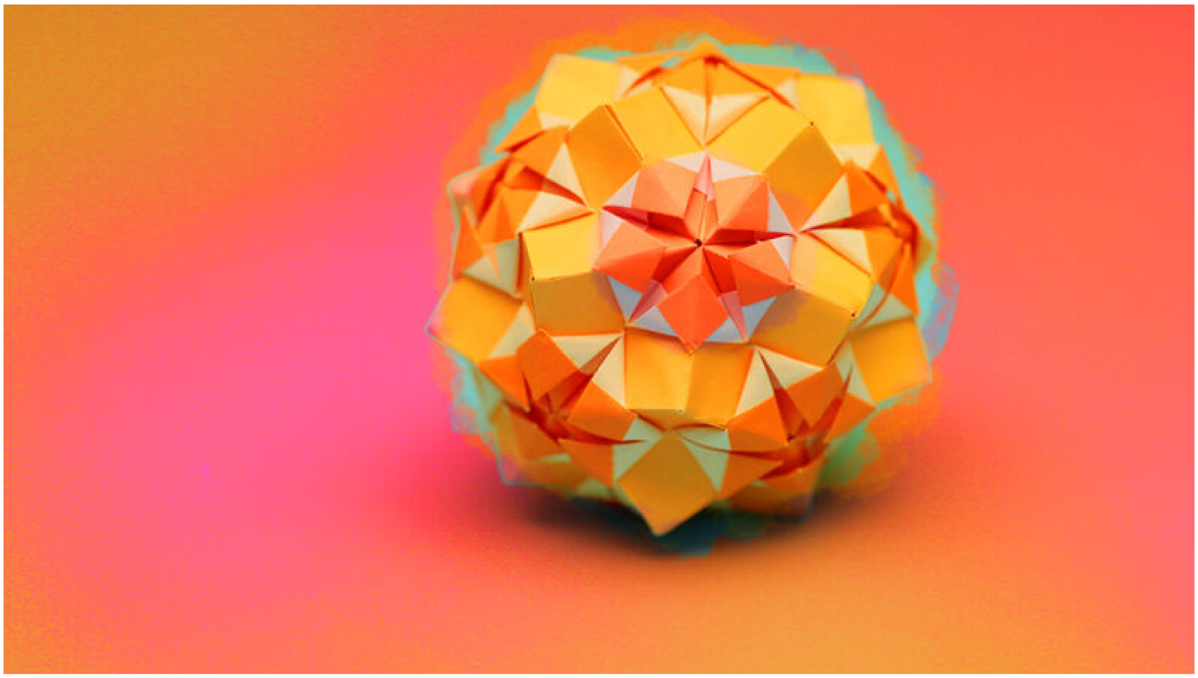
FEATURES

A curious observer's guide to quantum mechanics, pt. 4: Looking at the stars

How do photons travel across light years? (Their quantum waviness enables modern telescopes.)

Miguel F. Morales - Jan 31, 2021 2:00 pm UTC



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Aurich Lawson / Getty Images

> ***One of the quietest revolutions*** *of our current century has been the entry of quantum mechanics into our everyday technology. It used to be that quantum effects were confined to physics laboratories and delicate experiments. But modern technology increasingly relies on quantum mechanics for its basic operation, and the importance of quantum effects will only grow in the decades to come. As such, physicist Miguel F. Morales has taken on the herculean task of explaining quantum mechanics to the rest of us laymen in this seven-part series (no math, we promise). Below is the fourth story in the series, but you can always find the starting story plus a landing page for the entire series thus far on site.*

Beautiful telescopic images of our Universe are often associated with the stately, classical physics of Newton. While quantum mechanics dominates the microscopic world of atoms and quarks, the motions of planets and galaxies follow the majestic clockwork of classical physics.

But there is no natural limit to the size of quantum effects. If we look closely at the images produced by telescopes, we see the fingerprints of quantum mechanics. That's because particles of light must travel across the vast reaches of space in a wave-like way to make the beautiful images we enjoy.

This week we'll concentrate on how photons travel across light years, and how their inherent quantum waviness enables modern telescopes, including interferometric telescopes the size of the Earth.

