Can an Inhomogeneous Universe mimic Dark Energy?

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[1] In collaboration with:
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Outline

The need for Dark Energy

- In Standard Cosmology we use the FLRW model.
- We compute D_L (or D_A) and z
- We use this to interpret several observations (SNIa, Hubble constant, CMB, Baryon Acoustic Oscillations, Matter Power Spectrum...)
- To fit the observations we need a $p < 0$ term (“Dark Energy”).

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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?)

Main pieces of evidence

- SNIa is incompatible with deceleration (independently on other observations)
  - Assuming them as standard candles.
  - Assuming them *not exactly* as standard candles

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

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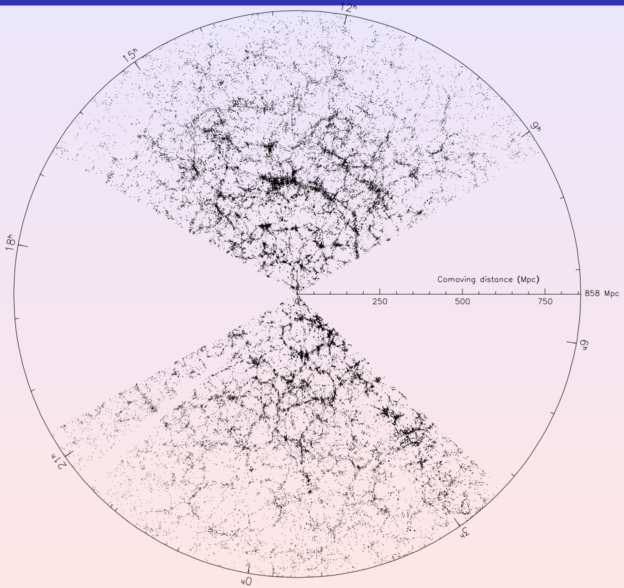
- Especially: can we rule out any other explanation, even if radical, based on observations?
- What happens to observations when we have departure from a *homogeneous* model?
- An opportunity to observationally test the Copernican principle

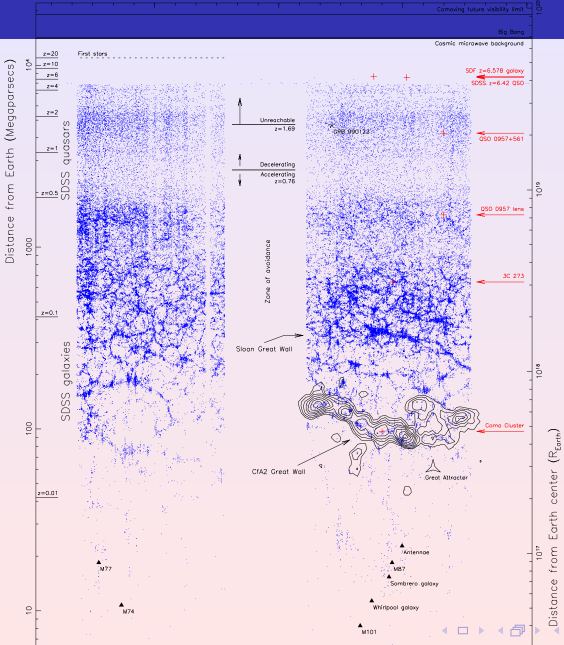
Homogenous Universe: a good approximation?

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

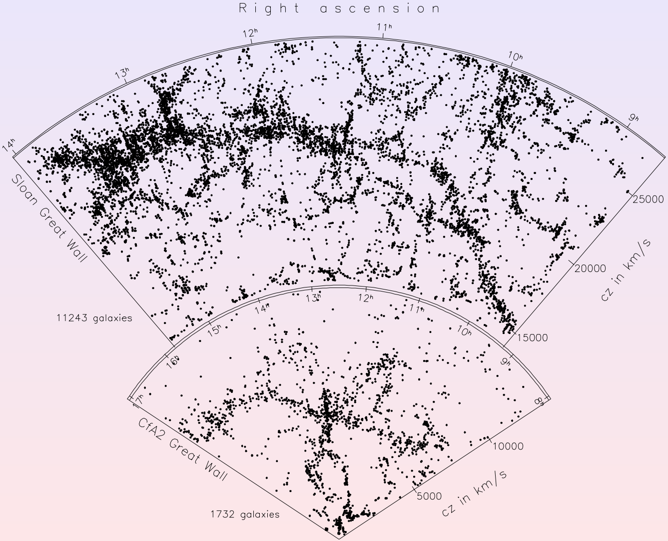
SDSS data ("The cosmic web")



SDSS data


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
10^4
1000
100
10
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
M77
M74
Antennae
M87
Sombrero galaxy
Whirlpool galaxy
M101
10^{20}
10^{19}
10^{18}
10^{17}
Distance from Earth center (R_{Earth})

SDSS data


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

Scale of Homogenity

Scale of convergence in SDSS data?

- $70\mathrm{Mpc}/h$: P.Sarkar et al 2009; J.Yadav et al. 2005; Hogg et al. 2005
- *No convergence*: Sylos Labini et al. 2007 & 2009

Three physical effects of inhomogeneities

In general:

- Backreaction

  perturbations affect the background

- Light propagation

  Light travels through voids and structures. Do they compensate?

- Large local fluctuation

  What if we live in a local void?

A local fluctuation?

- Suppose that we live in a peculiar local region
- $\Rightarrow$ low z observations may be very different from average.
- Acceleration is inferred comparing low z with high z...
- Can this mimic acceleration [3]?

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[3] Tomita '98, Tomita '00, Celerier '01, Wiltshire '05, Moffat '05, Alnes et al. '05, Mansouri et al. '06, Biswas & A.N.'07, Garcia-Bellido and Haugboelle '08, Zibin et al. '08 ...

