Tension in the Void

arXiv:1201.2790

Miguel Zumalacárregui

Institute of Cosmos Sciences, University of Barcelona

with Juan Garcia-Bellido and Pilar Ruiz-Lapuente

Modern Cosmology Workshop 2012, Benasque

Outline

1. A-Void Dark Energy
   - The Standard Cosmological Model
   - Inhomogeneous Universes

2. Observational constraints
   - The BAO scale in LTB universes
   - MCMC analysis

3) Conclusions

The Standard Model of Cosmology

Commercial name: ΛCDM©

Ingredients

GR + FRW + **Inflation** + **SM** + **CDM** + Λ

- Theory of Gravitation: General Relativity
- Ansatz for the metric: Homogeneous + Isotropic
- Initial conditions: Inflationary perturbations
- Standard particle content: γ, ν's, p^+, n, e^-
- Cold Dark Matter: some new particle species
- Cosmological constant: Λ

Beyond Homogeneity

Homogeneity + Isotropy $\longrightarrow$ Spherical Symmetry

The Lemaitre-Tolman-Bondi metric

$$ds^2 = -dt^2 + \frac{A'^2(r,t)}{1-k(r)}\,dr^2 + A^2(r,t)\,d\Omega^2$$

Beyond Homogeneity

Homogeneity + Isotropy $\longrightarrow$ Spherical Symmetry

The Lemaitre-Tolman-Bondi metric

$$ds^2 = -dt^2 + \frac{A'^2(r,t)}{1-k(r)}\,dr^2 + A^2(r,t)\,d\Omega^2$$

- Two expansion rates: $H_R = \dot{A}'/A' \neq \dot{A}/A = H_T$

Beyond Homogeneity

Homogeneity + Isotropy $\longrightarrow$ Spherical Symmetry

The Lemaitre-Tolman-Bondi metric

$$ds^2 = -dt^2 + \frac{A'^2(r,t)}{1-k(r)}\,dr^2 + A^2(r,t)\,d\Omega^2$$

- Two expansion rates: $H_R = \dot{A}'/A' \neq \dot{A}/A = H_T$
- Matter/curvature profile $k(r) \Rightarrow \Omega_M(r)$

Beyond Homogeneity

Homogeneity + Isotropy $\longrightarrow$ Spherical Symmetry

The Lemaitre-Tolman-Bondi metric

$$ds^2 = -dt^2 + \frac{A'^2(r,t)}{1-k(r)}\,dr^2 + A^2(r,t)\,d\Omega^2$$

- Two expansion rates: $H_R = \dot{A}'/A' \neq \dot{A}/A = H_T$
- Matter/curvature profile $k(r) \Rightarrow \Omega_M(r)$
- Expansion rate $H_0(r) \Rightarrow$ time to big-bang $t_{\rm BB}(r)$

Beyond Homogeneity

Homogeneity + Isotropy $\longrightarrow$ Spherical Symmetry

The Lemaitre-Tolman-Bondi metric

$$ds^2 = -dt^2 + \frac{A'^2(r,t)}{1-k(r)}\,dr^2 + A^2(r,t)\,d\Omega^2$$

- Two expansion rates: $H_R = \dot{A}'/A' \neq \dot{A}/A = H_T$
- Matter/curvature profile $k(r) \Rightarrow \Omega_M(r)$
- Expansion rate $H_0(r) \Rightarrow$ time to big-bang $t_{\rm BB}(r)$

Homogeneous Big-Bang: $t_{BB}(r) = t_0$

- Relates $H_0(r) \leftrightarrow \Omega_M(r)$ up to a constant $H_0 \leftrightarrow t_0$
- ◀◀ Evolution from very homogeneous state at early times

