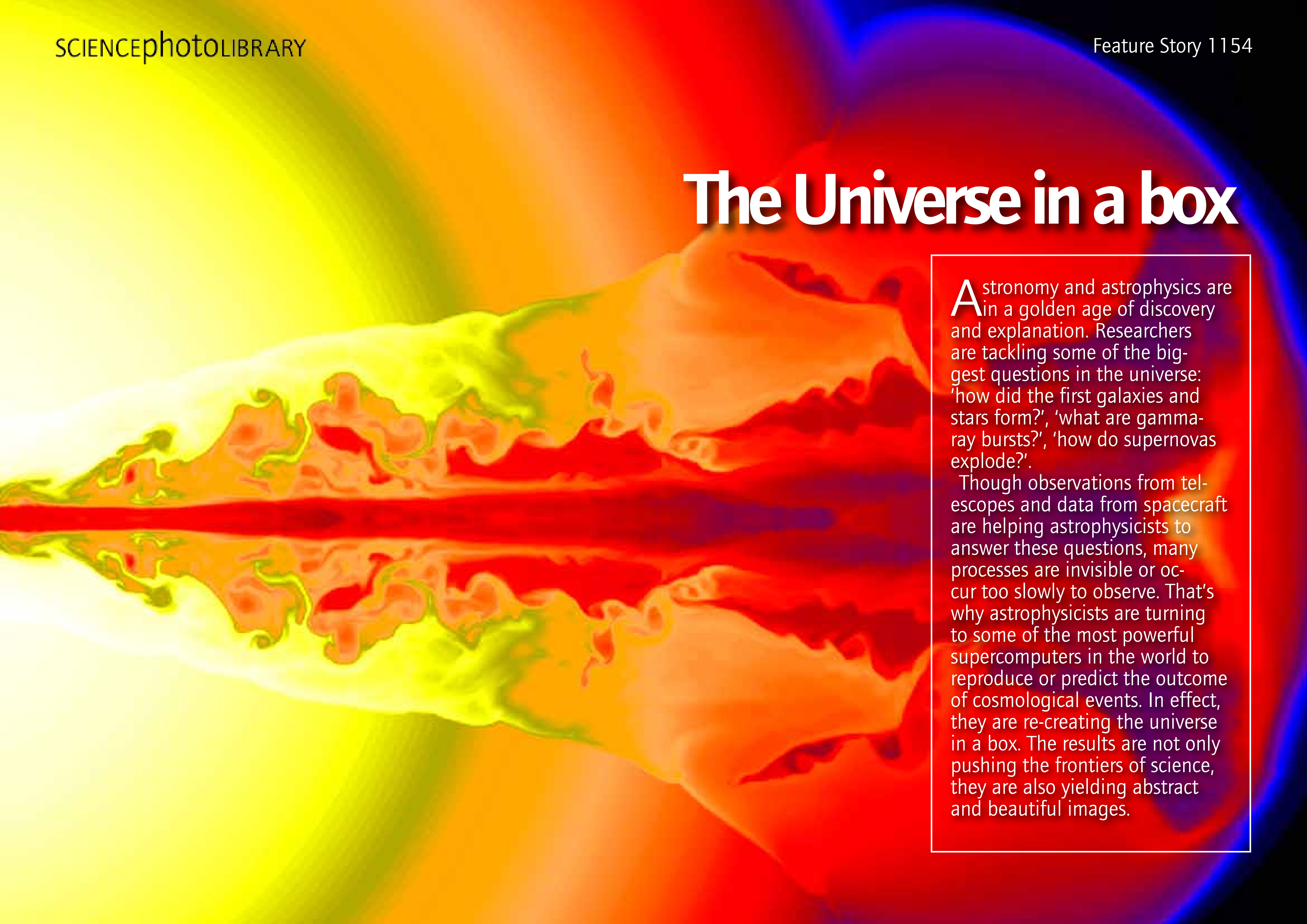
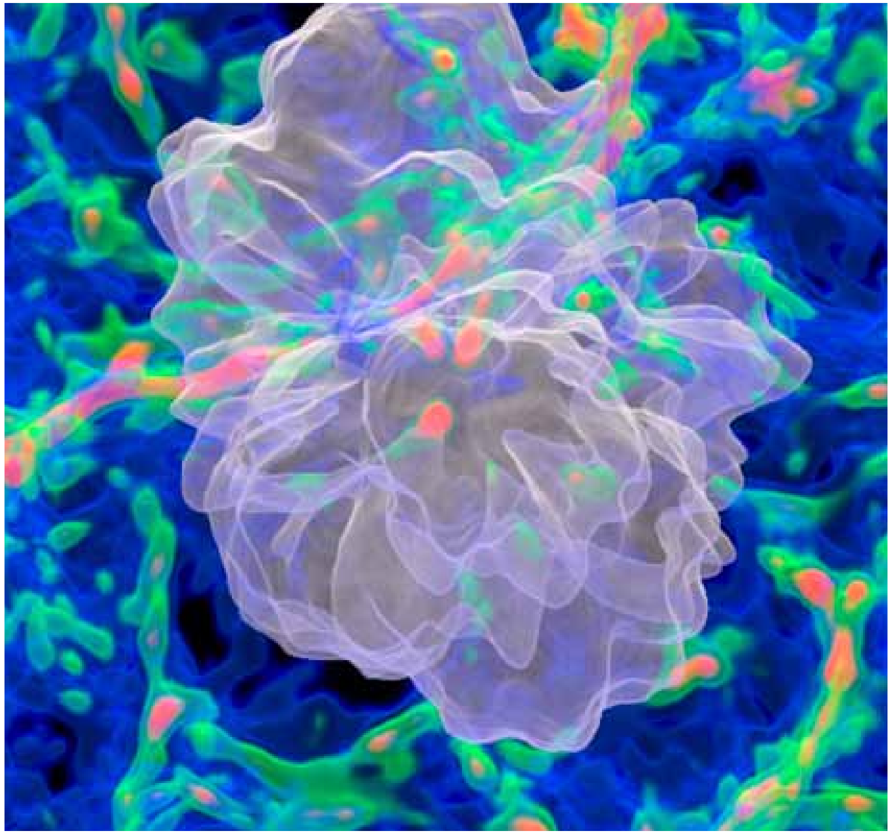


