Examining the Power of Astrophysical Simulations by Deconstructing Three Modeled Galaxies

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1. Introduction

Before pilots can fly a plane, they must go through 10 to 20 hours of training in an Aviation Training Device.[1] This device is a modeled airplane cockpit mounted on actuators, with screens displaying a simulated view for a desired flight path. The visual display reacts to the input from the pilot's controls, along with physical feedback from the moving cockpit. The device takes into account the simulated airplane's aerodynamics and thrust, along with air turbulence, temperature, and the gravitational pull of the earth below.[2] The result is an experience that expertly mirrors the feeling of flying a plane, without having to leave the ground. The same type of simulator can be used as a flight deck to train astronauts for space shuttle missions, or to collect launch data without the cost of actually sending up a shuttle.[3] While these simulations cost tens of thousands of dollars due to the advanced machinery, the core of the physics, and the knowledge that comes with it, lies in the code.

A simulation ('sim' for short) is a visual representation of a model, which can be any physical system approximated by computation (Banks et al. 2001). Astrophysical simulations specifically are those simulations that invoke models pertaining to the study of astrophysics. Simulations allow us to create realistic scenarios that we can observe and study over time to achieve a better understanding of the implemented physics. We can affect the outcome of simulations by changing variables in the underlying code or, as is the case with the flight simulators, allowing for user input as long as the simulation is running in real time. While real time simulations can be invaluable in training for dangerous or costly experiences, the power of simulations far exceeds that of this subset. Even the most basic simulations can have a profound impact on our understanding of the universe.

One of the first modern "physics simulations" was carried out by Sebastian von Hoerner in the late 1950's, who attempted to tackle the *N-body problem* (Hoerner 1960). The term *N-body* means a specific number (*N*) of particles or point sources (*bodies*) with forces acting on or between them. The typical N-body problem is the interaction between gravitationally bound objects. Von Hoerner worked at the Astronomisches Rechen-Institut in Heidelberg, Germany, on what was at the time very high tech computer running up to 2000 operations per second. He was attempting to show the natural motion of gravitationally bound particles when initialized in a circular ring geometry (Hoerner 1960). His N-body simulations showed chaotic motion that was very dependent on initial conditions. While solving the orbital motion of a binary system is one of the basic tools in astronomy and is very well understood (Stephenson 1994), solving a system mathematically for any number of particles greater than two can be extremely difficult without

[1] FAA "FAA Issues New Flight Simulator Regulations", 2016
https://www.faa.gov/news/updates/?newsId=85426
[2] AMS "Redbird AMS", 2017 http://simulators.redbirdflight.com/products/ams
[3] NASA "Simulators", 2015
https://www.nasa.gov/centers/dryden/multimedia/imagegallery/Simulator/Simulator_proj_desc.html

using simulations (Trenti & Hut 2008). Simulations allow us to evaluate how complicated systems evolve over time, without the necessity of rigorous time integration mathematics and thousands of handwritten calculations. The output of simulations can be formatted whatever way is most useful in the circumstance; it could be a visual representation or a plain-text datafile.

The largest barrier in simulation capability, which von Hoerner knew very well, is computing power. Simulations allow us to speed up physical processes to thousands or millions times the speed at which they occur naturally, but we are still limited by how many calculations we can make per second. Moore's Law, foretold by Gordon Moore in 1965, states that the number of transistors which can be fit onto a single integrated circuit should double every two years in exponential fashion. Amazingly, this "law" has held nearly perfectly true in the 50 years since the prediction (Moore 1965). We can see the consequences of this technology growth by comparing von Hoerner's "supercomputer," running 2000 operations/sec, to a modern day supercomputer: The XSEDE Stampede supercomputer cluster, which many high level astrophysical simulations are run on, can process approximately 346 billion floating point operations per second (GFLOPS), on a single cluster.[4] Now relate these computation times to processing interactions between many particles in a physical simulation. Every individual particle must check its interaction with every other particle in the simulation, meaning the computation time goes as $O(n^2)$ (Note: some modern algorithms can reduce this computational complexity to around $O(N \log(N))$) (Barnes & Hut 1986). When only dealing with a few particles this isn't much of an issue, but when trying to accurately simulate a galaxy with 100 billion stars, gas/dust density and dark matter distributions, things start to slow down.[5]

2. Types of Simulations

For the purpose of this paper I will refer to two subsets of simulations: Observational and Physical. In no way are these qualifications known or well defined in the literature, but the distinction will be useful to further certain points in following sections. I will define the characteristics of each type of simulation as follows:

An *observational simulation* is not a simulation in the traditional sense, as it is not based on physical models. That is, it does not incorporate physics equations or structures into its code. Instead, an observational simulation relies on observations and visualization techniques to create something that *looks* correct. An observational simulation could be a movie of the sun, or an interactive application using a graphics library which lets you explore the solar system. *Observational simulations* do not implement the physics at work behind the scenes for the systems to evolve or remain in stability, but still can provide excellent visualizations of systems beyond the scale of our own sight.