Beyond Homogeneity

Homogeneity + Isotropy $\longrightarrow$ Spherical Symmetry

The Lemaitre-Tolman-Bondi metric

$$ds^2 = -dt^2 + \frac{A'^2(r,t)}{1-k(r)}\, dr^2 + A^2(r,t)\, d\Omega^2$$

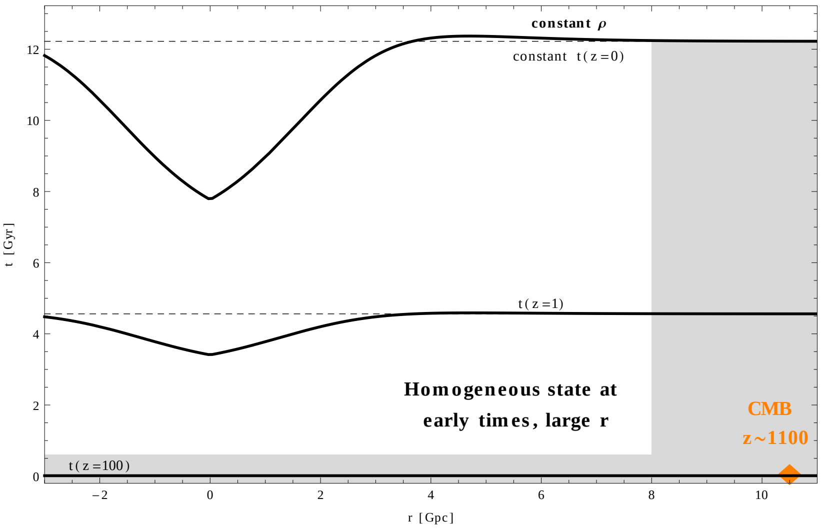
- Two expansion rates: $H_R = \dot{A}'/A' \neq \dot{A}/A = H_T$
- Matter/curvature profile $k(r) \Rightarrow \Omega_M(r)$
- Expansion rate $H_0(r) \Rightarrow$ time to big-bang $t_{\mathrm{BB}}(r)$

Homogeneous Big-Bang: $t_{BB}(r) = t_0$

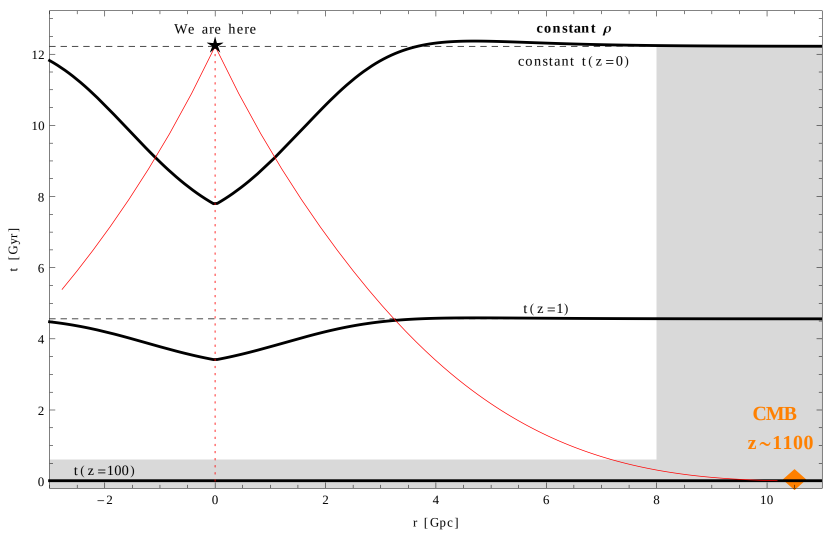
- Relates $H_0(r) \leftrightarrow \Omega_M(r)$ up to a constant $H_0 \leftrightarrow t_0$
- ◀◀ Evolution from very homogeneous state at early times

$+\ \rho_b \propto \rho_m\ \rightarrow$ growth of an spherical adiabatic perturbation

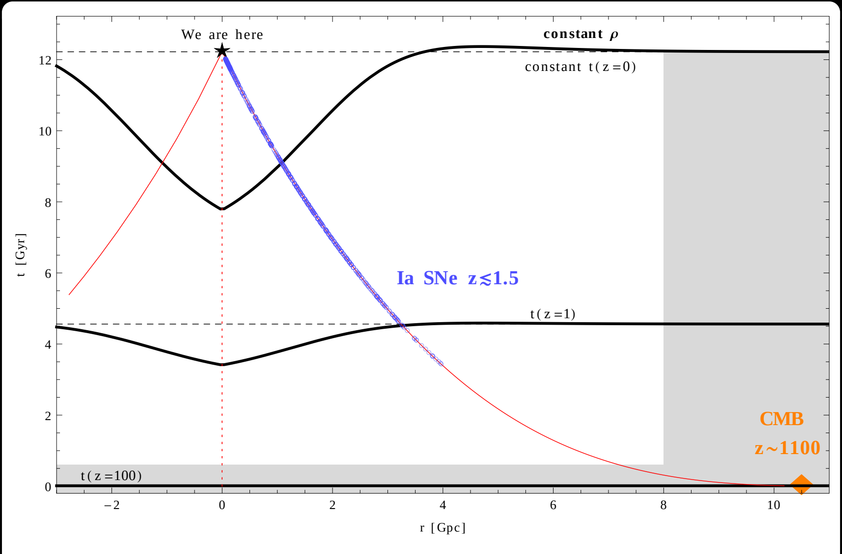
Observations in *adiabatic* LTB universes