The Universe in a box

Astronomy and astrophysics are in a golden age of discovery and explanation. Researchers are tackling some of the biggest questions in the universe: 'how did the first galaxies and stars form?', 'what are gamma-ray bursts?', 'how do supernovas explode?'.

Though observations from telescopes and data from spacecraft are helping astrophysicists to answer these questions, many processes are invisible or occur too slowly to observe. That's why astrophysicists are turning to some of the most powerful supercomputers in the world to reproduce or predict the outcome of cosmological events. In effect, they are re-creating the universe in a box. The results are not only pushing the frontiers of science, they are also yielding abstract and beautiful images.

Marcelo Alvarez sits down for a normal day's work at his computer. But 'normal' for Alvarez, an astrophysics researcher at the University of Texas, USA, means running complex calculations on a state-of-the-art supercomputer. [SEE BOX: HOW SCIENTISTS CREATE COSMIC SIMULATIONS]



Alvarez's research focuses on the very first objects to appear in the universe - so called Population III (Pop III) stars. These massive stars, about 100 times the size of the Sun, were born from the cosmic soup of simple elements created just after the Big Bang. None exist today, but it is thought that when Pop III stars died they exploded with such violence that they seeded the universe with the crucial ingredients to form new stars, planets and ultimately life itself:

"To understand Population III star formation is to understand the quantum fluctuations created in the early universe," says Alvarez. "We must know how the first stars formed and evolved in order to understand the generations that followed."

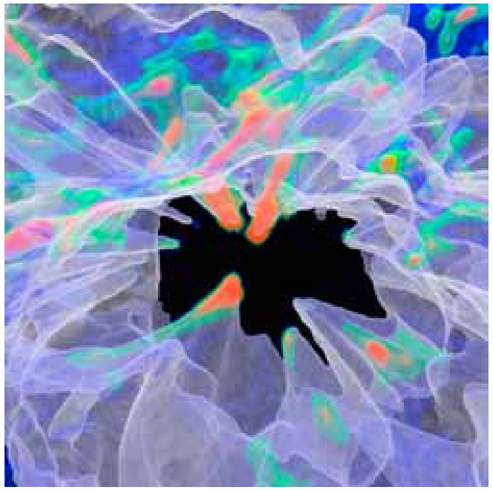
But Pop III formation is just a theory. In order to prove the theory is viable, Alvarez used two supercomputers to calculate data, turning paper theories and mathematics equatwions into an animated three-dimensional visualisation of exploding bubbles and expanding gas. These stunning visuals, together with numerical data, help Alvarez assess the accuracy of his theories and guide further research:

"We look at a three-dimensional computer generated image of the simulation to get an intuitive feel for what is going on."

