Effects of the inhomogeneities of the matter/energy density distribution in astrophysics and cosmology

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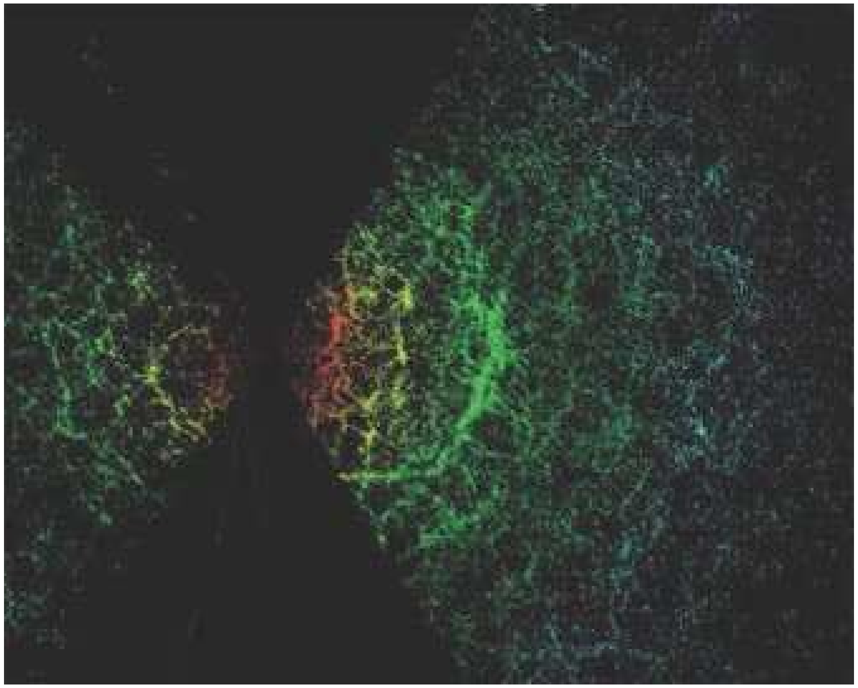
Introduction

Woody Allen

"I am astounded to hear there are people trying to understand the Universe while it is already so difficult to find one's way in Chinatown."

The inhomogeneous Universe



Sloan Digital Sky Survey (false colors)

The Universe is not homogeneous. We see voids, groups of galaxies, clusters, superclusters, walls, filaments, etc. However, it is usually argued it should be nearly homogeneous at large scales (thus Friedmannian models for cosmology and linear perturbation theory for structure formation); but how large are these scales and what does nearly imply?

Methods to take inhomogeneities into account

- **Linear perturbation theory:** valid when both the curvature and density contrasts remain small. Not the case in the non-linear regime of structure formation and where the SNe Ia are observed (cosmology).

- **Averaging methods “à la Buchert”:** promising but needing to be improved.

- **Exact inhomogeneous solutions:** valid at all scales, exact perturbations of the Friedmann background which they can reproduce as a limit with any precision.

Exact inhomogeneous solutions used in astrophysics and cosmology

- **Lemaître – Tolman (L–T) models:** spherically symmetric dust solution of Einstein's equations. Determined by 1 coordinate choice + 2 free functions of the radial coordinate. FLRW is a subcase.

- **Lemaître models (usually known as Misner-Sharp)** – not an explicit solution but a metric determined by a set of 2 differential equations: spherically symmetric perfect fluid with pressure gradient.

- **Quasispherical Szekeres models:** dust solution of Einstein's equations with no symmetry. Defined by 1 coordinate choice + 5 free functions of the radial coordinate. L–T and FLRW are subcases.

- **Spherically symmetric Stephani models:** homogeneous-energy density, inhomogeneous-pressure solutions.

Spherical symmetry of L–T models with a central observer: a drawback?

NO!

When using a single patch L–T model in cosmology, we do not claim we are at the centre of any actual spherically symmetric large scale inhomogeneity.

RATHER these models must be considered as preliminary steps. Here, inhomogeneities are smoothed over all angles and only their radial component remains (improvement as regards FLRW where the inhomogeneities are smoothed over the whole space).

The exact central location of the observer is a mere artifact of the smoothing.

HENCE these models cannot take anisotropies into account, are of no use to study them and can in no way be tested by them (e.g., CMB dipole and low multipoles, ...).

