Restraining void models for cosmological acceleration

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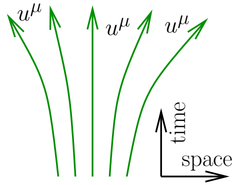
Based on JZ, PRD **78**, 043504 (2008), arXiv:0804.1787;
JZ, A. Moss, and D. Scott, arXiv:0808.xxxx

Acceleration

- In GR, volume expansion rate $\theta = u^\mu{}_{;\mu}$ satisfies

$$\dot\theta + \frac{\theta^2}{3} = -4\pi G(\rho + 3P) + \Lambda + a^\mu{}_{;\mu} - \sigma^{\mu\nu}\sigma_{\mu\nu} + \omega^{\mu\nu}\omega_{\mu\nu}$$



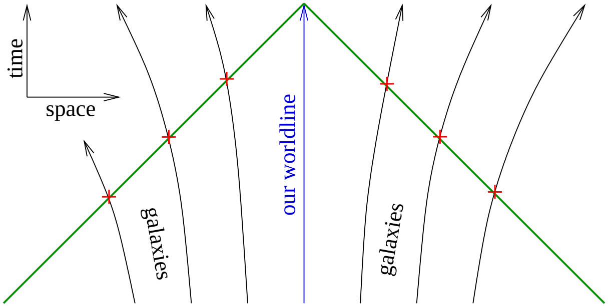
- For acceleration require $P < -\rho/3$ or $\Lambda > 0$, or modified gravity

$\rightsquigarrow$ Third option: standard matter + GR, but inhomogeneous

- *Scenario:* One large spherical void in a flat EdS background

(Will not consider "Swiss cheese" models for acceleration)

Spatial inhomogeneity can mimic acceleration from dark energy:



To fit supernova data, clearly require nonlinear void out to $z \sim 1$, i.e. $\delta\rho/\rho \sim 1$ on Gpc scales!

Occam's Entities

- Gpc-scale voids extremely unlikely in standard structure formation scenarios (Hunt and Sarkar, arXiv:0807.4508)

So something unusual required: $+1$ Entity

- Second problem: we must be very near void centre to avoid large CMB dipole [Alnes and Amarzguioui, PRD **74**, 103520 (2006)]: strongly anti-Copernican! $+1$ Entity

- But some point out we don't understand origin of DE or coincidence problem... -1 Entity?

$\rightsquigarrow$ Important to consider alternatives!

We should determine the nature of the Universe through observation and deduction, rather than philosophical postulate!

Can void models survive in the Age of Precision Cosmology?

• SN, CMB, BAO, LSS (lensing), ISW (correlations), etc all pointing sharply to ΛFRW!

⇝ Any viable alternative to ΛFRW has much explaining to do...

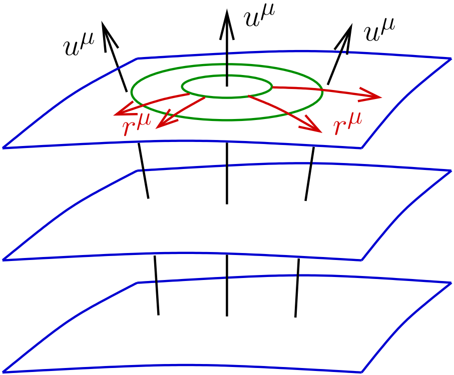
• Early studies concentrated on SN, more recently CMB, BAO, etc. are constraining void models.

⇝ Very promising: observations sensitive to remote CMB dipole (CMB spectral distortions, kSZ effect)

• New handle on voids: evolution of *perturbations* expected to differ from standard ΛFRW

$1+1+2$ Decomposition for Spherical Symmetry

Decompose geometry, matter with respect to comoving congruence u^μ and radial r^μ:



Covariant Quantities

Matter side: Consider *dust* source, $T_{\mu\nu} = \rho u_\mu u_\nu$

Geometry side: $u_{\mu;\nu} = \frac{1}{3}\theta h_{\mu\nu} + \sigma_{\mu\nu}$

$$E_{\mu\nu} = C_{\mu\lambda\nu\rho} u^\lambda u^\rho \quad H_{\mu\nu} = \frac{1}{2}\epsilon_\mu{}^{\lambda\rho} C_{\lambda\rho\nu\kappa} u^\kappa$$

($h^\mu{}_\nu \equiv \delta^\mu{}_\nu + u^\mu u_\nu$, $C_{\mu\lambda\nu\rho}$ Weyl tensor)

Under spherical symmetry, *all 2-vectors and 2-tensors must vanish*

$\rightsquigarrow$ Only need 2-scalars ρ, θ, $\Sigma \equiv \sigma_{\mu\nu} r^\mu r^\nu$, $\mathcal{E} \equiv \mathcal{E}_{\mu\nu} r^\mu r^\nu$