From gas to stars

How are stars, galaxies and planets formed from simple clouds of gas? It's a question that Matthew Bate, from the University of Exeter, England, wanted to answer by enlisting the power of a supercomputer. Bate wrote computer programs and fed data into the UKAFF (UK Astrophysical Fluids Facility) supercomputer, Leicester, England. The program calculated the evolution of a huge ball of gas, 2.6 light years across and 500 times the mass of the Sun. The resulting animated sequence showed that, under the weight of gravity, the gas ball collapses and form clusters of stars and brown dwarfs. But the simulation also reveals how star formation is a ruthless business, with stars competing with one another for a finite gas supply. The sequence clearly shows how bigger stars greedily gather more and more gas, while the smaller, weaker stars, starved of gas, are eventually expelled from the cluster to lead low-energy lives as brown dwarf stars. The simulation provides strong evidence to back the theory that the galaxy is packed with many more brown dwarfs than previously thought:

"We now know much more about how stars



and planets form as a direct result of these calculations," says Bate.

Researchers Masao Mori and Masayuki Umemura used the Earth Simulator supercomputer in Japan to produce a stunning three-dimensional visualisation of galaxy formation. They are the highest resolution simulations ever produced, but they are not just pretty pictures. These visuals allowed the researchers to study in minute detail the evolution of a galaxy - from primordial blob of gas to dynamic star factory - over a billion year period.

Previous theories suggested that galaxy formation was a slow process, taking 10 billion years or so to reach maturity. But the new simulation revealed that it was a much faster process. After only one billion years, the gas bubbles formed early versions of galaxies known as Lyman-break galaxies, which contain almost all the heavier elements that present day galaxies have - a good example of how computer simulations have helped redefine current theories.

