CASE STUDY

Intel® oneAPI Rendering Toolkit

Visualizing the Physics of the Cosmos

Rendering enormous simulations to understand the most extreme phenomena in the universe.

The Stephen Hawking Centre for Theoretical Cosmology (CTC) at Cambridge University is on a mission to gain new insights into the fundamental structure of the universe and its origin. The CTC focuses on mathematical models of extreme, pivotal physical events—specifically, black holes and the Big Bang itself—and it confronts those models with a growing body of observational data. As Professor Paul Shellard, Director of the CTC, puts it, "We're answering the big questions about the fundamental structure of the universe and the theories that describe it."[1]

Einstein's general theory of relativity provides the starting point for the work of the center. Hawking was an early proponent of using computational methods with observational data to approach questions as fundamental as the beginning of time and the lifespan of black holes. The central idea is to create models based on extraordinarily complex relativistic equations and run massive simulations that compare the results of those models with huge amounts of observed data. An elegant equation is no longer sufficient; now, it must be shown to match the massive available data. The CTC therefore faces challenges not unlike other scientific and industrial fields, but on a larger scale.

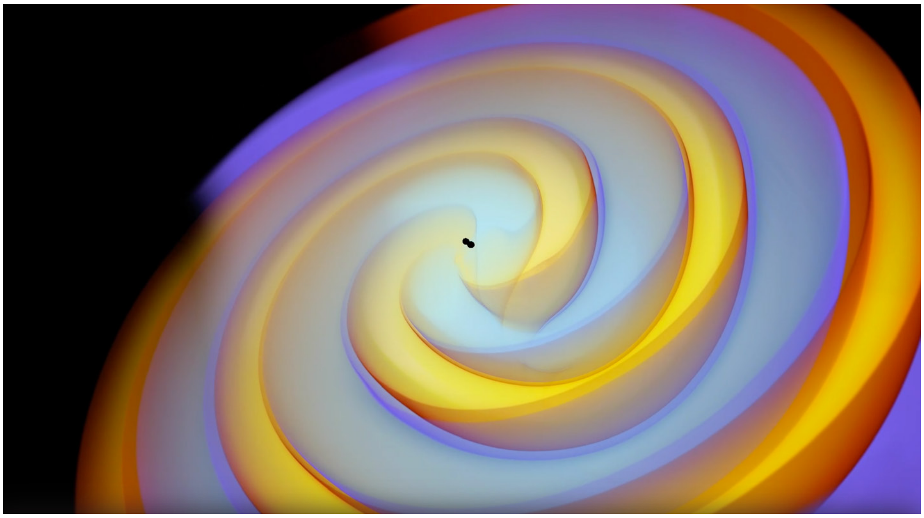

Figure 1. Visualization of gravity waves produced by two black holes colliding

"Without supercomputers, we would just be philosophers."
— Professor Stephen Hawking[3]

Challenges of Cosmology

"Einstein's equations that describe a black hole and the Big Bang are incredibly long and complex," according to Professor Shellard, "so one needs a computer to solve them." One challenge is the complex nature of non-linear relativistic models and their many free (unfixed) parameters. Combine this complexity with the need to run simulations tens of thousands of times in order to optimize those parameters to match observed data, and the computational requirements become intense.

Another challenge lies in the sheer volume of observational data against which the models must be tested. This data is growing rapidly in size, types, and precision. Many years ago, there was hardly any data to look at for a relativist and cosmologist. This all changed with the advent of National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) satellites providing exquisite views of the cosmic microwave sky, the relic radiation left over from the Big Bang. Now, with the recent discovery of gravitational waves, scientists have new insight about the properties of black holes and their violent mergers. Huge, high-precision datasets have emerged, so scientists' simulations must keep pace by matching them in both quality and resolution.

