

# Apparent acceleration and Large Voids: possible alternatives to Dark Energy?

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# Outline

Void vs Dark  
Energy

Backreaction

Light  
propagation

Local Void

The Cold Spot

- 1 Backreaction
- 2 Light propagation
- 3 Local Void
- 4 The Cold Spot

# The need for Dark Energy

Void vs Dark Energy

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- In Standard Cosmology: homogeneous metric (with source  $\rho$  and  $p$ )
- We compute  $D_L$  (or  $D_A$ ) and  $z$  of distant sources
- To fit the observations we need a  $p < 0$  term (“Dark Energy”) with  $\rho_\Lambda \approx \rho_M$ .
- **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

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- **SN Ia** is incompatible with deceleration (independently on other observations)
- **CMB**: best-fit with power-law ( $k^{n_s}$ ) primordial spectrum has  $\Omega_\Lambda \sim 0.7$ .  
But good fit<sup>2</sup> also with  $\Omega_M = 1$ :
  - low- $h$  (0.45)
  - non-standard primordial spectrum
- Other observations (**BAO** and **LSS...**) fit consistently

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<sup>2</sup>Blanchard et al. '03, Sarkar and Hunt '04, '07 

# Homogenous Universe: a good approximation?

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- What happens to observations when we have departure from a *homogeneous* model?
- CMB: we observe tiny density fluctuations on all scales on the Last Scattering Surface.
- ... but today:

# SDSS data ("The cosmic web")

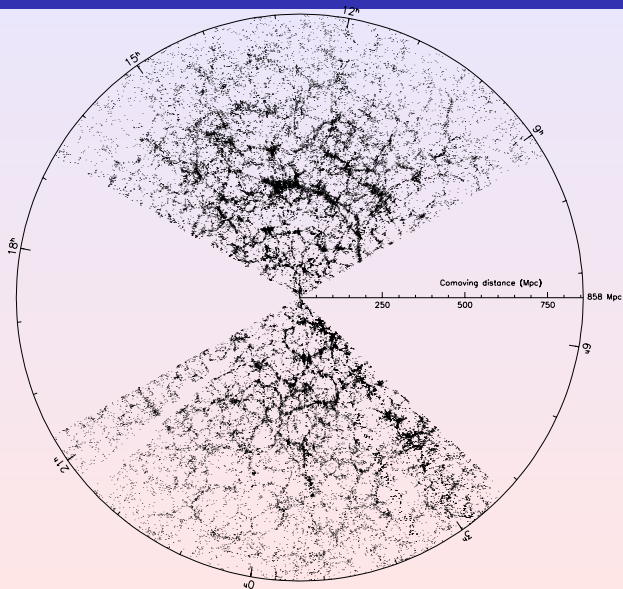
Void vs Dark Energy

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# Three approaches

Void vs Dark  
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In general:

- Backreaction
- Light propagation
- Large local fluctuation

# A few words on backreaction

Void vs Dark  
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- Averaging of Einstein's Equations  
Nonlinearity  $\Rightarrow$  extra terms in Friedmann equations<sup>3</sup>
- In a **inhomogeneous** metric ( $p=0$ )

$$ds^2 = -dt^2 + a^2(t) dx^i dx^j h_{ij}(t, \mathbf{x})$$

- Effective  $\rho$  and  $p$ :

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

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<sup>3</sup>G.Ellis-W.Stoeger '67, Futamase, Sakai et al, Buchert '95, S. Rasanen '03 ,

# How large?

- Perturbatively: 2<sup>nd</sup> order:  $\mathcal{O}(10^{-5})$  (L. Hui-U. Seljak '95, S. Rasanen'03, E. W. Kolb-S. Matarrese-A. N.-A. Riotto '04, ...)
- Higher orders go as:

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

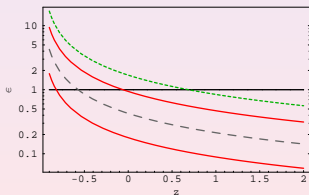


Figure: A.N. '04

Void vs Dark Energy

Backreaction

Light propagation

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# Light propagation in Swiss-Cheese

Void vs Dark  
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- Consider **Lemaître-Tolman-Bondi** exact solutions:
  - inhomogeneous
  - nonlinear
  - Spherically symmetric

