Universe(s) in a box

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Abstract

The IllustrisTNG simulations (www.tng-project.org) are a novel laboratory to explore galaxy physics and to quantify the assembly and evolution of galaxy populations across an unprecedented range of masses, environments, evolutionary stages and cosmic times. IllustrisTNG is an ongoing program of large cosmological volume simulations where gravity, magnetohydrodynamics, and prescriptions for star formation, stellar evolution, the enrichment of gas with chemical elements beyond Helium, cooling and heating of the gas, galactic outflows and feedback from the supermassive black holes are all taken into account within the LCDM cosmology, i.e. the standard cosmological paradigm. In practice, in these simulations we simultaneously resolve and model the structural details of thousands of galaxies together with the large-scale cosmic web. Here, we summarize our efforts to generate and effectively exploit such simulations, showcase some of the insights they are allowing us to uncover and quantify, and describe our strategies for dissemination.

Keywords: methods: numerical – galaxies: formation – galaxies: evolution – galaxies: haloes – general cosmology: theory

1. The IllustrisTNG Simulation Series

IllustrisTNG (Fig. 1) is the follow-up project of the Illustris simulation (www.illustris-project.org). Upon completion, it will consist of three large cosmological volumes, TNG50, TNG100, and TNG300 of about 50, 100, and 300 Mpc on a side, respectively. TNG100 features the same resolution and initial condition phases as Illustris, while TNG50 and TNG300 extend the series to a better resolution and a larger volume, respectively.

IllustrisTNG uses the AREPO code to solve the coupled equations of gravity and magneto hydrodynamics in an expanding universe. Additionally, within the simulations, a comprehensive galaxy formation model allows us to follow the coevolution of dark matter, cosmic gas, stars, supermassive black holes and magnetic fields. This follows radiative gas cooling modulated by a time-variable ultraviolet background, star formation regulated by a subgrid model for the interstellar medium, galactic wind feedback powered by supernova explosions, a detailed metal enrichment model that tracks nine elements and uses metallicity-dependent yields from SN-II, SN-Ia, and asymptotic giant branch stars, growth of supermassive BHs through Bondi gas accretion and BH mergers, as well as thermal quasar feedback in high accretion rate states, and kinetic BH wind feedback in low accretion rate states of the BHs. The magnetic fields are followed with ideal MHD and are dynamically coupled to the gas through the magnetic pressure includes a new kinetic black hole (BH) feedback and a revised scheme for galactic winds, among other changes.

The flagship runs of the IllustrisTNG project have been calculated at the Hornet and Hazel Hen supercomputers of the High Performance Computing Center in Stuttgart (Ger-

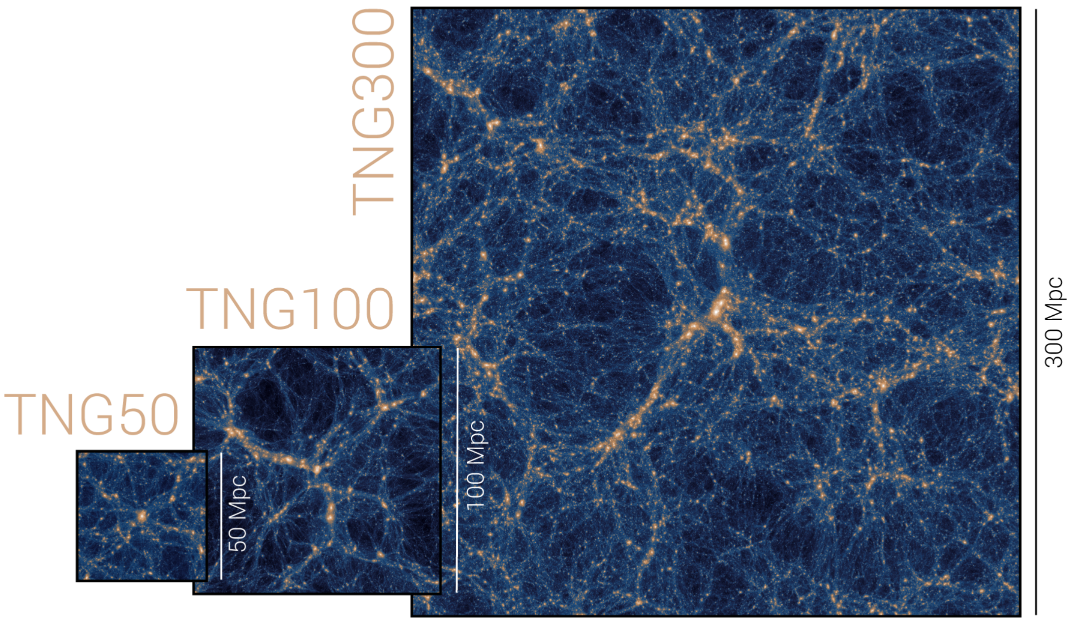

Figure 1: The three flagship runs of the IllustrisTNG series. The number in the name is the approximate side length in comoving Mpc of the periodic boundary simulated cubes. The images depict the dark-matter projected density.

many), with field-leading computational investments of more than 180 million core hours in total with massively parallel runs on up to 24k compute cores.

