Gravitational Lenses

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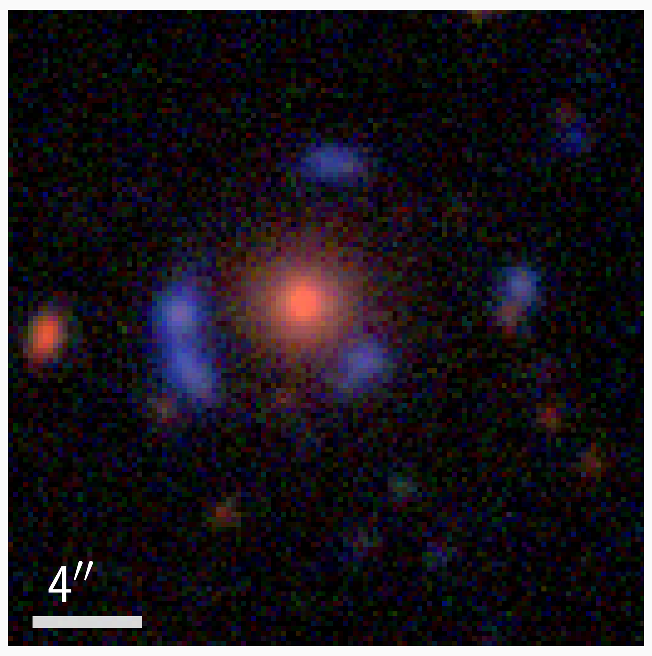
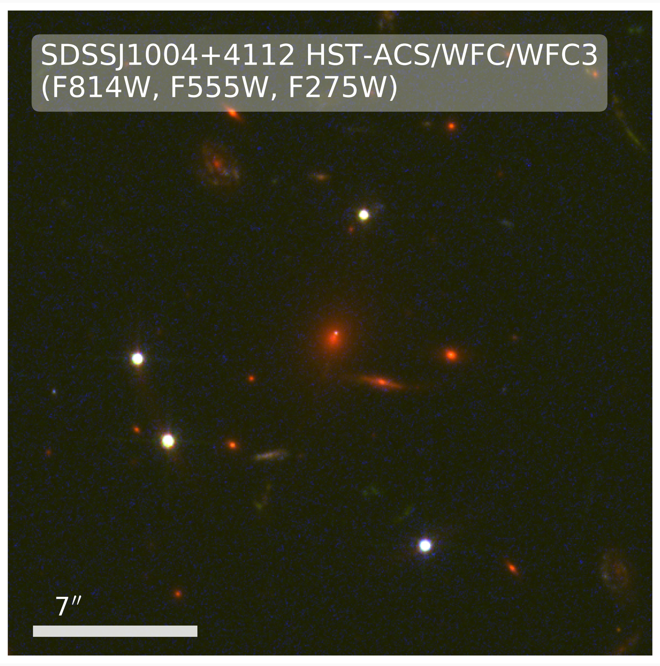
Once upon a time, a lens was a piece of glass that looked like a lentil seed (*Lens culinaris*). Nowadays a lens can be any system with non-trivial optical paths. The term "gravitational lens" refers to a mass whose gravitational field produces an optical path that is somehow interesting. The lensing mass can be a star or even a planet, but the most-studied gravitational lenses tend to be galaxies or clusters of galaxies.

Gravitational lenses are useful for three things: first, for studying the distribution and properties of dark matter, since galaxy and cluster lenses are dominated by dark matter; second, for measuring the expanding universe, since the latter is part of the optical path; and third, like a traditional lens for making objects appear bigger and brighter.