A *physical simulation* is what most people envision when they hear the word simulation. It is any sim with the actual physics written into the code. The key characteristic of a *physical simulation* is that it can evolve over a non-predetermined time period or time scale. This means the simulation can run with a timestep (the time between two frames of the simulation, see Sec. 5) of Δt = 5 minutes or Δt = 5 hours, and the physics will not break down. The N-body

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[4] XSEDE. "Stampede User Guide", March 24, 2017 (https://portal.xsede.org/tacc-stampede)
[5] BBC. "Milky Way". Archived from the original on March 2, 2012. https://web.archive.org/web/20120302071454/http://www.bbc.co.uk/science/space/universe/key_places/milky_way

simulations referred to in the first section are a typical example of a perfectly *physical* simulation, because they can be processed at any time rate and will still give meaningful results.

In practice, the divide between the two types isn't nearly black and white. Many physical simulations can incorporate observational aspects, or use observational techniques to view the output. Imagine a simulated galaxy, with each star being approximated as a point source in the code. In the visualization of the simulation output, each point source is displayed as a spherical particle, textured to look like a star. Although in the computation the star has no structure to it, the visualization gives it structure based off observations of what we believe the object should look like.

3. Simulation Scale and Accuracy

Both observational and physical simulations can span a huge range of scales. In fact, there are simulations at the extreme ends of the physical scales that we understand, from the cosmological universe (Bertschinger & Gelb 1991) down to the Standard Model of particles (Corcella et al. 2001). Some of the most common scales for astrophysical simulations are planetary, galactic, and cosmological. While a planetary sim would simulate a single star system, a galactic sim models a single galaxy, and a cosmological sim models the large-scale structure of the universe (Primack 2012). For a *physical simulation* the accuracy is intimately tied to its scale. The two major factors when determining the correctness of the sim output are what I like to call the *model accuracy* and *scale precision*.

M*odel accuracy* encompasses both the precision of the physics being tested, and the accuracy of said physics written in the code. *Model accuracy* is indisputably the most important part of the simulation; running an N-body simulation with the force of gravity scaling with distance by $F_g \propto R^{-3}$ instead of $F_g \propto R^{-2}$ would produce wildly different and extremely inaccurate results compared to the measurements we make in our universe. Every modern advancement in physics unveils new models, many of which we can incorporate into current simulations to increase the overall accuracy of the results. I will continue to build on the idea of *model accuracy* in the following sections of this paper.

Scale precision is a bit more nuanced. The scale precision is how many particles in the equivalent real world scenario are being approximated into one particle or mesh density unit in the simulation. Aside from subatomic-level sims, every simulation drops some scale precision, simply due to limitations in computing power. If we were to simulate a chunk of 22 liters of some gas we would need approximately 10^{23} individual particles to retain full scale precision, since 1 mol of an ideal gas contains roughly that many molecules (and this isn't even considering modeling the interaction of atoms within each molecule, or quarks within each atom) (Moran & Shapiro 2000). It is easy to see that the numbers quickly get out of hand, so in nearly all simulations we must sacrifice some scale accuracy. Fortunately we have very accurate approximations (*i.e. high model accuracy*) of how large quantities of particles and gasses interact, so very little overall simulation accuracy is lost when losing this scale precision. This being said, as we move to galactic and cosmological scales, this scale precision loss can be significant when we must approximate entire star system as point sources or static systems. Luckily, the recent advancements in computational power allow us to create sims with significantly higher scale precision than previously thought possible.

4. Examining Three Galactic Scale Simulations

To better understand the inner workings and implications of astrophysical simulations, it is useful to consider different types and levels of modern simulations. A significant portion of the remainder of this paper will be dedicated to understanding and building knowledge off of three astrophysical simulations. Each simulation is meant to model a spiral galaxy, similar to the one in which our solar system resides. I will highlight one *observational simulation*, one *physical simulation with low scale precision and model accuracy*, and one *physical simulation with high scale precision and model accuracy*. Links to explore and read more about each of the following simulations can be found at the end of the paper.

