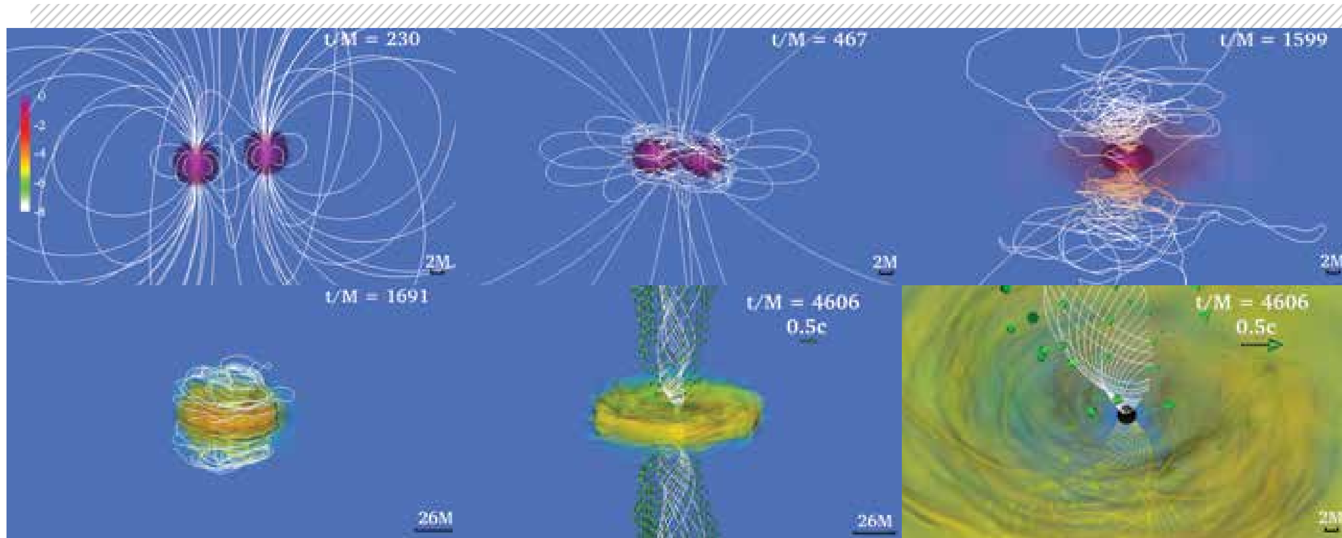

FIGURE 1: Snapshots of the rest-mass density, normalized to its initial maximum value (log scale), at selected times for the Pulsar-like case. Arrows indicate plasma velocities and white lines show the magnetic field lines. Bottom panels highlight the system after an incipient jet is launched.

to be the initial endowment of the NS with a dipole B field that extends into the NS exterior, as in a pulsar magnetosphere. By contrast, if the initial B field is confined to the interior of the NS, no jet is observed [3]. These results prompt the query of whether NSNS mergers produce jets in the same way as BHNS systems, or does of the mechanism requires an initial BH.

Previous ideal GRMHD simulations by Rezolla et al. suggest that NSNS mergers may launch a relativistic jet [4], while those by Kiuchi et al., which focus on different initial configurations, show otherwise [5]. Both of these studies have considered only scenarios where the B-field is initially confined to the interior of the two NSs.

Using our latest adaptive-mesh refinement GRMHD code we performed simulations of equal mass NSNS binaries initially on a quasicircular orbit that undergo merger [6]. The initial stars are irrotational, n=1 polytropes and are magnetized. We explore two types of B field geometries: one where each star is endowed with a dipolar B field extending from the interior into the exterior (Fig. 1, upper left), as in a pulsar, and the other where the dipolar field is initially confined to the interior. In both cases, the adopted B fields are dynamically unimportant initially. To ensure reliable evolution of the exterior field and properly mimic the conditions that likely characterize the exterior magnetosphere, in the pulsar-like case, we initially imposed a low-density atmosphere such that the NS exterior was described by a constant plasma parameter, defined as the ratio of the gas pressure to the magnetic pressure. We then continued the evolution through the merger of the two NS and subsequent formation of a hypermassive NS (Fig. 1, upper center and right) that undergoes delayed collapse to a BH immersed in a magnetized accretion disk (Fig. 1, lower left and center).