Exact Solution

- Spherical dust solution found by Lemaître, Tolman, and Bondi (LTB)

- Evolution essentially like a separate FRW dust universe, with different "bang time" for each r

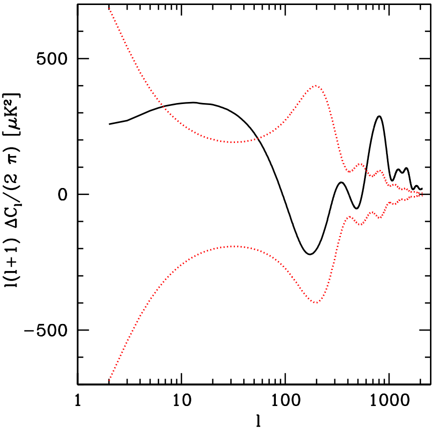
- Solution specified by *two free radial functions*, corresponding to *growing and decaying modes* in the linear regime about FRW

- Fluctuations in *bang time* give the *decaying* mode

⇝ Fundamental assumption: choose LTB void profiles without decaying mode

- ▶ Avoids extreme inhomogeneity at early times, which would conflict with the standard inflationary paradigm
- ▶ Allows standard treatment of perturbations (including BAO) at *early* times

Best fit to CMB + Union SN, using COSMOMC (Parameterize initial profile with two free parameters, width and depth)



⇝ Fine tuned primordial spectrum required: +1 Entity!

Perturbations

Linearize exact set about LTB background:

$$\delta\dot{\rho} = -\theta\delta\rho - \rho\delta\theta$$

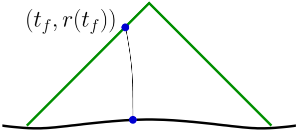
$$\delta\dot{\theta} = -\frac{2}{3}\theta\delta\theta - 3\Sigma\delta\Sigma - 4\pi G\delta\rho$$

$$\delta\dot{\Sigma} = -\left(\frac{2}{3}\theta + \Sigma\right)\delta\Sigma - \frac{2}{3}\Sigma\delta\theta - \delta\mathcal{E}$$

$$\delta\dot{\mathcal{E}} = \left(\frac{3}{2}\Sigma - \theta\right)\delta\mathcal{E} + \mathcal{E}\left(\frac{3}{2}\delta\Sigma - \delta\theta\right) - 4\pi G(\rho\delta\Sigma + \Sigma\delta\rho)$$

- Only approximation is ignored tensor-scalar coupling

Can do harmonic expansion on initial slice (can't in general on LTB!), and propagate initial perturbations forward using a new set of LTB transfer functions:



Isotropy of background implies:

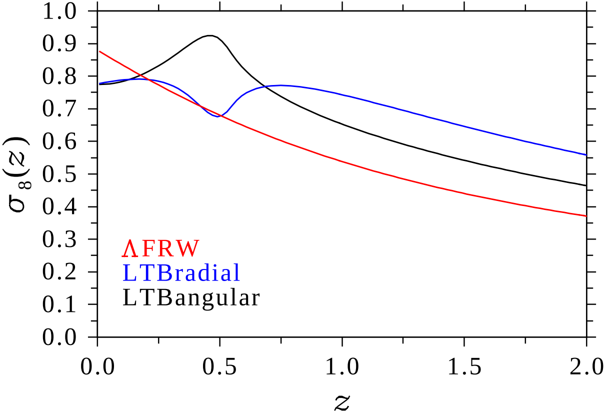
$$\delta X_i(t, r, \theta, \phi) = T_{ij}(t, r)\delta X_j(t_i, r, \theta, \phi), \quad \text{where } X_i = \rho, \theta, \Sigma, \mathcal{E}$$

- Local FRW property $\Rightarrow$ evolution at centre of void same as open FRW

$\rightsquigarrow$ Expect *suppression* of power at centre

- Does σ_8 conflict with observations?

Result for SN-best-fit void:



$\sigma_8(z)$ is *anisotropic* and *non-monotonic*

Baryon Acoustic Oscillations

- Physics before recombination imprints a fixed (comoving) scale, r_{BAO}, into the matter power spectrum

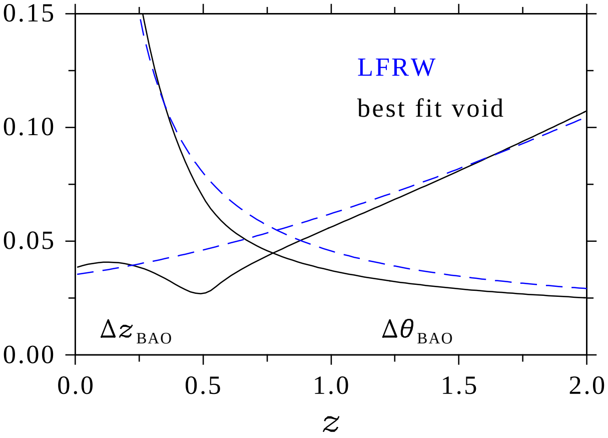
- What do we actually measure?