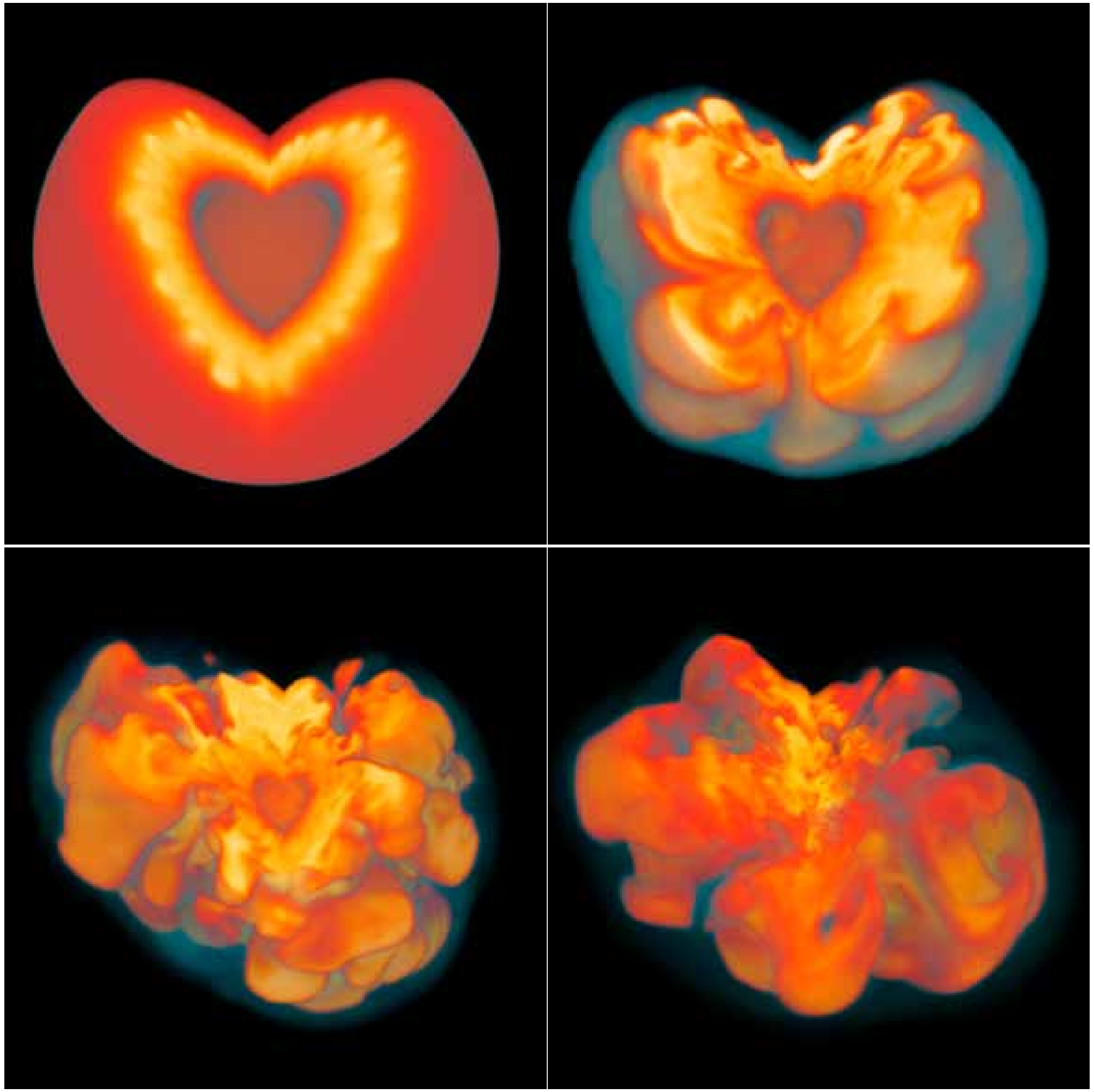
The biggest explosion

Few cosmic events match the spectacle of a supernova explosion. As a massive star runs out of nuclear fuel, its core collapses to form an extremely dense neutron star. The dense core triggers a shockwave that causes an explosion huge enough to be observed millions of light years away. Supernovae are considered important because they give birth to black holes and neutron stars, and allow new stars and planets to form by seeding the universe with the chemical elements necessary for life.

Astronomers have been attempting to model the dynamics of supernovae explosions since the 1960s. Despite decades of work, they admit to still not knowing how they really explode. But, thanks to supercomputers, some answers are beginning to emerge.

One of the biggest problems that researchers face with the current model is that the shockwave produced by the core would not be enough to power a supernova explosion. As the shockwave races back up through the star, it has to push through huge amounts of matter still plunging inwards - which should bring the shockwave to a halt before breaking out of the star. So there must be another mechanism that powers the explosion.

Adam Burrows, from the University of Arizona, USA, believes that sound waves play a part. His simulations show that a collapsing star causes



the core to oscillate as an acoustic pulse - a sound wave on a giant scale. The sound waves could be enough to power a supernova explosion:

"Sound also generates pressure, which pushes the streams of in-falling matter to the opposite side of the core, further driving the oscillations in a runaway process," he says. "The sound waves reinforce the shock waves until it finally explodes."

Not everyone agrees with the new finding. 3-D simulations created by Konstantinos Kifonidis and Leonhard Scheck from the Max Planck Institute for Astrophysics in Germany show how rising and falling gas heated by sub-atomic particles known as neutrinos create violent turbulence and enough convective energy to trigger a supernova explosion. Clearly, the supernovae question is still unresolved, despite the help of supercomputers.

Black holes

The power to simulate scenarios that would be impossible in real life is the major appeal of using supercomputers.

Take the collision of two massive black holes, for example. According to Einstein's general theory of relativity, such an event between two such high-mass bodies would cause ripples to occur in space-time. These ripples travel at the speed of light and are known as gravitational waves. No one has ever detected gravitational waves, so the theory remains unproven and, until now, the complexity of the calculations has caused most computers to crash.

For researchers at NASA, it helps to rely on the fourth fastest machine in the world - the Columbia Supercomputer. The NASA researchers successfully simulated the merger of two black holes and, after several days of computation, revealed that black holes do indeed produce gravitational waves. The finding is crucial for NASA and ESA - both of whom have plans to launch space observatories dedicated to detecting gravitational waves from extremely distant sources.

Supercomputers have also shown how black holes play a vital role in the formation and growth of galaxies, stars and planets. According to recent simulations at the Max Planck Institute for Astrophysics, Germany, black holes are the very powerhouses behind new galaxy formation.

In their simulation, two spiral galaxies are made to collide. As they do so, the temperature of the gas that surrounds the centre builds up to enormous levels and feeds a supermassive black hole more than a billion times the mass of our Sun.

This supermassive black hole gathers matter surrounding it and eventually releases enormous heat energy that drives out the surrounding gas. All that remains is a gas-less elliptical galaxy. Because there is no gas, there is no material to form new stars and the remaining stars age rapidly to develop red spectral colours. The simulation provides a solid explanation for the observation that many elliptical galaxies observed from telescopes are very red.