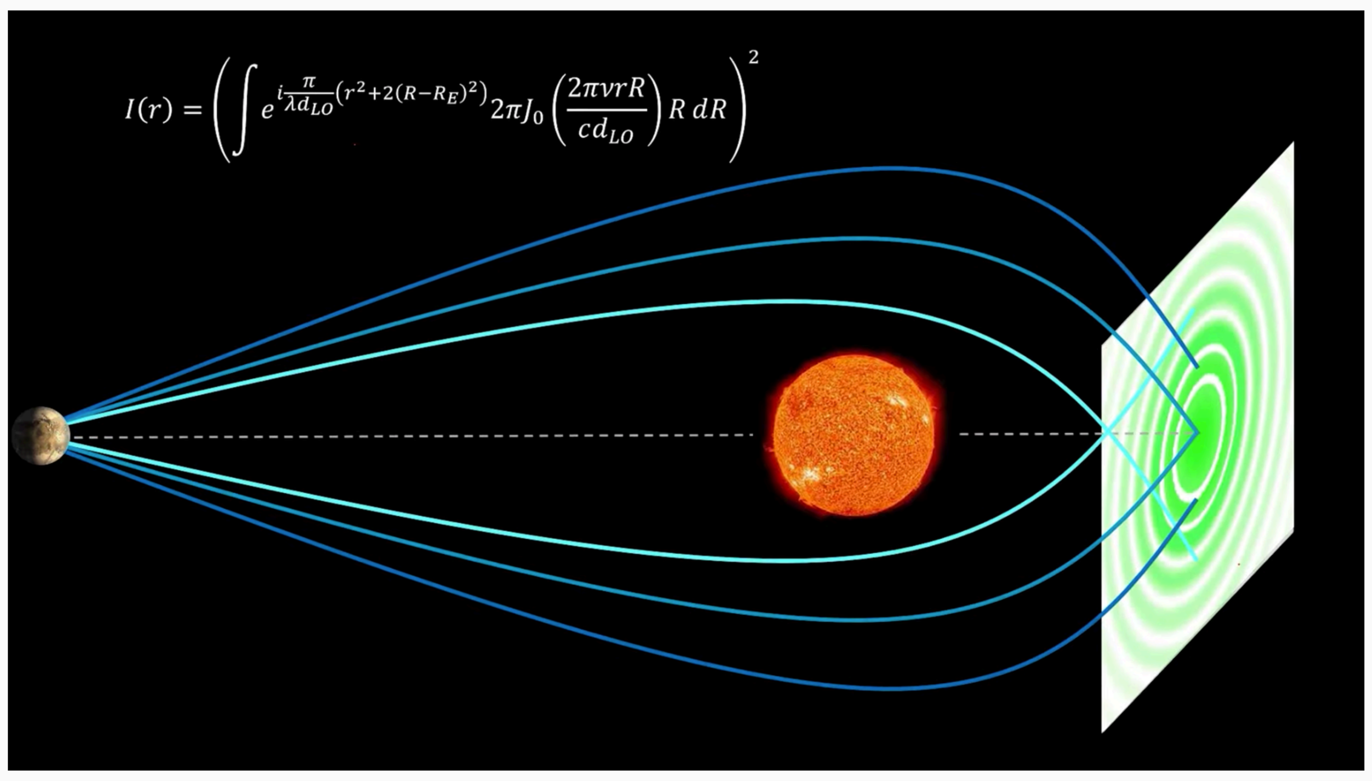
Galaxy and cluster lenses





Here are two examples of multiple mirages formed by gravitational lensing. On the left we see a galaxy (the orange blob) with a quartet of four galaxies (blue blobs) around it. [Other blobs are foreground objects, which we can ignore.] On the right we see a cluster of galaxies with a quartet of four quasars around it. The quartets are mirages, the real object in each case is near the middle but much further away.

The Sun as a gravitational lens



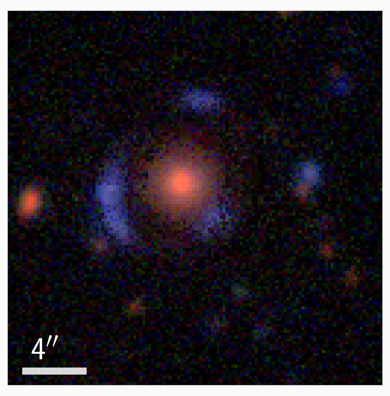
The Sun (when suitably covered up by a coronograph or eclipse) really does behave like a gigantic lens. Unfortunately, the focus is too far away to use as a telescope yet — Voyager I will be able to, if its cameras are still working in 2150! To find out more, check out the third QR code to the right.

References

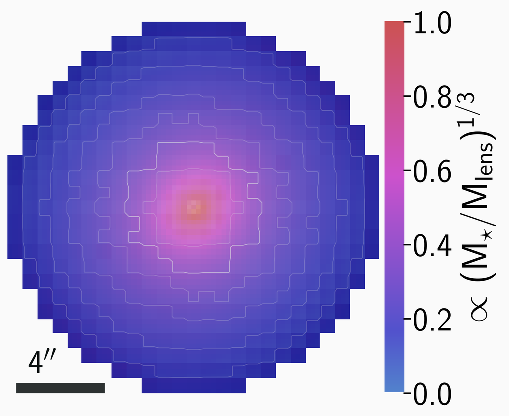
A galactic fossil?