Qualitatively

- Consider a “compensated Void” : a spherical Void plus an external shell of matter (on average same density as “external” FLRW)
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- How much contrast δ and how large L is needed?

About Voids

- Before going to the quantitative analysis...
- Let us review some literature and observations on Voids

Large 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 ($L \sim 200$ 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 Large Void (Inoue and Silk ’06)
- The Cold Spot in the CMB claimed to be correlated with an underdense region in the LSS, Radio sources (Rudnick, Brown and Williams ’07, but see Smith & Huterer ’08 ...)
- It could be detected via lensing (S. Das and D. Spergel ’08, I.Masina and A.N ’08-’09) and via non-gaussian coupling Rees-Sciama effect - lensing (I.Masina and A.N ’09)

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. '03)
- It would represent a 4σ fluctuation, at odds with ΛCDM.

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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)

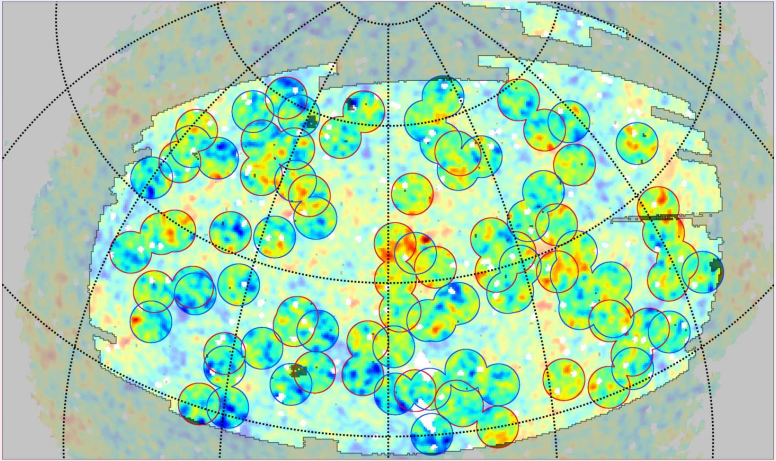

Figure: Granett, Neyrinck & Szapudi ’08

Large bulk motion?

- Recent measurement (Kashlinsky et al.'08): very large coherent motion on $300\mathrm{Mpc}/h$ scale, inconsistent with ΛCDM
- Could be due to very large scale inhomogeneous matter distribution
- Watkins, Feldman & Hudson '08: use peculiar velocities of various (4500) objects in a $100\ \mathrm{Mpc}/h$ radius. Find $400\ \mathrm{km}/\mathrm{sec}$ (expected $100\ \mathrm{km}/\mathrm{sec}$)

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- $r_{\mathrm{Void}} \sim 200 - 250$ Mpc$/h$ and $\delta \sim -0.4$

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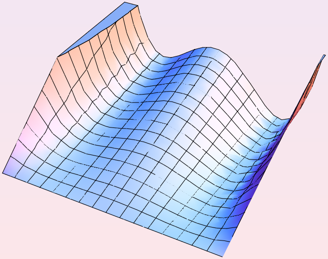
  On this scale the typical contrast is:
  $\delta \sim 0.03 - 0.05$, using *linear* and *Gaussian* spectrum
- A *Gpc* Void seems required to fit all observations

Which primordial origin?

- Can we get huge Voids?
  - Percolation of Voids?
  - Non-gaussianity (for example of primordial spherical shape)?
  - Nucleation of primordial Bubbles (first order phase transition during inflation)



- Main tuning: why observer at centre?

LTB exact solutions

- Consider Lemaître-Tolman-Bondi exact solutions of E.E. (with $p = 0$) which is
  - inhomogeneous
  - nonlinear
  - Spherically symmetric
- LTB sphere embedded in FLRW ("Swiss-Cheese")
- We study null geodesic in this metric

Earlier literature

- Mustapha, Hellaby, Ellis '97: show that LTB can reproduce *any* $D_L - z$ curve
- Celerier '99: showed that LTB can mimic ΛCDM
- Tomita '01: Compensated Void $200 - 300\,\mathrm{Mpc}/h$ scale

Outline

1. Motivations
2. LTB metrics
    - Building the model
    - Results
3. Local Void: Fitting the data
    - SNIa Hubble diagram
    - WMAP
    - BAO
    - Large-Scale structure(LRG)
    - Gpc Void
    - Other observations
4. The Cold Spot
    - Redshift (low-ℓ)
    - Lensing (high-ℓ)

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.

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

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

- $k(r) = 0$,

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

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- $k = 0$ flat FLRW, $k = \pm 1$ open/closed FLRW.
- The idea is to describe structure formation (start with $\delta(r, t_I) \ll 1$ and end up with $\delta(r, t_{\rm now}) \gg 1$)
- 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:

$$\begin{aligned} k'(0) &= k'(L) = 0\,, \\ k(L) &= \frac{4\pi\Omega_k}{3(1-\Omega_k)} \end{aligned}$$

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We use:

-

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

$$k(r) = 0 \text{ (flat)} \qquad (\text{for } r > L)$$

- Two parameters, L and k_{max}.

The density

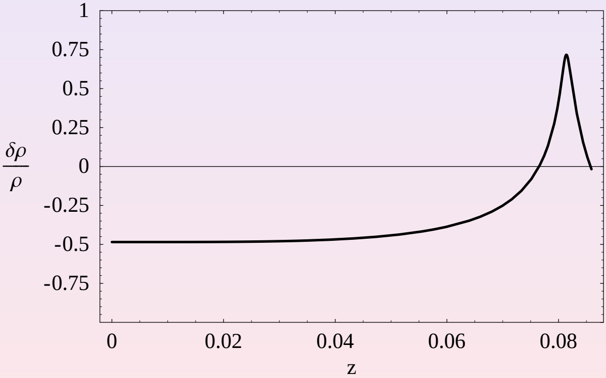
- Roughly:

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

$$\text{where } \langle\rho\rangle(t) \equiv \frac{M_p^2}{6\pi t^2}\,, \qquad \text{and } \epsilon(r) \equiv 3k(r) + rk'(r)\,.$$

- $\epsilon \ll 1$ linear growth
- ϵ not small: δ grows rapidly (as in Zel'dovich approx)
- We work at most with $\delta \sim \mathcal{O}(1)$.