The goal is to compare the observational data with mathematical models to test whether one's theory of the universe matches the actual observed universe. For example, analysis of cosmic microwave maps surveyed by the Planck satellite was a key objective of the Cambridge team, but now they are shifting their focus to huge surveys determining the positions of billions of galaxies. And they face new types of data—such as ultra-precise readings from the Laser Interferometer Gravitational-Wave Observatory (LIGO)—which they are confronting with simulations of colliding black holes (Figure 1).[2]

There is also the significant challenge of visualizing these cosmic simulations. The real limiting factor for computation is not in running the simulation itself, but in simultaneously analyzing and producing a visualization of the state of the simulation. In other words, the challenge is to run the simulation and the visualization together in real time; as Professor Shellard calls it, *"on the fly"* or *"in situ."* The alternative of post-processing by dumping terabytes of intermediary data and then trying to find patterns and correlations by comparing snapshots is not workable. For this reason, the in-memory compute method of real-time analysis and visualization is critical to the success of the project.

Dr. Hawking's vision was always to validate theoretical concepts by confronting them with observations of the universe. As Professor Shellard reminds us, this is now only possible using high-performance computing (HPC)—first, to analyze the huge datasets, and second, to simulate the theory, or as Hawking put it, to "breathe fire into the equations."[3]

Solutions in Computing and Visualization

Intel has a close and longstanding relationship with the CTC, which Professor Shellard leads, together with Dr. Kacper Kornet (Project Manager). Intel contributed some of the funding for the original COSMOS supercomputer installation at Cambridge in 2012, and, in 2014, Intel named COSMOS an Intel® Parallel Computing Center (Intel® PCC).[4] The collaborative relationship has included participation together at the Intel® Technology Provider Conference. Most importantly, the CTC has been an early user of Intel® visualization technologies during their development, benefiting from Intel domain expertise, specifying user requirements, and offering early feedback on the developing technologies.

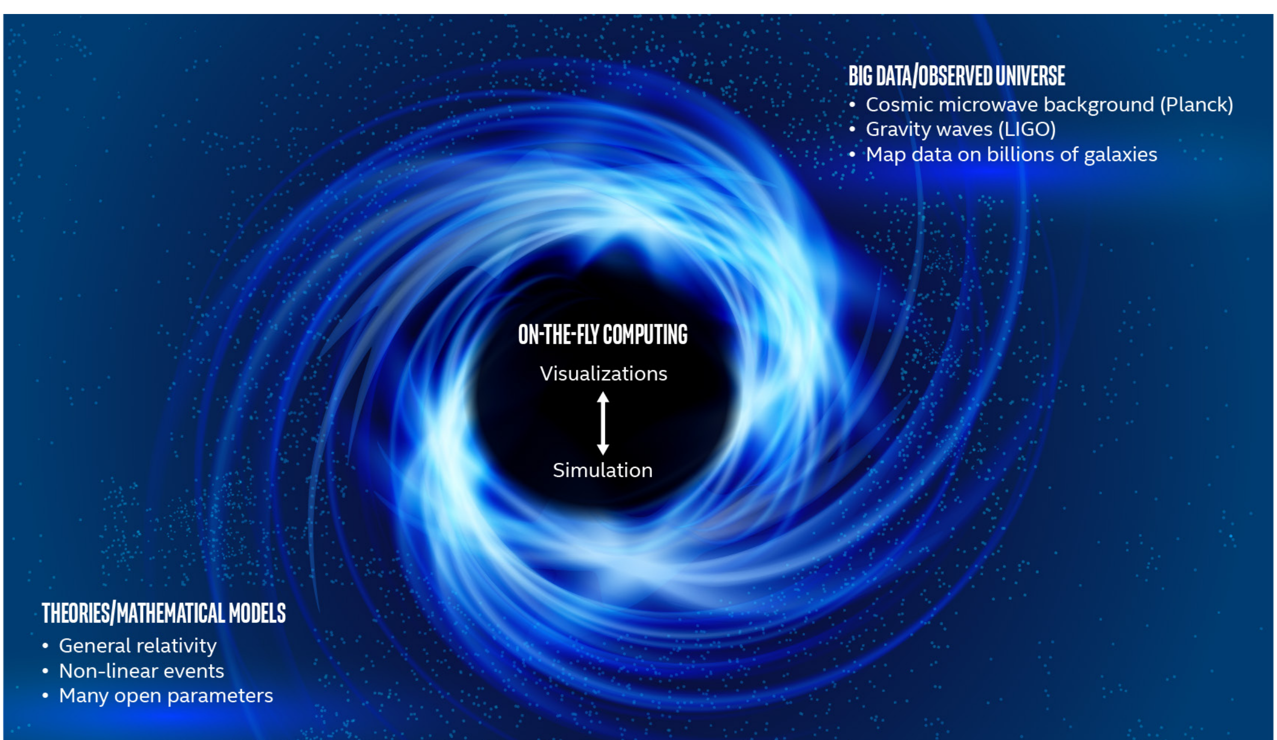

Figure 2. The challenge of real-time visualization of cosmological simulations

Figure 3. Professor Stephen Hawking with the COSMOS and SGI teams at the installation of the COSMOS supercomputer