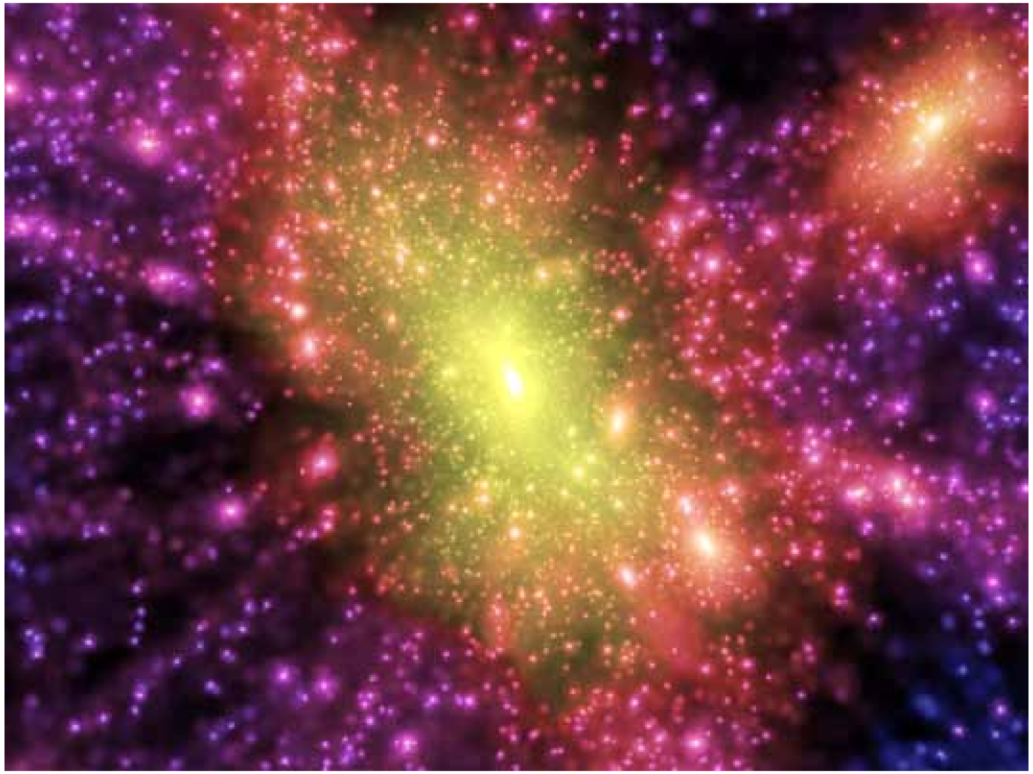
Gamma ray explosions

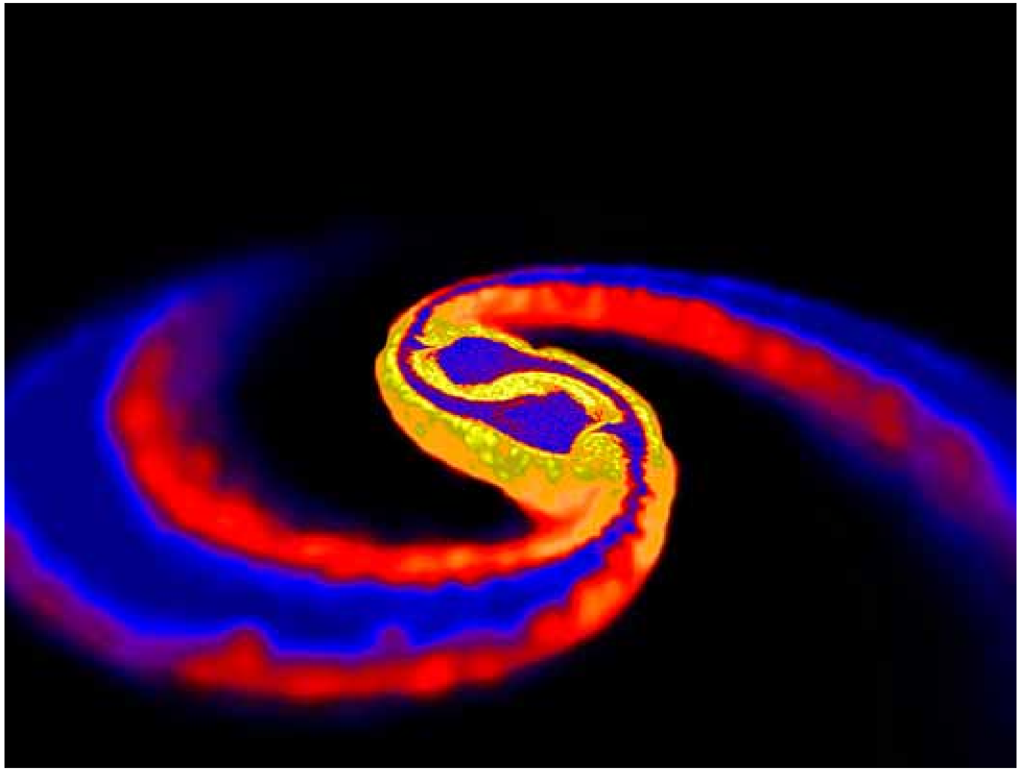
Gamma-ray bursts (GRBs) are some of the most powerful deep space explosions in the universe - equivalent to the energy of 100 million billion suns. Astronomers believe they are important stages in the lifecycle of certain stars, but because GRBs are very short lasting a few seconds to a few minutes - they are difficult to study.

