$ Combine with the Minimal Void scenario

h in the Bump model

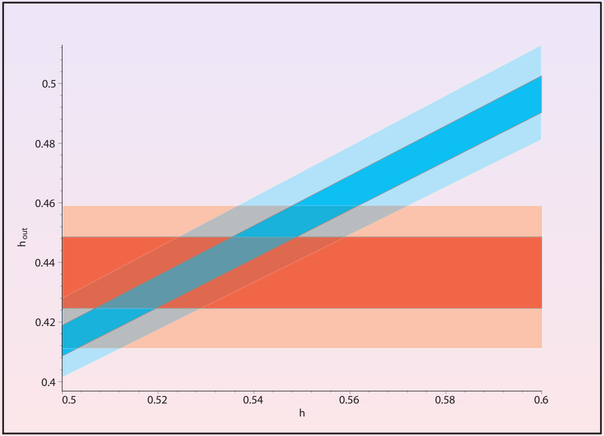

Figure: 1-σ and 2-σ Contour plots for h vs. h_{out}.

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- Caveat:
  - Constraints are derived *using* ΛCDM

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- Using $n_s \sim 0.73$ the constraint is:

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- Not consistent with Eisenstein et al., 2005:

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  - Fit CMB with higher h (Non-compensated Void?)

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- Zibin, Moss & Scott '08: it does not fit (*Gpc* Void) together with full CMB (which they fit with very low h and non-compensated Void)
- Garcia-Bellido & Haugboelle '08: it fits as well as ΛCDM (*Gpc* Void), but only first peak location and SN Union (no full CMB).

CMB Dipole

- How much Observer can be off-center?

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- Observer at Distance d_O
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- Higher multipoles go as higher powers of v_O: negligible[10].
- Bulk dipole of the same size of our dipole $600\mathrm{km/s}$ (Kashlinsky et al. '08: $600 - 1000\mathrm{km/s}$)

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- Goodman '95: $v/c \lesssim 0.01$ (at $z \sim 0.2$)
- Caldwell-Stebbins '07-'08: rule out Voids with $z_b > 0.9$

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- Exclude $L > 1.5 Gpc$, with $\Omega_{IN} = 0.23$.
- But Kashlinsky et al. measure high $\frac{v}{c} \sim 1000 km/sec$ on $300\,\mathrm{Mpc}/h$ (they *assume* kSZ, but do not see spectral distortions).

Other ways to test the Copernican principle

- Clarkson, Bassett and Lu '08: a consistency relation: $\mathcal{C}(z) = 0$ for FLRW, at *all* z,

$$\mathcal{C}(z) \equiv 1 + H^2(DD'' - D'^2) + HH'DD'$$

- Uzan, Clarkson and Ellis '08: Time drift of the redshift (over 10 years)

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- Also to be explored: non-sphericity of Void

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- Can we get this in our scenario?
  - Inside the Void
  - If there is curvature
  - If there are other big Voids in the sky $\Rightarrow$ nonlinear evolution of Φ
- Effect of order $(L/r_{\rm hor})^3 \sim \mathcal{O}(10^{-5})$

Assessment

- A Void of at least $L \sim 200 - 250$ Mpc/h scale consistent with WMAP and SNIa (Riess data), and local h
- δ quite large (~ 0.4)

  Incompatible with the expected value ($\delta \sim 0.04$).

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Void:

- Many observations to reconcile together
- Before considering it as a valid alternative to ΛCDM
- More work to be done (and more data will soon discriminate)

Can an Inhomogeneous Universe mimic Dark Energy?

Alessio Notari [12]

CERN

Dec. 2008 / Workshop @ KEK

[12] In collaboration with:
Rocky Kolb, Antonio Riotto, Sabino Matarrese, Tirthabir Biswas , Stephon Alexander, Deepak Vaid, Reza Mansouri