Inhomogeneous Cosmology, Swiss-Cheese, Voids: can it mimic Dark Energy?

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Motivations and Goals
- Evidence for Dark Energy
- Inhomogeneities?

Backreaction
- $2^{nd}$ order
- Higher orders

Light propagation

Exact models
- Constructing the models
- Geodesics
- Results

Local Void
- SNIa fit
- CMB fit

Conclusions
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To fit the observations we need a $p < 0$ term ("Dark Energy").

**Problem:** We do not understand

- the amount (why of the same amount as Matter today)?
- its nature (is it vacuum energy?)
Is there any alternative?

- Look for some interesting critical point of view and other logical possibilities
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- What happens to observations when we have departure from a *homogeneous* model?
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- What happens to observations when we have departure from a *homogeneous* model?

- Can we accommodate for this evidence if we relax (to some degree) homogeneity?
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- \textit{at late times} $\delta \equiv \frac{\delta \rho}{\rho} > 1$ for all scales $L \lesssim \mathcal{O}(10)/h\text{Mpc}$ (1% of Hubble radius)
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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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SDSS data
Three physical effects of inhomogeneities

In general:

- Backreaction
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- **Backreaction** perturbations affect the background
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In general:

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  - Perturbations affect the background (see S. Rasanen's talk)

- **Light propagation**
  - Light meets voids and structures. Do they compensate?

- **Large local fluctuation**
  - What if we live in a local void?
A few words on backreaction

Averaging of Einstein’s Equations (Buchert ’95)
Nonlinearity $\Rightarrow$ extra terms in Friedmann equations\(^2\)

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  \[
  \frac{\ddot{a}_D}{a_D} = -\frac{4\pi G}{3} \left(\rho_{\text{eff}} + 3P_{\text{eff}}\right),
  \]
  \[
  \left(\frac{\dot{a}_D}{a_D}\right)^2 = \frac{8\pi G}{3} \rho_{\text{eff}},
  \]

The extra terms

Where

\[ \rho_{\text{eff}} = \langle \rho \rangle_D - \frac{Q_D}{16\pi G} - \frac{\langle R \rangle_D}{16\pi G} \]

\[ P_{\text{eff}} = -\frac{Q_D}{16\pi G} + \frac{\langle R \rangle_D}{48\pi G}, \]
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- The real question: how large is it?
On a large Domain the dominant term has the form$^3$:

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

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$^3$L. Hui-U. Seljak ‘95, S. Rasanen’03, E. W. Kolb-S. Matarrese-A. N. -A. Riotto ’04...
Perturbatively: 2\textsuperscript{nd} order

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

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$$\frac{H_D - H}{H} \sim 10^{-5}$$

- Small,

---

3. L. Hui-U. Seljak '95, S. Rasanen'03, E. W. Kolb-S. Matarrese-A. N.-A. Riotto '04...
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Small, but not \( 10^{-10}! \) Enhanced by \((k_{EQ}/H_0)^2\)
Outline

1. Motivations and Goals
   - Evidence for Dark Energy
   - Inhomogeneities?

2. Backreaction
   - 2\textsuperscript{nd} order
   - Higher orders

3. Light propagation

4. Exact models
   - Constructing the models
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5. Local Void
   - SNIa fit
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Conclusions
What about higher ($n^{th}$) orders 4?
Power counting

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\(^4\) A. N. ’06
What about higher ($n^{th}$) orders? They go as

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We can write the $n^{th}$ order as

$$10^{-5} \epsilon^{n-1}$$

where roughly

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

with

$$\text{Int} = \int dq T^2(q) \approx 0.02$$
Higher orders

\[ \epsilon = \mathcal{O}(1) \text{ today} \]
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- Note: $\epsilon \ll 1$ at high $z$
Figure: Grey dashed line: central value, Red solid lines: $2\sigma$ ranges (We used the growth factor as in matter domination. For comparison, green dotted line: $\Omega_M = 1$).
Photons in inhomogeneous metric