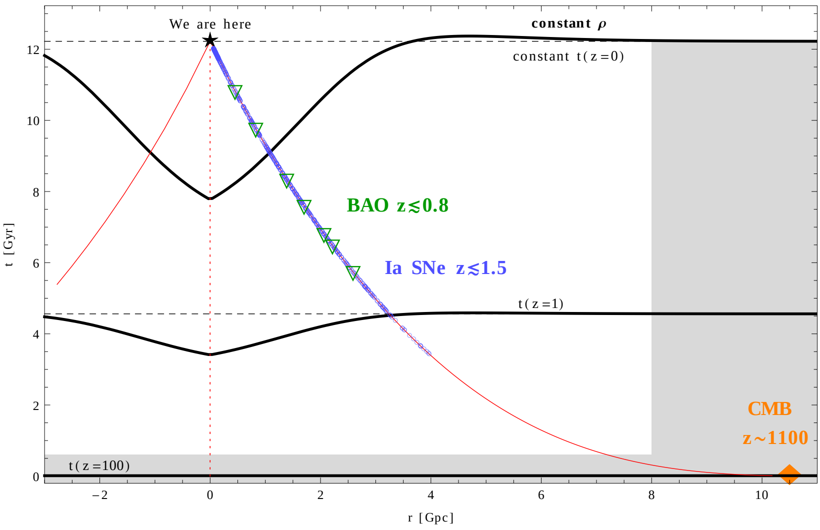
Observations in *adiabatic* LTB universes



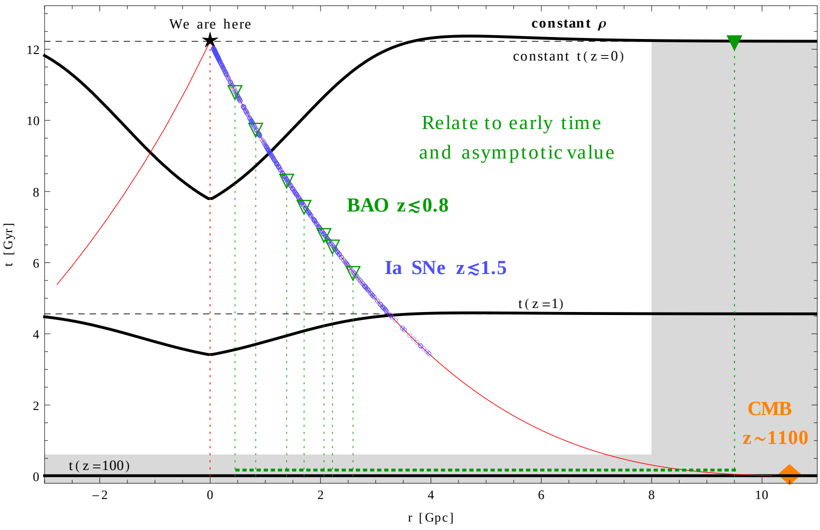
Observations in *adiabatic* LTB universes



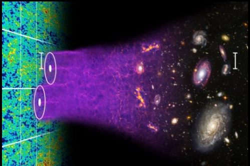
Observations in *adiabatic* LTB universes



Observations in *adiabatic* LTB universes



Baryon acoustic oscillations - Standard Rulers

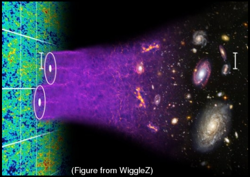

(Figure from WiggleZ)

-Sound waves in the baryon-photon plasma travel a finite distance

-Initial baryon clumps $\rightarrow$ more galaxies

-Statistical standard ruler

Baryon acoustic oscillations - Standard Rulers



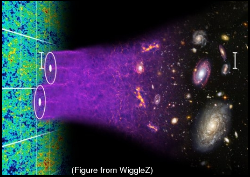
-Sound waves in the baryon-photon plasma travel a finite distance