Together with the Intel visualization team, the CTC has been among the first to demonstrate these technologies at SC* and ISC* supercomputing events using simulations of the cosmic microwave sky and gravitational waves. Additionally, more exascale computing centers like the CTC are adopting the new in-situ, or software-defined visualization, approach: perform large-scale simulations and visualizations simultaneously, rather than performing post-processing on a dedicated visualization cluster. For the CTC, this approach would not be possible without using advanced rendering technologies known as Intel® oneAPI Rendering Toolkit.

At the foundation of the Intel oneAPI Rendering Toolkit are its software-defined visualization (SDVis) libraries. These open source libraries offer CPU-based software that delivers high-performance solutions for visualizations, including large 3D data visualizations that are not typically achievable with graphics processing unit (GPU)-based solutions. When running a large simulation in a typical scientific workflow, large amounts of data are written to disk, and much time is spent on post-processing. A disk-based data-management infrastructure limits how often scientists can produce results and the fidelity of analysis. Furthermore, performance bottlenecks with a separate GPU cluster reduce computing productivity because of the limited memory capacity and input/output (I/O) problems that occur in this arrangement. Performing in-situ analytics allows for higher fidelity processing and optimizes resource usage for scientific workflows. Running the software libraries from Intel oneAPI Rendering Toolkit on CPUs avoids the need for a discrete GPU, which allows the scientists at the CTC to use one holistic platform for both simulations and visualizations. Among the Intel visualization tools the CTC uses are:

- **Intel® Embree**—A high performance, extensible, open source ray-tracing library with a vast feature set for complex rendering.
- **Intel® OSPRay**—A cluster-capable, scalable, ray-tracing rendering toolkit that includes path tracing and volume rendering. OSPRay efficiently uses threading and vectorization to create interactive, high-fidelity applications on CPUs from Intel.
- **Intel® OpenSWR**—An OpenGL* low-level CPU-based rasterization library to achieve high rendering performance.
- **Intel® Open Image Denoise**—An open source library of image denoising and filtering algorithms to improve visual quality and reduce rendering times.