Unlike in the BHNS case, the B field does not grow following BH formation: the existence of the HMNS phase instead allows the B field to build to saturation levels prior to BH formation. We do observe a gradual growth in the ratio B2/2ρ above the BH pole due to the emptying of the funnel as matter accretes onto the BH. At ~66 ms, following the merger of the two NSs, incipient jets are launched even when the initial B field is confined to the interior of the stars (Fig. 1, lower right). The duration of the accretion and the lifetime of the jet is ~0.1 seconds, which is consistent with short-duration short gamma ray bursts. The luminosity is 1051 erg/s, also consistent with observed short gamma ray bursts values. Our simulations provide theoretical corroboration that mergers of NSNS systems can indeed launch jets and be the central engines that power short gamma ray bursts.

WHY BLUE WATERS

By adding OpenMP support to our message interface passing (MPI)-based code, scalability on multi-core machines has improved greatly. With the Blue Waters next-generation interconnect and processors, our hybrid OpenMP/MPI code exhibits greater scalability and performance than on any other supercomputer we have used. Recently, we were able to build our code with the Blue Waters Intel compilers. This resulted in a 30% boost of our code's performance, making Blue Waters unique for tackling the astrophysical problems we want to address.

Blue Waters is also used by our undergraduate research team to make visualizations (e.g., Fig. 1) and movies of our simulations with the VisIT software.

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THE MOST MASSIVE GALAXIES AND BLACK HOLES AT THE COSMIC DAWN OF THE UNIVERSE

Allocation: NSF PRAC/2.89 Mnh
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EXECUTIVE SUMMARY

Our team has led the development of cosmological codes adapted to petascale supercomputers and used Blue Waters to understand how the first massive black holes and galaxies were formed, from the smallest to the rarest and most luminous. Using nearly one trillion particles, we have carried out the BlueTides simulation on Blue Waters. BlueTides can answer questions in cosmology which require simulations of the entire visible universe at high mass and spatial resolution. We can directly predict what should be seen in future observations that will probe the cosmic dawn of the universe and the formation of the first galaxies and black holes.

INTRODUCTION

Survey astronomy has enabled the study of galaxy and large-scale structure formation at low redshifts to mature into a precise science. Current galaxy surveys at high redshift, however, have covered very small volumes of space in the early universe during the epoch of formation of the first galaxies and quasars. The search for the earliest objects in the universe is extremely challenging. From the observational point of view, the field will be transformed by the next generation telescopes (JWST, WFIRST, etc.). In the coming decade, a new generation of astronomical instruments will observe the universe at the time of the formation of the first stars and quasars, opening up the "last frontier" in astronomy and cosmology.