Starlight

How should we think about the light from a distant star? Last week we used the analogy of dropping a pebble into a lake, with the ring of ripples on the water standing in for the wave-like motion of photons. This analogy helped us understand the length of a particle ripple and how photons overlap and bunch together.

We can continue that analogy. Every star similar to the Sun, in that it makes a *lot* of photons. As opposed to someone carefully dropping single pebbles into a mirror-smooth lake, it's more like they poured in a bucket of gravel. Each pebble makes a ring of ripples, and the ripples from each stone spread out as before. But now the ripples are constantly mixing and overlapping. As we watch the waves lap against Earth's distant shore, we don't see the ripples from each individual pebble; instead the combination of many individual ripples have added together.

EXPLORING THE QUANTUM WORLD

A curious observer's guide to quantum mechanics, pt. 4: Looking at the stars

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A "no math" (but seven-part) guide to modern quantum mechanics

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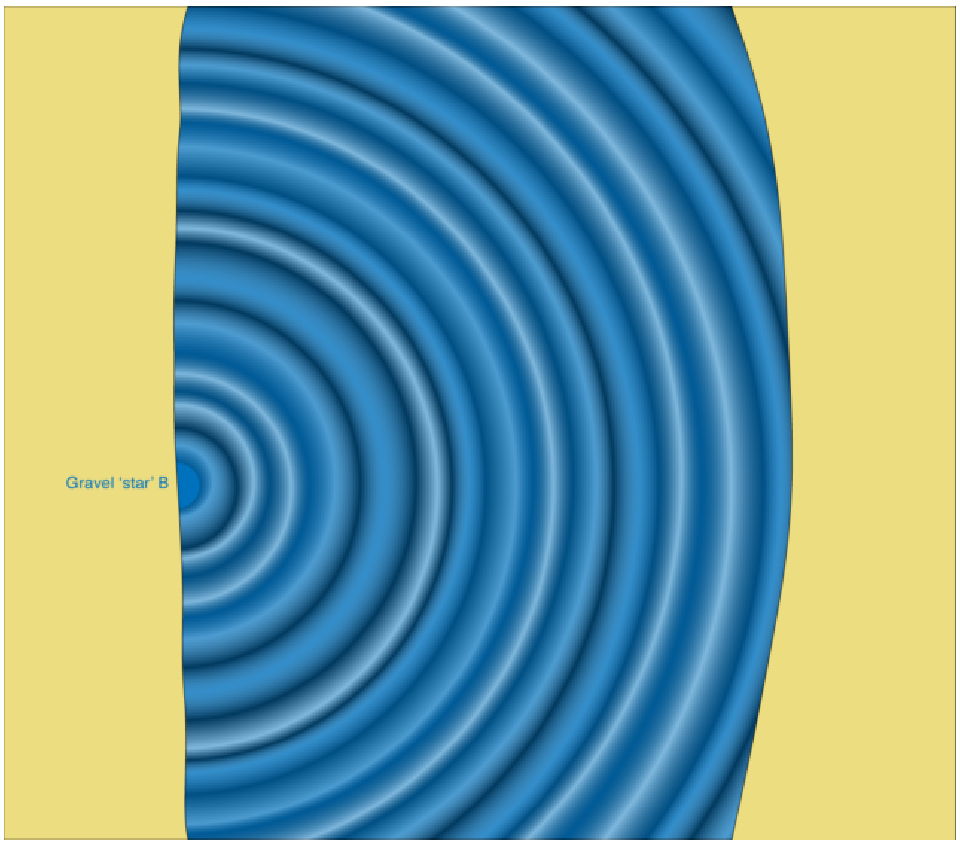


Enlarge / The chaotic waves from a gravel star crossing our pond. The ripples of many pebbles overlap, creating a complex set of waves.
Miguel Morales