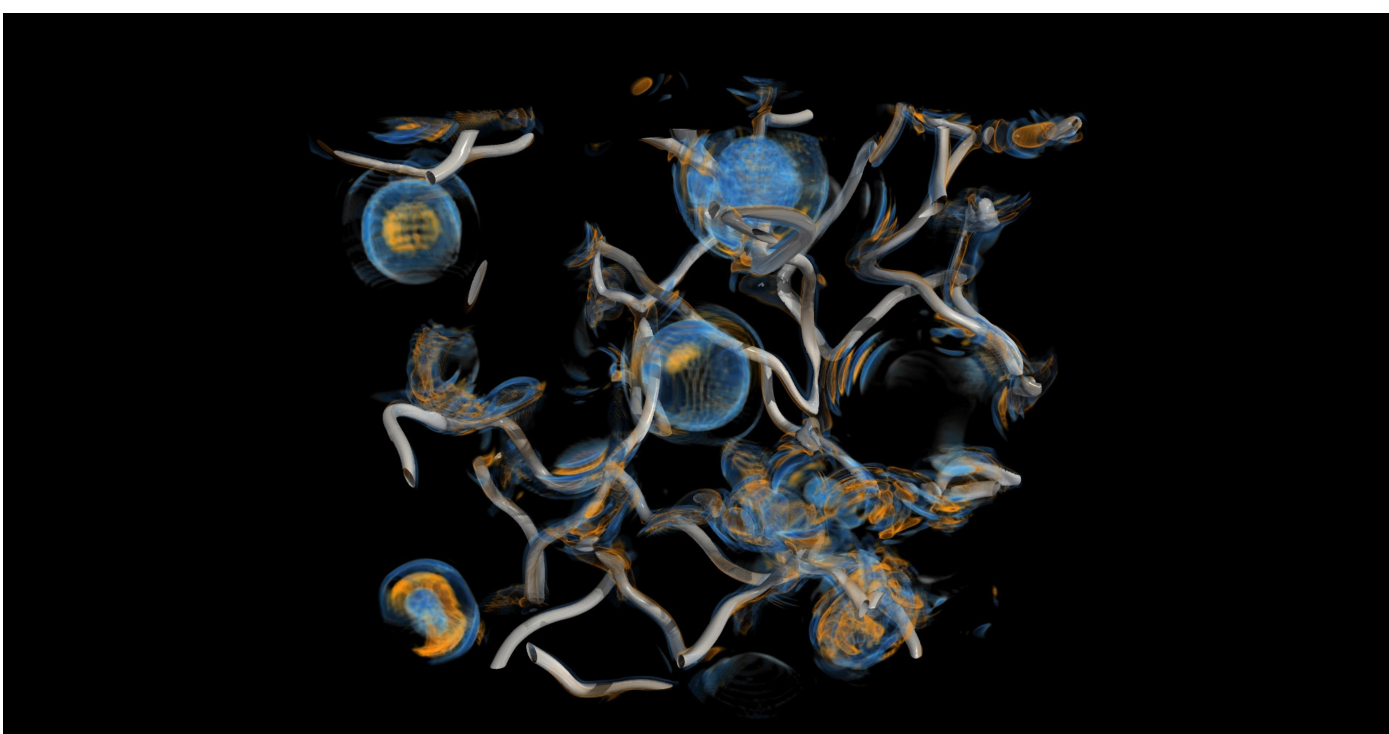

Figure 4. Visualization of a supercomputer simulation of cosmic strings and potential relics from the early universe, together with their radiation fields that could be detected by the LIGO/Virgo gravitational waves experiment[5]

Results at an Amazing Scale

The Intel oneAPI Rendering Toolkit and processor architecture provide the in-memory computing power required by the CTC to advance its research using enormous simulations and visualizations of extreme cosmic phenomena. To be clear, it's not just a matter of running simulations and visualizations faster, it's the ability to run them at all that's made possible by the COSMOS supercomputer and the Intel oneAPI Rendering Toolkit. The scale is remarkable: creating many thousands of mock universes in simulations based on pages-long relativistic non-linear equations with a huge parameter space, evaluated against gigabytes of observed datasets. And while all this is going on, the same system is simultaneously generating high-resolution visualizations of the state of the simulations.

Visualization is the key to better simulations, according to Professor Shellard:

"With such a complex set of equations, you don't really know what's going on unless you can look at diagnostics generated from these equations, like the energy density of the gravitational waves produced by colliding black holes. Observing these quantities visually is vital for developing our physical intuition and, before that, it's also important for debugging our code pipelines. When you have such a complex system, you want to know where you have made the mistake, where is it going wrong, whether on the boundary of the grid or, perhaps, the horizon of the black hole. So by visualizing the data in real time, we get faster development timescales, as well as much better insight, and there are also efficiencies from computational steering for costly production runs by showing which are worth pursuing to their conclusion."

The Sky Is Not the Limit

Humans have always looked to the sky in wonderment. But only relatively recently have people turned to supercomputers for help in understanding the origins and fundamental physics of the universe. Nowhere is this effort being pursued more vigorously than at the Stephen Hawking Centre for Theoretical Cosmology, where the most advanced computing resources and visualization software are "breathing fire" into theoretical work with massive amounts of observational data.

The pioneering efforts of the CTC to combine big theory and big data are leading the way for scientists and engineers in other fields. While studying extreme cosmological events like black holes and the origins of the universe might not appear to offer significant practical benefits, the methods and technologies being used represent a ground-breaking proof of concept for what can be accomplished with massively parallel processing, enormous in-memory datasets, and advanced visualization methods. If the CTC can run simulations of the entire cosmos to refine relativistic and quantum theories of physics, then imagine what can be accomplished in other fields of scientific and technological enquiry. The sky is no longer the limit.