Stan Woosley and his team from the University of California, Santa Cruz, first proposed that GRBs could be formed from very hot, fast-rotating, massive stars known as Wolf-Rayet stars. To prove this, he used supercomputer simulations to model the effects of a dying massive star.

The simulation showed that when these stars run out of fuel, they can form a 'collapsar'. These are essentially massive, spinning black holes believed to be the fastest objects in the universe - so fast, in fact, that two extremely powerful, narrow jets of energy are released along the spinning axis of the black hole. These jets are thought to be the source of GRBs, or more specifically, 'long' GRBs that last more than 2 seconds.

But for a long time astronomers have not known what creates a second category of GRBs, known as 'short' GRBs, that last less than 2 seconds. German astrophysicist Stephan Rosswog and his UK colleague Daniel Price used supercomputers to calculate the collision of two neutron stars. Their simulations reveal that two merging neutron stars release a huge amount





of magnetic energy within fractions of a second and in a pattern very similar to observed data on short GRBs:

"We have managed to simulate, for the first time, what happens to the magnetic field when neutron stars collide," says Price. "It seems possible that the magnetic field produced could be sufficient to spark the creation of gamma-ray bursts."

The Millennium Project

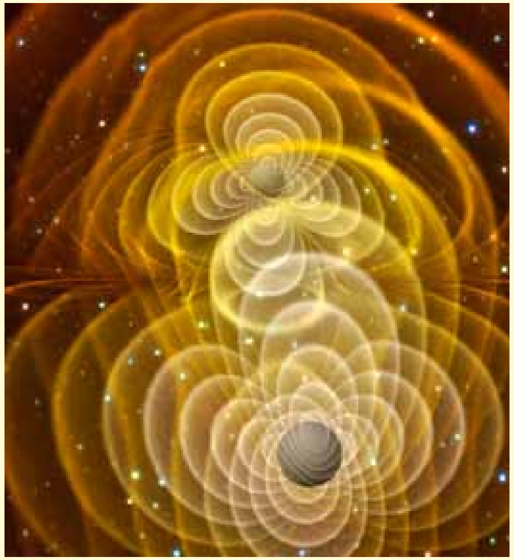
One of the most ambitious cosmology projects attempts to simulate the evolution of the entire universe from the Big Bang to the present day. This is the goal of the international team of scientists who form the Virgo Consortium. Their project, known as the Millennium Run, has already produced the largest-ever simulation of its kind. Using a supercomputer belonging to the Max-Planck-Institute in Germany, the simulation features 10 billion 'points of mass' spread over a 3 billion light year stretch of the universe. Each point of mass - the resolution of the simulation - refers to the gravity of a stellar object about a billion times the mass of the Sun. The sheer size and detail of the visualisation has allowed astronomers to zoom in at huge magnifications and reveal tiny details.

The simulation was shown to be a realistic model when compared with observed data. Crucially, it confirmed current ideas about how the universe evolved from collapsing regions of dark matter to vast halos that attracted normal matter to form galaxies, stars and planets the so-called Cold Dark Matter theory.

A big surprise was the discovery that powerful quasars and supermassive black holes could be formed in the early universe - something that was previously thought impossible.

Astronomers hope to repeat the success of the Millennium Run with increasingly sophisticated visualisations. By 2060, they estimate that computers will be powerful enough to simulate the entire universe with 'points of mass' equal to the mass of the Sun. Then they will say that they have truly created the universe in a box.