Although the universe is expanding, galaxies that are close together, like the Milky Way and Andromeda, are actually coming closer together and will eventually merge. Groups of galaxies that have completed the merger process are imaginatively known as fossil groups. Our study of the galaxy lens above suggests that it may be an early-fossilised galaxy group. Gravitational lensing allows us to reconstruct the mass distribution of the lensing galaxy and compare it with the inferred mass in stars (see panels to the right). The synthetic ray-traced image reproduces the observed mirages very well. We find that the galaxy is almost entirely dark matter, with the stellar fraction being significant only in the central region. Galaxy-formation simulations do produce objects in this mass range, but no early-forming fossils like this one. For details, see the first of the QR codes.

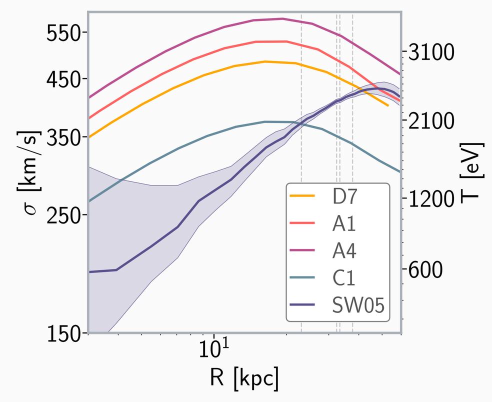
Synthetic



Stellar fraction



vs Simulations



Time delays and the Hubble tension

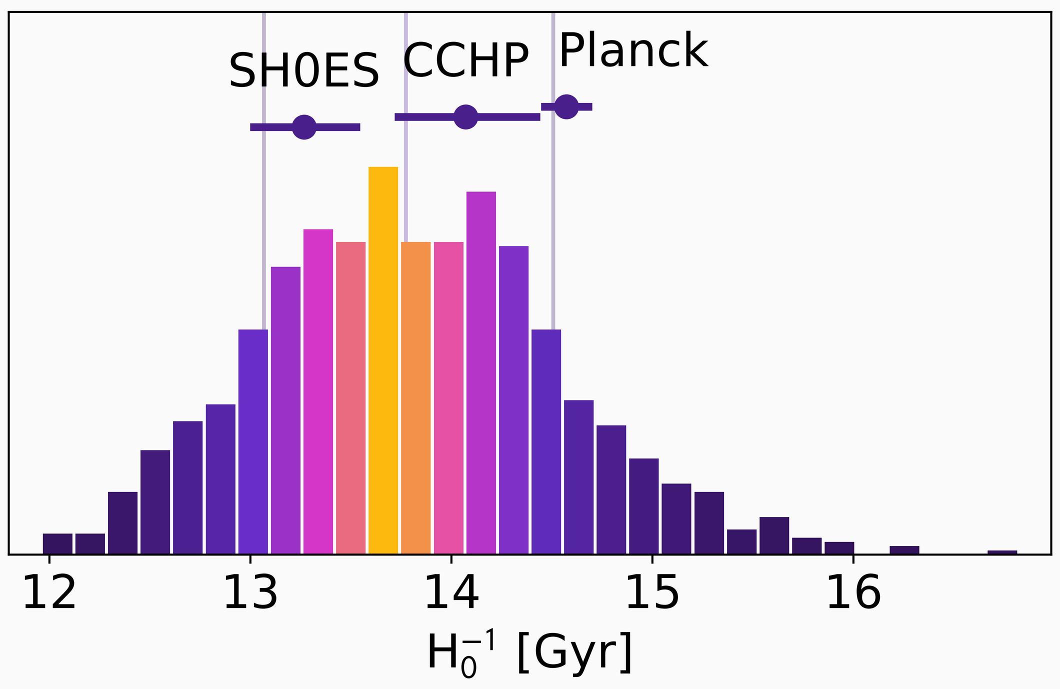
One of the remarkable feature of multiple mirages in gravitational lensing is that they let you measure the scale of the universe, or the Hubble parameter.