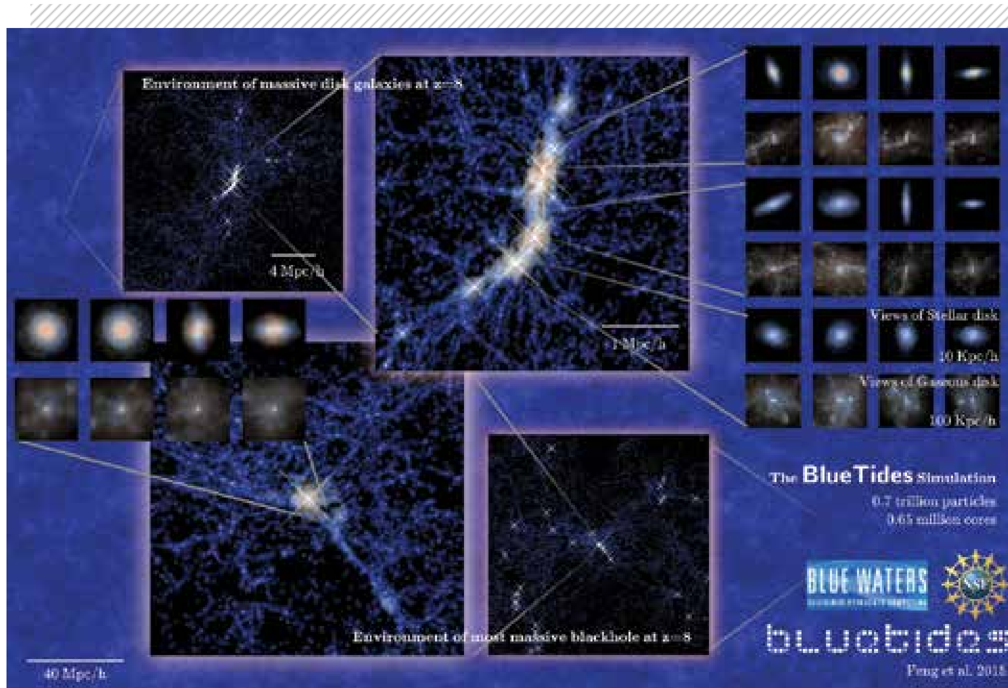

FIGURE 1 : Image of the BlueTides simulation. The large scale density field of the early universe is shown in the background. The insets show zooms of two regions of the large scale density where the first disk galaxies form (galaxies shown in the small left images) and the most massive black hole (left side).

Numerical simulations of galaxy formation have been limited by the volume at which they can evolve. From the simulation-theoretical perspective, large-scale uniform volume hydrodynamic simulations of the high redshift universe are a problem ideally suited to modern petascale facilities like Blue Waters. It is now feasible to run memory-limited computations with the resources that computer time panels can allocate, and therefore reach **unprecedented** volumes and resolutions in the early universe. We have carried out a program to simulate high redshift quasars and first galaxies using Blue Waters and the MP-Gadget cosmological hydrodynamic simulation code. Radical updates to the code efficiency, and hydrodynamic formulation and star formation modeling allow us to meet the challenge of simulating the next generation fields and effectively utilize Blue Waters. The BlueTides simulation is unique in that it probes directly the range of scales (masses and epochs) of galaxies and quasars that will be discovered shortly.

METHODS & RESULTS

Massive disk galaxies in the early universe

Our current run of BlueTides allowed us to apply observational selection algorithms (SourceExtractor) to the simulated sky maps and build catalogs of millions of galaxies. The high resolution of BlueTides made it possible to produce detailed images of individual galaxies and uncover a striking and unexpected population of large Milky Way-sized disk galaxies (Fig. 2) present when the universe was 5% of its present age. Both of these achievements will be of great benefit to the burgeoning frontier fields that will utilize JWST and WFIRST.

The origin of the first massive black holes

Quasars, powered by supermassive black holes, represent a fascinating and unique population of objects at the intersection of cosmology and astrophysics. The growth of the most massive black holes in the early universe, consistent with the detection of highly luminous quasars before the universe is a billion years old, implies that a sustained accretion of material is required to grow and power them. Given a black hole seed scenario, the question remains as to what the fundamental condition in the early universe was to allow the fastest black hole growth. BlueTides allows us to explore the conditions conducive to the growth of the earliest supermassive black holes. The most massive black holes approach 100 million solar masses at z=8 and are found in extremely compact spheroid-dominated host galaxies. More importantly, the role of the initial tidal field sets the condition for early black hole growth. In regions of low tidal fields, gas accretes