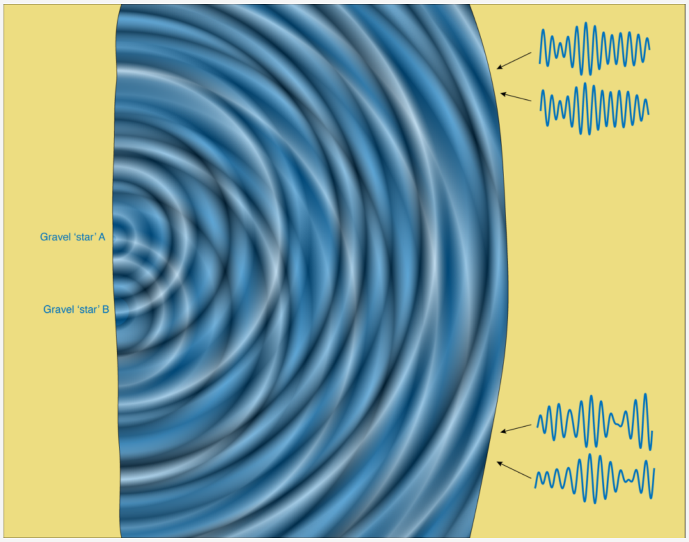
So let's imagine we're standing on the shore of a lake as the waves wash in, looking at our gravel 'star' with a telescope for water waves. The lens of the telescope focuses the waves from the star onto a spot: the place on the camera sensor where the light from that star lands.

If a second bucket of gravel is dropped into the lake farther along the opposite shore, the ripples will overlap at our shore, but will be focused by the telescope into two distinct spots on the detector. Similarly, a telescope can sort the light from the stars into two distinct groups—photons from star A and photons from star B.

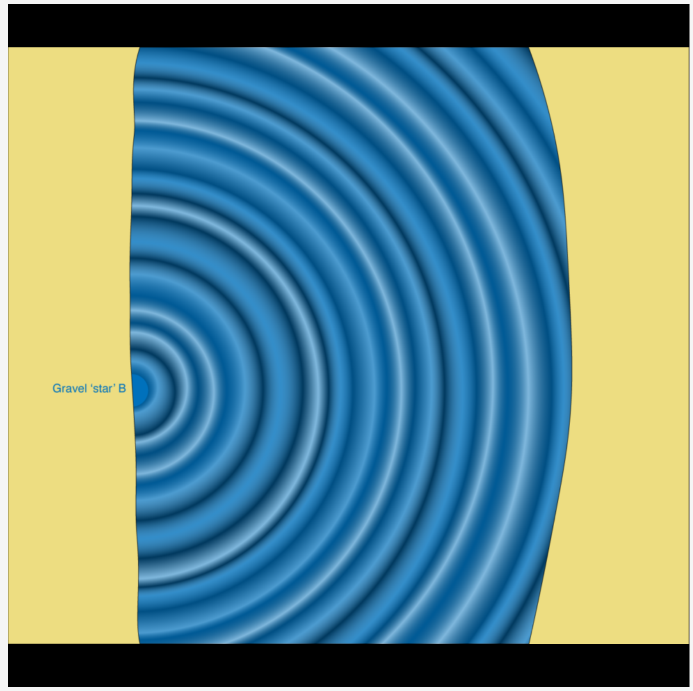
But what if the stars are very close together? Most of the 'stars' we see at night are actually double stars—two suns so close together they appear as one bright pinprick of light. When they're in distant galaxies, stars can be separated by light years yet look like a single spot in professional telescopes. We'd need a telescope that could somehow sort the photons produced by the different stars to resolve them. Similar things apply if we want to image features like sunspots or flares on the surface of a star.

To return to the lake, there is nothing special about the ripples made by different pebbles—the ripples from one pebble are indistinguishable from the ripples made by another. Our wave telescope does not care if the ripples came from different pebbles in one bucket or different buckets altogether—a ripple is a ripple. The question is how far apart must two pebbles be dropped for our telescope to distinguish that the ripples came from different locations?