Structure evolution with exact inhomogeneous models

Structure evolution with L–T models

- **Rich galaxy cluster:** **A pure velocity perturbation can nearly produce a galaxy cluster. A mere density perturbation fails to do it. Velocity perturbations generate structures much more efficiently than density perturbations Krasiński and Hellaby 2004.**

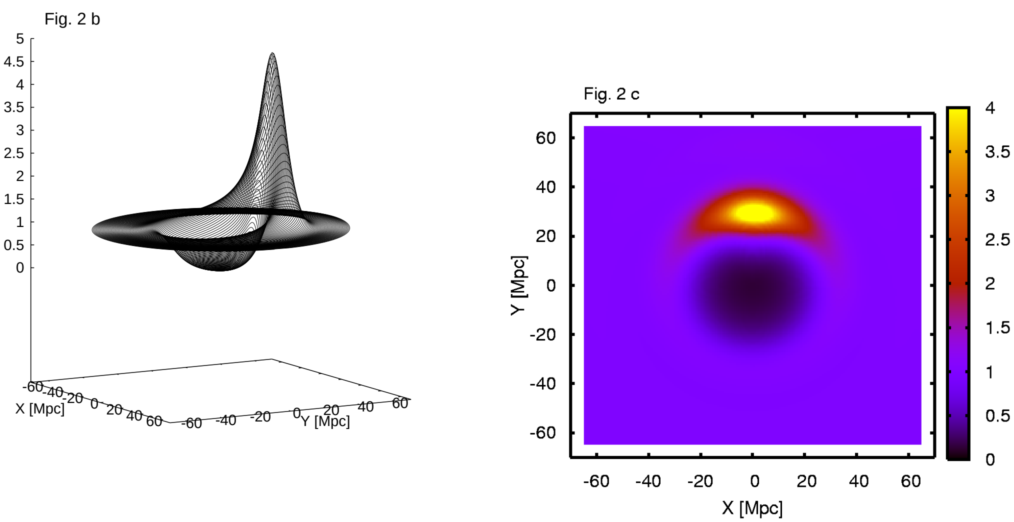
- **Void:** **A void consistent with observational data (density contrast less than $\delta = -0.94$, smooth edges and high density in the surrounding regions) is very hard to obtain with L–T models without shell crossing Bolejko, Krasiński and Hellaby 2005.**

- **Adding a realistic distribution of radiation (using Tolman models) helps forming such voids Bolejko 2006.**