The Hubble parameter H_0 (also called the Hubble constant) is defined as the expansion rate of the Universe. Being a rate, H_0 formally has units of hertz and its value is 2.3(2) attohertz. Nobody writes H_0 that way, though. The reciprocal H_0^{-1} is basically the time since the Big Bang, so it is more useful to write $H_0^{-1} = 14(1)$ Gyr. Another equivalent quantity is the cosmological mean density $\rho_c = 3H_0^2/(8\pi G)$ including the dark sector. Finally, H_0 can be expressed as a velocity gradient as $70(5)$ km/s/Mpc. There are techniques ways to measure the Hubble parameter, and they mostly give consistent results, but there are disagreements at the 10% level. This is often called the Hubble tension.

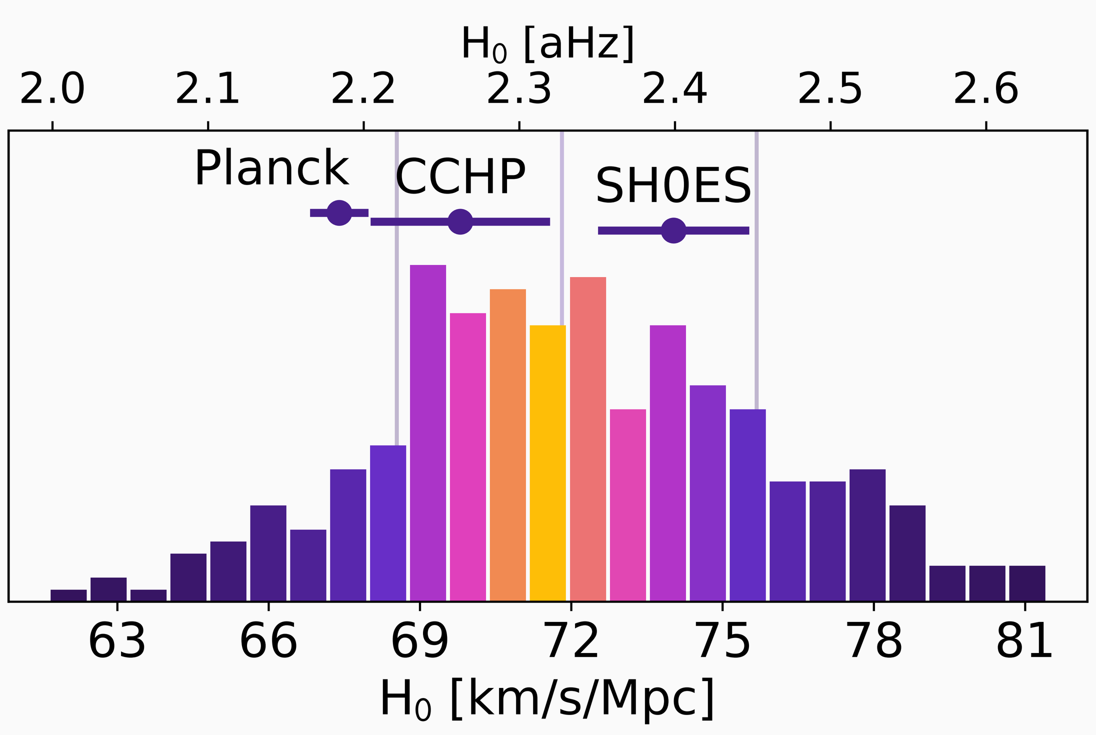
In a multiple-mirage system, for the different mirages light rays take different paths from their source to our telescopes. In most cases however, the background source objects do not emit constant light, but exhibit some flickering. These fluctuations in brightness can be detected in each mirage separately, but at different times. Such differences of arrival times between mirages are called time delays. Besides the obvious difference in path lengths, time delays occur due to the varying gravitational influence by the lens itself, but also due to the expansion of the Universe, which affects each path slightly differently. Thus, accounting for the gravitational influence of the lens by modelling its mass distribution, allows us to infer the Hubble parameter.

In the panels below, we show our results on the Hubble parameter expressed in all the different ways described above: as the age of the universe H_0^{-1}, as the expansion rate H_0 or as the cosmological mean density $3H_0^2/(8\pi G)$. No tension is indicated at the present level of uncertainty. For details see the middle one of the QR codes.

The age of the universe



The expansion rate



The cosmological mean density