-Initial baryon clumps $\rightarrow$ more galaxies

-Statistical standard ruler

- LTB: Do these clumps/galaxies move? $\rightarrow$ Geodesics

Baryon acoustic oscillations - Standard Rulers


(Figure from WiggleZ)

-Sound waves in the baryon-photon plasma travel a finite distance

-Initial baryon clumps $\rightarrow$ more galaxies

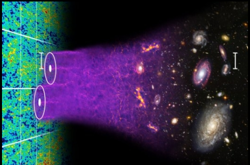
-Statistical standard ruler

- LTB: Do these clumps/galaxies move? $\rightarrow$ Geodesics

$$\ddot{r} + \left[\frac{k'}{2(1-k)} + \frac{A''}{A'}\right]\dot{r}^2 + 2\frac{\dot{A}'}{A'}\dot{t}\dot{r} = 0$$

$\dot{t} \gg \dot{r} \Rightarrow$ Constant coordinate separation (zero order)

Baryon acoustic oscillations - Standard Rulers



(Figure from WiggleZ)

-Sound waves in the baryon-photon plasma travel a finite distance

-Initial baryon clumps → more galaxies

-Statistical standard ruler

- LTB: Do these clumps/galaxies move? → Geodesics

$$\ddot{r} + \left[\frac{k'}{2(1-k)} + \frac{A''}{A'}\right]\dot{r}^2 + 2\frac{\dot{A}'}{A'}\dot{t}\dot{r} = 0$$

$\dot{t} \gg \dot{r} \Rightarrow$ Constant <u>coordinate</u> separation (zero order)

- Alonso *et al.* 1204.3532: N-body ⇒ locally ∼ FRW w $\Omega_M(r)$

February *et al.* 1206.1602: Linear PT ⇒ $\sim 1\%$ shift

The physical BAO scale

- Coordinate BAO scale on lightcone known ✓

The physical BAO scale

- Coordinate BAO scale on lightcone known ✓
- Physical distances given by $g_{rr} = \frac{A'^2(r,t)}{1-k(r)}$, $g_{\theta\theta} = A^2(r,t)$

The physical BAO scale

- Coordinate BAO scale on lightcone known ✓
- Physical distances given by $g_{rr} = \frac{A'^2(r,t)}{1-k(r)}$, $g_{\theta\theta} = A^2(r,t)$

$$l_R(r,t) = \frac{A'(r,t)}{A'(r,t_e)} l_{\text{early}}, \quad l_T(r,t) = \frac{A(r,t)}{A(r,t_e)} l_{\text{early}}$$

The physical BAO scale

- Coordinate BAO scale on lightcone known ✓
- Physical distances given by $g_{rr} = \frac{A'^2(r,t)}{1-k(r)}$, $g_{\theta\theta} = A^2(r,t)$

$$l_R(r,t) = \frac{A'(r,t)}{A'(r,t_e)} l_{\text{early}}, \quad l_T(r,t) = \frac{A(r,t)}{A(r,t_e)} l_{\text{early}}$$

- LTB: evolving (t), inhomogeneous (r) and anisotropic $l_T \neq l_R$

  FRW $\rightarrow$ only time evolution!

The observed BAO scale

Observations $\rightarrow$ galaxy correlation in angular and redshift space

Geometric mean $\quad d \equiv \left(\delta\theta^2 \delta z\right)^{1/3}$

$$\delta\theta = \frac{l_T(z)}{D_A(z)}, \quad \delta z = (1+z) H_R(z)\, l_R(z)$$

The observed BAO scale

Observations → galaxy correlation in angular and redshift space

Geometric mean $d \equiv \left(\delta\theta^2 \delta z\right)^{1/3}$

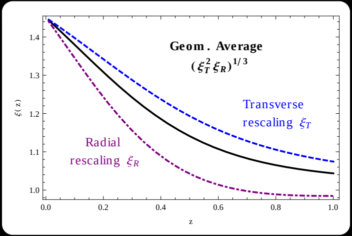
$$\delta\theta = \frac{l_T(z)}{D_A(z)}, \quad \delta z = (1+z) H_R(z)\, l_R(z)$$

