Skies And Universes: Accessing cosmological simulations and theoretical predictions.

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ABSTRACT

Numerical simulations play a key important role in modern cosmology. Examples are plenty including the cosmic web – large scale structure of the distribution of galaxies in space – which was first observed in N-body simulations and later discovered in observations. The cuspy dark matter halo profiles, the overabundance of satellites, the Too-Big-Too-Fail problem are other examples of theoretical predictions that have a dramatic impact on recent developments in cosmology and galaxy formation. Large observational surveys such as e.g. SDSS, Euclid, and LSST are intimately connected with extensive cosmological simulations that provide statistical errors and tests for systematics. Accurate predictions for baryonic acoustic oscillations and redshift space distortions from high-resolution and large-volume cosmological simulations are required for interpretation of these large-scale galaxy/qso surveys. However, most of the results from extensive computer simulations, that would be greatly beneficial if publicly available, are still in hands of few research groups. Even when the simulation data is available, sharing vast amounts of data can be overwhelming. We argue that there is an effective and simple path to expand the data access and dissemination of numerous results from different cosmological models. Here we demonstrate that public access can be effectively provided with relatively modest resources. Among different results, we release for the astronomical community terabytes of raw data of the popular Bolshoi and MultiDark simulations. We also provide numerous results that are focused on mimicking observational data and galaxy surveys for major projects. Skies and Universes is a community effort: data are produced and shared by many research groups. We offer to other cosmologists and astronomers to host their data products in the skiesanduniverses.org space.

Key words: methods - cosmology - survey

1 INTRODUCTION

Modern cosmology is a diverse science that to a large degree has changed our views on the Universe. Numerical simulations always played and still play a special role in cosmology. The fact that the large-scale distribution of mass is a complex cosmic web – a system of filaments connecting large clusters of galaxies – was first revealed by numerical simulations [Doroshkevich et al. 1980; Klypin & Shandarin 1983] and later was discovered in observations [de Lapparent et al. 1986]. N-body simulations of the evolution of primordial fluctuations made a number of startling predictions including cuspy dark matter profiles [Flores & Primack 1994; Moore 1994; Navarro et al. 1997] in collapsed halos and diverging numbers of small dark matter satellites orbiting inside galaxies like our Milky Way [Klypin et al. 1999; Moore et al. 1999].

For most of the time the results of large cosmological simulations were available only to a small number of research groups that invested substantial resources in code development and had access to supercomputers. There were no motivations or even means to make the results available for everybody. Dynamics of the field with the fast progress in methods and computer hardware was also a factor impeding dissemination of the computational data: results were becoming outdated way too fast. However, the situation is changing because of a number of reasons. One is the quality of simulations. At some moment the simulations became so good that they stay very useful for a very long time. Examples include the Millennium...
Mock galaxy catalogs is an example of a popular product. Because the process of producing products can be very complex, it is useful to provide public access to these products in an efficient platform.

In response to these demands – both from the theory and observations – we developed tools and assembled large data sets to facilitate public access to different types of products. These data are available on akiesanduniverses.org.

In Section 2, we list different available types of data. In Section 3, we discuss tools to access and analyse the data. Section 4 presents ways of expanding the data sets.

2 DATA

Raw data from N-body simulations

There are different types of “raw” data available on akiesanduniverses.org. These include positions and velocities of particles for many snapshots of Bolshoi, MultiDark, and GLAM simulations:

- GLAM simulations (Klypin & Prada 2017) are done with a new Parallel PM code that uses a large homogenous mesh. As any PM simulation, GLAM simulations are mostly limited by available memory. GLAM simulations have force resolution ranging from 200 kpc to 1 Mpc. The number of particles is typically 1-4 billion. We make available 10 realisations of these simulations with some simulations being available with many snapshots. In the near future we plan to release many more realisations.

- Bolshoi (Klypin et al. 2011, 2016) simulations were done with the Adaptive Mesh Refinement (AMR) type code ART (Kravtsov et al. 1997; Gottloeber & Klypin 2002). Bolshoi simulations have 8 billion particles and reach the force resolution of 1 kpc. A large number of snapshots are released for the public.

- MultiDark simulations (Klypin et al. 2014) were performed with a TREE code GADGET-3 (Springel 2005). They have 56 billion particles and resolution 1-10 kpc. Because of the size of these simulations, only 1-4 snapshots are available for each of the MultiDark simulations. More will be made available in the near future.

