# Multi-Scale Simulations of the Universe: Comparisons of IllustrisTNG, Thesan, and EPOCH

Qian Wu[a]
*Birkbeck, University of London, London, U.K.*

Keywords: Cosmological Simulations, Galaxy Formation and Evolution, Reionisation, Particle-in-cell (PIC) Plasma Physics, Radiation Hydrodynamics.

Abstract: Contemporarily, various multi-scale simulations of the universe are proposed. This study compares three advanced astrophysical simulation frameworks, i.e., IllustrisTNG, Thesan, and EPOCH, each designed to model different cosmic phenomena across varying physical scales. IllustrisTNG simulates galaxy formation and large-scale structure evolution using moving-mesh hydrodynamics and gravitational equations from early cosmic times to the present. Thesan focuses on the Epoch of Reionization, incorporating radiation-hydrodynamics, dust physics, and magnetohydrodynamics to model the ionization of the intergalactic medium by early galaxies. EPOCH applies the particle-in-cell (PIC) method to simulate kinetic plasma processes under strong electromagnetic fields, solving Maxwell's equations and the Lorentz force law to capture phenomena such as shock acceleration and magnetic reconnection. These simulations offer complementary strengths: from cosmic web formation to feedback-driven ionization and relativistic plasma dynamics. By comparing their physical models, resolution strategies, and limitations, this paper reveals the need for multi-scale, multi-physics integration to bridge gaps between microphysical plasma processes and the evolution of large-scale cosmic structure.

## 1 INTRODUCTION

Astrophysical simulations can studies galaxy formation to plasma physics and understand the cosmic phenomena. There are several fundamental physics equations to explain are based on these simulations, such as Newton gravity to model the large-scale cosmic structures, relativistic fluid dynamics solve the high-energy processes and magnetohydrodynamics to simulate the stellar evolutions.

The history of theory and observations is linked to astrophysical simulations of stars in the mid-20th century; there are two methods: Monte Carlo methods and N-body and N-body simulations (Aarseth, 2003). In 1943, Chandrasekhar used random sampling to avoid $O(N^2)$ complexity by using random sampling instead of computing all pairs of gravitational forces, which makes it faster for computing large-scale simulations, and it can be used to estimate stellar interactions statistically (Garaldi, et al., 2022). Subsequently, in the 1963s, N-body simulations calculated the gravitational forces between stars using Newton's law of gravity, which is exerted on each particle (star) by every other particle in a system (Yeh et al., 2023). This method developed higher-order integration schemes to improve simulation accuracy, but it was limited by computational limits; increasing the number of stars would significantly slow down the calculations. Building on these two methods, the Smoothed Particle Hydrodynamics techniques (1970s) and the Barnes-Hut method (1986) improved the modelling of gas dynamics in star formation (Monaghan, 2005), reducing the computational complexity from $O(N^2)$ to $O(N \log N)$ respectively (Session 2-2). Since 2000, advanced particle-in-cell (PIC) simulations have allowed detailed studies of kinetic plasma processes in magnetised environments, such as magnetic reconnection and cosmic ray acceleration. Starting with early astrophysical environments such as stellar winds, supernova remnants and accretion disks, PIC methods became essential for exploring how charged particles

[a] https://orcid.org/0009-0002-8801-6068



Wu, Q.
Multi-Scale Simulations of the Universe: Comparisons of IllustrisTNG, Thesan, and EPOCH.
DOI: 10.5220/0013824100004708

In *Proceedings of the 2nd International Conference on Innovations in Applied Mathematics, Physics, and Astronomy (IAMPA 2025)*, pages 272-280
ISBN: 978-989-758-774-0

behave in strong electric and magnetic fields (Hansen, et al., 2024).

The resulting codes, such as EPOCH, use kinetic plasma models and solve Maxwell's equations alongside the Lorentz force law to simulate particle dynamics in highly magnetised regions. This allows realistic simulations of magnetic reconnection, plasma heating and shock-driven acceleration in environments such as black hole jets, pulsar magnetospheres and relativistic shocks (Hansen, et al., 2024). Unlike traditional fluid codes, EPOCH tracks individual particle motions rather than averaging over large volumes, making it suitable for small-scale, high-energy astrophysical scenarios.

Otherwise, there is a simulation called Millennium, which focused only on dark matter structure formation, but did not include baryonic physics such as gas dynamics or radiation transfer, making it less relevant for today's multiphysics simulations (Vogelsberger, et al., 2020). Therefore, after all these previous simulations, modern astrophysical simulations are developed; for example, the IllustrisTNG and Thesan simulations are developed. These two simulations can modify galaxy formation and cosmic reionisation more accurately.