- Even in absence of average effect on $H(z)$
Photons in inhomogeneous metric

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- Cannot disentangle this from backreaction
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- Compute $\frac{\Delta z}{1+z}$ and $\frac{\Delta D}{D}$ in the presence of structures
Consider Lemaître-Tolman-Bondi exact solutions of E.E. (with \( p = 0 \)) which is
LTB exact solutions

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- LTB spheres embedded in FLRW ("Swiss-Cheese")
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- LTB with shells of periodically varying density ("Onion")
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- We study null geodesics in this metric
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LTB metrics

\[ ds^2 = -dt^2 + \frac{R'^2(r, t)}{1 + 2r^2k(r)} dr^2 + R^2(r, t)(d\theta^2 + \sin^2 \theta d\phi^2) \]
LTB metrics

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

It has the solutions:

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

\[ R = \frac{GM(r)}{2r^2 |k(r)|} [\cos h(u) - 1], \quad (4.1) \]

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

- \( k(r) = 0 \),

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

- There are 3 free functions of $r$
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- The idea is to describe structure formation (start with $\delta(r, t_I) \ll 1$ and end up with $\delta(r, t_{\text{now}}) \gg 1$)
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- The idea is to describe structure formation (start with $\delta(r, t_I) \ll 1$ and end up with $\delta(r, t_{\text{now}}) \gg 1$)
- We play with $k(r)$ to describe $\delta(r, t_I)$. 
Onion profile

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

$$k'(0) = k'(L) = 0,$$

$$k(L) = \frac{4\pi}{3} \Omega_k, \quad \text{for } |\Omega_k| \ll 1,$$
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We use:

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k(r) = k_{\max} \left[ \left( \frac{r}{L} \right)^4 - 1 \right]^2 \quad \text{(for } r < L)\]

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k(r) = 0 \text{ (flat)} \quad \text{(for } r > L)\]
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Two parameters, size $L$ and amplitude $k_{\text{max}}$. 
The hole in the cheese
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Redshift

\[ \text{Solve } ds^2 = 0 \Rightarrow \text{get } t(r) \]
Redshift

- Solve $ds^2 = 0 \Rightarrow \text{get } t(r)$

- Then solve for

$$\frac{dz(r)}{dr} = \frac{(1 + z(r))\dot{R}'(r, t(r))}{\sqrt{1 + 2r^2k(r)}}.$$
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- (Numerically also non-radial trajectories)
Luminosity (Angular) Distance

Always in GR, luminosity distance and angular distance:

\[ D_L = D_A(1 + z)^2. \]
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\[ D_A^2 \equiv \frac{dA}{d\Omega} = \frac{d\theta_S d\phi_S \sqrt{g_{\theta\theta} g_{\phi\phi}}}{d\theta_O d\phi_O} \]
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- If observer in the center:
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- For generic observer (but radial trajectory):
  \[
  D_A = R_S \left( R_O \int_{r_O}^{r_S} \frac{R'(r, t(r))}{(1 + 2E(r))(1 + z(r)) R(r, t(r))^2} \, dr \right),
  \]
Outline

1. Motivations and Goals
   - Evidence for Dark Energy
   - Inhomogeneities?

2. Backreaction
   - 2\textsuperscript{nd} order
   - Higher orders

3. Light propagation

4. Exact models
   - Constructing the models
   - Geodesics
   - Results

5. Local Void
   - SNIa fit
   - CMB fit

Conclusions
Redshift

Net effect from one hole:\[ \frac{\Delta z}{1+z} \approx \left(\frac{L}{r_H}\right)^3 f(\delta) \]
Redshift

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- At 2\(^{nd}\) order usual Rees-Sciama effect \( (L/r_H)^3 \delta^2 \)

\(^5\) T. Biswas-A. N. '06-'07
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- But it should have zero angular average (unlike $z$) \(^7\)

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A local fluctuation?

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- Can this mimick acceleration $^8$?

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- Recent interest in proving the Copernican principle \(^9\)
- How much contrast \( \delta \) and how large \( L \) is needed?

---

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Qualitatively

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- This can mimic acceleration (as we will see...)