Different result than FRW

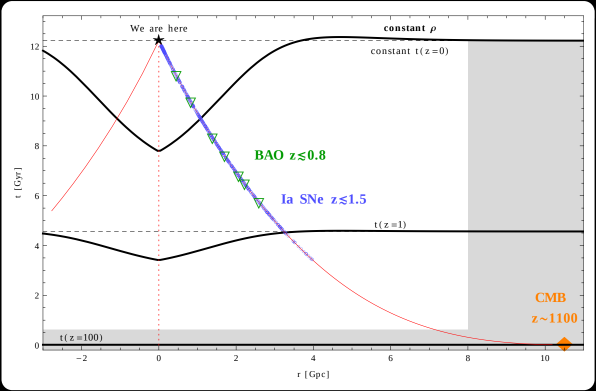
$$d_{\rm LTB}(z) = \xi(z)\, d_{\rm FRW}(z)$$

$\xi(z) =$ rescaling $= (\xi_T^2\, \xi_R)^{1/3}$

Inhomogeneous, anisotropic



MCMC data and models



-**GBH profile:** $\Omega_{\rm in}$, $\Omega_{\rm out}$, R, ΔR, H_0, f_b

- WiggleZ + Carnero *et al.*

- Union 2 Compilation

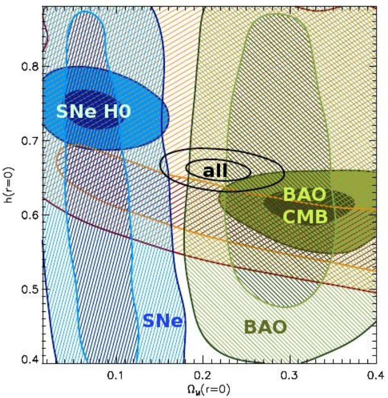
- $H_0 = 73.8 \pm 2.4$
$\rightarrow$ SNe luminosity prior

- CMB peaks information (simplified analysis)

Adiabatic LTB models: $\Omega_{\rm out} = 1$ and open $\Omega_{\rm out} \leq 1$

Adiabatic GBH, asympt. flat $\Omega_{\rm out} = 1$

Filled: **SNe+H0**, **BAO+CMB**, Dashed: BAO , CMB peaks, Supernovae



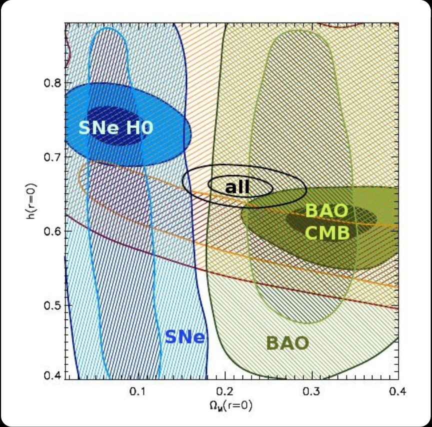
Adiabatic GBH, asympt. flat $\Omega_{\text{out}} = 1$

Filled: **SNe+H0**, **BAO+CMB**, Dashed: BAO , CMB peaks, Supernovae

Depth of the Void:

- SNe $\rightarrow \Omega_{\text{in}} \approx 0.1\ (< 0.18)$
- BAO $\rightarrow \Omega_{\text{in}} \approx 0.3\ (> 0.2)$

New: 3σ Away!!!



Adiabatic GBH, asympt. flat $\Omega_{\rm out} = 1$

Filled: **SNe+H0**, **BAO+CMB**, Dashed: BAO , CMB peaks, Supernovae

Depth of the Void:

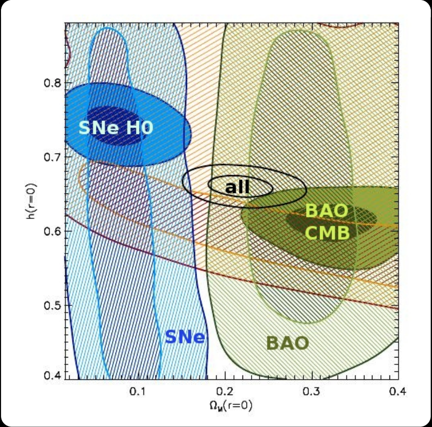
- SNe $\rightarrow \Omega_{\rm in} \approx 0.1\ (< 0.18)$
- BAO $\rightarrow \Omega_{\rm in} \approx 0.3\ (> 0.2)$

New: 3σ Away!!!