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

- LTB spheres embedded in FLRW ("**Swiss-Cheese**")

# Redshift & Distance

Void vs Dark Energy

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- Along a  $ds^2 = 0$  trajectory solve for  $z(r)$

- The distance

$$D_A^2(r) \equiv \frac{dA}{d\Omega} = \frac{d\theta_S d\phi_S \sqrt{g_{\theta\theta} g_{\phi\phi}}}{d\theta_O d\phi_O}$$

# Observer outside: $z$

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- *Redshift*: Net effect for one hole:  $\sim \mathcal{O}(L/r_H)^3$   
(T. Biswas-A. N. '06-'07)
- Tight packing:  $N_{\text{holes}} \times \mathcal{O}(L/r_H)^3 \sim \mathcal{O}(L/r_H)^2$
  
- *Distance*: net effect scales as  $(L/r_H)^2$  Brouzakis-Tetradis-Tzavara '06,  
Kolb-Matarrese-Riotto '07, T. Biswas-A. N. '07
- Tight packing:  $N_{\text{holes}} \mathcal{O}(L/r_H)^2 = \mathcal{O}(L/r_H)$
  
- But it should have zero angular average (unlike  $z$ )  
S. Weinberg '76, Brouzakis et al. '06-'07!
- Negligible (unless Selection effects?)

# A local fluctuation?

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- Consider a “compensated LTB Void” : a spherical huge Void plus an external shell of matter <sup>4</sup>
- Assumption: we live near the center
- A void expands faster than the “external” FLRW
  - ⇒ So, nearby objects inside the void redshift more
  - ⇒ This can mimic acceleration

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<sup>4</sup>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 ...

# The density profile

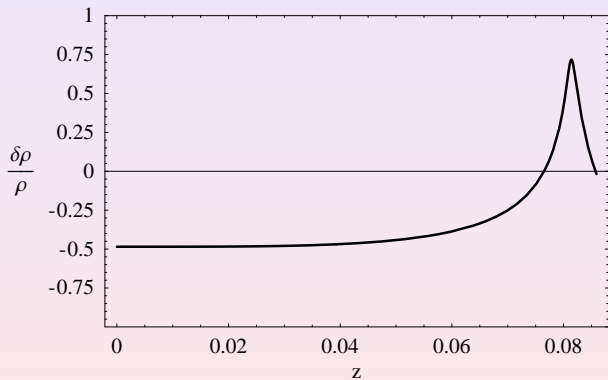
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# Roughly

Void vs Dark  
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- At **low  $z$**  "open-like" Universe with a **different  $H$**
- Two Hubble parameters:  **$h$**  and  **$h_{out}$**
- Outside: FLRW curve (plus small corrections  $\mathcal{O}(\frac{L}{r_{Hor}})^2$ )

# $\Delta m$ for different models

Void vs Dark Energy

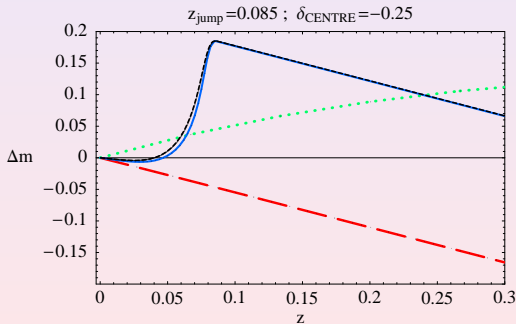
Backreaction

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



# $m - z$ diagram: Riess data

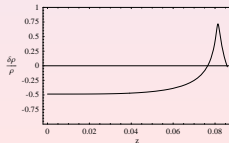
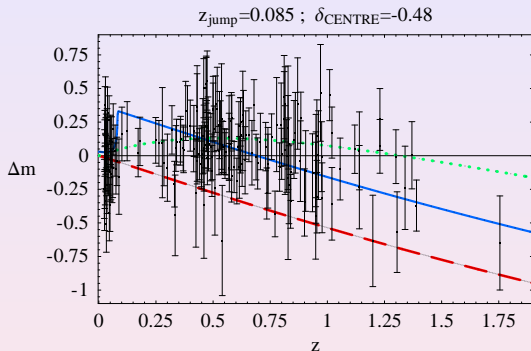
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# $\chi^2$ : UNION data

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**Table:** Comparison with data (Union data)