Qualitatively
About Voids

Before going to the analysis...
About Voids

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Let’s review some literature and observations on Voids
Inoue and Silk '06: some features of the low multipole anomalies in the CMB data could be explained by a pair of huge Voids ($L \sim 200 \text{ Mpc}/h$, $\delta \sim -0.3$)
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The CMB has a Cold Spot \( (\text{M. Cruz et al. ('06 and '07)}) \): it could be explained by another similar Big Void \( (\text{Inoue and Silk '06}) \)
Other uses of Voids

- Inoue and Silk '06: some features of the low multipole anomalies in the CMB data could be explained by a pair of huge Voids ($L \sim 200 \, \text{Mpc}/h, \delta \sim -0.3$)

- The CMB has a Cold Spot (M. Cruz et al. ('06 and '07)): it could be explained by another similar Big Void (Inoue and Silk '06)

- The Cold Spot in the CMB claimed to be correlated with an underdense region in the LSS (Rudnick, Brown and Williams '07)
Observational Status

- Some observational evidence for a local large underdense region ($\sim 25\%$ less dense, $r \sim 200 \text{ Mpc}/h$) from number counts of galaxies (Frith et al. Mon. Not. Roy. Astron. Soc. 345, 1049 (2003))

- It would represent a $4\sigma$ fluctuation, at odds with $\Lambda$CDM.
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Einasto (arXiv:astro-ph/0609686): claims discrepancy (by a factor of 5) between observed abundance of superclusters and N-body simulations
Our “Minimal” Void

What is the size we need to mimic Acceleration for CMB+SNIa observations?
Our “Minimal” Void

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- It turns out that a Minimal Void needs roughly the same size *(for SNIa and WMAP)*
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Problem: the typical contrast on this scale is: $\sqrt{\langle \delta^2 \rangle} \sim 0.03 - 0.05$, using linear and Gaussian spectrum
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- Can one ever get these Voids?
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Can one ever get these Voids?
  - Percolation of Voids?
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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 \(0.4 \lesssim z \lesssim 1\))
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Evidence for acceleration comes from a mismatch between:

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SDSS-II taking data at intermediate redshift

We choose large $r_{\text{Void}}$ (at $z \approx 0.07$)
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- Rapid transition between $h$ and $h_{\text{out}}$
\( \Delta m \) for different models

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

\[
\Delta m = 0.085; \quad \delta_{\text{CENTRE}} = -0.48
\]

\[
\text{Magnitude is } m \equiv 5 \log_{10} D(z)
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$m - z$ diagram

$z_{\text{jump}} = 0.085; \ \delta_{\text{CENTRE}} = -0.48$
Figure: Riess et al. dataset, astro-ph/0611576, 182 datapoints. We show $1\sigma$, $2\sigma$, $3\sigma$ and $4\sigma$ intervals (using likelihood $\propto e^{-\chi^2/2}$).
Fitting SNIa with a Jump

Figure: The red dashed lines are 10% and 1% goodness-of-fit (182 data points)
Table: Comparison with data (full data set of Riess et al.)

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2$ (181 d.o.f.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$CDM (with $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.73$)</td>
<td>150</td>
</tr>
<tr>
<td>EdS (with $\Omega_M = 1$, $\Omega_{\Lambda} = 0$)</td>
<td>274</td>
</tr>
<tr>
<td>Void ($\sqrt{\langle \delta^2 \rangle} \approx 0.4$ on $L = 250/h\text{Mpc}$)</td>
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</table>

Two remarks:

- If one includes only instrumental error: no smooth curve can give a good fit
- Estimated error from intrinsic variability added in quadrature
Inhomogeneous Universe and Dark Energy

Motivations and Goals
- Evidence for Dark Energy
- Inhomogeneities?