Local Expansion Rate:

- **SNe+H0** $\rightarrow h_{\rm in} \approx 0.74$
- **BAO+CMB** $\rightarrow h_{\rm in} \approx 0.62$

known, worse if full CMB used



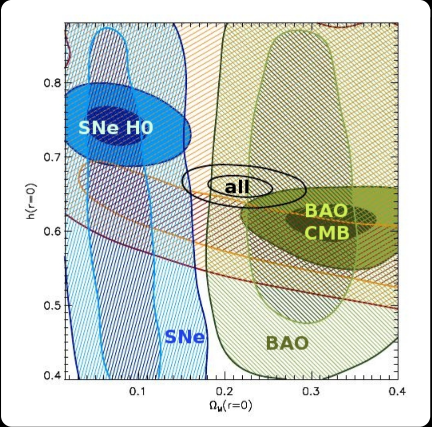
Adiabatic GBH, asympt. flat $\Omega_{\text{out}} = 1$

Filled: **SNe+H0**, **BAO+CMB**, Dashed: BAO , CMB peaks, Supernovae

Depth of the Void:

- SNe $\rightarrow \Omega_{\text{in}} \approx 0.1 \ (< 0.18)$
- BAO $\rightarrow \Omega_{\text{in}} \approx 0.3 \ (> 0.2)$

New: 3σ Away!!!



Local Expansion Rate:

- **SNe+H0** $\rightarrow h_{\text{in}} \approx 0.74$
- **BAO+CMB** $\rightarrow h_{\text{in}} \approx 0.62$

known, worse if full CMB used

Do asymptotically open models work better?

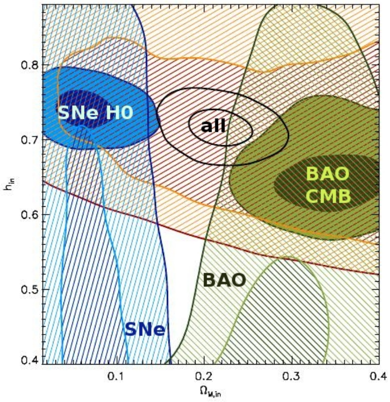
Adiabatic GBH, asympt. open $\Omega_{\rm out} = 1$ $\Omega_{\rm out} \leq 1$

Filled: **SNe+H0**, **BAO+CMB**, Dashed: BAO , CMB peaks, Supernovae

Depth of the Void:

- SNe $\rightarrow \Omega_{\rm in} \approx 0.1$
- BAO $\rightarrow \Omega_{\rm in} \approx 0.3$

Still 3σ Away!!!



Local Expansion Rate:

$\Omega_{\rm out} \approx 0.85 \leftrightarrow$ higher $H_{\rm in}$

$t_0 \propto 1/H_{\rm in} \rightarrow t_0 \lesssim 12$Gyr

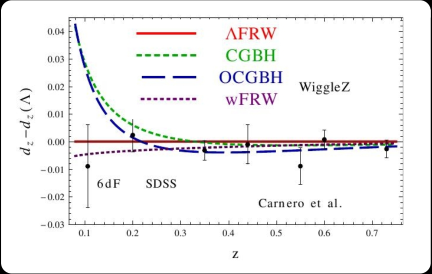
Only better H_0, but Universe too young

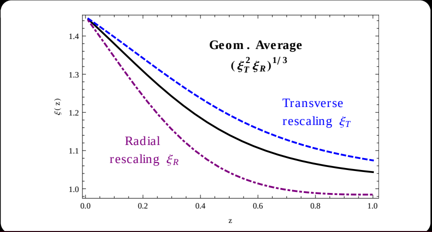
Best fit models

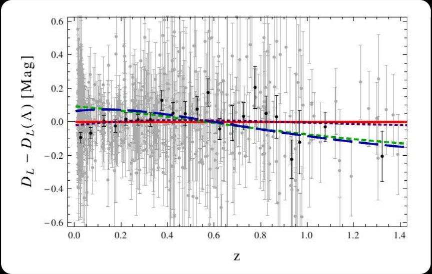
Tension in the Void

- Bad fit to SNe and BAO
- SNe measure distance
  BAO: distance+rescaling

  complementary probes
- Strongly ruled out







Conclusions

- BAO and SNe alone strongly rule out the GBH model with homogeneous Big Bang and baryon fraction

Conclusions

- BAO and SNe alone strongly rule out the GBH model with homogeneous Big Bang and baryon fraction
- Possible ways to save large void models:
  - Change the profile $\Omega_M(r)$?

