We introduce a set of four new publicly available $N$-body simulations, the most recent additions to the Texas P$^3$M Database. Our models probe the less studied parameter space region of moderate volume ($100h^{-1}$Mpc box) combined with fine mass resolution ($\propto 10^{12}M_\odot$, roughly comparable to a $L_\star$ galaxy), making these simulations especially suitable for study of major large-scale structure (LSS) features such as voids, and for comparison with the largest three-dimensional redshift surveys currently available. Our cosmological models (LCDM, TOCDM, OCDM, TCDM) are all COBE-normalized, and when possible (LCDM and TOCDM) also cluster-normalized, based on the X-ray cluster $M$–$T$ relation. The COBE- and cluster-normalized LCDM model reiterates the attractiveness of this currently favored model which does not require the introduction of tilt in order to fit the constraints imposed by observations of other cosmological parameters.

1 Introduction

$N$-body simulations are an essential tool for probing LSS and galaxy formation. As large, high-resolution simulations are computationally costly, one has to carefully consider the added effort resulting from increasing the simulations’ volume or from improving their resolution. In this context, most simulations gravitate towards a design stressing either of these two conflicting goals. The largest three-dimensional redshift surveys currently available are situated somewhere in between these two extremes: a $M_\star$ galaxy in the CfA2 survey is visible out to $100h^{-1}$Mpc. A simulation designed to match these surveys must have both the required resolution to identify the dark matter (DM) halos associated with such galaxies, and this moderately large volume.

The other essential consideration of simulation design is the choice of cosmological models probed. Ideally, one would want to examine a certain range of the relevant cosmological parameters ($H_0, \Omega_0, \lambda_0, \Omega_B, n, \sigma_8$), but this is often not an attainable goal. In this work we focus on cosmological models with currently favored values of $H_0, \Omega_0$ (and $\lambda_0$), and require that all
models will be *COBE*-normalized. The above constraints can still be fulfilled through a variety of primordial power spectrum tilt $n$ and $\sigma_8$ combinations. We attempt to achieve also cluster normalization, hence determining the value of $\sigma_8$ (and thus fixing a tilt value).

## 2 Models

These simulations were designed with the goal of maximizing their volume while still being able to resolve DM halos associated with $L_*$ galaxies. Adopting a mass-to-light ratio of $100M_\odot/L_\odot$, we thus require that we will be able to identify $M_{\text{halo}} \gtrsim 10^{12}M_\odot$ halos. A simulation with $140^3$ particles in a $100h^{-1}\text{Mpc}$ box will have $M_{\text{particle}} = 1.01 \times 10^{11}Ω_0h^{-1}M_\odot$. Identifying all DM halos with 20 particles or more, this parameter specification matches the stated requirements.

Failure to identify halos all the way down to this resolution renders such simulations inappropriate for the study of many LSS features. Specifically, it would be impossible to identify correctly voids in such simulations. Such studies often originate from DM simulations, and use some form of halo populating scheme in order to match the observed properties of the distribution of galaxies. These populating schemes (also known as bias recipes) assign a number of galaxies to each halo. But for such schemes to have a fighting chance at reproducing the distribution of galaxies, one must initially know the locations of the halos that should be populated—including halos that would be populated by just one galaxy.

We estimated that 20 particles per halo is the minimal number required in order to reliably identify halos. As this is getting close to the simulation’s mass resolution limit, we tested the lower end of our DM halo mass function by constructing a matching set of smaller simulation boxes with $M_{\text{particle}}$ an order of magnitude smaller (see Table 1). We can then compare the number density of DM halos in the two sets of boxes and see if indeed we manage to recover the correct number of small halos in the larger simulation boxes.

All simulations were started at an initial redshift $z_i = 24$ and evolved over 600–1000 timesteps using a P$^3$M code over a $256^3$ grid. More details on the simulations can be found elsewhere.

In Table 1 we summarize the cosmological parameters defining our models. Column 1 indicates the models’ acronyms. Columns 2–5 detail the models’ values of the Hubble parameter $h$, density parameter $Ω_0$, cosmological constant $λ_0$, and tilt $n$. Column 6 lists the theoretical $σ_8^{\text{cluster}}$ based on X-ray cluster temperatures. Column 7 lists $σ_8^{\text{cont}}$, the actual value corresponding to each cosmological model. If these two values match, we state that the model is cluster-normalized (Column 8).