A large number of halo catalogs for Bolshoi and MultiDark simulations are available. The halos were identified with spherical-overdensity halo finders Bound Density Maximum (BDM, Riebe et al. 2013) and/or Robust Overdensity Calculation using K-Space Topologically Adaptive Refinement (RockStar, Behroozi et al. 2013). BDM is described in Appendix A of Riebe et al. (2011). RockStar and BDM halo finders were extensively studied and compared (Knebe et al. 2011, Behroozi et al. 2014, 2013). Both BDM and RockStar identify distinct halo and subhalos, but they use different algorithms to do it. The main difference between BDM in RockStar is in the masses of subhalos with RockStar giving bigger masses. Circular velocities show much smaller differences.

Halo identification for GLAM simulations is done with a strip-down version of BDM halo finder. In this case only distinct halos are identified and listed in catalogs.

There are two types of BDM catalogs that differ by the definition of the viral radius. Catalogs with filenames having capital letter V (e.g., CatshortV.0416.DAT) are for the
overdensity $360 \rho_{\text{back}}$ (background density). Catalogs with capital letter W are for $200 \rho_{\text{crit}}$ (critical density) for defining the halo boundary.

We also made available simulation data generated by other groups. At present the user can find halo catalogs for the Lomonosov suite of cosmological simulations Pilipenko et al. (2017). Our site is offered to other groups who have the interest to make publicly available their data and products.

Processed data of N-body simulations

There are a variety of products related with large cosmological simulations on Skies and Universes. Halo catalogs are an example of these products. Other products include halo mass functions and velocity functions measured by Comparat et al. (2017). We also present nonlinear dark matter power spectra for 15,000 realisations of GLAM simulations. Those can be used to study the power spectrum covariance matrix – the stepping stone for producing mock catalogs. Dark matter density distribution functions for 5000 simulations with different resolution, filtering scales and box sizes are given on Skies and Universes.

Mock galaxy catalogs

Different types of mock galaxy/qso catalogs can be found on skiesanduniverses.org. We expect that more will be available in the near future for eBOSS, Euclid, DESI and eROSITA. Currently we provide:

- Galaxy and QSO mock catalogs for the SDSS DR7 (Favole et al. 2017), BOSS DR12 (Rodríguez-Torres et al. 2016; Kitaura et al. 2016) and eBOSS (Favole et al. 2016; Rodríguez-Torres et al. 2017).
- MultiDark-Galaxies Catalogs of galaxies made with the GALACTICUS, SAG and SAGE semi-analytical models of galaxy formation (Knebe et al. 2017).
- MultiDarkLens provides to the scientific community high quality weak lensing data using the MultiDark cosmological N-body simulations (Giocoli et al. 2016)
- LoRCA (Comparat et al. 2016a) Galaxy mock catalogs for the Calar Alto Local Universe survey.

Observational products

We also host galaxy spectra as well as catalogs of measured galaxy emission lines that constitute the basis to two studies of the emission line luminosity functions (see Comparat et al. 2013, 2016b). These are available with the pull down menu under Products, Observations.

3 ANALYSIS

The raw particle data are written as unformatted fortran files. Routines to read the data are provided and description of data formats are given. These routines should be used as templates for building analysis tools. The particle data sets are so large that one should use parallel programming tools – either MPI or OpenMP – to analyse the data. The data format used to store the data was developed to facilitate the parallel processing. Data were split into a large number of boxes covering the whole computational domain. Each box is surrounded with $\sim 5$ Mpc-wide buffer allowing users to analyse each box separately and then combine the results to produce final result for the whole simulation. This splitting of the simulation was also designed to make MPI parallelization easier. Other data products are written as compressed ASCII tables.

Users should be aware about the size of available data sets. Downloading of these large files may take days. We do not provide support with data analysis. People, who access the data in skiesanduniverses.org are supposed to download the data they need and to build their own tools to analyse the data. However, there are some codes that we plan to make available to facilitate reading e.g. the MultiDark-Galaxy data and also perform part of the analysis.

4 EXPANDING THE NET

The main goal of the Skies and Universes space is to provide access for the astronomical community with results from cosmological simulations. These results are useful on their own to understand processes related with the non-linear evolution of cosmic structures. Some other products are specifically focused on large survey observational projects. To facilitate the interaction between the theory and observations we also provide links to recent observational projects.

This data repository is not designed for an easy and simple access to a small portion of large data sets. There are other sites, that provide this type of access. Data on our site are for analysis that requires extensive computer resources. Users are expected to carefully choose the data they need and download them once.

While the amount and diversity of data on skiesanduniverses.org are substantial, it is important to emphasise that this is just a proof of concept to demonstrate that it is possible to provide access to the general astronomical community to a vast amount of data having only very limited computer resources. This is the reason why we stay away from creating traditional databases, which are used in cosmosim.org and millennium database.

It is relatively straightforward to expand the data available through skiesanduniverses.org We can host significant data sets. Larger datasets can be made available by cross-linking data visible on the internet.

We encourage other groups to contact us if they are interested to host their simulation products in skiesanduniverses.org

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