Backreaction
- $2^{nd}$ order
- Higher orders

Light propagation

Exact models
- Constructing the models
- Geodesics
- Results

Local Void
- SNIa fit
- CMB fit

Conclusions
The $\Lambda$CDM fit

Fit of the WMAP (3-yr) data
The $\Lambda$CDM fit

- Fit of the WMAP (3-yr) data
- We looked at TT and TE correlations, using COSMOMC
In principle: we should compute propagation in EdS from $z = 1100$ to $z \sim 0.1$, and then in the Bubble
How do we fit?

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- Ignore possible “secondary” effects in the Bubble:
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  - $n_s$ plus running $\alpha_s$
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Fit to WMAP3

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Conclusions
Goodness-of-fit

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2_{\text{eff}}$</th>
<th>G.F.</th>
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<th>$\chi^2_{\text{eff}}$</th>
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</thead>
<tbody>
<tr>
<td>Concordant $\Lambda$CDM</td>
<td>1038.9</td>
<td>4.7%</td>
<td>1455.2</td>
<td>11.3%</td>
<td>3538.6</td>
<td>41%</td>
</tr>
<tr>
<td>EdS $\alpha_s = 0$</td>
<td>1124.6</td>
<td>0%</td>
<td>1711.9</td>
<td>0%</td>
<td>3652.3</td>
<td>6%</td>
</tr>
<tr>
<td>EdS $\alpha_s \neq 0$</td>
<td>1057.8</td>
<td>1.9%</td>
<td>1475.5</td>
<td>5.7%</td>
<td>3577.4</td>
<td>24.6%</td>
</tr>
<tr>
<td>EdS $\alpha_s, \Omega_k \neq 0$</td>
<td>1048.7</td>
<td>2.9%</td>
<td>1466</td>
<td>7.9%</td>
<td>3560.9</td>
<td>31.1%</td>
</tr>
</tbody>
</table>

Table:

1\textsuperscript{st} column: high-$l$ TT ($31 \leq l \leq 1000$)

2\textsuperscript{nd} column: high-$l$ TT ($31 \leq l \leq 1000$) and TE ($24 \leq l \leq 450$)

3\textsuperscript{rd} column: total of TT ($2 \leq l \leq 1000$) and TE ($2 \leq l \leq 450$)
The EdS model, with running, has:

- low $h_{\text{OUT}}$ (about $\sim 0.45$)$^{10}$

---

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- larger value of $\Omega_M/\Omega_b$ (around 10 instead of 6)

- $\Omega_b h^2_{\text{out}}$ ($\sim 0.018^{+0.001}_{-0.002}$) consistent with BBN constraint
  (which is $0.017 \leq \Omega_b h^2_{\text{out}} \leq 0.024$, at 95% C.L.)

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Is this compatible with local $h$?

A crucial point: we have

- a low $h_{\text{out}}$
- a constraint on $\mathcal{J} = h/h_{\text{out}}$
Is this compatible with local $h$?

- A crucial point: we have
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- A crucial point: we have
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  - a constraint on $J = h/h_{\text{out}}$

- We get a constraint on $h$. Compatible with local observations?
  - $h = 0.72 \pm 0.08$ 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.)
  - $h = 0.54_{-0.03}^{+0.04}$ SZ effect ($z \approx 1$) (E. D. Reese et al., Astrophys. J. 581, 53 (2002))
Figure: 1-σ and 2-σ Contour plots for $h$ vs. $h_{out}$. 

Parameter Contours
Baryon Acoustic Oscillations

- Measurement of baryon acoustic peak in the galaxy distribution (Eisenstein et al., 2005).

- The position of the peak measures the ratio of the sound horizon at recombination \( \text{vs.} \) angular distance at \( z = 0.35 \).
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  - One should re-do the analysis with the running, as well.
Baryon Acoustic Oscillations

- If we use the numbers at face value:

---

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If we use the numbers at face value:

Using $n_s \sim 0.73$ the constraint is:

$$\Omega_m h^2_{\text{out}} = 0.185 \pm 0.011,$$

It agrees with our value $(0.205 \pm 0.01)$ within $2\sigma$.

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On the other hand:

$D_A(0.35) = 1375\text{ Mpc}$ for $\Lambda CDM$

$D_A(0.35) = 1800\text{ Mpc}$ for EdS with $h_{\text{out}} \sim 0.45$.