This article focuses on three major modern simulations: Illus trisTNG, THesan and EPOCH. These simulations have their unique discoveries. First, IllustrisTNG has significant dark matter results and simulates galaxies' evolution from the Big Bang to the present (Nelson, et al., 2019). It shows that dark matter halos control galaxy formation, and the cosmic web structure in this simulation is consistent with real observations (Nelson, et al., 2019). In addition, IllustrisTNG explains star formation in galaxies by showing that the rate of star birth peaked 10 billion years ago and that supernova explosions and black hole feedback regulate star growth (Pillepich, et al., 2018). It also proves that supermassive black holes at galactic centres release AGN feedback, which heats the surrounding gas and prevents star formation, showing how large galaxies stop forming stars (Pillepich, et al., 2018). The IllustrisTNG simulation also shows the strengthening of the magnetic field in galaxies over time (Marinacci, et al., 2018)and the baryon cycle (where gas falls into galaxies, forms stars and is then ejected by galactic winds) (Pillepich, et al., 2018). These processes model the movement of gas and the enrichment of elements in the Universe. Second, Thesan's simulation shows the process of early stars and galaxies emitting ultraviolet radiation, which ionizes the neutral hydrogen in the intergalactic medium (IGM) (Kannan, et al., 2022). Currently, it simulates how ionization bubbles form around the first galaxies and gradually expands, creating a dense region that ionizes earlier and showing an inhomogeneous reionization pattern. This process can show that low-mass galaxies are more efficient at letting UV photons escape, while high-mass galaxies trap more radiation and slow down the reionization process (Kannan, et al., 2022). Thesan also shows that reionization has a significant effect on galaxy clustering. Galaxies that form earlier tend to cluster more densely, forming dense clusters with surrounding neutral voids (Garaldi, et al., 2024).

Finally, PIC and EPOCH simulations are very important for studying plasma physics and high-energy astrophysics. EPOCH uses the particle-in-cell (PIC) approach to model how electrically charged particles and fields interact with each other (Arber, et al., 2015). This is done at very high resolutions that show how things move and change over time and space. In this simulation, magnetic fields are recreated and break down, and then reform, which creates plasmoids and speeds up particles in fast jets (Smith, et al., 2021). EPOCH also reproduces physical conditions found in supernova remnants, where shock waves interact with magnetized plasma (Arber, et al., 2015). Through solving Maxwell's equations and the Lorentz force law, EPOCH tracks the behavior of electrons and ions during these violent events, showing how energy is converted from magnetic fields into particle motion and radiation (Arber, et al., 2015). These kinetic-scale processes cannot be resolved by fluid-based simulations, making EPOCH essential for studying relativistic jets, pulsar magnetospheres, and cosmic ray acceleration in extreme astrophysical settings (Smith, et al., 2021).

This paper compares three astrophysical simulations: IllustrisTNG, Thesan and EPOCH. Each section will investigate the equations, capabilities, and recent results of these simulations. Finally, a comparative analysis will highlight their strengths, limitations, and future directions for improving astrophysical modelling.

# 2 DESCRIPTIONS OF ASTROPHYSICS SIMULATIONS

The IllustrisTNG, Thesan and EPOCH methods are major astrophysical simulations used to model various cosmic processes. These simulations attempt to reproduce the complex physical interactions in space. They use sophisticated numerical approaches to describe how galaxies, dark matter, stars, and plasma have evolved. Mass distributions, velocity field distributions and charge distributions are the main outputs of these simulations (Nelson, et al., 2019). First, they produce maps showing how mass is distributed - including where galaxies, dark matter and stars are located in space (Springel, et al., 2005). They trace the gravitational clustering of matter through time. Then, they build structure models, including galaxy clusters and dark matter halos (Pillepich, et al., 2018). These maps simulate the large-scale formation of cosmic structure through the visual representation of the cosmic web of filaments and clusters (Springel, et al., 2005). Dark matter halos provide the gravitational scaffolding from which galaxies form, and galaxies cluster along filaments, creating an area of high-density nodes. Based on the IllustrisTNG simulations, such models provide a good representation of how small density fluctuations of the early Universe grew through gravity, leading to the formation of the cosmic web as one knows it today. Second, the velocity field distribution shows how cosmic objects like gas, stars, and dark matter move through time. It uses fundamental equations such as Newton's law of gravity (gas flows in galaxies) to show cosmic structures such as galaxy clusters (Pillepich, et al., 2018), Navier-Stokes equations (stars move under gravitational binding) to solve the formation of dark matter halos (Vogelsberger, et al., 2014), and magnetohydrodynamics equations (magnetic forces affect plasma motion) that evolve over billions of years (Kannan, et al., 2022). All three main simulations solve these equations to produce dynamic velocity maps that reveal cosmic objects' motion patterns and interactions. Last, charge distribution is very useful in plasma physics and tells us about the current distribution in the space where charged particles like electrons and ions are present (Fonseca, et al., 2022). This directly modifies the evolution and interaction of the electric and magnetic fields with charged particles, which is critical for the investigation of magnetic field interactions and plasma instabilities (Springel, et al., 2005). Maxwell's equations describe charge distribution, e.g. Gauss's law relates electric field divergence to charge density, and Ampere's law relates magnetic field curvature to current density (Arber, et al., 2015). These are the equations for how moving charges create magnetic fields. This distribution model is used by the Particle-in-Cell simulation to calculate the movement of charged particles by electromagnetic forces, but also keeps track of how the electric and magnetic fields change (Fonseca, et al., 2022).

