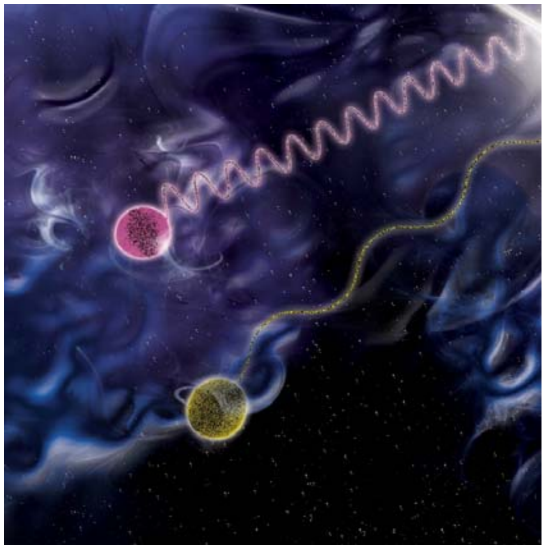

An artistic impression of two gamma-ray photons traveling through a lumpy space (Courtesy: NASA /Sonoma State University/Aurore Simonnet.)

The most advanced theories of how gravity works have proposed that empty space is not smooth, but may be filled by invisible limps and bumps that distort space into a froth of bubbles that are billions of times smaller than atomic nuclei. That's why we have not detected them in laboratory experiments thus far.

By studying how intense gamma-rays travel through the vast spaces between galaxies in the universe, NASA's Fermi Gamma-ray Observatory may have placed limits on this frothiness that eliminate many of the theories being explored to date.

As the gamma-rays travel through space, the shortest-wavelength gamma-rays take a slightly different path through space than the longer-wavelength gamma-rays. Although all gamma-rays travel at the speed of light, the invisible lumps in space scatter the short-wavelength (high-energy) gamma rays more than the long-wavelength (low-energy) ones so that there is a difference in the travel times of the long and short-wavelength gamma rays. This means that in traveling a distance, L, to Earth, the time should be about t = L/c where c is the speed of light. The theories predict that the lumps in space cause the arrival times for the long and short-wavelength gamma-rays to differ by an amount **T = (L/c) x (d/λ).** In this equation, λ is the wavelength difference between the two gamma-rays (related to their energy-difference), **d** is the length scale corresponding to the lumpiness in space, and **c** is the speed of light, 3 x 10^{10} cm/sec.

Problem 1 – Suppose two rays of visible light differed in wavelength by 100 nanometers ($\lambda = 10^{-9}$ cm) and traveled from the sun to Earth (L=150 million kilometers) through space with a lumpiness of about the scale of an atomic nucleus (d=10^{-14} cm). What would be the arrival time delay in seconds at Earth between the two visible light photons?

Problem 2 – Suppose there is no indication that arriving visible light photons (10^{-9} cm) experience any delays in arrival time longer than 1 second, from quasars as far away as 5 billion light years. What is the maximum size of the lumps in space that are consistent with this limit?

Problem 3 – The Fermi Telescope measured a gamma-ray pulse from a distant object located 10 billion light years from Earth. The time delay was no more than 0.7 seconds. The wavelength difference in the gamma-rays was 4.0 x 10^{-12} centimeters (33 billion electron volts of energy). What is the largest size that can be involved in the lumpiness of empty space given this Fermi measurement.

Problem 1 – Suppose two rays of visible light differed by 100 nanometers (10^{-9} cm) in wavelength, and traveled from the sun to earth (150 million kilometers) through space with a lumpiness of about the scale of an atomic nucleus (10^{-14} cm). What would be the arrival time delay in seconds at Earth between the two visible light photons?

Answer: $T = (1.5 \times 10^{13}\text{ cm}) \times (1.0 \times 10^{-14}) / (3 \times 10^{10} \times 1.0 \times 10^{-9})$

= 0.005 seconds.

Problem 2 – Suppose there is no indication that arriving visible light photons (10^{-9} cm) experience any delays in arrival longer than one second, from quasars as far away as 5 billion light years. What is the maximum size of the lumps in space that are consistent with this limit?

Answer: L = 5 billion light years; $\lambda = 10^{-9}$ cm ; T = 1 second

Also L/c = 5 billion light years/c

= 5 billion years.

$= 5 \times 10^{9}$ years $\times 3.1 \times 10^{7}$ sec/year

$= 1.6 \times 10^{17}$ seconds

So $d = T \lambda c / L$

= (1 sec) $\times (1.0 \times 10^{-9}$ cm)/ $(1.6 \times 10^{17}$ sec)

= **6.3×10^{-27} centimeters.**

Note: This is 10 trillion times smaller than the size of an atomic nucleus!

Problem 3 – The Fermi Telescope measured a gamma-ray pulse from a distant object located 10 billion light years from Earth. The time delay was no more than 0.7 seconds. The wavelength difference in the gamma-rays was 4.0×10^{-12} centimeters. What is the largest size that can be involved in the lumpiness of empty space given this Fermi measurement.

Answer: L = 10 billion light years; $\lambda = 4.0 \times 10^{-12}$ cm ; T = 0.7 second

Also L/c = 10 billion light years/c

= 10 billion years.

$= 1.0 \times 10^{10}$ years $\times 3.1 \times 10^{7}$ sec/year

$= 3.1 \times 10^{17}$ seconds

So $d = T \lambda c / L$

= (0.7 sec) $\times (1.0 \times 10^{-12}$ cm)/ $(3.1 \times 10^{17}$ sec)

= **2.2×10^{-30} centimeters.**

Note: This is 22,000 trillion times smaller than the size of an atomic nucleus! According to some theories of the structure of space, the fundamental limit is about 1.6×10^{-33} centimeters and is called the Planck Length. The Fermi limit corresponds to about 1,400 Planck Lengths or smaller.