100,000 Stars: Observational Simulation

"100,000 Stars" is an interactive webpage made by Google employees where the viewer can explore the closest 100,000 stars to the Sun in detail while getting a sense of the position and scale of these stars within the Milky Way galaxy. By using the mouse scroll wheel to zoom in and out and the mouse to pan, the user can click on a cataloged star to inspect it up close and read facts about its discovery and our current knowledge of its characteristics. The stars are artificially textured with WebGL and other browser plugins to match observations of size and color. This webpage provides a seamless experience for the user to learn about the size scale of our galaxy and see simultaneously how much we do and do not know about the surrounding stars. Though 100,000 Stars is a great example of a simulation that is both useful and interesting, it fails to qualify as a *physical simulation* because it has no temporal component; neither the individual stars nor the galaxy as a whole evolve through time, which limits the fundamental knowledge that we can extract from this sim.

Galaxy2: Physical Simulation, Low Scale Precision and Model Accuracy

"Galaxy2" is a project which I worked on throughout most of 2016 that was meant to simulate the evolution of a spiral galaxy. The sim aimed to produce spiral density waves from a set of particles with initial conditions similar to current Milky Way observations of velocity and radial distribution. The model approximated N number of stars as point sources and calculated the gravity interaction between each point and logged the results in an output file, which could then be visualized in three dimensions by a specialized reader program. Aside from the *N-body* gravity model, the only other implementation of physics was in a rudimentary dark matter density approximation using the Navarro-Frenk-White (NFW) profile (Navarro et al. 1996). The initial conditions were implemented by randomly scattering the stars radially away from the center on a star density distribution of $n \propto e^{r/Rs}$ where r is the distance of from the center of the galaxy to the star and Rs is a radius scaling constant for the galaxy (Freeman 1970). The masses of stars are distributed in an Initial Mass Function (IMF) and scaled to match measurements of the total mass of the milky way particulate matter (Chabrier 2003). The initial velocities were set to match measurements of the radial velocities in the Milky Way, approximately 220 *km/s* for all stars outside the inner 1 *kpc* of the galaxy's center (Koupelis & Kuhn 2007). With these initial conditions and basic models we can evolve the galaxy over time, observe the results, and generalize findings to a number of scenarios. Using appropriate constants for the NFW profile, we observe a gravitationally bound system that evolves in the same manner as a spiral galaxy. Although the *model accuracy* and *scale precision* in this sim are very low, we are immediately able to confirm the existence of a common mystery in astrophysics: the existence of dark matter.

By simply disabling the NFW dark matter density profile and running the galaxy under the same initial conditions, the vast majority of the stars escape the gravitational pull of the galaxy. We know dark matter must exist because simulating the conditions we observe in our own galaxy without the presence of another significant gravitational source fails to produce the gravitationally bound system we expect.

FIRE-2: Physical Simulation, High Scale Precision and Model Accuracy

"FIRE-2," short for "Feedback In Realistic Environments (2)," is the cutting edge in astrophysical simulations. The FIRE group, led by Phil Hopkins at CalTech, has run several of the most comprehensive galaxy formation sims in history, using the FIRE-1 and FIRE-2 code built off GIZMO (detailed further in Sec. 5). It is a full scale "zoomed-in box" cosmological simulation. The simulation starts at *low scale precision* to form initial clumps of mass to seed a galaxy, and once the low precision simulation has run, the target clumps are identified and re-simulated at *high scale precision* to measure the effects of stellar feedback and star formation on the evolution of the galaxy. The FIRE-2 simulation code combines numerous models, which we know are present in galaxy and star formation, with a multitude of techniques to minimize computational complexity. The *high model accuracy* enabled by these optimizations allows the FIRE-2 code to create galaxies that match observations to resounding accuracy. From this suite of simulations we have gained knowledge of the impact of certain stellar feedback events like supernovae and mass loss on rates of star formation and overall galaxy structure (Hopkins et al. 2017).

5. Components of Simulations

To truly understand what we can learn from simulations, we must examine the inner workings of the code. Many *observational simulations* are fairly straightforward, so I will spend the majority of the time detailing *physical simulations*, though it is still important to understand how we go from observations to visualizations.