The density profile



Redshift

- Solve for $t(r)$ along a $ds^2 = 0$ trajectory
- Then solve for $z(r)$

$$\frac{dz}{dr} = \frac{(1+z(r))\dot{R}'(r,t(r))}{\sqrt{1+2r^2k(r)}} .$$

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- The result $z(r)$ can be found numerically
- We also have some very good analytical approximations

Luminosity (Angular) Distance

- Always in GR, luminosity distance and angular distance:

$$D_L = D_A(1+z)^2 \,.$$

- $$D_A^2 \equiv \frac{dA}{d\Omega} = \frac{d\theta_S d\phi_S \sqrt{g_{\theta\theta} g_{\phi\phi}}}{d\bar{\theta}_O d\bar{\phi}_O} R^2|_S \,,$$

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- If observer in the center:

$$D_A^2 = R^2|_S \, .$$

- 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

$$f \equiv \frac{\sqrt[3]{2}(\cosh(u)-1)}{3^{2/3}(\sinh(u)-u)^{2/3}} - 1 \tag{2.2}$$

$$u_0 = 6^{1/3}(\sinh(u)-u)^{1/3}\,. \tag{2.3}$$

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

$$\tau(r) = \tau_0 - \frac{\pi}{9}\gamma^2\bar{M}r[1+f(\gamma^2\tau_0^2k(r))]\,, \tag{2.4}$$

$$1+z(r) = \left(\frac{\tau_0}{\tau(r)}\right)^2 \exp\left[\frac{4\pi\gamma^2\bar{M}r}{9}f(\gamma^2\tau_0^2k(r))\right] \tag{2.5}$$

$$D_L(r) = \frac{\pi}{3}\gamma^2 r\tau(r)^2[1+f(\gamma^2\tau_0^2k(r))][1+z(r)]^2 \tag{2.6}$$

$$\tau_0 = \left(\frac{2\bar{M}}{3H_0}\right)^{1/3} \tag{2.7}$$

$$\gamma = \left(\frac{9\sqrt{2}}{\pi}\right)^{1/3} \tag{2.8}$$

Outline

Observer outside: z

- Net effect from one hole[4] : $\frac{\Delta z}{1+z} \approx (L/r_H)^3 f(\delta)$
- At 2nd order usual Rees-Sciama effect $(L/r_H)^3\delta^2$
- $f(\delta)$ does *not* compensate the suppression for $\delta \gg 1$
- Tight packing: $N_{\text{holes}} \times \mathcal{O}(L/r_H)^3 \sim \mathcal{O}(L/r_H)^2$
- Still small (for late acceleration)
- Interesting in the CMB, as a Rees-Sciama effect.

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

Observer outside: Distance

- Net effect scales as $\frac{\Delta z}{1+z} \approx (L/r_H)^2 f(\delta)$ [5]
- $f(\delta)$ does *not* compensate the suppression for $\delta \gg 1$
- Tight packing: $N_{\text{holes}} \mathcal{O}(L/r_H)^3 = \mathcal{O}(L/r_H)$
- Not so small...
- But it should have zero angular average (unlike z)[6]

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[5] Brouzakis-Tetradis-Tzavara '06, Kolb-Matarrese-Riotto '07, T. Biswas-A. N. '07

[6] S. Weinberg '76, Brouzakis et al. '06-'07

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- Reliable result or limited by the symmetries of the model?
- LTB model swiss-cheese: special case
- The cheese feels *no backreaction* by construction
- What happens without spherical symmetry?
- Szekeres swiss-cheese model with asymmetric holes (Bolejko '08)
- But still special: the cheese feels *no backreaction* of the holes

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 $0.4 \lesssim z \lesssim 1$)
- We choose large $r_{\texttt{Void}}$
- $\Rightarrow$ The Local Bubble is different from the average.

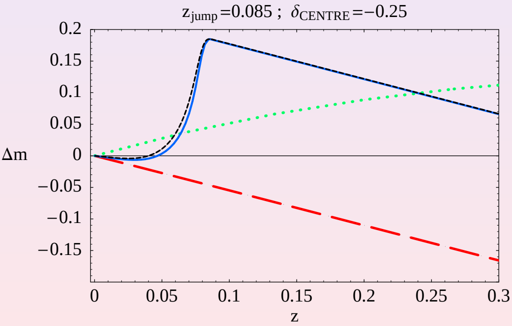
Outside just FLRW curve (plus small corrections $\mathcal{O}(\frac{L}{rhor})^2$)

Roughly

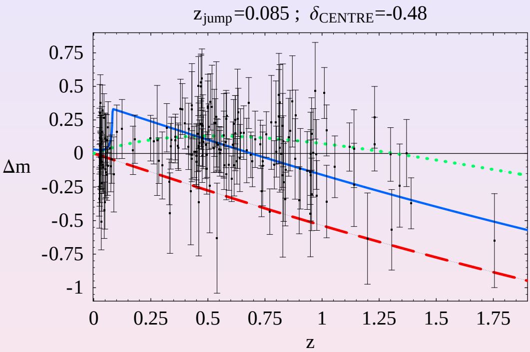
- At high z ($z \gtrsim 0.1$), just FLRW
- At low z "open-like" Universe with a different H
- Two Hubble parameters: h and h_{out}
- Rapid transition near the shell-like structure

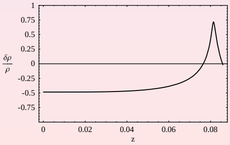
Δm for different models

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



$m - z$ diagram: Riess data





Finding the best fit

- We fix several values of L
- What matters is just the Jump: $\mathcal{J} \equiv \frac{h}{h_{OUT}}$
- This is also related to the central density contrast: $\mathcal{J} = 2 - (1 - \delta_0)^{1/3}$
- We vary $\mathcal{J}$ and compute the χ^2.