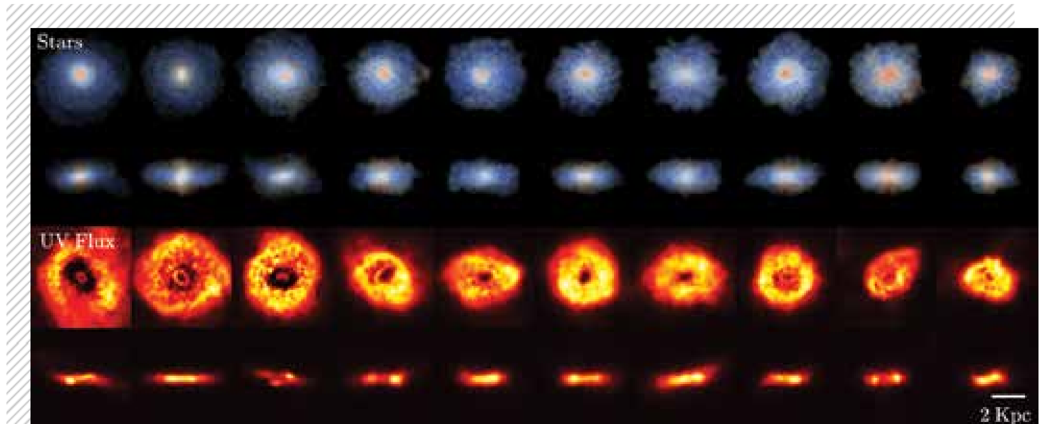

FIGURE 2: A sample of disk galaxies selected from the BlueTides simulation at redshift z=8. We show galaxies identified kinematically to be rotating disks. For each galaxy we show a face-on and side-on view. The colors of the top two rows represent the stellar surface density coded by the stellar age, face-on and side-on. The colors of the bottom two rows represent the star-formation surface density. The face-on images have included the effect of dust-extinction.

"cold" onto the black hole and falls along thin, radial filaments straight into the center, forming the most compact galaxies and most massive black holes at earliest times (Fig. 2). In regions of high tidal fields, larger, more coherent angular momenta influence the formation of the first population of massive compact disks (Fig. 1).

WHY BLUE WATERS

A complete simulation of the universe at the epochs we are studying requires a small enough particle mass to model the dwarf galaxies which significantly contribute to the summed ionizing photon output of all sources. It also calls for an enormous volume: 1 cubic Gigaparsec (3x1019 cubic light years) to capture the rarest and brightest objects—the first quasars. The first requirement is, therefore, equivalent to a high particle density and the second to a large particle volume.

Blue Waters made this qualitative advance possible, producing arguably the **first** complete simulation (at least regarding hydrodynamics and gravitational physics) of the creation of the earliest galaxies and large-scale structures in the universe. Our application runs required almost full system capacity: we used 20,250 nodes (648,000 core equivalents—the new version of the code can scale higher, but we left a safety margin) using 57 GB/node (89%). This application thus uses 1.15 PB of memory—something only Blue Waters can provide, and which is **90% of the available memory**.

Our project establishes a theoretical framework for understanding the cosmic dawn of the universe, the results of which will benefit a broad spectrum of scientific communities, including cosmology, high-energy astrophysics, and anybody studying galaxy evolution. This study will provide answers to broad questions about the history and future evolution of the universe and the formation of structure.