Components of Observational Simulations

1. Observations and Data

For the 100,000 Stars simulation, the data comes from a variety of sources. A significant portion of the data is compiled from the "HYG Database" by Astronomy Nexus.[6] This database tracks numerous stars with many data fields, including right ascension and declination, distance, magnitude and color spectrum.[7] The data is pulled from this database to make a star object which is matched with a texture derived from Wikipedia's Stellar Classification page (Habets & Heinze 1981). This workflow is very similar for most observational sims; a dataset is compiled from telescope observations, processed, and forwarded to a visualization scheme.

2. Visualization

Once the star object with the specified data and texture is processed, the 100,000 Stars page creates a virtual three dimensional space with WebGL (Web Graphics Library). Each star in the database is then placed in the space with specified coordinates and texture. The

[6] Chrome Experiments."100,000 Stars" (2017) http://stars.chromeexperiments.com/
[7] HYG Database. Astronomy Nexus, March 18, 2006, http://www.astronexus.com/hyg

implementation of the 3D space allows for panning, zooming and interactive clicking. The end result is an *observational simulation* that represents real data in an easily consumable form for users.

Components of Physical Simulations

1. Models

The first step in creating a physical sim is identifying the desired models for testing. In the case of Galaxy2, the models I aimed to examine were *N-body gravitational interactions* and the *NFW density profile* as components in a spiral galaxy system. Though these two models themselves were implemented accurately, Galaxy2 had overall *low model accuracy* because it failed to implement countless other models that are present in observed spiral galaxies, like interstellar medium and star feedback.

Meanwhile, FIRE-2 has *high model accuracy* because it implements the majority of models that are known to have an impact on galaxy formation. The original FIRE-1 simulations, currently comprising most of the trials, all used identical source code. However as of February 2017 the enhanced FIRE-2 simulations use a newer version of the code, which has generally improved computational efficiency and implementation of some new physics. Both versions of the code are run with a library written by Phil Hopkins called GIZMO (Hopkins et al. 2017), which is in turn built on GADGET (Springel 2005). GADGET is a cosmological scale simulation package to compute gravity and Smoothed Particle Hydrodynamics (SPH) (Gingold & Monaghan 1977). GIZMO expands GADGET to include models for magnetic fields, radiation hydrodynamics, dark matter and more (Hopkins 2015). While Hopkins et al (2017) details each model explicitly, I will briefly cover the most important features and differences between FIRE-2 and Galaxy2.

The most similar feature between FIRE-2 and Galaxy2, and the easiest to understand in both simulations, is the gravity code. Though the *N-body* interactions between stars are nearly identical in appearance, FIRE-2 runs an optimized Tree-PM solver to reduce computational complexity (Hopkins et al. 2014). Tree-PM denotes "Tree-Particle-Mesh," which employs a particle mesh system for solving *N-body* problems (Bode et al. 2000). Using a "mesh" is the process dividing the space of the simulation into a three dimensional grid, and approximating mass or energy densities based on the contents of each grid space. The "Tree" means the algorithm will only calculate the gravitational attraction from sections in close proximity to the current chunk it is processing. In addition, the gravity code runs approximations on dark matter interactions, along with being fully implemented in the hydrodynamics system for communicating with the gas and dust in the interstellar medium.

The biggest reason for the move from FIRE-1 to FIRE-2 was the use of the new hydrodynamics code. The original FIRE-1 simulations used "P-SPH," a variant of the Smoothed Particle Hydrodynamics from the GADGET package. The FIRE-2 simulations now implement a type of "mesh-free Godunov hydrodynamics." Though the mesh is a common tool in hydrodynamic calculations, both the P-SPH and the Godunov hydrodynamics systems are "mesh-free," meaning they employ other tactics to calculate the interaction between "fluids" like the gas and dust in the interstellar medium. The mathematical differences between these two methods are exceedingly technical for this paper, but the Godunov method can be thought of as similar to a dynamical "moving-mesh," whereas SPH methods follow a "quasi-Lagrangian" system of particles. Though SPH methods are widely used in hydrodynamic computing, there are a number of well understood flaws, including issues with fluid mixing, viscosity, and low-order numerical errors (Hopkins 2015). Tests show that the Godunov hydrodynamics consistently provide more accurate and quicker results than the P-SPH method (See Table 1, Hopkins 2015), while simultaneously enabling coupling with the new FIRE-2 magnetic field models (Hopkins et al. 2017).