We fixed all models to be *COBE*-normalized with $T_{\text{CMB}} = 2.7K$, assuming no contribution from tensor modes. Also, we used $Ω_{B0} = 0.015h^{-2}$ throughout, in concordance with the Texas P$^3$M Database. When practical (all models but TCDM) we adopt a Hubble constant $H_0 = 65\text{km s}^{-1}\text{Mpc}^{-1}$. In addition to *COBE* normalization, we have also tried to achieve cluster normalization. Using the X-ray cluster $M–T$ relation we derived the required $σ_8$ value for each of our models. For each combination of $Ω_0$, $λ_0$, and $H_0$, we computed the tilt required in order to achieve cluster normalization and examined whether it is acceptable in view of the limits allowed by the 4-year *COBE* data.

For two of the models—LCDM and TOCDM—we found an acceptable tilt value and man-
Table 2: Model Parameters

| Model  | \( h \) | \( \Omega_0 \) | \( \lambda_0 \) | \( n \) | \( \sigma_8^{\text{cluster}} \) | \( \sigma_8^{\text{cont}} \) | Cluster-Normalized? |
|--------|--------|------------|-------------|------|----------------|----------------|-------------------|
| TOCDM  | 0.65   | 0.3        | 0           | 1.3  | \( 0.91 \pm 0.09 \) | \( 0.91 \)     | yes               |
| OCDM   | 0.65   | 0.3        | 0           | 1    | \( 0.91 \pm 0.09 \) | \( 0.46 \)     | no                |
| LCDM   | 0.65   | 0.3        | 0.7         | 1    | \( 1.00 \pm 0.09 \) | \( 0.95 \)     | yes               |
| TCDM   | 0.55   | 1          | 0           | 0.7  | \( 0.53 \pm 0.05 \) | \( 0.72 \)     | no                |
| SCDM   | 0.5    | 1          | 0           | 1    | \( 0.53 \pm 0.05 \) | \( 1.27 \)     | no                |

Figure 1: CMB Angular Power Spectra: Observations vs. Models

Table 2 shows the model parameters used for the simulations. The TOCDM model was designed to achieve cluster normalization. The two other models are not cluster-normalized. The OCDM model was designed as a direct companion to the LCDM model, where all the cosmological parameters in both these models—except the value of \( \lambda_0 \)—are the same. The TCDM model is our best attempt with an \( \Omega_0 = 1 \) model, where we used the lowest possible \( \sigma_8 \) value which does not require \( h < 0.55 \) or \( n < 0.7 \). For comparison, we have also included in Table 2 (and in Fig. 1) the familiar SCDM model, although it is not one of the cosmological models simulated.

3 Results

In Fig. 2 we compare the theoretical CMB angular power spectra of the models simulated here with the recent BOOMERanG anisotropy measurements. In Fig. 3 we present cumulative halo mass functions for the two sets of models simulated. Our two cluster-normalized models, LCDM and TOCDM, reproduce similar mass functions. The observational point in the figure \( n (T > 4.0 \text{keV}) = 1.5 \pm 0.4 \times 10^{-6} h^3 \text{Mpc}^{-3} \) is in good agreement with the LCDM cluster abundance. The TOCDM curve follows closely the LCDM curve, but for the former cosmology the observational point would be shifted along the horizontal axis by a factor 0.31/3. However, it should be noted that there are still significant uncertainties associated with both the observational measurements of cluster abundance and the theoretical modeling of the \( M-T \) relation.

There are two curves for each cosmological model in Fig. 2—one representing the mass function as measured in the 100\( h^{-1}\text{Mpc} \) box, the other measured in the 40\( h^{-1}\text{Mpc} \) box. As illustrated in the figure, for each model there is excellent agreement between the two curves.
4 Summary

In this paper we introduce two matching sets of four cosmological models. We derive halo mass functions for all models and use the small box, high resolution simulations in order to verify the validity of the mass function in the large box for halos as small as $\approx 10^{12} \Omega_0 h^{-1} M_\odot$. The simulations presented here are unique as they both cover a volume comparable to current large three-dimensional redshift surveys and at the same time resolve cluster masses down to $M_*$. While the simulations were designed mostly in order to achieve COBE—and, when possible (LCDM and TOCDM), also cluster—normalization, they also serve to demonstrate the attractiveness of the LCDM model. Requests for the simulations presented in this paper, or for other data from the Texas P$^3$M Database, should be sent to database@galileo.as.utexas.edu.

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