Structure evolution with Szekeres models

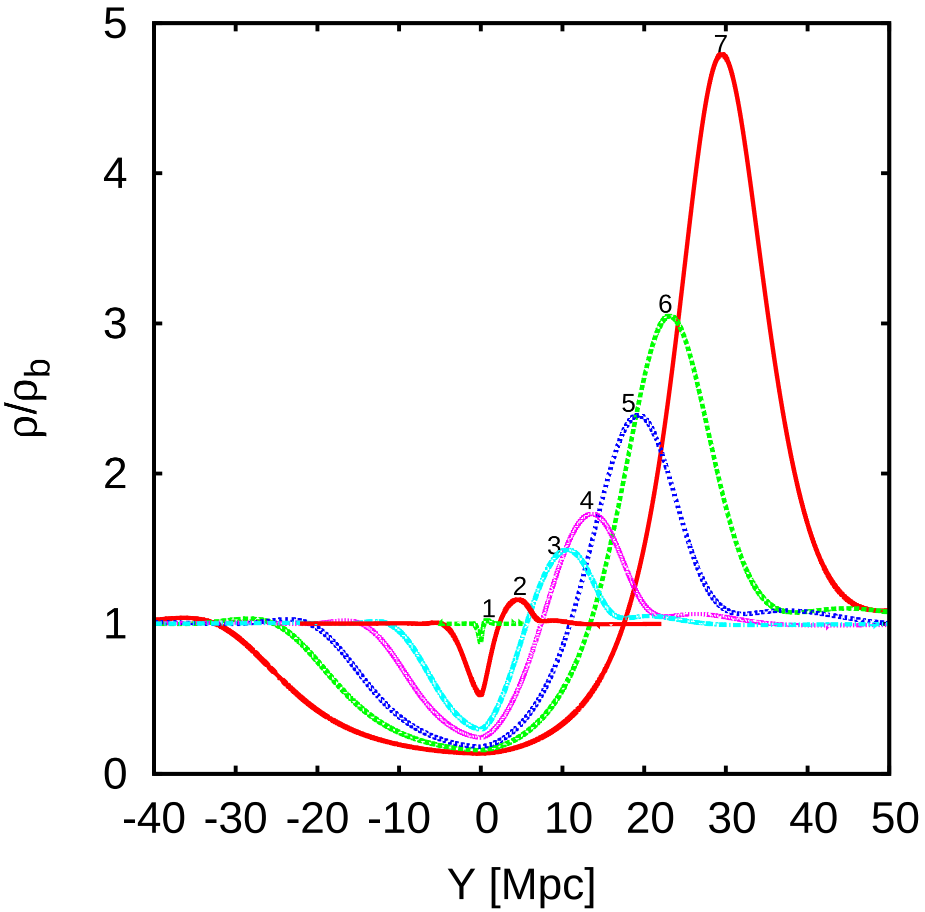
Double structure evolution

Model of a void with an adjourning supercluster evolved inside an homogeneous background Bolejko 2006.



Current density distribution in background units.

To estimate how two neighbouring structures influence each other, the evolution of a double structure in QSS models has been compared with that of single structures in L–T models and linear perturbation theory.

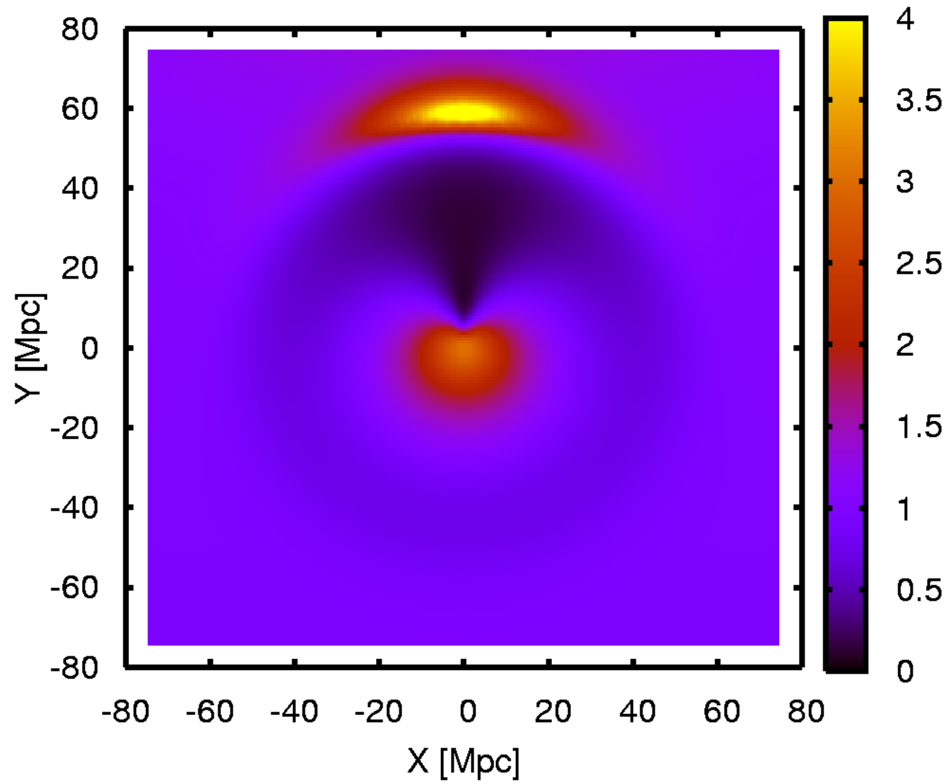


Evolution of the density profile from 100 Myr after the Big Bang (1) up to the present time (7).