Cooling is also known to play a large factor in the evolution of the galaxies. Cooling of the interstellar medium can come in many different forms, so to have an accurate cooling model many sub-models for cooling must be used. The full list of sub-models in the FIRE-2 simulations is as follows: “free-free, photo-ionization/recombination, Compton, photoelectric, metal-line, molecular, fine-structure, dust collisional, and cosmic ray processes” (Hopkins et al. 2017).

Star formation and stellar feedback both play significant roles in the evolution of galaxies. While there are numerous sub-models to describe the formation of stars (Jean’s Unstable, etc.), the more fascinating aspect is the feedback once the star has begun to evolve. As stated in Sec. 4, one of the most compelling pieces of knowledge gained from the FIRE simulations is the effect that stellar feedback has on galaxy formation and evolution, specifically supernovae and continuous mass loss from the late stage stellar evolution. Every star has a characteristic age, which equals $t_* = t - t_{form}$ (the current sim time minus the time of formation). Depending on the age of the star and certain other features like mass and radius, the star has a probability of exhibiting one or more of these stellar feedback features. We now know that these processes have a profound effect on the galaxy formation because tweaking the numbers in these models slightly can produce wildly different results.

2. Initial Conditions

Every simulation must have a set of initial conditions so the sim knows where to start. For Galaxy2, the initial conditions are the distribution of stars and the star initial velocities. The general initial conditions of FIRE-2 were described briefly in Section 4. Specifically, each run of the FIRE simulations had slightly different initial conditions. The variables changed between these runs include, but are not limited to: Virial mass, virial radius, mass of gas particles, gravitational force softening parameters, etc (See Table 1, Hopkins et al. 2017). Even with a perfect model, improper initial conditions can produce undesirable results.

3. Timestep

The key characteristic of a *physical simulation* is its ability to evolve over time, and this is accomplished with a mechanic called a *timestep*. The concept is to have the initial conditions in place and to integrate each model from simulation time t=0 to t=Δt (where Δt is your timestep); the new state of your simulation is the initial condition to calculate your models on the next timestep. We will call the state of a simulation over one timestep a *frame*. This timestep process will repeat for as many frames as the simulation is instructed to run. For a simple model like gravity, integrating over a timestep can be as easy as summing the total force on a particle for the current frame and using $F = m \bullet a$, $v = a \bullet \Delta t$, and $d = v \bullet \Delta t$ to control the acceleration, velocity, and position of your particles over one frame. Some models that have a more complicated time dependence can be trickier to manipulate over a single frame, therefore advanced integration techniques must be used, as demonstrated in Hopkins et al (2017). *Timestep* is intimately tied to *scale precision* in that the larger Δt used, the less precise the calculations will be. This is because using a timestep of many hundreds or thousands of years, like many astrophysical simulations must, dilutes every individual mechanism within that timestep to a single motion or action. To avoid some loss of *scale precision*, many advanced simulations, including Hopkins et al (2017), have smaller timesteps for certain individual processes.

4. Output and Visualization

The output of a *physical simulation* can be extremely similar to that of an *observational simulation* if the output is visual in the form of a clip or movie, though it can be difficult to make *physical simulations* interactive because they often require significantly more computation time than their counterparts. Some types of simulations can output useful results in the form of a simple text or data file. Whereas *observational simulation* visualization is primarily for consumer viewing purposes, a *physical sim* can have its own specialized output type depending on its unique purpose.

6. Merging Observations and Models

Studying simulations allows us to project how our world will evolve over time, assuming our models are correct. Running an incorrect or incomplete model may confound our understanding of how a system functions. Thankfully, we can verify most of our models by comparing simulations with observations at snapshots in time. Though the timescales of most astrophysical processes are far longer than the average human lifespan (or human existence entirely), there are massive amounts of objects for us to observe in just the local universe. Consequently, it is highly likely that we can find objects spanning each phase of a chosen system's evolution. Using this knowledge, we can use optical images and spectra of an astrophysical system to compare with a simulation at a certain point in time to understand whether our model of the system at a specific stage of its evolution is correct.

FIRE-2 is an excellent example of how we can analyze simulation results and correlate them with observations. Since spiral galaxies are among the most numerous astrophysical objects and are easy to observe due to their extremely high luminosity, we have logged hundreds of thousands of galaxies. With these myriad observations we have detected galaxies in essentially every phase of formation or evolution, so there are countless benchmarks with which to compare FIRE-2 simulations. For nearly any frame of a FIRE-2 sim we can point to an observation of a real galaxy with similar properties, demonstrating that these models are highly accurate.