ENDS 1920 WORDS
Written by Seymour Yang



BOX: HOW SCIENTISTS CREATE COSMIC SIMULATIONS

Having access to a machine costing hundreds of millions of dollars is one thing – it's what you do with it that counts. Before a supercomputer is even touched, astrophysicists usually begin their research with a question - such as 'how did the first stars form?'. Then, they propose a theory about how an astrophysical process works. This can rely on data from telescope observations or spacecraft but many of the processes studied, such as black holes or gamma ray bursts, are not directly visible.

Marcelo Alvarez, an astrophysics researcher at the University of Texas, explains: "Theoretical astrophysicists have always been quite resourceful using paper-and-pencil calculations, but that can only get you so far. Without powerful computers it would be impossible to do most of the cutting-edge work currently underway."

Astrophysicists use supercomputers to produce both visual and numerical simulations that flesh out their theories. Producing a visual model of how two bodies collide and interact, for example, relies on countless hours of computing time. The more detailed the simulation, the more computing time needed. Many astrophysical models are based closely on how liquids and gases move according to known laws of physics, a discipline known as fluid dynamics. When trying to predict something like a supernova explosion, the fluid dynamic calculations needed are staggering. To give a measure of what the researchers are trying to achieve, imagine trying to calculate how a single particle moves in space and time when it is subject to changing velocity, pressure, temperature and density - then multiply it a billion-fold.

Leonhard Scheck from the Max Planck Institute for Astrophysics, Germany, explains the process: "First we need some information about the initial state of the objects we want to simulate, for example, temperature or density. These can be considered as a set of mathematical variables.

"Then the most important physical processes in the problem have to be identified and formulated as a set of mathematical equations. These equations describe the change of the variables with time. Repeatedly solving the equations yields information for later and later times, so that we end up with information about the full physical process we wanted to simulate."

The mathematical equations used for the simulations are complex. That is why astrophysicists need the help of powerful computers.

To compare the power of today's supercomputers, their performance is measured in FLOPS Floating Point Operations Per Second. A pocket calculator is capable of about 10 FLOPS. A typical desktop computer in the home or office running a Pentium 4 processor will be able to calculate data in the region of several gigaflops - one 'giga' equals 10^9, or 1,000,000,000. In contrast to calculators and desktops, supercomputers perform calculations in terms of several teraFLOPS a 'tera' is equivalent to 10^12, or a trillion calculations per second. The Earth Simulator computer in Japan, for example, is capable of 35.86 teraFLOPS.

NASA's Columbia Supercomputer is even more powerful, capable of up to 50 teraFLOPS. That's over a thousand times more powerful than a desktop computer.

Despite their awesome power, it still takes a typical simulation weeks or even months to complete:

"Just to calculate a few milliseconds of a single collision takes several weeks on a supercomputer," says Daniel Price, astrophysics researcher at the University of Exeter, England.

The computer uses specialised software to analyse each variable and plot a sequence of events based on the mathematical formulae. Software such as GADGET, written by Volker Springel from the Max Planck Institute for Astrophysics, is commonly used to simulate collisions of large cosmological objects. This and other software are able to interpret the hard results and produce an animated 2-D or 3-D visualisation. Colours are decided by the researcher, usually to indicate one variable, such as extremes of temperature or density.

Once the simulation is finished, it is analysed and the results compared to the theories and observed data. Simulations can either enhance a theory, or expose serious flaws. In most cases, astrophysicists must continue their work by modifying the variables and creating further simulations.

There are still so many questions about our understanding of the universe that astrophysicists will be kept busy using ever more powerful supercomputers for many years to come. But behind the brute muscle of computing power lies the simplicity and elegance of the original theory and equations. Marcelo Alvarez sums up:

"The 'paper and pencil' analytical theory is often times very helpful because of its elegance and clarity, but assumptions must often be made, and computer calculations allow us to verify the validity of those assumptions.

"In this way, numerical and analytical work complement each other quite well since we definitely need both in theoretical astrophysics."