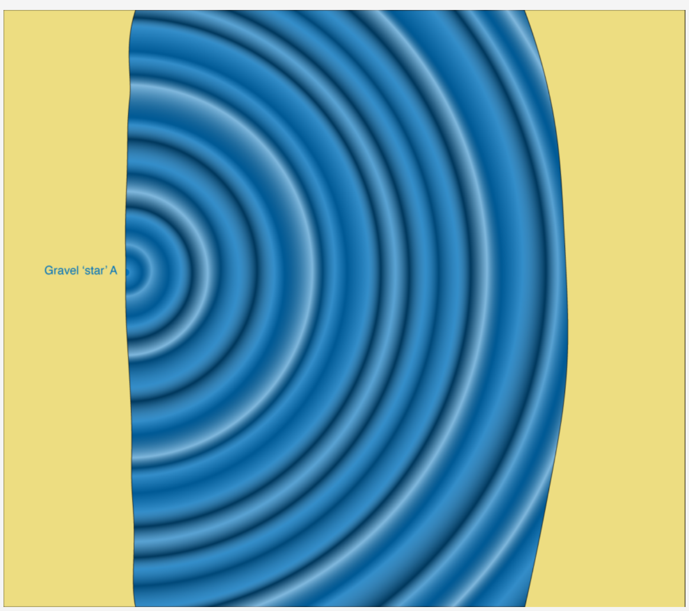
Sometimes when you're stumped, it's best to take a slow walk along the beach. So we'll have two friends sit on the far shore dropping pebbles, while we walk along our shore, looking at the waves and thinking deep thoughts. As we walk along the beach we see that the waves from our friends overlap everywhere, and that the waves come in randomly. There appears to be no pattern.



The waves from two gravel "stars." The waves from each star are circular (see next panels), but combine in an apparent jumble. However, we notice that while the wave train at each location is chaotic, at locations close to each other on the beach, the wave trains are very similar. At locations far down the beach, we see a completely different wave train. [credit: Miguel Morales]



The waves from just one star. [credit: Miguel Morales]



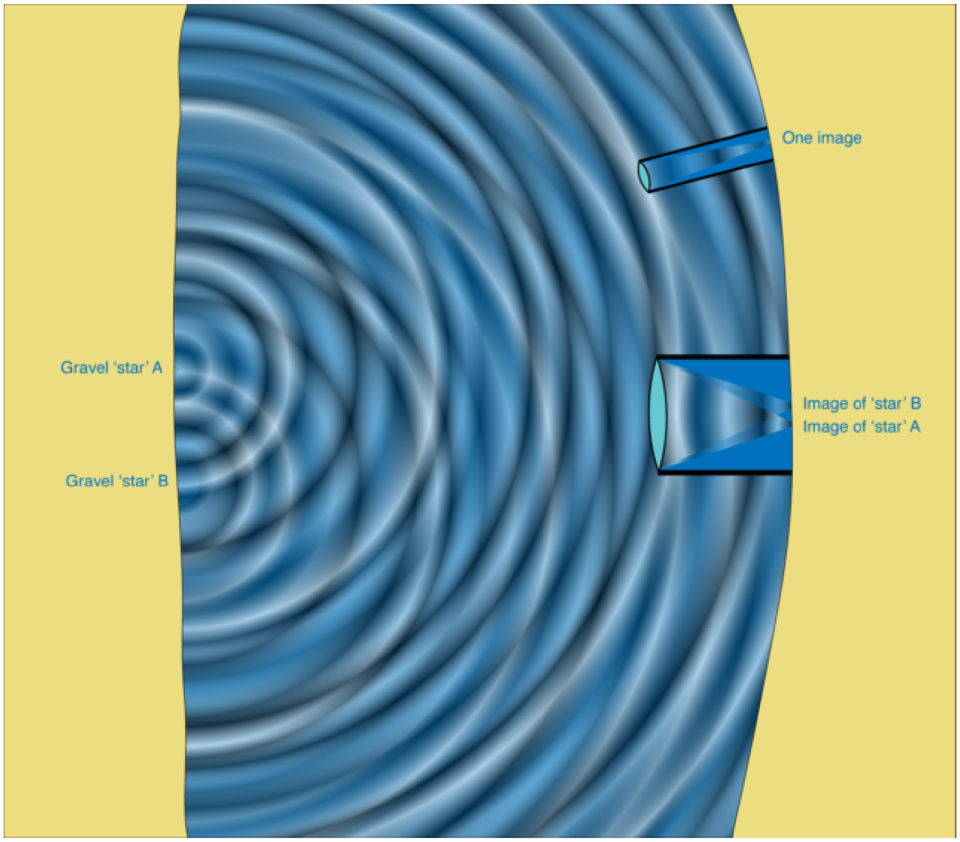
The waves from the other star. The waves can be combined to produce the wave pattern seen in the first panel. [credit: Miguel Morales]