What is most astounding is that FIRE-2 produces simulated galaxies at such a high level that they are not only similar to observations of real galaxies, but nearly indistinguishable from them. The success of FIRE-2 is mostly due to *high model accuracy and scale precision*, although minor visualization techniques are used to produce a consumable output for the standard viewer. In contrast, Galaxy2 has relatively *poor model accuracy*, *low scale precision*, and extremely basic visualization techniques, generating a galaxy that varies significantly from observations. A comparison between a FIRE-2 simulation, a Galaxy2 simulation, and an observed spiral galaxy is shown at the conclusion of this paper. This spiral galaxy case study suggest that as our models improve and our computational techniques and hardware evolve, the closer our simulations will approach our observations. Though the FIRE-2 simulations are currently state-of-the-art, there is still room for advancement; both *model accuracy* and *scale precision* can be improved. For some systems it could take decades for simulation technology and model accuracy to advance to the point where sims mirror observations as precisely as FIRE-2 mirrors a real galaxy. For some complex systems that are hard to study (e.g. black holes) it could simply never happen. However certain systems have already been simulated at an even higher level than these galaxies.

As recently as the late 1970's there were a number of theories to describe how planets form in a star system. While many of the models were held in high regard by leading astrophysicists, only one is currently accepted by most in the field, in large part due to simulation verification. The nebular hypothesis, first theorized in 1755 by Immanuel Kant, describes the solar system initially forming from collapsing nebulous material (Woolfson 1993). The nebular hypothesis is now the most widely accepted model of star and planet formation in the cosmological model (Montmerle et al. 2006). Most impactfully, the nebular hypothesis can explain planet formation, one of astronomy's most sought after questions, through protoplanetary disks (Raymond et al. 2007). Protoplanetary disks form around newborn stars, where the surrounding dust flattens due to the conservation of angular momentum (Blum 2010). The larger particles coagulate into bigger structures, which eventually gain enough mass to become gravitationally attractive and accrete more rapidly. This model supports the theory of planetary migration caused by angular momentum transfer through the accretion disk (Montmerle et al. 2006), which explains the highly debated issue of "Hot Jupiters," the very massive planets on extremely close orbits around their star (Winn et al. 2010). The reason we know this model supports these theories is because we have simulated this situation to astounding accuracy. Only recently have we been able to observationally verify this model with ALMA (Atacama Large Millimeter/submillimeter Array) observing the HL Tauri protoplanetary disk (Brogan et al. 2015). The protoplanetary disk simulations run by Montesinos et al. (2015), along with a number of other high level simulations produce results that match the situation observed in the HL Tau region to a high degree of accuracy (Montesinos et al. 2015). Since these simulations are modeling a much smaller scale than a galactic sim, the *scale precision* is inherently high. Therefore a simulation that mirrors observations at a high level must contain *high model accuracy*. Comparison between HL Tau observations and protoplanetary disk simulations accompany the FIRE-2 and spiral galaxy images.