# 3 LARGE-SCALE COSMOLOGICAL MODELLING WITH ILLUSTRISTNG

Large cosmological simulations such as IllustrisTNG, which includes the evolution of dark matter, baryonic matter and complex baryon-dominated processes such as supernova feedback, galaxy mergers, galaxy quenching and outflows (Pillepich, et al., 2018). The original Illustris simulation has been significantly improved, using better computational techniques and physical laws in the new simulation (Pillepich, et al., 2018). Firstly, IllustrisTNG uses the AREPO code, which uses a moving mesh approach to solve the hydrodynamical equations and follow the evolution of gas, stars, dark matter and black holes within cosmic volumes ranging from 50 Mpc to 300 Mpc on a side (Marinacci, et al., 2018). This technique involves billions of particles representing units of mass, velocity and energy. Thus, the basic equations implemented in IllustrisTNG consist of the equations of gravity and hydrodynamics (and thus an accurate calculation of the formation of cosmic structures) (Vogelsberger, et al., 2014). First, the gravity equations are based on Newtonian gravity and general relativity, using Newton's Law of Gravitation equation (Smith, et al., 2021). F in equation means the gravitational force, G is the gravitational constant, m1and m2 are the masses of interacting particles, r is he distance between them. While, to calculate the gravitational potential, the simulation uses Poisson's equation: $\nabla 2\Phi=4\pi G\rho$. The $\nabla$ means divergence, $\Phi$ is he gravitational potential; $\rho$ is the mass density. The results of these modelling can make more accurate gravitational clustering and the formation of dark matter halos. Second, hydrodynamic equations are modelled using Smoothed Particle Hydrodynamics (SPH), where gas dynamics are treated as fluid particles with basic physic properties like mass, velocity, and pressure. Explaining mass conservation can use the continuity equation:

$$\left(\frac{\partial \rho}{\partial t}\right) + \nabla j = 0 \qquad (1)$$

Here, j is the flux of q (It is flowing, which described by its flux), also means a vector field. j = ρv, which v is the velocity field that describes the motion of the quantity q. While, explaining pressure gradients and gravitational forces acting on the gas use the Navier–Stokes momentum conservation equation:

$$\left(\frac{\partial v}{\partial t}\right) = -\left(\frac{1}{\rho}\right) \nabla P - \nabla \Phi \qquad (2)$$

which P is the pressure. Last, among the most important parameters are up to three types of feedback involved in star formation: supernova feedback (the phenomenon in which massive stars explode and eject energy and gas into space, creating shock waves that heat the surrounding gas) (Springel, et al., 2005). This heating prevents the gas from cooling down and collapsing, which slows down the star formation rate of the galaxy. Also, there are stellar winds - streams of charged particles blown away from stars, driven by radiation pressure or magnetic activity. These winds sweep away surrounding gas and heat the interstellar medium (ISM), reducing the gas density and slowing star formation. Finally, there is the feedback from active galactic nuclei, where a supermassive black hole at the centre of a galaxy emits jets and winds that heat gas and drive it outwards. This mechanism is responsible for cooling the gas and thus for star formation. In addition, IllustrisTNG has five main functions and outputs. The first is the mapping of these dark matter halos, which tracks how halos form and evolve, and illustrates how they cluster along these cosmic filaments.

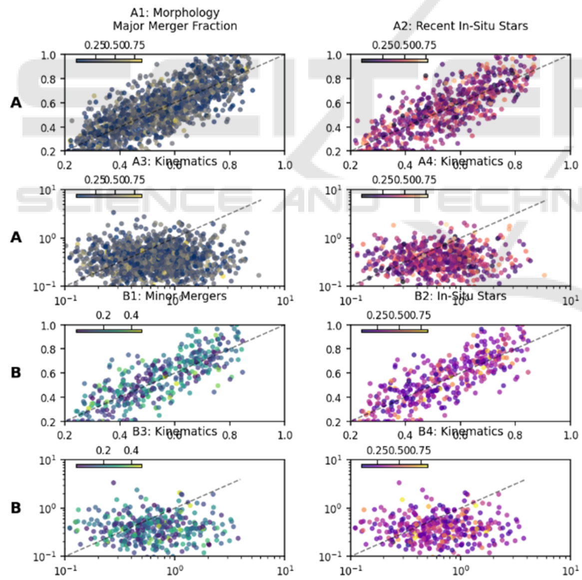


Figure 1: Impact of mergers on stellar-dark matter alignment in IllustrisTNG galaxies (Garaldi, et al., 2021).