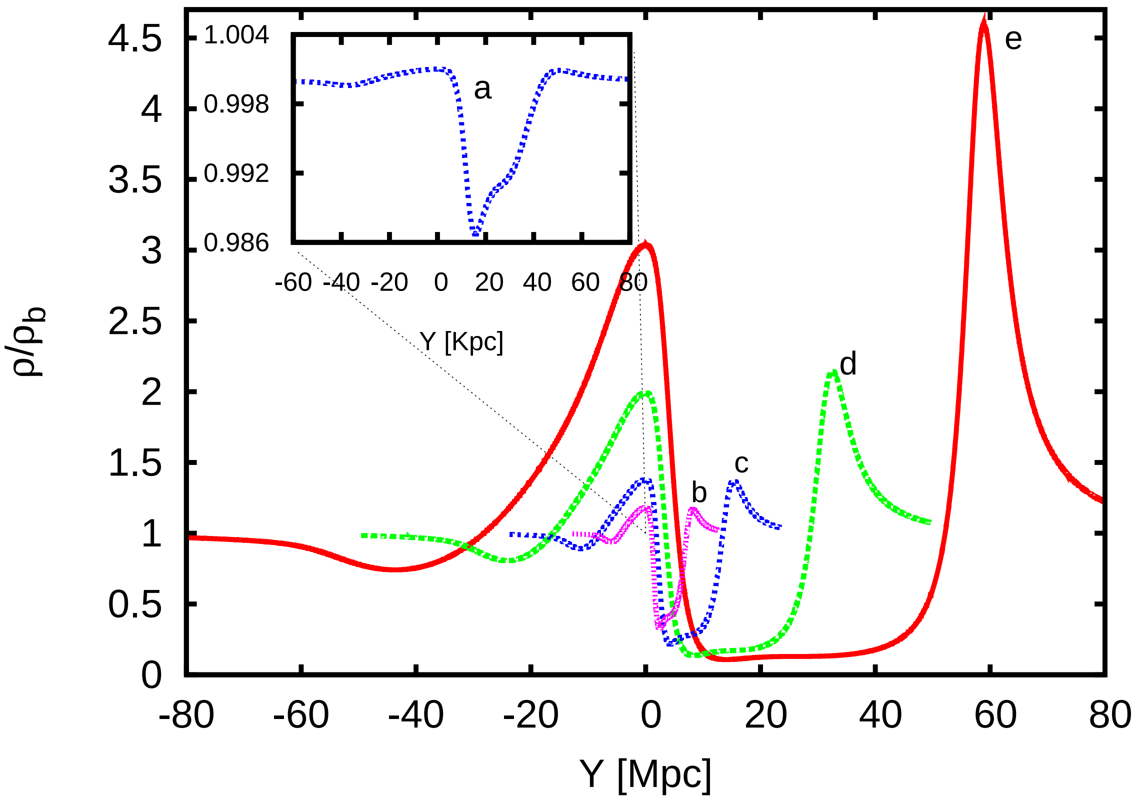
In the QSS models studied, the growth of the density contrast is 5 times faster than in L–T models and 8 times faster than in the linear approach.

Triple structure evolution

The model is composed of an overdense region at the origin, followed by a small void which spreads to a given r coordinate. At a larger distance from the origin, the void is huge and its larger side is adjacent to an overdense region Bolejko 2007.



Current density distribution.



Evolution of the density profile from 0.5 Myr after the Big Bang (a) up to the present time (e).

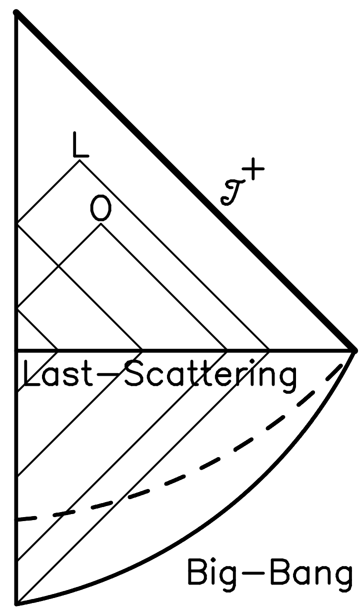
Where the void is large, it evolves much faster than the underdense region closer to the "central" cluster. The exterior overdense region close to the void along a large area evolves much faster than the more compact supercluster at the centre. This suggests that, in the Universe, small voids surrounded by large high densities evolve much more slowly than large isolated voids.