But on closer inspection, we notice that spots on the beach very near each other see nearly identical waves. The waves *are* random in time, but locations on the beach a few paces apart see the *same* random train of waves. But if we look at waves hitting far down the beach, that wave train is completely different than the one hitting near us. Any two places on the beach that are close together will see nearly identical wave trains, but widely separated locations on the beach see different wave trains.

This makes sense if we think of the waves on the beach as being the combination of little ripples from hundreds of pebbles. At nearby locations on the beach, the ripples from the pebbles dropped by both friends add up in the same way. But farther along the beach, the ripples from one friend will have to travel farther, so the ripples add up in a different way, giving us a new wave train.

While we can no longer see the ripples of individual pebbles once they have combined into waves, we can pace off how far we need to walk to see a new wave train. And that tells us something about how the ripples are adding together.

We can confirm this by asking our two pebble-dropping friends to move closer together. When our friends are close together, we notice that we have to walk a long way along our beach to see the ripples add up in a different way. But when our friends are far apart, just a few steps on our beach will make the wave trains look different. By pacing off how far we need to walk before the waves look different, we can determine how far apart our pebble-dropping friends are.



Enlarge / Large and small telescopes looking at the same two stars. Because the waves appear different at the far edges of the large telescope, it can sort the waves into two sources. For the small telescope, the waves look the same across the lens, so it sees the two stars as a single unresolved source.
Miguel Morales

The same effect happens with photon waves, which can help us understand the resolution of a telescope. Looking at a distant binary star, if the light waves entering opposite edges of the telescope look different, then the telescope can sort the photons into two distinct groups—the photons from star A and the photons from star B. But if the light waves entering opposite edges of the telescope look the same, then the telescope can no longer sort the photons into two groups and the binary star will look like one spot to our telescope.

If you want to resolve nearby objects, the obvious thing to do is to make the diameter of the telescope bigger. The farther apart the edges of the telescope, the more close the stars can be and still be distinguished. Bigger telescopes have better resolution than small telescopes, and can separate the light from more closely spaced sources. This is one of the driving ideas behind building truly enormous 30 or even 100 meter diameter telescopes—the bigger the telescope, the better the resolution. (This is always true in space, and true on the ground with adaptive optics to correct for atmospheric distortions.)

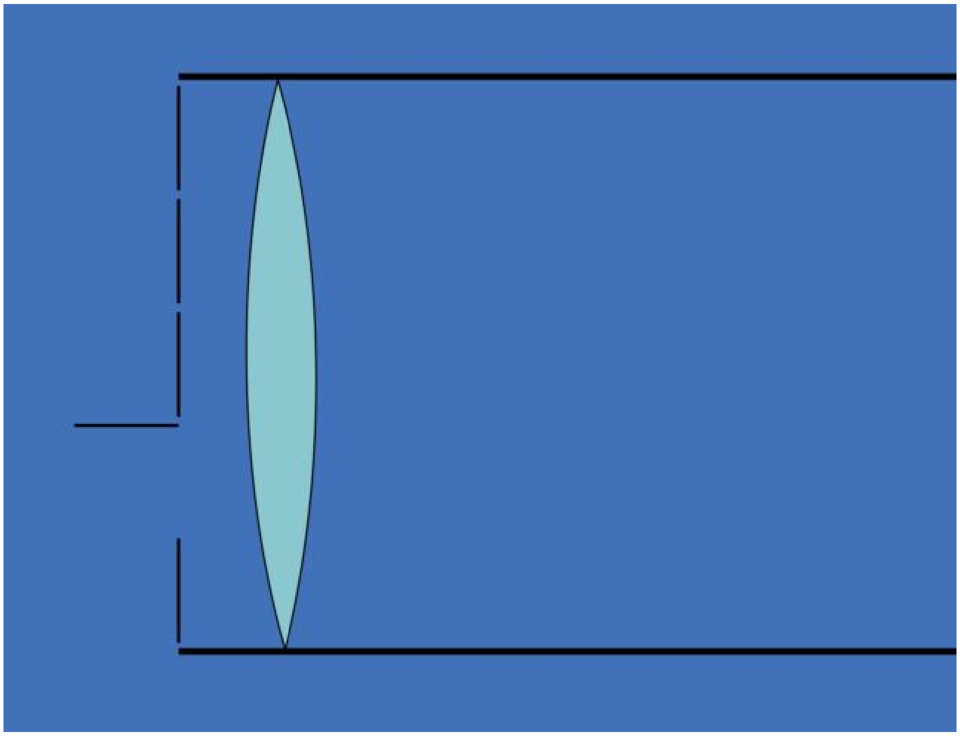
For telescopes bigger really is better.