Fitting SNIa with a Jump

- Outside $\Omega_M = 1$

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

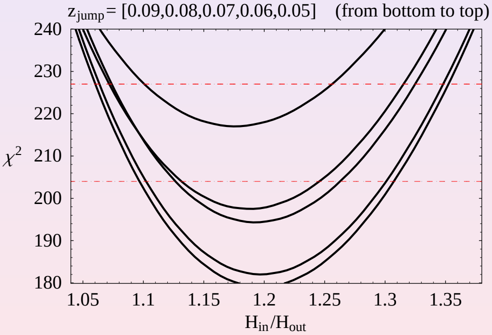


Figure: Red dashed lines: 10% and 1% goodness-of-fit (182 data points)

LTB Void fit

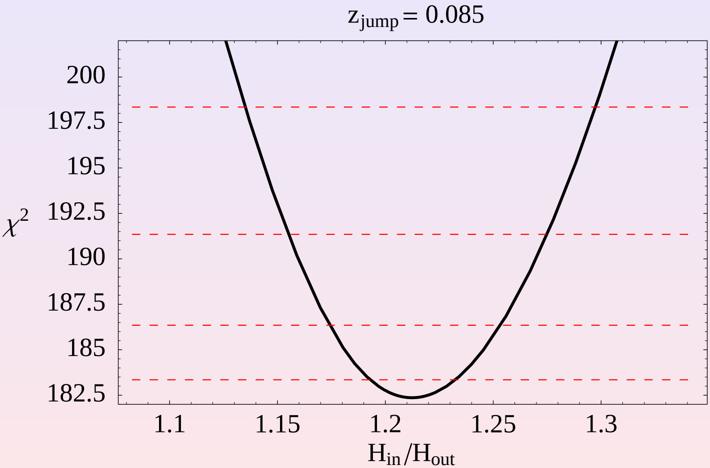


Figure: Full LTB model. We show 1σ, 2σ, 3σ and 4σ intervals (using likelihood $\propto e^{-\chi^2/2}$).

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

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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*
- SDSS-II will improve a lot: $\Delta\chi^2 \sim 60$

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The WMAP data

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- “Secondary” effect in the Bubble:
  - Small offset to D_A and T_0 of $\mathcal{O}(r_{\texttt{Void}}/r_{\texttt{Hor}})^2$
  - Relevant only for *Gpc* Void
  - Small because of compensation

We ignore:

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- We look 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
- "Secondary" effect in the Bubble:
  - Small offset to D_A and T_0 of $\mathcal{O}(r_{\mathtt{Void}}/r_{\mathtt{Hor}})^2$
  - Relevant only for *Gpc* Void
  - Small because of compensation

We ignore:

- Off-center location: dipole
- Non-sphericity (again effect on low-l)

Priors (ΛCDM)

The usual prior set is:

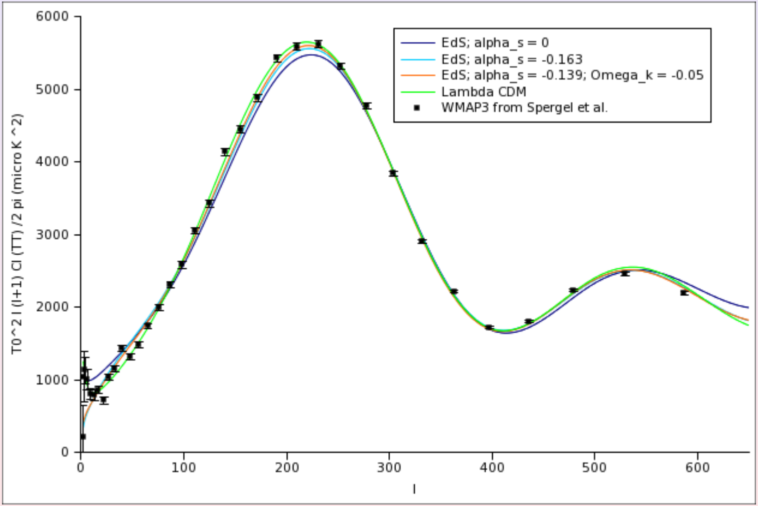
- Allow for nonzero Ω_Λ.
- Power-law spectrum with index n_s and running α_s.
- $P(k) \propto k^{n_s(k_0)+\frac{1}{2}ln(k/k_0)\alpha_s}$

Priors: without Λ

A different prior set, that we use:

- Not allow for Ω_Λ.
- Power-law spectrum with index n_s and running α_s..
- $P(k) \propto k^{n_s(k_0)+\frac{1}{2}ln(k/k_0)\alpha_s}$
- (we also allow for some curvature)

Fit to WMAP3


6000
5000
4000
3000
2000
1000
0
T0^2 l (l+1) Cl (TT) /2 pi (micro K ^2)
0
100
200
300
400
500
600
l
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

Table: Fit of WMAP

	Total	
Model	χ^2_{eff}	G.F.
Concordant ΛCDM	3538.6	41%
EdS $\alpha_s \neq 0$	3577.4	24.6%
EdS $\alpha_s, \ \Omega_k \neq 0$	3560.9	31.1%

Result for parameters

The EdS model, with running, has:

- low h_{OUT} (about ~ 0.45)
  It has to be consistent with the SNIa analysis and the local measurements of h
- low n_S (about ~ 0.73)
  and large negative α_S (about ~ -0.16)
- 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 likelihood