The horizon problem

Horizon problem and inflation

The problem. **The comoving region over which the CMB is observed as quasi-homogeneous at the last-scattering surface is much larger than the intersection of this surface with future light cones issuing from the BB surface. This problem develops sooner or later in any universe model with a spacelike BB singularity.**

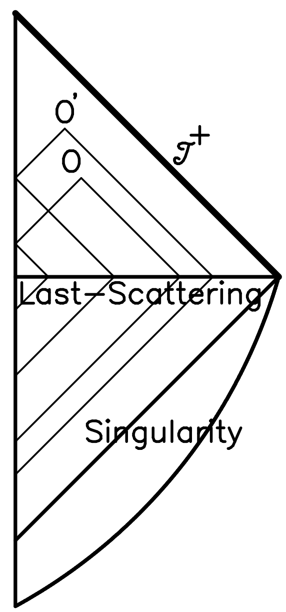
Inflation only postpones the occurrence of the problem.



Permanent solution: DBB L–T model

Theorem: **a spherically symmetric model with** $g_{00} = [t - b(r)]^a f(r, t)$ **exhibits a timelike shell-crossing surface at** $t = b(r)$ **if** $a > 1/2$ **and** $g'_{00} \neq 0$**.**

We have shown that a L–T model with $t'_B(r) > 0$ **for all** r **(delayed Big-Bang) and some other properties exhibits the conditions of application of the above theorem allowing us to solve permanently the horizon problem with no inflation MNC and Schneider 1998, MNC 2000, MNC and Szekeres 2002.**



The dark energy puzzle

The homogeneous "concordance" model. A reminder

Assumption: the Universe is spatially homogeneous at all scales.

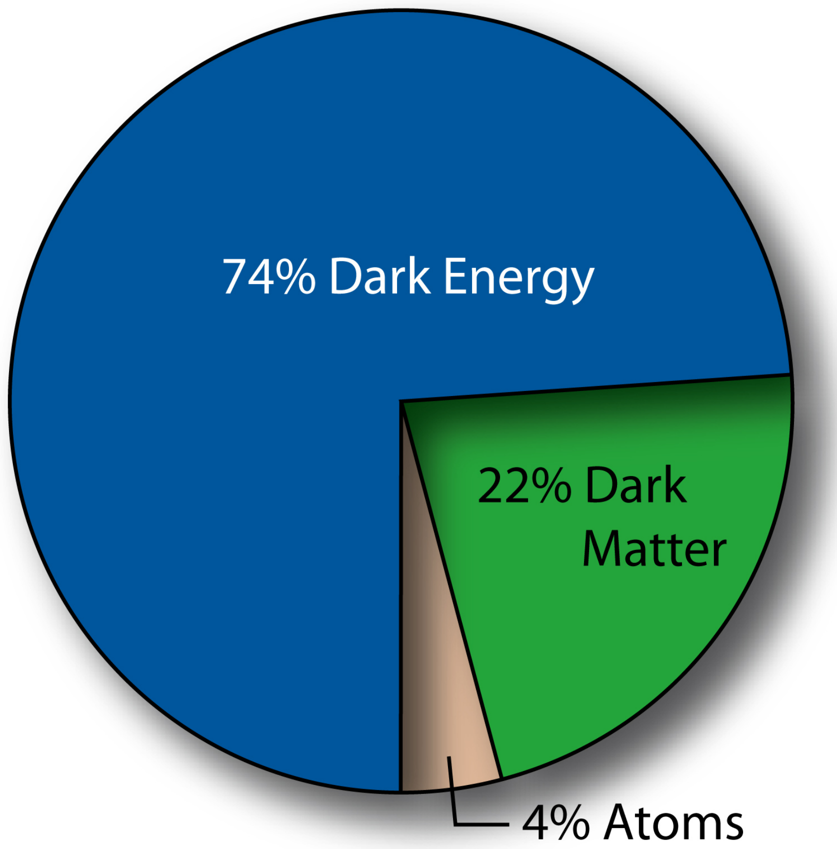
Consequence: the models used to describe its geometry and its dynamics are Friedmann-Lemaître-Robertson-Walker models.

In these models, the observables measured on our past light cone, $mn(z)$, $H(z)$, $D_A(z)$, etc. are described by functions of the redshift z and of a finite number of (generally) constant parameters, the main ones being Ω_b, Ω_m, Ω_Λ, Ω_k.

The values of these parameters are fixed by fitting the parameters to the cosmological data. Hence the "concordance" model:

$$\Omega_b \sim 0.04 \quad \Omega_m \sim 0.24 \quad \Omega_\Lambda \sim 0.76 \quad \Omega_k \sim 0.$$

The homogeneous “concordance” model. Content



The dark energy puzzle

Since its discovery (Riess et al. 1998, Perlmutter et al. 1999) the dimming of distant SNe Ia, as interpreted in a Friedmannian framework, has been mostly ascribed to the influence of a mysterious "dark energy" component.