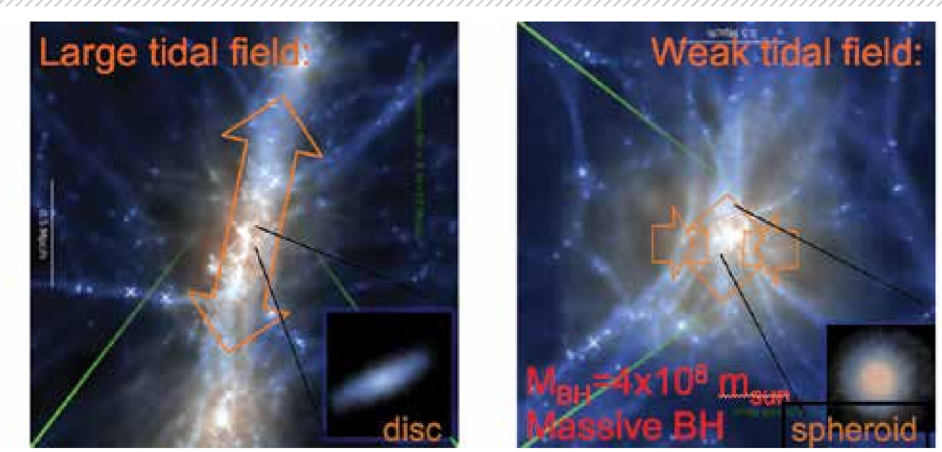

FIGURE 3: The most massive disk galaxy environment is compared to the most massive black hole and host galaxy. Tidal fields are strong and form large scale filaments and the formation of first disk galaxies (top), low tidal fields allow the formation of the most massive black holes in the center (bottom panels).

NEXT GENERATION WORK

BlueTides is a **path-finder** for developing methods and calculations for future cosmological hydrodynamic simulations of galaxy formation with volumes and resolutions suitable for creating models for next-generation surveys. Our simulations are important as they blaze a trail for future calculations in the future Track 1 systems. Currently, we are evolving models forward in time for only one billion years, rather than the 14 billion years necessary to cover the history of the universe to the present day that next generation systems, assuming they have enough memory capacity, would enable.

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CORE-COLLAPSE SUPERNOVAE THROUGH COSMIC TIME

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EXECUTIVE SUMMARY

Explosions of massive stars (core-collapse supernovae; CCSNe) have a significant impact on the development of galaxies and their heavy element content. We compute 3D simulations of CCSNe that include the complex range of CCSN physics, across the range of input conditions representing the history of massive stars in the universe to obtain the variety of outcomes seen in nature. Our computations account for the appropriate nuclear processes needed to generate and eject heavy elements that are needed to form planets. We have discovered a **previously unseen** nuclear burning behavior that can only be observed through the completeness of our simulations and the included nuclear physics.

INTRODUCTION

Massive stars (mass greater than eight solar masses) are relatively rare, yet they play a significant role in the evolution of galaxies, particularly through their explosive finales as CCSNe. Energy from CCSNe triggers new star formation and elements synthesized in massive stars and CCSNe are the ingredients for terrestrial planets in those star systems. The conversion of gravitational potential energy from the collapse of the stellar core into an expulsion of the stellar envelope is a complex physical process. This physical process combines gravitation, nuclear physics, neutrino physics (neutrinos transport the needed energy to drive the explosion from the collapsed core), and turbulent fluid dynamics with a rich phenomenology.

METHODS & RESULTS

To compute CCSN models in the necessary 3D, we have developed *Chimera*, a program that accounts for neutrino transport and opacities, nuclear equations of state and reaction networks, compressible fluid dynamics, and self-gravity [1, 2]. This project addresses the wide range of pre-supernova stellar configurations from the range of initial masses and the build-up of heavy elements (mostly from previous CCSNe) through cosmic history by sampling in both dimensions. From these models we will address the nature of the CCSN mechanism and the production of elements in the explosions.

In the low-mass, primordial composition simulation in our grid, we have identified a previously unseen burning mode in stellar collapse. During collapse, compression of the silicon shell intensifies the burning of the remaining oxygen at the bottom of the layer until it triggers a silicon flash. The silicon flash burns much of the silicon shell to iron-peak elements and some of the overlying oxygen-neon shell to silicon. The deposited energy alters the collapse dynamics and helps intensify the explosion driven by neutrino heating from the collapsed iron core interior. Silicon flashes have been observed in pre-supernova stellar evolution models for similar progenitors [3], but were not seen in previous work with the same progenitor [4] as nuclear burning was not adequately included.

WHY BLUE WATERS

Computing stellar explosions in 3D requires large and long computations. Blue Waters provides the capacity needed to accommodate our simulation requirements.

NEXT GENERATION WORK

More powerful and capable machines will permit improvements in the computationally expensive portions of CCSN simulations (neutrino transport, nuclear networks, resolution). This will help to better realize the nature of the explosions and increased simulation counts to better account for the variety of inputs and outcomes.