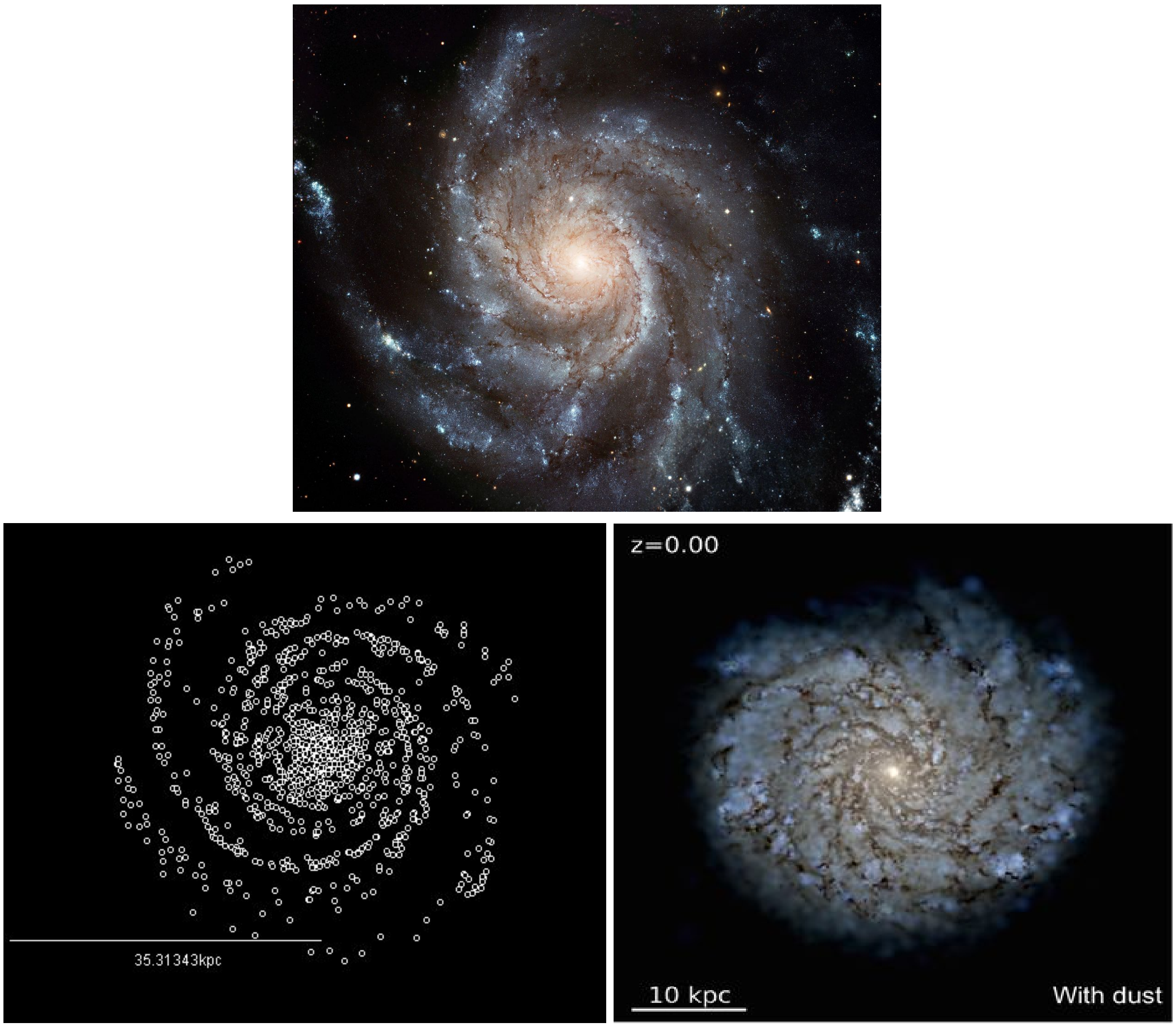
The models that simulations can confirm for us currently are numerous, yet limited. Although many roadblocks lie in the way of simulating some astrophysical situations due to non unified models or inadequate computing capabilities, advances in both fields continue every day. While the knowledge gained from simulations already has been invaluable, there is much more to come.

7. Looking Forward

Though the progress made in the field of astrophysical simulations throughout the past few decades has been staggering, there is still plenty of room to grow. Just as we can approximate where the solar system was hundreds of years ago in relation to its current position, many models may have the ability to be time-reversed. In theory we may be able to take initial condition from observations, like the current state of the solar system, and rewind it through time to see the evolution that has taken place. Though time itself appears to to be "asymmetric," meaning that the laws of physics do not act the same going backwards (Bednorz et al. 2013), many systems, like *N-body systems*, can be traced back in time using approximations (Dehnen & Read 2011). For a model to be time-reversible it must be *complete*, having the highest model accuracy possible in order to minimize the possibility of improper prediction. While *scale precision* would still be important, there is an intrinsic limit to the precision possible as a result of quantum mechanics and uncertainty. Since at an atomic level we can never truly be certain of both the position and momentum of a particle, there is an element of randomness in our current models of the physical world (Sen 2014). Right now this randomness is impossible to predict in both forward and backward time. This indicates that the farther we attempt to turn back time in a reversed simulation, the chance of this randomness deviating the results from truth becomes greater. Although this limitation means the time-reversed simulations will never be completely accurate, general trends and specific interactions can be useful in understanding the history of observed processes. While it is possible that at some point an alternative to quantum mechanics, without the necessity of the uncertainty principle, will be advanced, for the time being it is the model we must rely on for small scale processes.