This "dark energy" acts as a negative pressure fluid (possibly a mere cosmological constant) which tends to accelerate the Universe expansion.

Even if, from some theoretical point view , a geometrical cosmological constant could be a natural component of the Einstein equations (Nottale 1993, 1996), its actual value remains to be confirmed.

It is well-known that the inhomogeneities observed in our Universe can have an effect upon the values of the cosmological parameters derived in the framework of a smoothed out Friedmannian model Ellis and Stoeger 1987.

Moreover, the onset of "dark energy" domination in a previously matter dominated Universe appears at the epoch when structure formation enters the non-linear regime. Hence the failure of linear perturbation theory at these scales.

Accelerated expansion: a mirage?

What we see in the supernova data is not an accelerated expansion (this is only the outcome of the Friedmannian assumption) but the "dimming" of the supernovae, or more exactly their luminosity distance-redshift relation. which can exhibit the same form in a non-zero Λ FLRW universe as in a zero Λ inhomogeneous model MNC 2000.

Some authors stressed that the definition of a deceleration parameter in an inhomogeneous model is misleading Hirata and Seljak 2005; Apostopoulos et al. 2006; Krasiński, Hellaby, Bolejko, MNC 2010.

Use of exact inhomogeneous models in cosmology

L–T models have been most widely used as exact inhomogeneous models in cosmology since they are the most tractable among the few available, but **QSS models** are currently slightly coming into play.

However, **L–T Swiss-cheeses** have also been studied to get rid of possible misleading features of spherical symmetry while still taking advantage of the simplicity of the L-T models,.

Degeneracy of L–T models

It is well-known, from the work of Mustapha, Hellaby and Ellis 1997, that an infinite class of L–T models can fit a given set of observations isotropic around the observer. This has been applied to the supernova data by MNC 2000.

The problem of finding THE spherically symmetric model able to mimic dark energy is therefore completely degenerate. It is the reason why many different central observer L–T models with vanishing Λ have been proposed and shown to do the job rather well.

Thus, to constrain the model further on, it is mandatory to fit it to other cosmological data.

Direct and inverse problem

Two procedures for trying to explain away dark energy with (L–T) models:

- **The direct way (smaller number of degrees of freedom than allowed):** first guess the form of the parameter functions defining a class of models supposed to represent our Universe with no cosmological constant, and write the dependence of these functions in terms of a **limited number of constant parameters;** then fit these constant parameters to the observed SN Ia data or to the luminosity distance-redshift relation of the standard ΛCDM model.
- **Alternative:** fix one of the two arbitrary functions of the L–T solution to a constant value and fit observations.

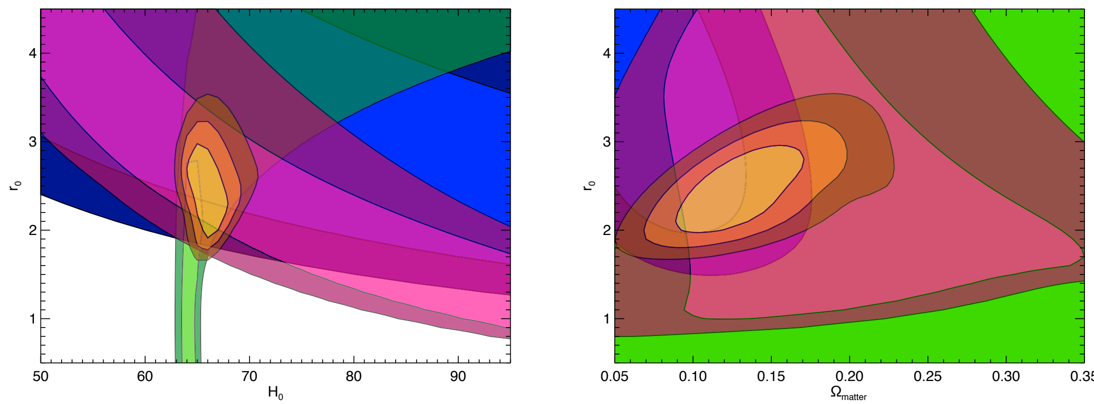
- **The inverse problem (more general):** consider the luminosity distance $D_L(z)$ as given by observations or by the ΛCDM model as an input and try to select a specific L–T model with zero cosmological constant best fitting this relation.