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

Remarks:

- It seems necessary to consider a **larger Void (Gpc scale)**

# UNION fit with 2 Gpc

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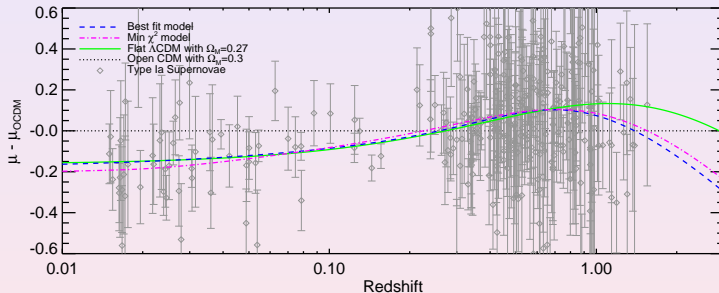


Figure: Taken from Garcia-Bellido & Haugboelle '08

# New data at intermediate $z$ (SDSS-II)

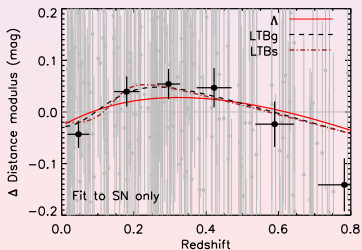
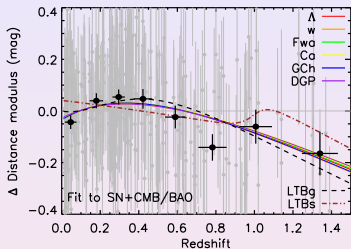
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# The WMAP data

Void vs Dark  
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- Same as homogeneous
- If Observer in the centre...
- ...apart for an offset to  $D_A$  of  $\mathcal{O}(L/r_{\text{Hor}})^2$

# Goodness-of-fit

Void vs Dark Energy

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Table: Fit of WMAP

|                                 | <b>Total</b>   |       |
|---------------------------------|----------------|-------|
| Model                           | $\chi_{eff}^2$ | G.F.  |
| Concordant $\Lambda$ CDM        | 3538.6         | 41%   |
| EdS $\alpha_s \neq 0$           | 3577.4         | 24.6% |
| EdS $\alpha_s, \Omega_k \neq 0$ | 3560.9         | 31.1% |

# Results & problems

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- low  $h_{\text{OUT}}$  (about  $\sim 0.45$ )  $h$  (about  $\sim 0.55$ )<sup>5</sup>
- low  $n_S$  ( $\sim 0.73$ )  
and large running.

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<sup>5</sup> As in A. Blanchard et al.'03 and P. Hunt & S. Sarkar '07

# Problems: BAO and Galaxy Power Spectrum

Void vs Dark Energy

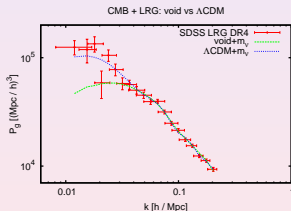
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- Measurement of baryon acoustic peak in the galaxy distribution:  $D$ - $z$  at **intermediate  $z$**  ( $= 0.35$ ) (Eisenstein et al., 2005).
- Luminous Red Galaxies  $0.2 \lesssim z \lesssim 0.5$



- WMAP prefers flat/closed universe. LRG prefers  $\Omega_M < 1$ .
- Problematic **if** in the **outer** region

# A Larger Void?

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- If we consider  $L \gtrsim 1\text{Gpc}/h$ ?
- BAO and Galaxy power spectrum may fit well (the data are **inside**...and inside the matter density is lower)
- Larger  $H_0$
- (combined fits: work in progress A.N., T. Biswas, W. Valkenburg)

# Other bounds

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- How much Observer can be off-center?
- CMB dipole  $\leq 10^{-3}$  if  $d_O \sim 15 - 20$  Mpc (Tomita et al., Alnes et al.'06, S.Alexander, T. Biswas, AN, D. Vaid '07)
  
- CMB light scatters on clusters Goodman '95
  
- $\Rightarrow$  spectrum distortions (kinetic SZ effect)
  
- Caldwell-Stebbins '07-'08, Garcia-Bellido & Haugboelle'08 : **rule out** Voids with  $L > 1.5 Gpc$ , with  $\Omega_{IN} = 0.23$ .