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- Not consistent with\textsuperscript{11} Eisenstein et al., 2005:

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Problem with BAO

- The problem is the **low value of $h_{\text{out}}$ from CMB**!

- $h_{\text{out}} \sim 0.56$ would work...

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- What about evolution of BAO scale inside large voids?

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CMB Dipole

- How much Observer can be off-center?
- Observer at Distance $d_O$ from center
  \[ \frac{\delta T}{T} \sim v_O \sim \dot{d}_O \]
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Local Void scenario

- It mimics Acceleration with at least $L \sim 200 - 250 \text{ Mpc}/h$
- $\delta$ quite large ($\sim 0.4$)
  - Disagrees with expected value ($\delta \sim 0.04$).
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Observer has to sit near the center (10% precision in radial position)
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- Check directly in galaxy Surveys data if this could be compatible
- Check if the higher $\Omega_m/\Omega_b$ is compatible with other data
Inhomogeneous Cosmology, Swiss-Cheese, Voids: can it mimic Dark Energy?

Alessio Notari

CERN

Apr. 2008, PONT d’Avignon

14 In collaboration with: Tirthabir Biswas, Stephon Alexander, Deepak Vaid (Penn State U.), Reza Mansouri (Sharif U., Iran)
The density

- Roughly:

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

where \( \langle \rho \rangle(t) \equiv \frac{M_p^2}{6\pi t^2} \), and \( \epsilon(r) \equiv 3k(r) + rk'(r) \).
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\[ \epsilon \ll 1 \text{ linear growth} \]
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\( \epsilon \) not small: \( \delta \) grows rapidly (as in Zel’dovich approx)
### Parameter values

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<thead>
<tr>
<th>Model</th>
<th>$\Lambda$CDM</th>
<th>EdS, $\alpha_S = 0$</th>
<th>Eds, $\alpha_S \neq 0$</th>
<th>Eds, $\alpha_S$, $\Omega_k \neq 0$</th>
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<tr>
<td>$\Omega_b h^2_{\text{out}}$</td>
<td>0.022$^{+0.002}_{-0.002}$</td>
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<td>0.018$^{+0.001}_{-0.002}$</td>
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<tr>
<td>$\Omega_m h^2_{\text{out}}$</td>
<td>0.106$^{+0.021}_{-0.013}$</td>
<td>0.198$^{+0.008}_{-0.011}$</td>
<td>0.186$^{+0.011}_{-0.009}$</td>
<td>0.167$^{+0.009}_{-0.007}$</td>
</tr>
<tr>
<td>$\Omega_{\Lambda}$</td>
<td>0.759$^{+0.041}_{-0.103}$</td>
<td>0.0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>$z_{\text{re}}$</td>
<td>11.734$^{+4.993}_{-7.619}$</td>
<td>8.697$^{+4.351}_{-6.694}$</td>
<td>13.754$^{+2.246}_{-5.752}$</td>
<td>13.342$^{+2.55}_{-5.011}$</td>
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<td>$\Omega_k$</td>
<td>0</td>
<td>0</td>
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<td>$-0.05$</td>
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<td>$n_S$</td>
<td>0.96$^{+0.04}_{-0.04}$</td>
<td>0.94$^{+0.021}_{-0.038}$</td>
<td>0.732$^{+0.07}_{-0.071}$</td>
<td>0.761$^{+0.069}_{-0.069}$</td>
</tr>
<tr>
<td>$\alpha_S$</td>
<td>0</td>
<td>0</td>
<td>$-0.161^{+0.044}_{-0.044}$</td>
<td>$-0.13^{+0.037}_{-0.048}$</td>
</tr>
<tr>
<td>$10^{10}A_S$</td>
<td>20.841$^{+3.116}_{-3.442}$</td>
<td>25.459$^{+2.135}_{-2.766}$</td>
<td>25.302$^{+2.182}_{-2.968}$</td>
<td>23.975$^{+2.198}_{-2.448}$</td>
</tr>
<tr>
<td>$\Omega_m/\Omega_b$</td>
<td>4.73$^{+0.999}_{-0.485}$</td>
<td>9.119$^{+0.341}_{-0.357}$</td>
<td>10.094$^{+0.645}_{-0.489}$</td>
<td>8.929$^{+0.512}_{-0.541}$</td>
</tr>
<tr>
<td>$h_{\text{out}}$</td>
<td>.72857$^{+0.05137}_{-0.07393}$</td>
<td>.46857$^{+0.00888}_{-0.01307}$</td>
<td>.4523$^{+0.01291}_{-0.01129}$</td>
<td>.42069$^{+0.01107}_{-0.00919}$</td>
</tr>
<tr>
<td>Age/GYr</td>
<td>13.733$^{+0.389}_{-0.369}$</td>
<td>13.908$^{+0.399}_{-0.258}$</td>
<td>14.408$^{+0.369}_{-0.4}$</td>
<td>15.338$^{+0.342}_{-0.393}$</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.77$^{+0.121}_{-0.109}$</td>
<td>1.012$^{+0.056}_{-0.081}$</td>
<td>0.919$^{+0.07}_{-0.075}$</td>
<td>0.862$^{+0.06}_{-0.063}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.095$^{+0.072}_{-0.074}$</td>
<td>0.047$^{+0.037}_{-0.041}$</td>
<td>0.079$^{+0.023}_{-0.044}$</td>
<td>0.081$^{+0.024}_{-0.041}$</td>
</tr>
</tbody>
</table>