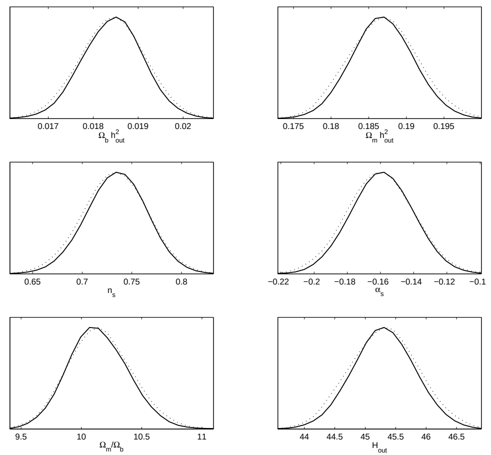


Figure: likelihoods to WMAP 3-yr for the run “EdS with α_s”

Parameter likelihood

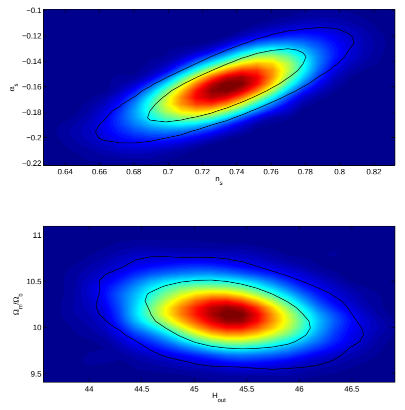


Figure: Contour likelihood plots to WMAP 3-yr for the run “EdS with α_s”

Low H_0

- low $h_{\rm OUT}$ (~ 0.45)[7]
- We get a constraint on local h (~ 0.55)

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[7] As in A. Blanchard et al.'03 and P. Hunt & S. Sarkar '07

Low H_0

- low h_{OUT} (~ 0.45)[7]
- We get a constraint on local h (~ 0.55)

Compatible with local observations?

- $h = 0.72 \pm 0.08$ from HST (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 ($z \approx 1$) (Reese *et al.* Ap. J. **581**, 53 (2002))
- $h = 0.48^{+.03}_{-.03}$ from lensing ($0.3 \lesssim z \lesssim 0.7$) (C. S. Kochanek and P. L. Schechter, arXiv:astro-ph/0306040.)

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[7] As in A. Blanchard et al.'03 and P. Hunt & S. Sarkar '07

Parameter Contours

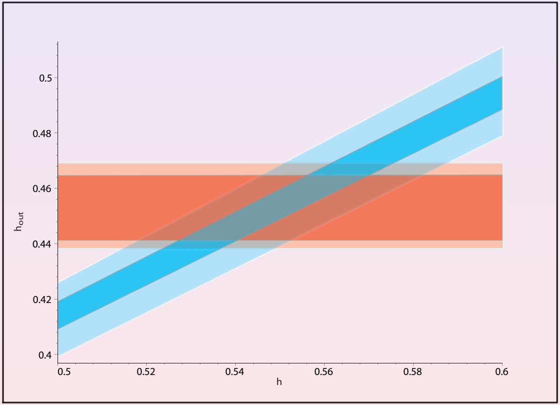

Figure: 1-σ and 2-σ Contour plots for h vs. h_{out}.

Summarizing the constraints

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

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

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

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

Outline

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 **vs.** angular distance at $z = 0.35$

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- 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 **vs.** angular distance at $z = 0.35$
- It constrains two quantities: $\Omega_m h^2$ and $D_A(0.35)$
- But it also depends on the spectral index n_s:

$$D_V = 1370 \pm 64 \quad \text{and} \quad \Omega_m h^2 = 0.130\,(n_s/0.98)^{-1.2} \pm 0.011$$

- Caveat:
  - Constraints are derived *using* ΛCDM

UNION data and BAO

Table: Comparison with data (UNION+BAO scale)

Model	χ^2 (308 points)
ΛCDM (with $\Omega_M = 0.27, \Omega_\Lambda = 0.73$)	310
Open Universe	318
Void in open Universe ($L = 450/h\mathrm{Mpc}$)	308

UNION fit with 2 Gpc

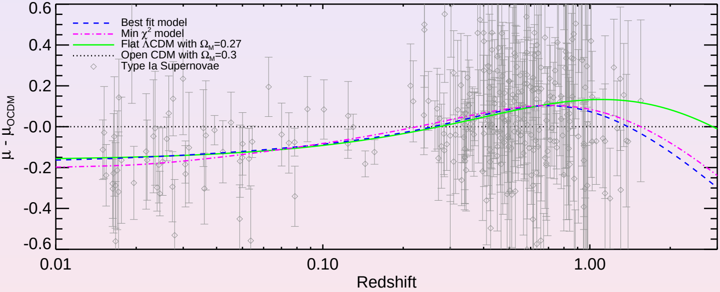
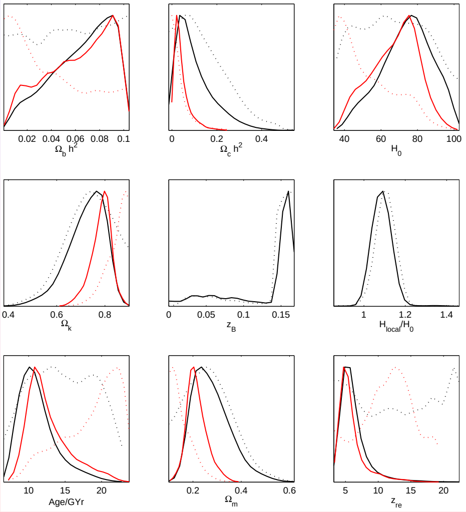


Figure: Taken from Garcia-Bellido & Haugboelle ’08 (similar fits also in Zibin et al. ’08)