2. The outcome of the IllustrisTNG Simulations

A number of outcomes from the IllustrisTNG simulations have been shown to be consistent with observations: e.g. the shape and width of the red sequence and the blue cloud of $z = 0$ galaxies (Nelson et al. 2018a), the distributions of metals in the intra-cluster medium at low redshifts (Vogelsberger et al. 2018), the evolution of the galaxy mass-metallicity relation (Torrey et al. 2018) and of the galaxy size-mass relation for star-forming and quiescent galaxies at $0 \lesssim z \lesssim 2$ (Genel et al. 2018), the amount and distribution of highly-ionized Oxygen around galaxies (Nelson et al. 2018b), and the dark matter fractions within the bodies of massive galaxies at $z = 0$ (Lovell et al. 2018). All these validations of the model make the IllustrisTNG simulations an ideal laboratory to further investigate galaxy formation and evolution, and are illustrated and partially summarized in Figure 2.

3. Dissemination strategies

At the time of writing, 24 scientific analysis papers have already been completed based on the IllustrisTNG simulations after 2017, in addition to about 110 ongoing analysis projects from a large group of researchers and their students to whom we have already made available the entire simulation outputs, prior to its more widespread public release. In fact, using the experience gained during the Illustris Public Data Release (Nelson et al. 2015), we have already publicly released the data from the TNG100 and TNG300 runs (see Nelson et al. 2019 and http://www.tng-project.org/data/).