Conclusions

- BAO and SNe alone strongly rule out the GBH model with homogeneous Big Bang and baryon fraction
- Possible ways to save large void models:
  - Change the profile $\Omega_M(r)$?
  - Inhomogeneous Big Bang $\leftrightarrow$ free H_0

Conclusions

- BAO and SNe alone strongly rule out the GBH model with homogeneous Big Bang and baryon fraction
- Possible ways to save large void models:
  - Change the profile $\Omega_M(r)$?
  - Inhomogeneous Big Bang $\leftrightarrow$ free H_0
  - Large scale isocurvature $\rho_b = f_b(r)\,\rho_m$

Conclusions

- BAO and SNe alone strongly rule out the GBH model with homogeneous Big Bang and baryon fraction
- Possible ways to save large void models:
  - Change the profile $\Omega_M(r)$?
  - Inhomogeneous Big Bang $\leftrightarrow$ free H_0
  - Large scale isocurvature $\rho_b = f_b(r)\,\rho_m$
- Purely geometrical result, whatever Luminosity & BAO scale $\Rightarrow$ Standard Rulers vs Standard Candles

Conclusions

- BAO and SNe alone strongly rule out the GBH model with homogeneous Big Bang and baryon fraction
- Possible ways to save large void models:
  - Change the profile $\Omega_M(r)$?
  - Inhomogeneous Big Bang $\leftrightarrow$ free H_0
  - Large scale isocurvature $\rho_b = f_b(r)\,\rho_m$
- Purely geometrical result, whatever Luminosity & BAO scale $\Rightarrow$ Standard Rulers vs Standard Candles
- BAO are a powerful complement to SNe in more *general* inhomogeneous models

Backup Slides

Supernova Ia - Standard Candles

- **Standar(izable) Candles:** $\approx$ Same (corrected) Luminosity

$$D_L(z) = \sqrt{\frac{\text{Luminosity}}{4\pi\,\text{Flux}}} = H_0^{-1} f(z, \Omega_\Lambda, \Omega_M) \text{ (FRW)}$$

difficult to model SNe $\Rightarrow$ Intrinsic Luminosity unknown!!

- For any L, comparison of low and high z SNe very useful

Supernova Ia - Standard Candles

- **Standar(izable) Candles:** $\approx$ Same (corrected) Luminosity

$$D_L(z) = \sqrt{\frac{\text{Luminosity}}{4\pi\,\text{Flux}}} = H_0^{-1} f(z, \Omega_\Lambda, \Omega_M) \quad \text{(FRW)}$$

difficult to model SNe $\Rightarrow$ Intrinsic Luminosity unknown!!

- For any L, comparison of low and high z SNe very useful
- FRW: Luminosity degenerate with Hubble rate
  $\Rightarrow$ need L to determine H_0

Supernova Ia - Standard Candles

- **Standar(izable) Candles:** $\approx$ Same (corrected) Luminosity

$$D_L(z) = \sqrt{\frac{\text{Luminosity}}{4\pi\,\text{Flux}}} = H_0^{-1} f(z, \Omega_\Lambda, \Omega_M) \quad \text{(FRW)}$$

difficult to model SNe $\Rightarrow$ Intrinsic Luminosity unknown!!

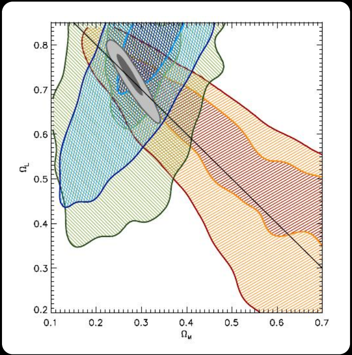
- For any L, comparison of low and high z SNe very useful
- FRW: Luminosity degenerate with Hubble rate
  $\Rightarrow$ need L to determine H_0
- In LTB not quite true $\Rightarrow$ convert constraint

$$H_0 = 73.8 \pm 2.4\,\text{Mpc/Km/s} \leftrightarrow L = -0.120 \pm 0.071 \text{ Mag}$$

MCMC: FRW-ΛCDM reference model

Using BAO scale, CMB peaks, Supernovae and H_0+BAO+CMB+SNe

- BAO $\sim$ SNe: Arbitrary length/luminosity (before adding CMB/H0)
- CMB constraints much weaker than usual $1 - \Omega_k \lesssim 1\%$



$\Rightarrow$ don't take our CMB constraints too seriously