Figure 1 compares the effect of major and minor mergers on the ratio of stars to dark matter (DM) in galaxies, using data from the IllustrisTNG simulation (TNG100-1) (Garaldi, et al., 2021). The figure contains 8 scatter plots, divided into Panel A (major mergers, top two rows) and Panel B (minor mergers, bottom two rows). Each panel shows how galaxy morphology ($q = c/a$, shape-axis ratio) and kinematics ($V/\sigma$, rotation-to-dispersion ratio) align between stars (x-axis) and DM (y-axis). Points above the diagonal indicate galaxies where the DM is rounder or less rotationally supported than the stars. Colour bars indicate different physical quantities: Panels A1 and B1 show stellar masses from mergers ($\Delta M$,major or $\Delta M$,minor / M), A2 and B2 show recent in-situ star formation since redshift $z = 1$ ( $\Delta$ insitu,$z \leqslant 1$), and A3-B4 show how these quantities influence galaxy motion. The results show that large mergers cause a stronger alignment between stars and DM in both shape and motion, while smaller mergers show weaker trends. Galaxies with little recent star formation (blue dots) retain tighter coupling, suggesting that dry mergers preserve structure better than gas-rich mergers. This data is taken from the IllustrisTNG website.

## 4 RADIATION HYDRODYNAMIC SIMULATIONS OF REIONIZATION

The Thesan project represents an innovative, extensive cosmological simulation focused on the Epoch of Reionization (EQR) (Kannan, et al., 2022). The final phase involves the formation of the first stars and galaxies, and the ionizing influence on neutral hydrogen in the intergalactic medium (IGM). The purpose of this simulation is to determine that the timing of reionization, how quickly it occurred, and identify the galaxies that played a crucial role in this process. There are physical processes of Thesan project, the most important is feedback from star formation, positioning it as one of the most thorough and realistic simulations of the early universe available to date (Garaldi, et al., 2024). Other processes are such as radiation-hydrodynamics, dust absorption, and magnetic fields (Garaldi, et al., 2022). First of all, Thesan's radiation hydrodynamics couples the motion of ionising photons to the heating, ionisation and dynamics of the gas. This is important because starlight affects the temperature and ionisation levels of the surrounding hydrogen gas, and thus the growth of galaxies. In contrast, Thesan uses the M1 moment method to handle the radiative transfer equations, allowing the calculation of both the energy and direction of the radiation, similar to IllustrisTNG. The radiation equations in Thesan are fully integrated with the gas evolution, allowing the ionised shells surrounding galaxies to be tracked in real time without relying on the assumption of a uniform UV background (Kannan, et al., 2022).

Secondly, Thesan also took into account the physics of cosmic dust, which affects the absorption and scattering of radiation. Dust particles can either scatter or absorb ionising photons, changing the amount of light emitted by galaxies. This phenomenon affects the observed luminosity of galaxies and the timing of reionisation. By taking dust into account, Thesan can accurately represent the physically realistic escape fractions of photons, which depend on factors such as galaxy mass, gas density and metallicity (Yeh et al., 2023).

Thirdly, Magnetic fields are modelled using the magneto-hydrodynamic (MHD) equations, which influence gas pressure, star formation and feedback mechanisms (Kannan, et al., 2022). Thesan develops the magnetic field B by using a revised set of MHD equations, which includes magnetic tension and pressure terms in the fluid momentum equation. This inclusion helps to explain the structure of cosmic filaments and the turbulence within galaxies (Garaldi, et al., 2022).

Finally, Thesan takes a complete feedback geometry from star formation feedback, with a particular focus on supernovae and stellar winds. When massive stars die, they explode, releasing energy into the surrounding gas. This energy input prevents the gas from collapsing and thus plays a role in regulating star formation. Thesan uses models that simulate energy injection and thermal feedback to represent this phenomenon. It also investigates the effect of this feedback on the escape fraction of ultraviolet (UV) light Thesan suggests that low-mass galaxies are likely to have higher escape fractions as they struggle to retain gas, while high-mass galaxies are more effective at trapping photons due to their denser gas environments (Yeh et al., 2023).