# Anomaly in the CMB?

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

# The Cold Spot

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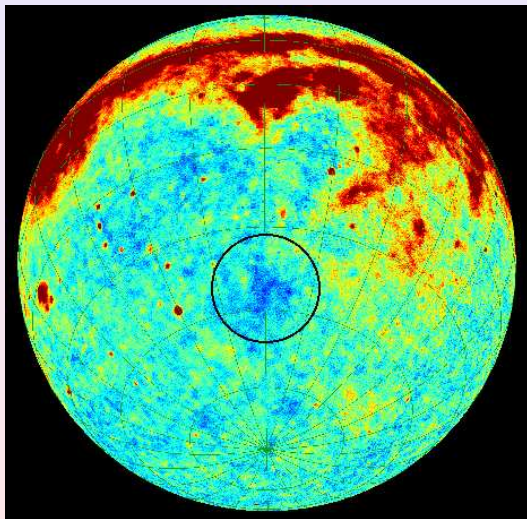


Figure: From Eriksen et al. '08

# The Cold Spot

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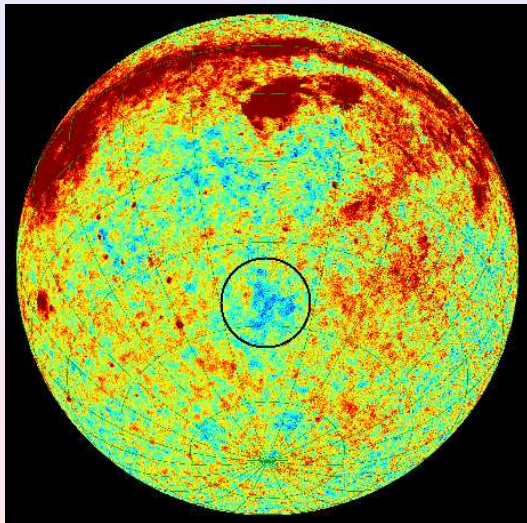


Figure: From Eriksen et al. '08

# Possible Explanations

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- A Statistical **accident**?
- How strange is it?
- About **1% chance** from Gaussian Monte Carlo simulations of the CMB map (Cruz et al.'05-'06)

# The Cold Spot due to a Void?

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- There could be a very **Large Void on the line-of-sight** ( $160\text{Mpc}/h - 1.5\text{Gpc}/h$ ) (Tomita'05-'06, Inoue & Silk '06)
- Perhaps correlated with galaxy distribution? (Rudnick, Brown & Williams '07).
- **Two effects**
  - (1) **Redshift**: colder photons Inoue & Silk '06, I.Masina & AN '08-'09
  - (2) **Lensing** of patterns behind S.Das & D.Spergel '08, I.Masina & AN '09

# Non-gaussian signal

Void vs Dark Energy

Backreaction

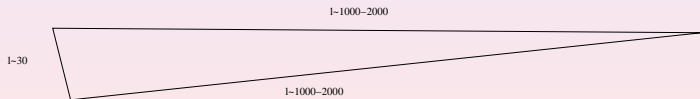
Light propagation

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- $\langle a_{\ell m}^{(P)} a_{\ell m}^{(L)} a_{\ell m}^{(R)} \rangle$

- Coupling between Redshift-Lensing-Primordial signals



# Signal-to-Noise

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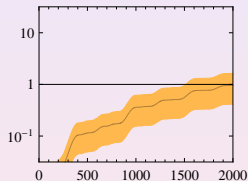
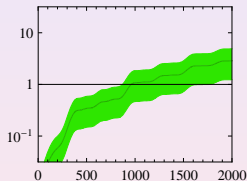
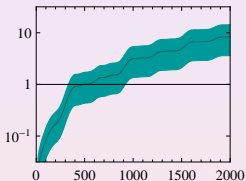
Local Void

The Cold Spot

$$L = 800 \text{ Mpc}/h$$

$$L = 400 \text{ Mpc}/h$$

$$L = 200 \text{ Mpc}/h$$



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

# Conclusions

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- **Backreaction**: perhaps more than  $10^{-5}$ ? Controversial.
- **Light propagation**: negligible (except if there are selection effects?)
- **Local Voids**: it works ( $Gpc$  size), but we'll see combining more data. Fine tuned.

# Which primordial origin?

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- 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?