UNION data and BAO



Problem 1

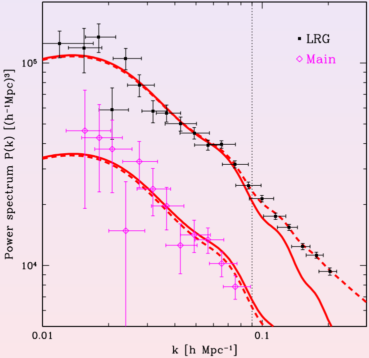
- Combining BAO+CMB+SN
- Problematic even adding curvature:

  - BAO+CMB+HST+SN (Riess) void: 3100
    BAO+CMB+HST+SN(Riess) ΛCDM: 2968
  - $\Delta\chi^2 \sim 140$

Outline

Galaxy power spectrum

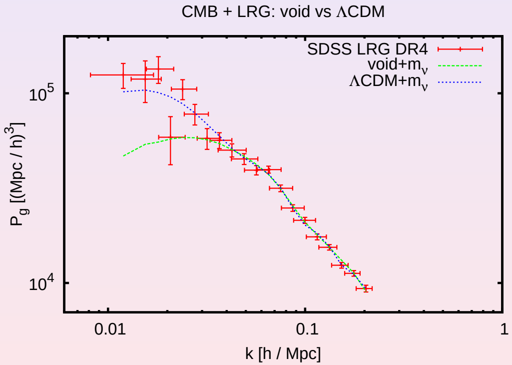
SDSS-main sample $z \lesssim 0.2$
Luminous Red Galaxies $0.2 \lesssim z \lesssim 0.5$



If the Void is small ($z \sim 0.1$), at least the LRG are in the outer region.

Problem 2: Galaxy power spectrum

- Combined fit with WMAP does *not* fit well LRG



- WMAP prefers flat/closed universe.
  LRG prefers $\Omega_M < 1$.

Outline

A Larger Void?

- If we consider $L \gtrsim 1\mathrm{Gpc}/h$

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- SN data fits better Alnes et al. ’07, Garcia-Bellido & Haugboelle ’07, Zibin et al.’08 ,...
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A Larger Void?

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- SN data fits better Alnes et al. ’07, Garcia-Bellido & Haugboelle ’07, Zibin et al.’08 ,...
- CMB first peak fits well Alnes et al. ’07
- Galaxy power spectrum could fit well (the data are inside...and inside the matter density is lower)
- BAO scale also changes
- Large monopole correction
- Work in progress... (A.N., T. Biswas, W. Valkenburg)

Radial BAO

- It is possible to look (Gaztanaga et al.'08) for the BAO scale only for the radial direction as Δz (model-independent)
- 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).

Outline

CMB Dipole

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

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- CMB dipole $\leq 10^{-3}$ if $d_O \sim 15 - 20\,\mathrm{Mpc}$ (Tomita et al., Alnes et al.'06)
- Bulk dipole of the same size of our dipole 600km/s (Kashlinsky et al. '08: $600 - 1000\mathrm{km}/\mathrm{s}$)

kSZ

- All objects inside the Void have some peculiar velocity
- This gives rise to $\frac{\delta T}{T} \sim \frac{v}{c}$ and spectrum distortions (kinetic SZ effect)

kSZ

- All objects inside the Void have some peculiar velocity
- This gives rise to $\frac{\delta T}{T} \sim \frac{v}{c}$ and spectrum distortions (kinetic SZ effect)
- Goodman '95: $v/c \lesssim 0.01$ (at $z \sim 0.2$)
- Caldwell-Stebbins '07-'08: rule out Voids with $z_b \gtrsim 0.9$

kSZ

- Garcia-Bellido & Haugboelle: using 9 clusters ($0.2 \leq z \leq 0.6$) with detection of spectral distortion one finds: $\bar{v} = 320\,\mathrm{km/sec}$ and $\sigma = 1600\,\mathrm{km/sec}$ (σ expected is only about $400\,\mathrm{km/sec!}$)

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- Exclude $L > 1.5 Gpc$, with $\Omega_{IN} = 0.23$.

kSZ

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  $\bar{v} = 320\,\mathrm{km/sec}$ and $\sigma = 1600\,\mathrm{km/sec}$
  (σ expected is only about $400\,\mathrm{km/sec!}$)
- Exclude $L > 1.5Gpc$, with $\Omega_{IN} = 0.23$.
- But Kashlinsky et al. measure high $\frac{v}{c} \sim 1000km/sec$ on $300\,\mathrm{Mpc}/h$
  (they *assume* kSZ, but do not see spectral distortions).

Anisotropy of H

- Similarly the expansion is anisotropic if d_O nonzero[8].
- Two papers claim significant anisotropy in H:
  - D.Schwarz & Weinhorst ’07: in the SNIa dataset ($> 95\% C.L.$)
  - McClure & Dyer ’07: in the *Hubble Key Project* data ($9 - 20 km/sec$)
- In addition this should be correlated with CMB dipole
- Also to be explored: non-sphericity of Void

---

[8] Tomita (2000), Alnes et al. (’06)

Anomaly in the CMB?

- The CMB has a Cold Region ("Cold Spot") (M. Cruz et al. ('06 and '07)), with diameter about 15°