Moreover, Thesan is built on the AREPO-RT code, an extension of the AREPO code that adds radiative transfer to a moving mesh system. This code solves the equations for mass, momentum, energy, and ionization state of gas on a mesh that moves with the gas flow. The moving mesh method allows for higher resolution where the gas is denser, such as in galaxies. Thesan also solves Poisson's equation:

$$\nabla^2\Phi = 4\pi G\rho \quad (3)$$

where $\Phi$ is gravitational potential and $\rho$ is mass density. This equation relates mass to gravity, helping simulate gravitational clustering. Thesan covers a volume of 200 comoving megaparsecs (Mpc), with a resolution of up to $2\times1536^3$ elements, which is better than IllustrisTNG. It also improves spatial and time resolution to better simulate reionization (Garaldi, et al., 2024).

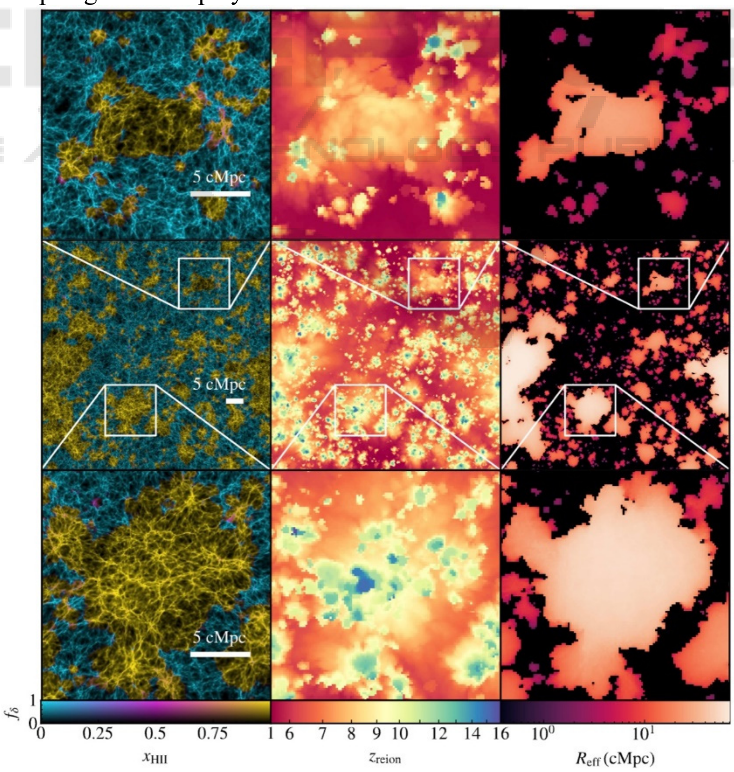


Figure 2: Visualization of the ionization structure and ionization history in Thesan-1 (Neyer, et al., 2024).

Compared to IllustrisTNG, Thesan offers several improvements. First, Thesan includes full radiative transfer instead of assuming a fixed UV background. Second, it calculates the escape fraction of radiation based on actual local gas conditions rather than fixed values (Yeh et al., 2023). Third, Thesan includes dust physics and magnetic fields, which allows it to simulate reionization as a patchy and dynamic process instead of a uniform one. These features allow Thesan to show how galaxy clustering is related to reionised regions, something that fixed background models cannot do (Garaldi, et al., 2022). However, Thesan has its limitations. It focuses on the early, high-redshift universe and does not evolve galaxies to the present day, unlike IllustrisTNG. Also, because it fully couples radiation with gas physics, it requires much more computing time and memory. Nevertheless, Thesan provides new insights into how galaxies, gas and light interacted during the epoch of reionisation, and will be a valuable tool for comparison with data from modern telescopes such as JWST and ALMA (Kannan, et al., 2022).

Figure 2 shows the Thesan-1 simulation box and zoom-in regions during the reionisation epoch. Each row shows a different spatial scale: the middle row is the full 200 cMpc box, and the top and bottom rows are zoom-in regions (marked by six white boxes). Each column shows a different property: the left column shows the ionised hydrogen fraction $x$ HII, the middle column shows the reionisation redshift $z$ reion, and the right column shows the effective ionised bubble size. The colours represent physical values - blue to yellow in $x$ HII mark neutral to ionized gas, with brightness based on overdensity $f$ $\delta$; $z$ region shows when each region was ionized (higher redshift means earlier), and $R$ eff shows how large each ionized region is (Neyer, et al., 2024). All 5 cMpc bars indicate the physical scale. The figure shows that reionisation is patchy, shaped by galaxies and gas. It supports Thesan's model of radiation hydrodynamics and feedback. It shows how Thesan tracks local radiation escape, bubble growth and galaxy clustering during reionisation. This demonstrates Thesan's strength in resolving the structure and timing of early cosmic light.