Professor Paul Shellard

When Paul Shellard first encountered popular science articles about Professor Stephen Hawking as a student in Australia, he was inspired. So inspired, in fact, that he ended up moving halfway around the world to Cambridge, England, in order to study under Stephen Hawking himself and to earn a Ph.D. on *Quantum Effects in the Early Universe*. Professors Shellard and Hawking became collaborators in the project of bringing the power of supercomputing to the study of cosmology, resulting in the COSMOS supercomputing facility. Currently Dr. Shellard is Professor of Cosmology and Director of the Stephen Hawking Centre for Theoretical Cosmology at the University of Cambridge.

COSMOS by the Numbers

The current incarnation of the COSMOS supercomputer made by HPE includes:

- One shared memory node with 32 x Intel® Xeon® Gold 6154 processors (18 cores, 3 GHz) and 6 TB RAM
- Four nodes with 2 x Intel® Xeon® Gold 6140 processors (18 cores, 2.3 GHz) and 384 GB RAM each
- Two nodes with 2 x NVIDIA Pascal P100* GPUs and 2 x Intel® Xeon® Gold 6140 processors (18 cores, 2.3 GHz) and 384 GB RAM each
- 24 nodes with 1 x Intel® Xeon Phi™ 7210 processors (64 cores, 1.3 GHz) and 96 GB RAM each
- One storage node with 120 TB of raw disk space HPE* solid state drive (SSD) disks on a 2-socket system with Intel® Xeon® Gold 5118 processors
- All the nodes are connected with Intel® Omni-Path Architecture via three Intel® Omni-Path Switch modules

Software utilized on the system includes:

- Intel® Parallel Studio (Intel® VTune™ tools, Intel® Advisor, and so on)
- Intel® oneAPI Rendering Toolkit (OSPRay*, mainly via ParaView* and Catalyst*)
- Intel® Distribution for Python*

Learn More

Visit the Stephen Hawking Center for Theoretical Cosmology

Learn more about the Intel oneAPI Rendering Toolkit

[1] Unless otherwise noted, all quotes by Professor Shellard are from an interview conducted March 26, 2019.

[2] Gravity waves were long predicted, but were only actually detected as recently as 2015 using LIGO. Since then, LIGO has been detecting and differentiating gravity waves from different kinds of cosmic events, such as two black holes merging or two neutron stars colliding. In April 2019 came the first data indicating an event where a black hole was eating a neutron star. Source: Nature. “Gravitational waves hint at detection of black hole eating star.” April 2019. nature.com/articles/d41586-019-01377-2.

[3] Quoted by Professor Shellard are in an interview conducted March 26, 2019.

[4] See the University of Cambridge Department of Applied Mathematics and Theoretical Physics website: cosmos.damtp.cam.ac.uk/. The largest single-image shared-memory computer in Europe at the time, COSMOS was dedicated to research in cosmology, astrophysics, and particle physics. When operating at peak performance, the COSMOS supercomputer could perform 38.6 trillion calculations per second (TFLOPS), and it is based on SGI UV 2000* systems with 1,856 Intel® Xeon® processor E5-2600 cores, 14.8 TB RAM, and 31 Intel® Xeon Phi™ coprocessors. Source: University of Cambridge. “UK's COSMOS supercomputing research facility becomes an Intel Parallel Computing Centre.” June 2014. cam.ac.uk/research/news/uks-cosmos-supercomputing-research-facility-becomes-an-intel-parallel-computing-centre. The COSMOS supercomputer center has since upgraded in 2017 to an HPE Superdome Flex* platform. Source: HPE. “HPE partners with Stephen Hawking's COSMOS Research Group and the Cambridge Faculty of Mathematics.” November 2017. hpe.com/us/en/newsroom/press-release/2017/11/hpe-partners-with-stephen-hawkings-cosmos-research-group-and-the-cambridge-faculty-of-mathematics.html.

[5] “Cosmic Strings.” Image credit: Amelia Drew, Paul Shellard (University of Cambridge), and Intel.

Printed in USA 0719/JJ/PRW/PDF Please Recycle 340606-001US