To avoid degeneracy, jump to a further step and try to reproduce more and **possibly all** the available observational data, Alnes et al. 2006, Bolejko 2008, Garcia-Bellido and Haugbolle 2008, Hellaby et al. 2007, 2008, MNC et al. 2009.

Example of a central void: the GBH model

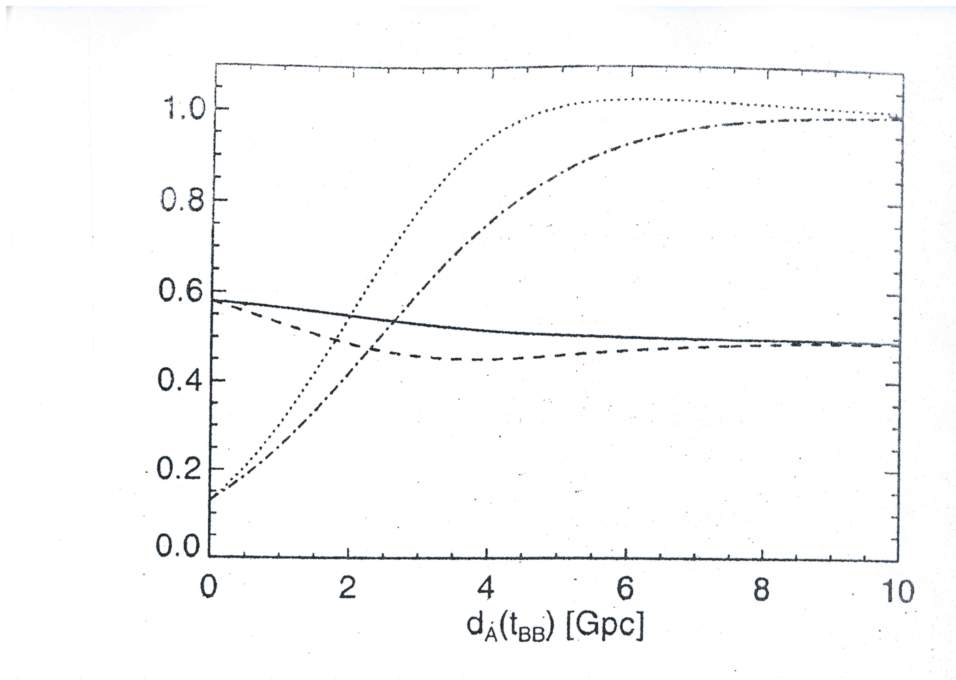
The GBH void class of L–T model (Garcia-Bellido and Haugbolle 2008a,b) is specified by its matter content $\Omega_{\mathrm{M}}(\mathrm{r})$ and its expansion rate $\mathrm{H}(\mathrm{r})$, governed by 5 free constant parameters and it matches to an E-deS universe at large scales.

These models are fitted to a series of observations (CMB, LSS, BAO, SN Ia, HST measure of H_0, age of the globular clusters, gas fraction in clusters, kinematic SZ effect for 9 distant galaxy clusters) to constrain their parameters.



Two of the six likelihoods for the GBH constrained model: in yellow with 1-, 2-, 3-σ contours = the likelihood for the combined data set; in blue, purple and green respectively with 1- and 2-σ contours = the likelihood for the individual SN Ia, BAO and CMB data sets.

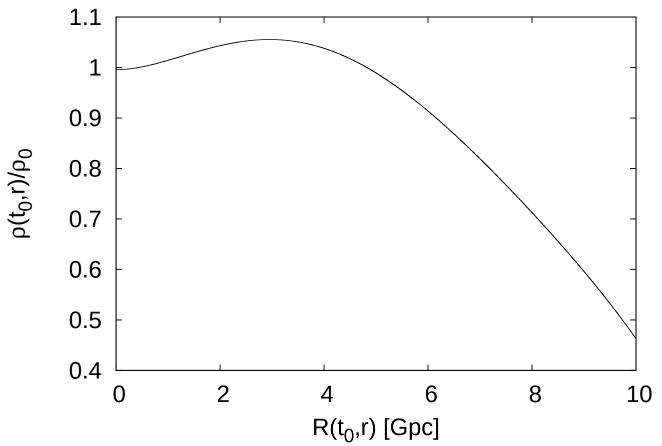
These models do not exclude the possibility that we leave close to the centre of a large (around 2.5 Gpc) void within an Einstein-de Sitter Universe, i. e., no dark energy.