# 5 ASTROPHYSICAL KINETIC PLASMA DYNAMICS

EPOCH (Extendable PIC Open Collaboration) is a simulation framework designed to study high-energy plasmas in astrophysical and laboratory environments. It differs from the other two cosmological computations mentioned in the last two software sections, which mainly study large-scale structures and the process of galaxy formation. EPOCH operates on kinetic scales, where the collective interactions of a few particles and electromagnetic fields govern the behaviour of matter (Arber, et al., 2015).

The PIC approach tracks particles with respect to phase space and solves Maxwell's equations on a grid. Every particle has position, velocity, charge, and mass. These particles drift in space and treat such translocations as inventive electric (E) and magnetic (B) fields. The fields then act on the particles via the Lorentz force law. This looping continues for time steps. The main Maxwell's equations are:

$$\nabla \cdot \mathrm{E} = \frac{\rho}{\varepsilon^0} \quad (4)$$

$$\nabla \cdot B = 0 \quad (5)$$

$$\nabla \cdot \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial \mathrm{t}} \quad (6)$$

$$\nabla \cdot \mathrm{B} = \mu_0 \mathrm{J} + \mu_0 \varepsilon_0 \frac{\partial \mathrm{E}}{\partial \mathrm{t}} \quad (7)$$

where E is the electric field, B is the magnetic field, ρ is charge density, J is current density, $\varepsilon_0$ is vacuum permittivity, and $\mu_0$ is vacuum permeability. These fields are propagated over a grid using a finite-difference time-domain (FDTD) method (Smith, et al., 2021). Moreover, the particles are accelerated via the Lorentz force law (for particle motion):

$$F = q(E + v \times B) \quad (8)$$

where F = force, q = particle charge, v = particle velocity, E and B = local electric and magnetic fields.

These calculations allow EPOCH to simulate non-linear plasma physics with the accuracy afforded by relativity. One example is the use of EPOCH for laser-plasma interactions, where an extremely high intensity laser beam is fired at plasma targets. This allows studies of the acceleration of ions and the generation of wake fields, which are important for energy transfer in astrophysical explosions (Arber, et al., 2015). A further highlight of EPOCH is its handling of magnetic reconnection, a physically relevant process in plasma environments where magnetic field lines break and reconnect (Smith, et al., 2021). This converts stored magnetic energy into kinetic and thermal energy, resulting in flares, jets and bursts. It is predicted that reconnection events lead to the release of gamma-ray bursts in the magnetospheres of pulsars, where neutron stars spin up and generate intense magnetic fields. EPOCH models the fine structure of the fields and the dynamics of the particle pairs produced (Smith, et al., 2021).

Compared to traditional fluid-based simulations such as IllustrisTNG or Thesan, which use hydrodynamic or magnetohydrodynamic (MHD) equations, EPOCH solves kinetic plasma equations at the particle level. It does not model gravity or large-scale cosmic structure, but addresses microphysics that fluid codes cannot resolve. This gives it high fidelity for studying plasma behaviour in atoropes or extreme conditions. Currently, EPOCH has its own limitations. It cannot model large galaxies or cosmological evolution in time. In addition, due to the small time steps and the need to track millions of particles in PIC simulations, EPOCH is extremely computationally expensive, especially in 3D runs (Arber, et al., 2015). In conclusion, EPOCH is not intended to replace large-scale simulations, but to complement them. It provides a more detailed understanding of the plasma microphysics responsible for radiation, energy transport and particle acceleration in many astrophysical settings, ranging from supernova remnants and neutron stars to active galactic nuclei (Arber, et al., 2015).

Figure 3 shows two 2D particle-in-cell (PIC) simulations using EPOCH. Both simulations use a 5 ps laser pulse, but the top panel has no pre-plasma, while the bottom panel has pre-plasma. The x-axis (μm) shows the distance along the laser direction and the y-axis shows the transverse spatial dimension. The colour bar on the right shows the plasma density from 3.0 × 10 cm-³ (blue, low density) to 3.0 × 10 22 cm-³ (yellow, high density) (Peebles, et al., 2017). In the top image, the laser enters clean plasma and focuses only near the dense target. The electric field is narrow and the electrons are accelerated later. In contrast, the lower image with pre-plasma shows relativistic self-focusing in front of the target (~100 μm), with strong filamentation and earlier electron generation. This shows how the pre-plasma modifies the laser-plasma interaction. The electric and magnetic field structures become more complex and energy is transferred more efficiently. This figure demonstrates the EPOCH software's ability to model microscopic plasma physics, including laser-plasma coupling, shock formation and electron acceleration, that cannot be resolved by fluid simulations such as Thesan or IllustrisTNG. EPOCH captures fine-scale electromagnetic effects critical to astrophysical plasmas and high-energy environments (Peebles, et al., 2017).