Where does the photon enter the telescope?

Modern telescopes are **big**, and distant stars are *faint*. Telescopes eight and 10 meters in diameter are common, 30 meter telescopes are under construction (GMT; TMT); given enough money, astronomers would love to build a 100 meter telescope. Even at that size, the light from distant stars is *so* faint that photons only hit the telescope once in a while—minutes may pass between photons. This is not to say that only one photon was emitted by the star; they were emitted in the bajillions. But over the vast reaches of space, the signal gets weaker and weaker and a photon reaches us only every once in a while.

A natural question then is, if only one photon of light from a distant star comes into the telescope, where did that particle enter? Did it enter near the left edge, the right, or somewhere in the middle?

To figure out where the photon entered, one could imagine covering the aperture of the telescope with many small doors, and we could open one door at a time. This would let us know where a photon entered the telescope. But when we look through the telescope with only one door open the image is *much* blurrier. Instead of a nice big, expensive telescope, the image is like we had a tiny telescope the size of the little open door.



Enlarge / A hypothetical telescope with many small doors covering the aperture

Miguel Morales

Because the telescope can only compare the photon waves at the edges of the open door—the other parts of the wave are blocked by the closed doors—our telescope can no longer sort photons effectively and the image blurs. Even when we send in only one photon at a time, the resolution of the telescope is determined by the size of the door. When we open all the little doors at once, suddenly the image of each photon snaps back into focus.

Looking back at the beach analogy, this makes a lot of sense. The wider the telescope, the longer the distance we can pace off along the shore, thus the better the resolution. What is remarkable is this works exactly the same when only one photon has arrived.

It turns out asking where the photon entered the telescope was a non-sensical question. Photons, like any particle, move like waves. The ripples from each individual photon fill the telescope aperture. In order for the star to be in sharp focus, the ripples from each photon have to be at least as wide as the telescope. Photons really do move like waves over the vast distances of space.

You can see this effect with your own eyes. On a dark night the faintest stars are in the single photon regime—approximately one photon at a time is entering your eye. But even faint stars still appear like sharp pinpricks. If particles didn't move like waves and fill your pupil, each photon from a faint star would land in a slightly different place on your retina and the faintest stars would appear blurry.

So if someone asks me why I believe in quantum mechanics, I say, "Because I can clearly see the stars at night."

Interferometers

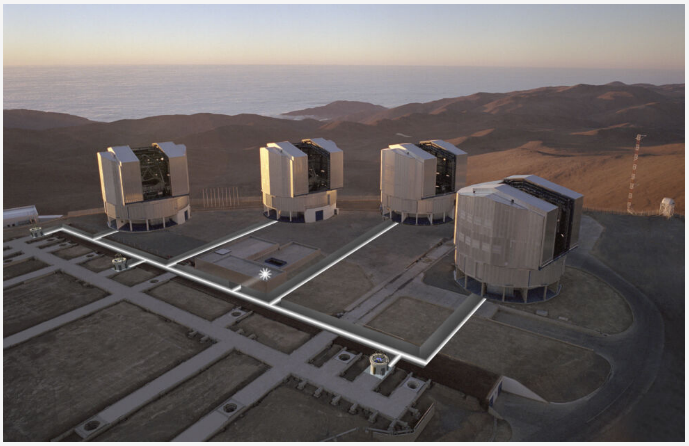
So how far can we take this? How wide can a photon wave get? (Insert sound of maniacal laughter.) Well…

Even when we build large traditional telescopes, there are limits to how big a single piece of glass can be before engineering and gravity gets in the way. Instead, the largest telescope mirrors are made by precisely gluing together many smaller pieces such as with the James Webb Space telescope.