The void at the current time for the GBH central observer. Dotted curve = matter density in units of the critical density. Dash-dot curve: Ω_M. Solid curve: H_T. Dashed curve: H_L.

We can do without the giant void

We have fitted a LT model with no cosmological constant to three functions of z – the angular diameter distance, the galaxy number counts and the expansion rate – all assumed to have the same form on our past light cone as in the ΛCDM model. The two left arbitrary L–T functions are determined without ”forcing” a priori their form (contrary to what is done by GBH) and give a very different mass distribution in spacetime.



The current density profile does not exhibit a giant void but a giant hump. We are located in a shallow and wide funnel on top of this hump MNC, Bolejko, Krasínski 2010.

Why a hump and not a void?

Here both functions determining the model are left arbitrary (no handpicked algebraic form containing a few constant parameters, no t_B or $E = \text{const}$), hence no artificial constraints on the solution.

However, as the GBH giant void, this hump is not directly observable: it exists in the space t=now of events simultaneous with our current instant.

By construction, it reproduces the galaxy number counts on our past light cone, hence, even more and more detailed surveys will not be able to see it, at variance with the giant void which does not reproduce the FLRW $\rho = \rho_0(1 + z)^3$.

Important remark: Do not take this toy model at face value. It is only designed to show i) the proper way of dealing with L–T models in cosmology and ii) that a giant void is not mandatory to reproduce observations.

Example of a L–T Swiss-cheese: Marra et al.'s model

The model: Lattice of L–T bubbles with radius $\geq$350 Mpc in E-de S background. Initially, the void at the center of each hole is dominated by negative curvature and a compensating overdensity matches smoothly the density and curvature EdS values at the border of the hole Marra et al. 2007.

Since the voids expand faster than the cheese, the overdense regions contract and become thin shells at the borders of the bubbles while underdense regions turn into emptier voids, eventually occupying most of the volume.

Conclusion: evolution of the voids, bends the photon paths and affects more photon physics than inhomogeneity geometry.

Future prospects: consider QSS models which exhibit enhanced structure evolution.

Extracting the cosmic metric from observations

The inverse problem of deriving the arbitrary functions of a L–T model from observations is very much involved. This is the reason why most of the authors who have tried to deal with this issue have added some a priori constraints to the model Vanderveld et al. 2006, Chung and Romano 2006, Tanimoto and Nambu 2007.

Lu and Hellaby 2007, McClure and Hellaby 2007 and Hellaby and Alfedeed 2009 initiated a program to extract the metric from observations. This is the full inverse problem and is not degenerate. To date it has assumed the metric has the L–T form, as a relatively simple case to start from, though the long term intention is to remove the assumption of spherical symmetry.

They developed and coded an algorithm that generates the L–T metric functions, given observational data on the redshifts, apparent luminosities or angular diameters, number counts of galaxies, estimates for the absolute luminosities or true diameters and source masses, as functions of z. This allows both of the physical functions of an L–T model to be determined without any a priori assumption on their form.

Conclusion

- **The increasing precision of observational data implies that FLRW models must now be considered just a zeroth order approximation, and linear perturbation theory a first order approximation whose domain of validity is an early, nearly homogeneous Universe.**

- **In the nonlinear regime, which was entered since structures formed, there is no escape from the use of exact methods (or of averaging schemes aiming at investigating this issue from the standpoint of backreaction).**

- **L–T models with a central observer are the next order approximations.**

- **In the era of "precision cosmology", inhomogeneity effects on the determination of cosmological models cannot be ignored even if a "dark energy"component is shown in the end to remain in the model. Inhomogeneous models constitute an exact perturbation of the Friedmann background and can reproduce it as a limit with any precision.**

- **Exact inhomogeneous solutions can be employed not only for studying the geometry and dynamics of the Universe (cosmology), but also to investigate the formation and evolution of structures and problems such as that of the horizon.**