Despite the issues with uncertainty and time asymmetry, one can't help but imagine the endless possibilities of time-reversed sims. We could simulate back our solar system to see the initial cloud of gas and dust that produced our sun and earth. Unlike the randomly generated galaxies from FIRE, we could view the evolution of our own Milky Way galaxy since its birth. It is even possible, one day in the distant future, that we could simulate the whole universe over its entire lifespan. If we could ever reach that point, we would essentially know everything that has ever happened, and anything that ever will.

Simulation and Observation Comparisons

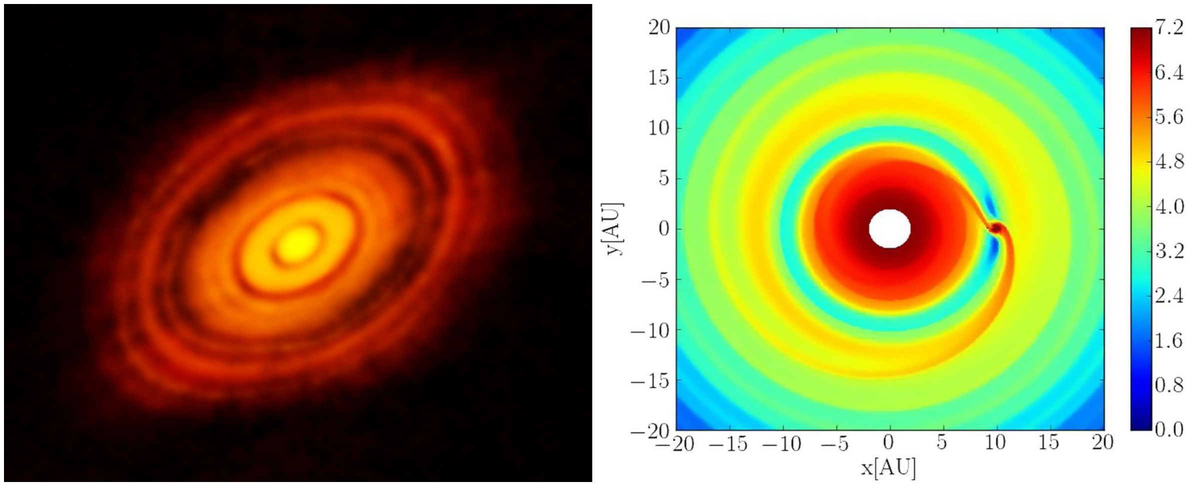


The Pinwheel Galaxy (top) compared with Galaxy2 (left) and FIRE-2 (right). Though Galaxy2 lacks any interstellar medium, the general star geometry in all three images is similar.

Pinwheel Galaxy: Image: European Space Agency & NASA Acknowledgements: Project Investigators for the original Hubble data: K.D. Kuntz (GSFC), F. Bresolin (University of Hawaii), J. Trauger (JPL), J. Mould (NOAO), and Y.-H. Chu (University of Illinois, Urbana) Image processing: Davide De Martin (ESA/Hubble) CFHT image: Canada-France-Hawaii Telescope/J.-C. Cuillandre/Coelum NOAO image: George Jacoby, Bruce Bohannan, Mark Hanna/NOAO/AURA/NSF - http://www.spacetelescope.org/news/html/heic0602.html

Galaxy2: Hollenbach S., https://github.com/samhollenbach/Galaxy2

FIRE2: Hopkins P., TAPIR http://www.tapir.caltech.edu/~phopkins/Site/Movies_cosmo.html



An image of the HL Tau protoplanetary disk from ALMA (left) and a simulation image of a protoplanetary disk from Montesinos et al. (2015) (right). The colors on the right represent blackbody flux per unit area, which can be compared to the apparent luminosity seen in the HL Tau disk image. This simulation includes only a single planetary embryo in formation, while the image on the left is thought to show upwards of 5 or 6 newly forming planets. Notice the striking similarity in ring geometry and surface brightness between simulation and observation.

HL Tau Image: ALMA (ESO/NAOJ/NRAO) - http://www.eso.org/public/images/eso1436a/
http://www.eso.org/public/archives/images/large/eso1436a.jpg

Simulation: Montesinos et al. (2015)

Sources for Mentioned Simulations

100,000 Stars: http://stars.chromeexperiments.com/
Galaxy2: https://github.com/samhollenbach/Galaxy2
FIRE-2: http://www.tapir.caltech.edu/~phopkins/Site/ and http://fire.northwestern.edu/
Protoplanetary Disk simulation example: https://vimeo.com/204085903

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