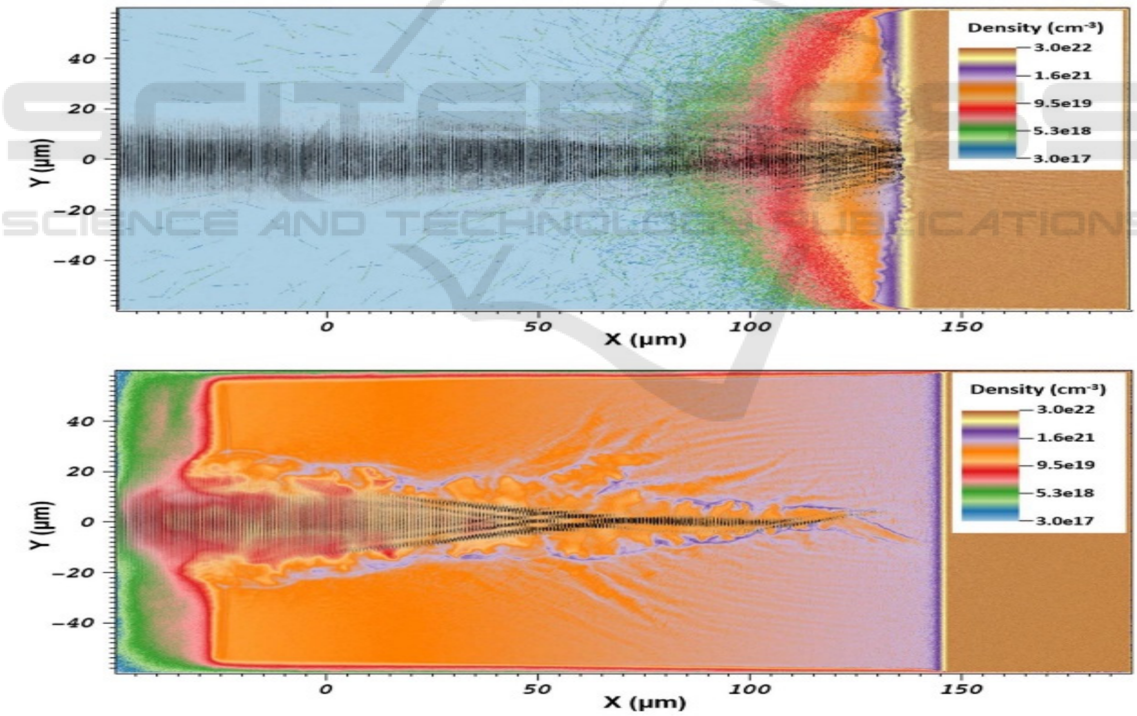


Figure 3: Density and electric field from EPOCH simulations with and without the pre-plasma (Peebles, et al., 2017).

## 6 CONCLUSIONS

This paper has presented a comparative analysis of three representative astrophysical simulation frameworks: IllustrisTNG, Thesan, and EPOCH. Each simulator targets a different scale and aspect of the universe, using distinct physical models to study complex cosmic phenomena. IllustrisTNG models the co-evolution of dark matter and baryonic matter from early times to the present, solving hydrodynamic and gravitational equations with moving-mesh technique, and incorporating feedback from star formation and active galactic nuclei. It successfully recreates the cosmic web and galaxy evolution but lacks radiative transfer and early-universe detail. Thesan, built upon AREPO-RT, focuses on the Epoch of Reionization and includes full radiation-hydrodynamics, cosmic dust physics, and magnetic fields. It models the escape fraction of ionizing photons and patchy reionization more realistically, revealing the clustered growth of ionized bubbles and the impact of feedback on galaxy environments. However, it does not evolve galaxies past high redshift and is computationally demanding. In contrast, EPOCH employs particle-in-cell (PIC) methods to simulate plasma dynamics in extreme electromagnetic environments. It solves Maxwell's equations and the Lorentz force law on kinetic scales, capturing processes such as magnetic reconnection, shock acceleration, and laser–plasma interactions. EPOCH provides unmatched detail in local field structures and energy transport but cannot model gravitational clustering or large-scale cosmic evolution due to scale and resource limits.