The Cold Spot

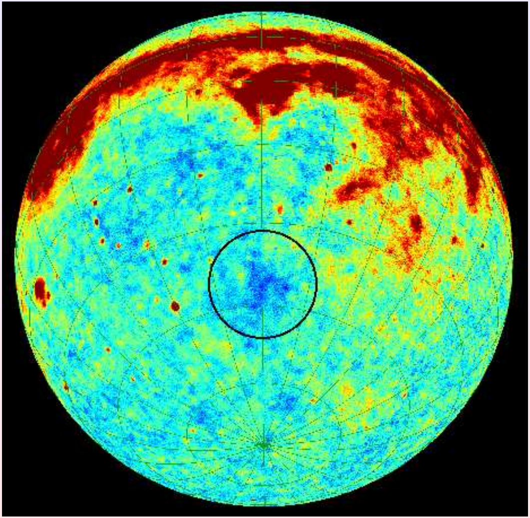

Figure: From Eriksen et al. '08

The Cold Spot

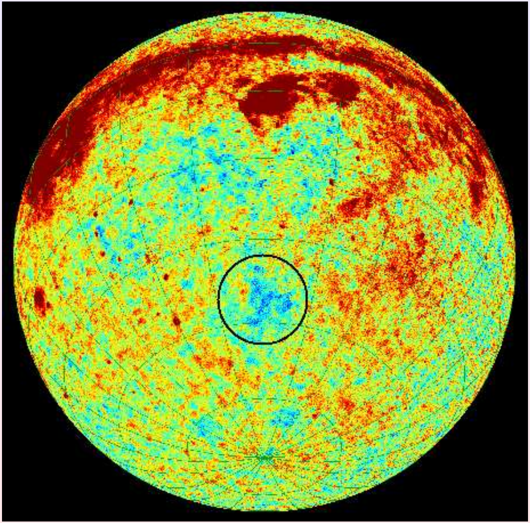

Figure: From Eriksen et al. '08

Possible Explanations

- A Statistical accident?
- It could be that our Universe is peculiar in such a way that Φ has this strange feature
- How strange is it?

Possible Explanations

- A Statistical accident?
- It could be that our Universe is peculiar in such a way that Φ has this strange feature
- How strange is it?
- About 1% chance from Gaussian Monte Carlo simulations of the CMB map (Cruz et al.'05-'06)

Other explanation

- Exotic explanation: it could be explained by the integrated effect along the line of sight
- There could be a very Large Void on the line-of-sight ($160\mathrm{Mpc}/h - 1.5\mathrm{Gpc}/h$) (Tomita'05-'06, Inoue & Silk '06)
- Claimed to be correlated with underdense region in the nearby galaxy distribution (Rudnick, Brown & Williams '07). This would mean that this "hole" is close to us.
- But this has been challenged by (Smith & Huterer '08)

The Cold Spot due to a Void?

- We assume an underdense region ("a Void"), on the line of sight
  with I.Masina; JCAP JCAP 0902:019,2009 and arXiv:0905.1073

The Cold Spot due to a Void?

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- Two effects
- First effect (Rees-Sciama, "integrated effect"):
  - A photon enters the potential of the Void
  - During the travel the potential evolves
  - The photon comes out with slightly lower energy (redshifts)

This would give a cold region (what we see by eye)

The Lensing effect

- Second effect (Lensing)
  - If behind the Void there is a pattern, ⇒ distorted
  - Also the very small angular scales (high ℓ) are affected

The Lensing effect

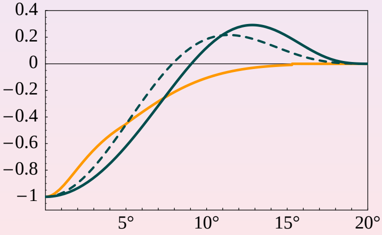
- Second effect (Lensing)
  - If behind the Void there is a pattern, $\Rightarrow$ distorted
  - Also the very small angular scales (high ℓ) are affected
- This, we cannot see by eye...
- If we see it $\Rightarrow$ there is something there: detection!

Outline

Shape of Temperature fluctuation

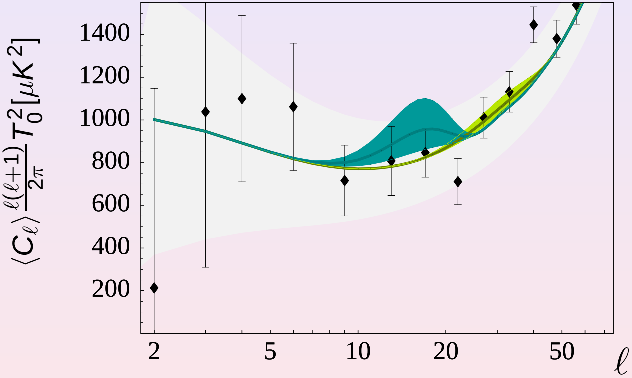
$$\Delta T/T^{(RS)}(\theta,\phi) = \begin{cases} A\, f(\theta) & \text{if } \theta < \theta_L \\ 0 & \text{if } \theta \geq \theta_L \end{cases}, \quad \tan\theta_L \equiv \frac{L}{D}\ ,$$

$$A \sim 0.5(L/r_{r_{hor}})^3\delta^2$$



Correction to the power spectrum at low-ℓ

- Compute the $a_{\ell m}$ for this profile $\Rightarrow C_\ell \equiv \sum_m \frac{|a_{\ell m}|^2}{2\ell+1}$



- The χ^2 changes by $\mathcal{O}(1)$
- The cosmological parameters would shift by some amount $\mathcal{O}(1\%)$

Bispectrum at high-ℓ

- The presence of a Void would be highly non-gaussian
- Consider $a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} = B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3}$
- They are zero on average for a Gaussian field

Bispectrum at high-ℓ

- More precisely we define a rotational invariant quantity:

$$B_{\ell_1\ell_2\ell_3} = \sum_{m_1 m_2 m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3}$$

- We want to compute $\langle B_{\ell_1\ell_2\ell_3} \rangle$, in a Universe with a Void

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- We want to compute $\langle B_{\ell_1\ell_2\ell_3}\rangle$, in a Universe with a Void
- Remember that $a^{(P)}_{\ell m}$ are Gaussian:

$$\langle a^{(P)}_{\ell_1m_1}a^{(P)}_{\ell_2m_2}\rangle = \delta_{\ell_1\ell_2}\delta_{m_1m_2}C_\ell$$