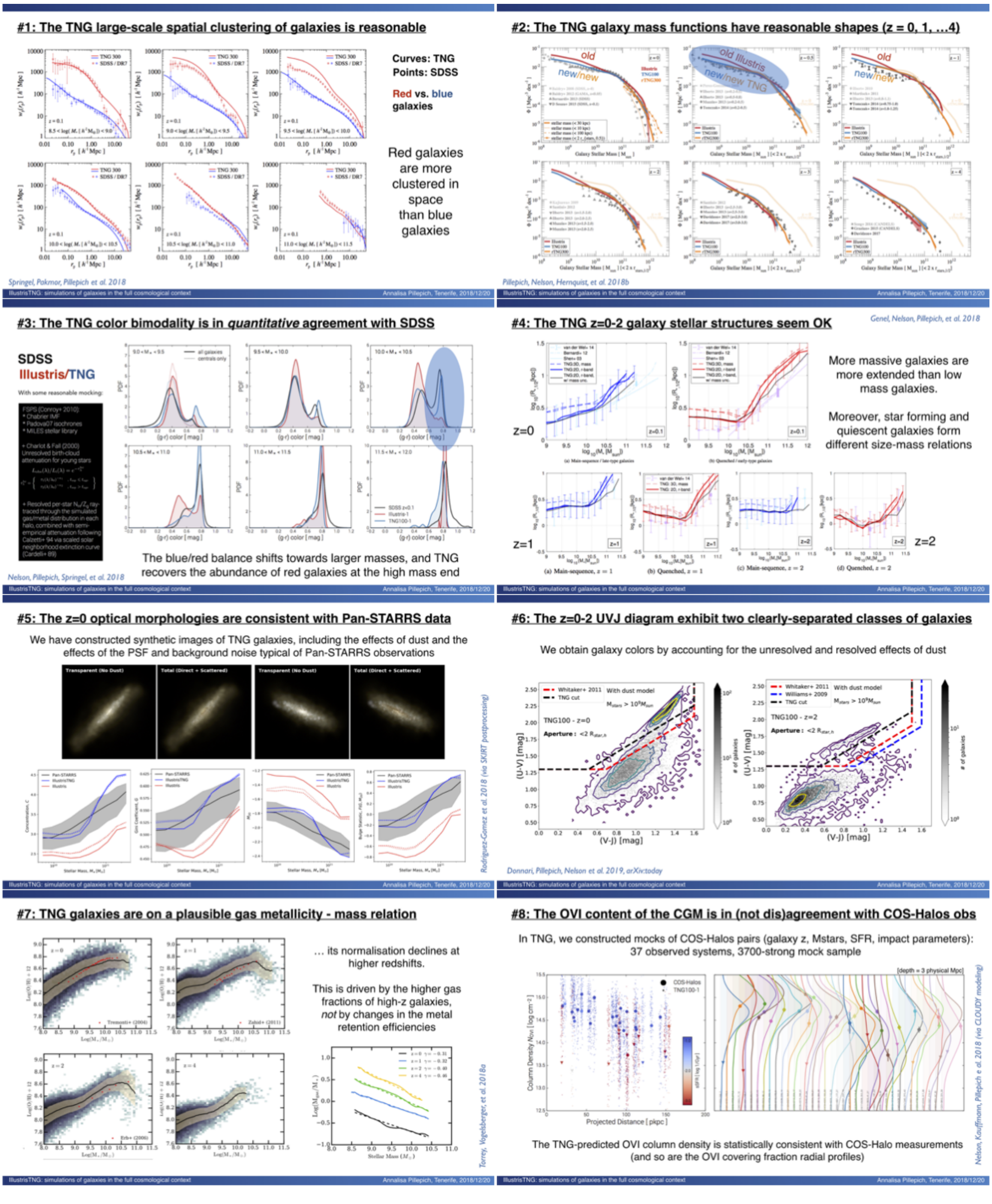

Figure 2: Illustration and summary of some of the qualitative and quantitative confirmations of the IllustrisTNG model against observational constraints on the statistical and structural properties of galaxies.

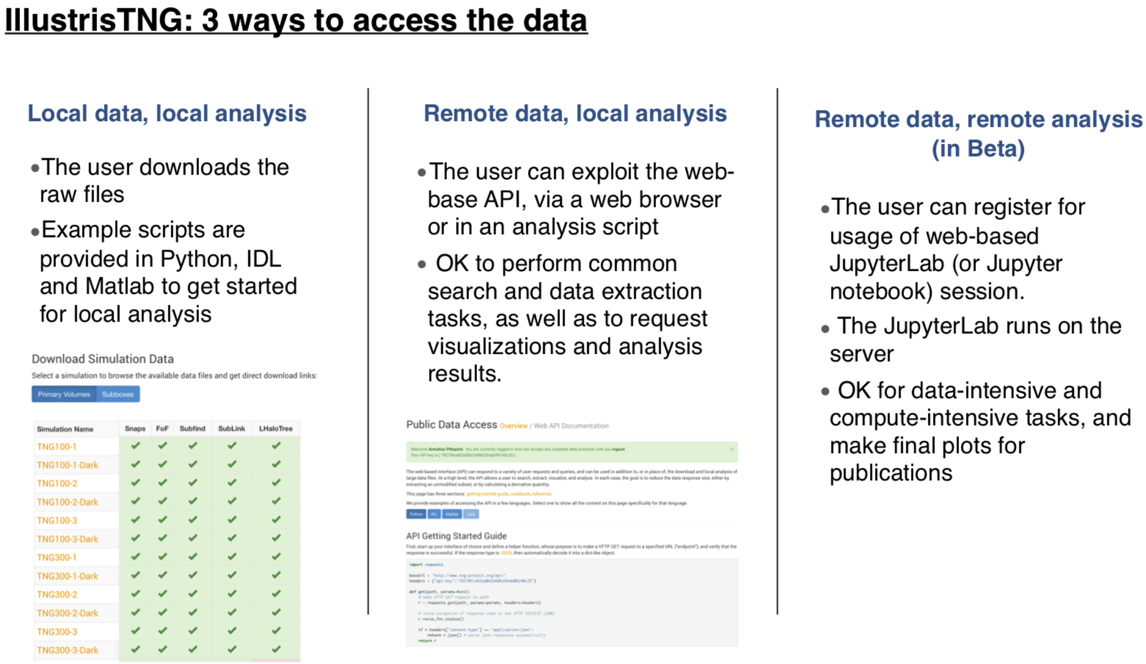

Figure 3: Illustration of the three main access strategies to the publicly available data of the Illustris/TNG simulation projects.

Since its release, the original Illustris public data has seen widespread adoption and use. To date, in the three and a half years since launch, 2122 new users have registered and made a total of 269 million API requests. The total data transfer for this simulation to date is about 2.15 PB. Since its launch, there has been a nearly constant number of 100-120 active users (on a monthly average). To date, 163 publications have directly resulted from, or included analysis results from, the Illustris simulation. Given the significantly expanded scope of IllustrisTNG with respect to Illustris, as well as the relatively more robust and reliable physical model and outcomes, we expect that uptake and usage will be similarly broad. The data volume from the Illustris/TNG simulations that is now directly accessible online is about 750 TB, including 1200 full volume snapshots and about 80,000 high time-resolution subbox snapshots. This will increase to about 1.1 PB with the future release of TNG50. Data access and analysis examples are available in IDL, Python, and Matlab and we have setup three main strategies to access the data, depending on the familiarity and goals of the diverse pool of users (see Fig. 3 for a scheme).

Acknowledgments

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Please refer to the websites www.illustris-project.org and www.tng-project.org for all bibliographic references.