Current limitations include the lack of integration between kinetic microphysics and large-scale cosmology. IllustrisTNG and Thesan rely on fluid approximations and cannot resolve particle-scale interactions, while EPOCH resolves these processes but sacrifices volume and gravitational modelling]. Additionally, all three simulations face increasing computational challenges, particularly Thesan and EPOCH, which require high resolution in time and space to maintain accuracy. Memory and runtime constraints limit the ability to simulate longer timescales or larger cosmic volumes. Future research could benefit from hybrid approaches combining radiation-hydrodynamics and kinetic plasma models, allowing simulations to bridge scales from reionization bubbles to relativistic jets. Better GPU parallelisation, adaptive mesh refinement and AI-assisted parameter tuning could reduce the number of resources needed. As telescopic observations from JWST, SKA, LISA, etc become more accurate, improved simulations capable of reproducing multi-physics signatures in space and time will be required. In summary, IllustrisTNG, Thesan and EPOCH each contribute their own view of the Universe, underscoring the need for multi-scale, multi-physics approaches in the next generations of astrophysical simulations.

# REFERENCES

Aarseth, S. J., 2003. *Gravitational N-body simulations: tools and algorithms*. Cambridge University Press.

Arber, T. D., Bennett, K., Brady, C. S., et al., 2015. Contemporary particle-in-cell approach to laser-plasma modelling. *Plasma Physics and Controlled Fusion*, 57(11), 113001.

Fonseca, R. A., Silva, L. O., Tsung, F. S., et al., 2002. OSIRIS: A three-dimensional, fully relativistic particle in cell code for modeling plasma based accelerators. *Computational Science—ICCS 2002: International Conference Amsterdam, The Netherlands, April 21–24, 2002 Proceedings*, Part III 2, 342-351.

Garaldi, E., Kannan, R., Smith, A., Springel, V., Pakmor, R., Vogelsberger, M., Hernquist, L., 2022. The THESAN project: properties of the intergalactic medium and its connection to reionization-era galaxies. *Monthly Notices of the Royal Astronomical Society*, 512(4), 4909-4933.

Garaldi, E., Kannan, R., Smith, A., et al., 2024. The thesan project: public data release of radiation-hydrodynamic simulations matching reionization-era JWST observations. Monthly Notices of the Royal Astronomical Society, 530(4), 3765-3786.

Hansen, E. C., Garcia-Rubio, F., Adams, M. B., et al., 2024. Feasibility and performance of the staged Z-pinch: A one-dimensional study with FLASH and MACH2. *Physics of Plasmas*, 31(4).

Kannan, R., Garaldi, E., Smith, A. E., Pakmor, R., Springel, V., Vogelsberger, M., Hernquist, L., 2022. Introducing the thesan project: radiation-magnetohydrodynamic simulations of the epoch of reionization. *Monthly Notices of the Royal Astronomical Society*, 511(3), 4005-4030.

Marinacci, F., Vogelsberger, M., Pakmor, R., et al., 2018. First results from the IllustrisTNG simulations: radio haloes and magnetic fields. *Monthly Notices of the Royal Astronomical Society*, 480(4), 5113-5139.

Monaghan, J. J., 2005. Smoothed particle hydrodynamics. *Reports on progress in physics*, 68(8), 1703.

Nelson, D., Springel, V., Pillepich, A., et al., 2019. The IllustrisTNG simulations: public data release. *Computational Astrophysics and Cosmology*, 6, 1-29.

Neyer, M., Smith, A., Kannan, R., et al., 2024. The THESAN project: connecting ionized bubble sizes to their local environments during the Epoch of Reionization. *Monthly Notices of the Royal Astronomical Society*, 531(3), 2943-2957.

Peebles, J., Wei, M. S., Arefiev, A. V., et al., 2017. Investigation of laser pulse length and pre-plasma scale length impact on hot electron generation on OMEGA-EP. *New Journal of Physics*, 19(2), 023008.

Pillepich, A., Springel, V., Nelson, D., 2018. Simulating galaxy formation with the IllustrisTNG model. Monthly *Notices of the Royal Astronomical Society*, 473(3), 4077-4106.

Smith, J. R., Orban, C., Rahman, N., McHugh, B., Oropeza, R., Chowdhury, E. A., 2021. A particle-in-cell code comparison for ion acceleration: EPOCH, LSP, and WarpX. *Physics of Plasmas*, 28(7).

Springel, V., White, S. D., Jenkins, A., et al., 2005. Simulations of the formation, evolution and clustering of galaxies and quasars. *Nature*, 435(7042), 629-636.

Vogelsberger, M., Genel, S., Springel, V., et al., 2014. Introducing the Illustris Project: simulating the coevolution of dark and visible matter in the Universe. *Monthly Notices of the Royal Astronomical Society*, 444(2), 1518-1547.

Vogelsberger, M., Marinacci, F., Torrey, P., Puchwein, E., 2020. Cosmological simulations of galaxy formation. *Nature Reviews Physics,* 2(1), 42-66.

Yeh, J. Y., Smith, A., Kannan, R., et al., 2023. The thesan project: ionizing escape fractions of reionization-era galaxies. *Monthly Notices of the Royal Astronomical Society*, 520(2), 2757-2780.