In LTB background, $\Delta\theta_{\mathrm{BAO}}(z) = \dfrac{r^{\perp}_{\mathrm{BAO}}}{d_A(z)}$

Similarly, $\Delta z_{\mathrm{BAO}}(z) = (1+z) r^{\parallel}_{\mathrm{BAO}} H^{\parallel}(z) \quad (H^{\parallel} \equiv \frac{1}{3}\theta + \sigma_{\mu\nu} r^{\mu} r^{\nu})$

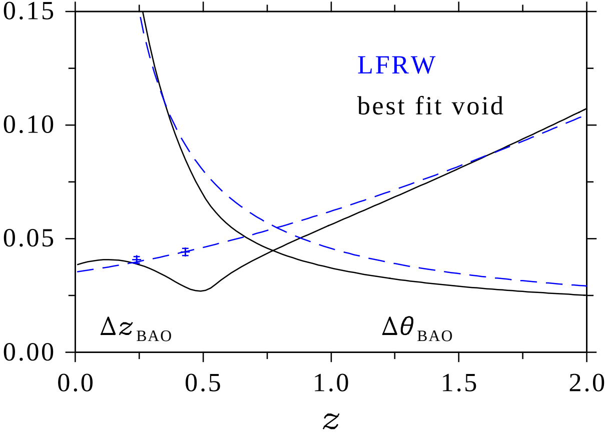
⇝ Important point: For $\Delta z_{\mathrm{BAO}}(z)$, two effects *reinforce* each other in the void periphery: $H^{\parallel}$ is low, which leads to low $r^{\parallel}_{\mathrm{BAO}}$!

Result:

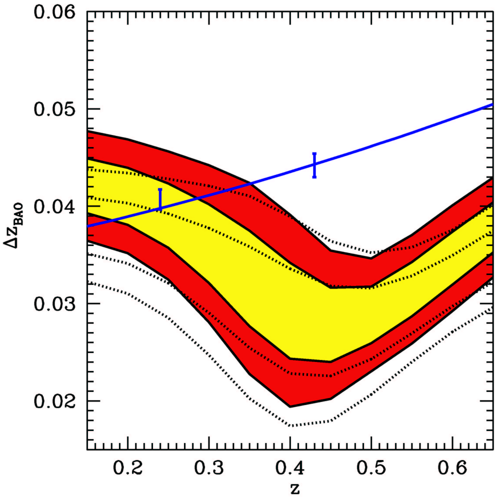


Previous void studies have only considered "isotropized" distance measure $D_V(z) \equiv \left[d_A^2(z)\frac{z}{H(z)}\right]^{1/3}$

Very recently *radial* BAO scale Δz_{BAO} detected in SDSS LRG (Gaztañaga *et al.*, arXiv:0808.1921):



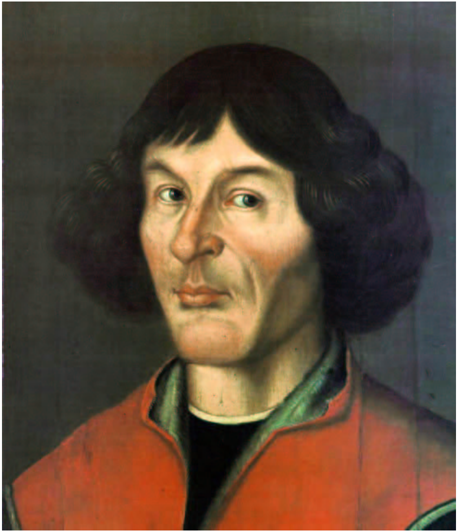
SN + CMB 1 and 2σ allowed regions from COSMOMC:



New radial BAO surveys planned (PAU, BOSS)...

Conclusions

- Identified three "Entities" that render void models unappealing:
  - Inconsistent with observed structure
  - Special location required
  - Fine tuned primordial spectrum required
- Tried to confront void models with real data
- Developed linear perturbation formalism, but found no strong constraints from amplitude (but, distinct z-dependence)
- Found (potentially) *very* strong constraint from *radial* BAO scale: all models consistent with SN + CMB are inconsistent with new BAO observations
- Relevant to homogeneity more generally



Nicolaus Copernicus, 1473 - 1543