FULL PICTURE SET

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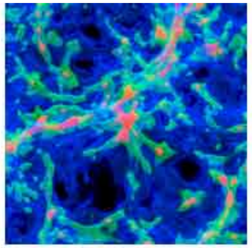
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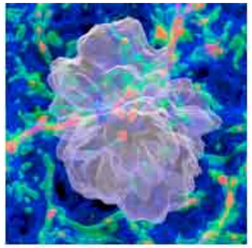
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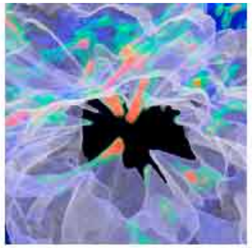
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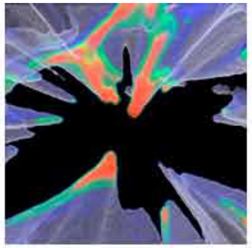
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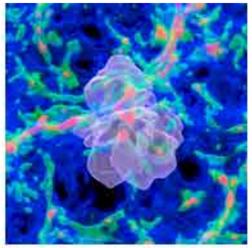
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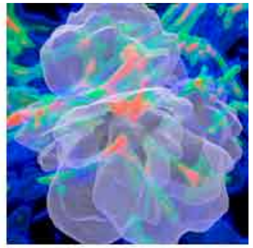
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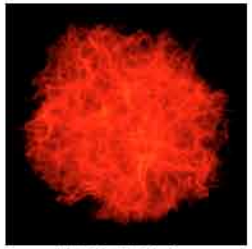
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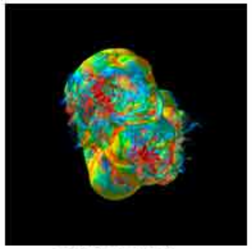
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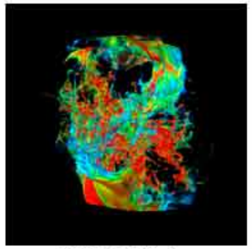
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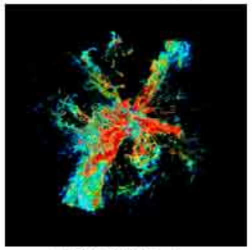
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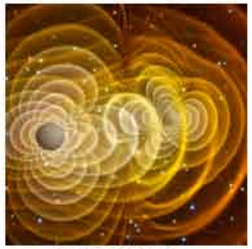
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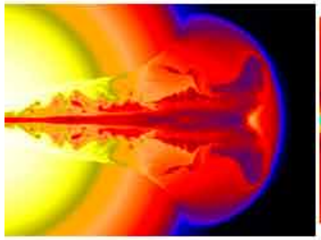
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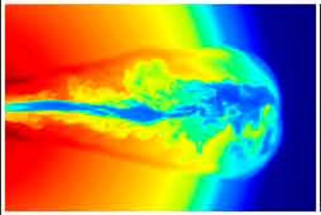
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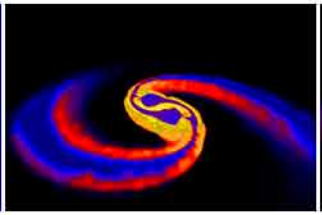
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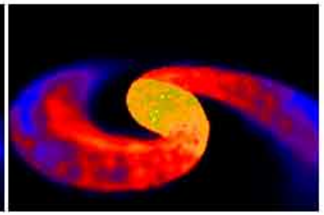
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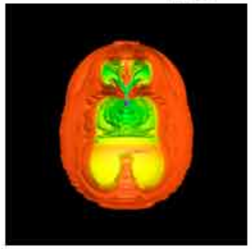
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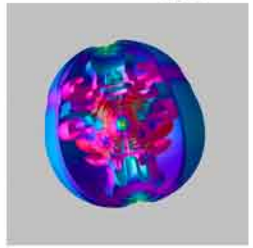
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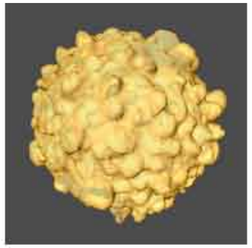
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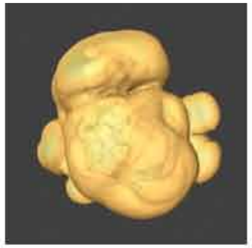
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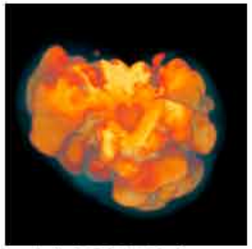
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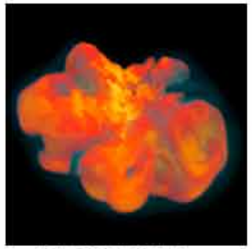
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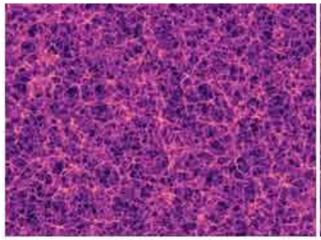
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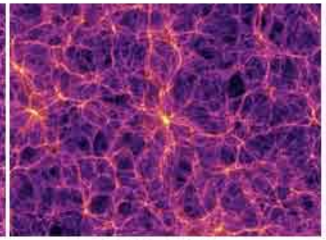
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