- Odd numbers of $a_{\ell m}$ ⇒ zero

Non-Gaussian correlations

$$\frac{\Delta T}{T} = \frac{\Delta T}{T}^{(P)} + \frac{\Delta T}{T}^{(RS)} + \frac{\Delta T}{T}^{(L)} ,$$

$$a_{\ell m} = a_{\ell m}^{(P)} + a_{\ell m}^{(RS)} + a_{\ell m}^{(L)} ,$$

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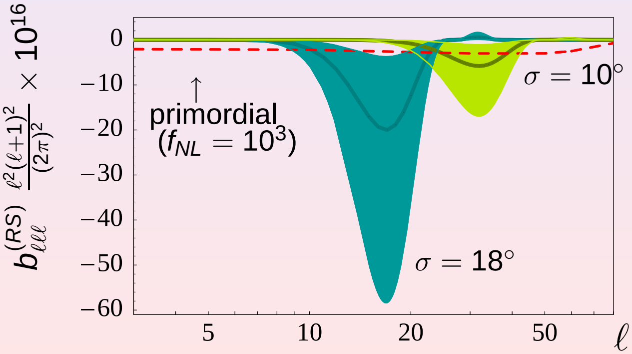
$$a_{\ell m} = a_{\ell m}^{(P)} + a_{\ell m}^{(RS)} + a_{\ell m}^{(L)} ,$$

- Two dominant terms:
- $\langle (a^{(RS)})^3 \rangle$
- $\langle a^{(P)} a^{(L)} a^{(RS)} \rangle$

$(a^{(RS)})^3$

$$B^{(RS)}_{\ell_1\ell_2\ell_3} = \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ 0 & 0 & 0 \end{pmatrix} a^{RS}_{\ell_1 0}\, a^{RS}_{\ell_2 0}\, a^{RS}_{\ell_3 0}\,.$$

- It should be visible ($S/N > 1$) already in WMAP bispectrum at $\ell \lesssim 40$



Outline

Lensing Effect

- Such Void lenses primordial fluctuations
- This is present only if there is something in the line-of-sight (unique signature) (Das & Spergel '08)

Signal-to-Noise

- Lensing introduces fluctuations because

$$\begin{aligned}\frac{\Delta T}{T}(\hat{n}') \quad &\sim \quad \frac{\Delta T^{(P)}}{T}(\hat{n}) + \partial_i \frac{\Delta T^{(P)}}{T}(\hat{n}) \partial^i \Theta(\hat{n}) + \\ &+ \quad \partial_i \partial_j \frac{\Delta T^{(P)}}{T}(\hat{n}) \partial^j \Theta(\hat{n}) \partial^i \Theta(\hat{n}) + \ \ldots\,.\end{aligned}$$

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- In order to compute this, we need Θ, the so-called Lensing potential:

$$\nabla_\perp \Theta = -2 \int_{\tau_{LSS}}^{\tau_O} d\tau \frac{\tau_O - \tau}{\tau_O} \nabla_\perp \Phi \,,$$

Signal-to-Noise

- Given $\Theta \Rightarrow b_{\ell m}$

Signal-to-Noise

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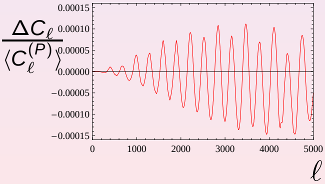
- $a^{(L)\,(1)}_{\ell m}$ lensing, given by:

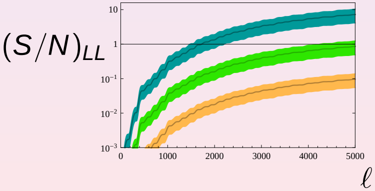
$$a^{(L)\,(1)}_{\ell m} = \sum_{\ell',\ell''} G^{-m m 0}_{\ell\ \ \ell'\ell''} \frac{\ell'(\ell'+1)-\ell(\ell+1)+\ell''(\ell''+1)}{2} a^{(P)*}_{\ell' -m} b_{\ell'' 0} \quad .$$

- We compute $\langle C^{(LL)}_{\ell} \rangle \equiv \sum_{m=-\ell}^{\ell} \frac{\langle a^{(L)(1)}_{\ell m} a^{(L)(1)\,*}_{\ell m} \rangle}{2\ell+1} \quad ,$

Signal-to-Noise

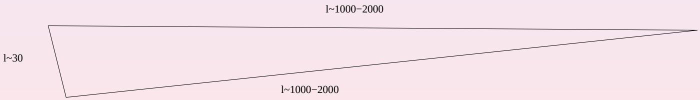
- Radius L large $\Rightarrow$ signal large
- Visible in the power spectrum by the Planck satellite ($\ell \sim 2000$) if $L \gtrsim 800\,\mathrm{Mpc}/h$





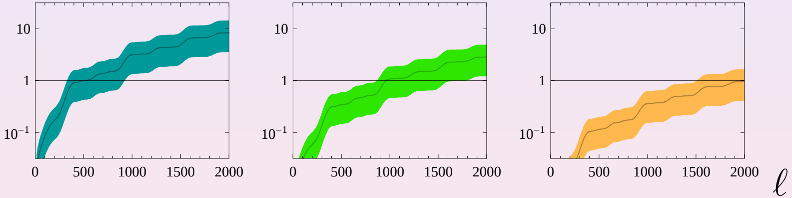
Non-gaussian signal

- $\langle a^{(P)} a^{(L)} a^{(RS)} \rangle$
- Coupling between RS-Primordial-Lensing effect



Signal-to-Noise

$L = 800\,\mathrm{Mpc}/h$ $L = 400\,\mathrm{Mpc}/h$ $L = 200\,\mathrm{Mpc}/h$



- Non-ambiguous signal, visible by high-resolution experiments (Planck and higher)

Assessment

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- But in trouble when combining other observations (BAO, LRG)
- Even adding curvature

- Need for larger Void ($L \gtrsim$ Gpc/h)
- Combined analyses and better data (kSZ, BAO) can rule it out

Assessment

- The Cold Spot - Void hypothesis can be ruled out by Planck and high-resolution experiments ($\ell_{\max} \gtrsim 2000$)