Enlarge / Technician standing near some of the segments of the James Webb Space Telescope primary mirror.
NASA

Interferometric telescopes or 'interferometers' take this one step further. The best way to think of an interferometric telescope is one *really* big telescope where we ran out of money part way through and only installed some of the pieces needed for the full mirror. Like an abandoned skyscraper where only some of the windows have been installed, you can see the outline of the full mirror. The alignment of the pieces you use still has to be extraordinary—it must match the surface of the rest of the mirror that you never got around to building. But this gives you the opportunity to build a mirror with an enormous diameter.

Interferometric telescopes are one of the great applications of quantum mechanics on big scales and are becoming crucial for everything from phased-array radar to efficient telecommunications to imaging planets and distant black holes.



The light from four telescopes in the Very Large Telescope in Chile can be combined to act as facets of one large mirror. [credit: Wikimedia Commons]

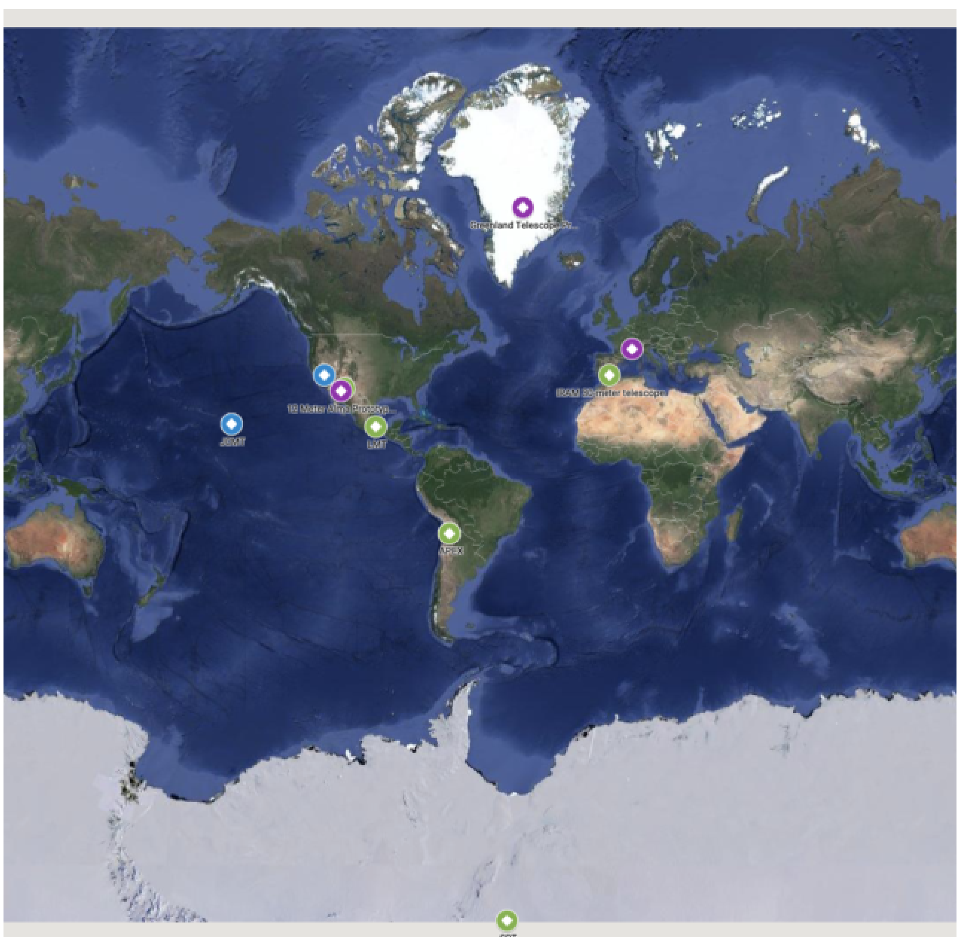
Both of the Keck telescopes in Hawaii can be combined into one large mirror. [credit: NASA/JPL]