**Table:** Most likely parameter values with 1 $\sigma$ errors for the various COSMOMC Runs
Parameter likelihood

Figure: likelihoods to WMAP 3-yr for the run “EdS with $\alpha_s$”
Parameter likelihood

Figure: Contour likelihood plots to WMAP 3-yr for the run “EdS with $\alpha_s$”
Inhomogeneous Universe and Dark Energy

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Table: The "acceptable-fit" has G.O.F. of about 10% for SN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$L$</th>
<th>$\Omega_b h^2_{\text{out}}$</th>
<th>$\Omega_m h^2_{\text{out}}$</th>
<th>$z_{re}$</th>
<th>$\sigma_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best-fit</td>
<td>250$/h$</td>
<td>0.018$^{+0.002}_{-0.002}$</td>
<td>0.19$^{+0.01}_{-0.01}$</td>
<td>13.8$^{+2.2}_{-5.8}$</td>
<td>0.92$^{+0.07}_{-0.08}$</td>
</tr>
<tr>
<td>Acceptable-fit</td>
<td>160$/h$</td>
<td>0.02</td>
<td>0.2</td>
<td>13.8</td>
<td>0.92</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$n_s$</th>
<th>$\alpha_s$</th>
<th>$\delta_0$</th>
<th>$h_{\text{out}}$</th>
<th>$h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best-fit</td>
<td>0.73$^{+0.07}_{-0.07}$</td>
<td>$-0.16^{+0.05}_{-0.04}$</td>
<td>0.51$^{+0.03}_{-0.04}$</td>
<td>0.452$^{+0.013}_{-0.011}$</td>
<td>0.55$^{+0.024}_{-0.023}$</td>
</tr>
<tr>
<td>Acceptable-fit</td>
<td>0.73</td>
<td>$-0.16$</td>
<td>0.44</td>
<td>0.47</td>
<td>0.55</td>
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$h$ in the Bump model

Figure: 1-\(\sigma\) and 2-\(\sigma\) Contour plots for $h$ vs. $h_{out}$. 
off-center location: dipole
off-center location: dipole and integrated effect (low-$l$)
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photons going through similar Voids $O(r_{\text{Void}}/r_{\text{Hor}})^3$: similar to ISW effect?
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Similarly the expansion is anisotropic if $d_O$ nonzero$^{15}$.

\[\text{\footnotesize\textsuperscript{15} Tomita (2000), Alnes et al. ('06)}\]
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Also to be explored: non-sphericity of Void

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ISW

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To be studied in detail...