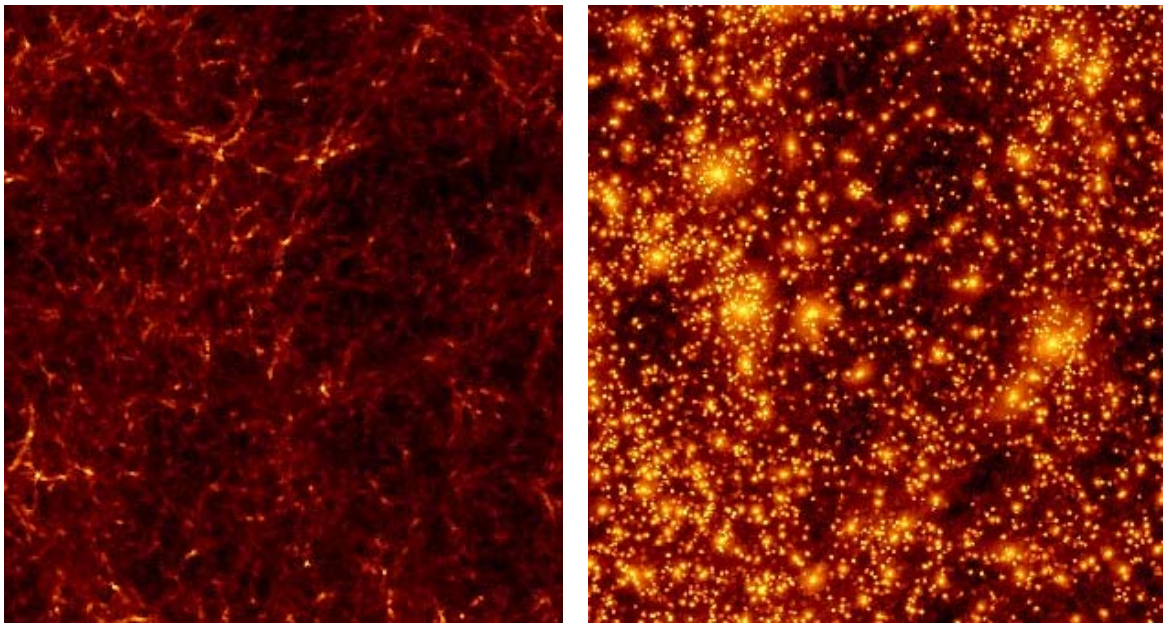

Supercomputers can do trillions of calculations each second, and follow the movement of billions of particles over time. In 2008, scientists at the University of Chicago used supercomputer simulations to investigate how dark matter. Dark matter is an invisible material of unknown composition that is estimated to be 5 times more abundant in our universe than ordinary matter. Astrophysicists believe that dark matter may have herded luminous matter in the universe from its initial smooth state into the cosmic web of galaxies and galaxy clusters that populate the universe today. These two images from the simulation of the evolution of the universe show a cubic volume of the universe measuring approximately 200 million light years wide. The images show how dark matter caused the distribution of the luminous matter to change from 470 million years after the big bang (left) to today, some 13.7 billion years after the big bang (right). (*Courtesy: University of Chicago: Andrey Kravtsov, Charlie Conroy and Risa Weschlser*).

Astronomers can use their catalogs of millions of distant galaxies to check these supercomputer calculations. The goal is to mathematically model the earliest epoch of galaxy formation and to use telescopes like the Webb Space Telescope to confirm the details of these models to within 20 million years after the big bang. Since no luminous stars existed then, this period from 1 million years to about 20 million years after the big bang is called the Dark Ages.

Problem 1 - Using a millimeter ruler; A) what is the scale of these two images in light years per millimeter? B) How large would the Milky Way be on the scale of these supercomputer images? C) The Local Group of galaxies, which is 10 million light years in diameter?

Problem 2 - The smallest mathematical feature that the supercomputer can follow in these calculations is about 100 light years across. If the entire volume modeled was 280 million light years on a side, how many cubic cells 100 light years wide are in this entire volume?

Problem 3 - If the time step between calculations was 1000 years, how many time steps did it take to complete a full 13.7 billion year calculation?

Problem 1 - Using a millimeter ruler; A) what is the scale of these two images in light years per millimeter? B) How large would the Milky Way be on the scale of these supercomputer images? C) The Local Group of galaxies, which is 10 million light years in diameter?

Answer: A) The width of each image is about 108 millimeters, so the scale is 200 million/108mm = **1.9 million light years/millimeter**.

B) The Milky Way would be about 100,000 light years x (1 mm/1.9 million) = **0.05 millimeters across!**

C) The Local Group = 10 million light years x (1 millimeter/1.9 million light years)

= **5.3 mm**.

Problem 2 - The smallest mathematical feature that the supercomputer can follow in these calculations is about 100 light years across. If the entire volume modeled was 280 million light years on a side, how many cubic cells 100 light years wide are in this entire volume?

Answer: The large volume has a width of 280,000,000 / 100 = 2,800,000 cells ,so the total number of cells in the volume is just N = $(2{,}800{,}000)^3$ = **2.2×10^{19} cells**

Problem 3 - If the time step between calculations was 1000 years, how many time steps did it take to complete a full 13.7 billion year calculation?

Answer: The total number of time steps is 13,700,000,000 / 1000 = **13.7 million**.

Note: The actual calculation used what is called a variable cell mesh so that for volumes of space where not much was happening, a large cell size many times larger than 100 light years was used. Only in regions where things were changing rapidly was a smaller cell size used, so the actual number of cells followed in the entire simulation was much less than 2.2 x 10^{19}. A similar variable mesh process was used for the time steps.

The Local Group of galaxies consists of the Milky Way, the Andromeda galaxy, and about 30 other smaller galaxies located within 5 million light years of the Milky Way.