The Y-shaped Navy Precision Optical Interferometer in northern Arizona can function like a telescope with a mirror 400 meters wide. [credit: Google Maps]

For optical and infrared light, we have interferometric telescopes a few hundred meters across. All of the telescopes at the Very Large Telescope and Keck Observatories can be combined into large virtual mirrors, and Ars recently featured the Navy Precision Optical Interferometer.

One of the world's great new telescopes is the Atacama Large Millimeter/submillimeter Array (ALMA). Working at the boundary of far infrared light and the highest radio frequencies, its individual mirrors can be moved around the desert with a special truck to provide optimal performance, with configurations up to 16 km in diameter.

At radio frequencies it is (slightly) easier to keep the mirror segments aligned, so radio telescopes can become truly enormous. A few notable examples include the Karl G. Jansky Very Large Array in New Mexico (25 kilometer across), the Giant Metre Wave Telescope in India, and one I helped design and build, the Murchison Widefield Array in Western Australia (video). The largest telescopes with the sharpest vision are the Event Horizon Telescope and Very Long Baseline Array telescopes, which span the Earth, and sometimes one of the mirror segments is put into space to avoid the size limitations of the little planet we live on.



Enlarge / The locations of the telescopes that contribute to the Event Horizon Telescope.

Once you start seeing interferometers, they appear everywhere. They are used on cell phone towers and are the basis of phased array radars used on ships and airplanes.

Interferometric telescopes can be truly enormous because the wave-like ripples of each photon spread out. By carefully collecting and focusing these waves, we can build virtual telescopes that are enormous, with the associated ability to sort and image light from very closely separated sources. Because photons move like waves, there is no fundamental limitation to how large we can build a telescope.

Cracking nuts with a steam roller

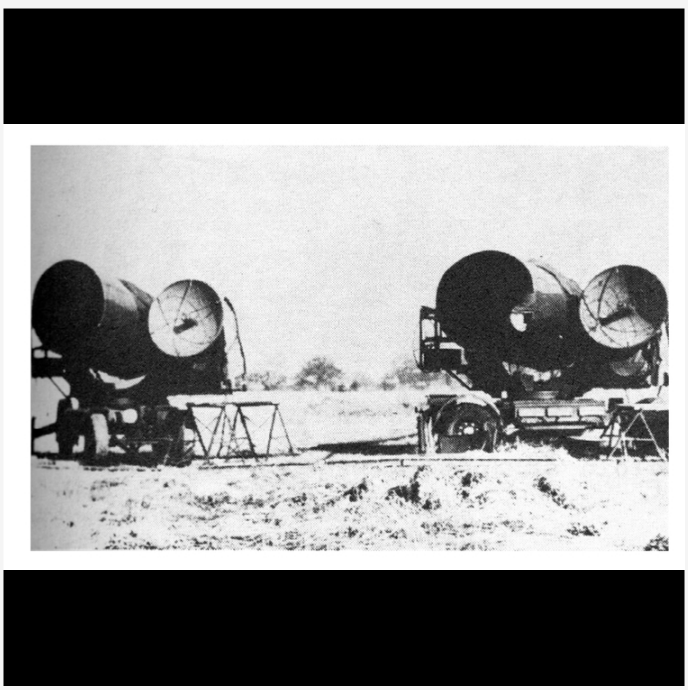
While size may not be a limit, there are others, like the requirement for a near-perfect alignment of all the mirror segments. In all the cases we examined, the photon waves from all the mirror segments must be carefully combined together. This can be done physically with additional mirrors or, in the case of radio light, electronically by synchronizing them using atomic clocks.

But what if we can't build a large virtual mirror, either because we can't get the alignment accurate enough or because we can't build the mirror pieces? This brings us to our last bit of quantum magic.

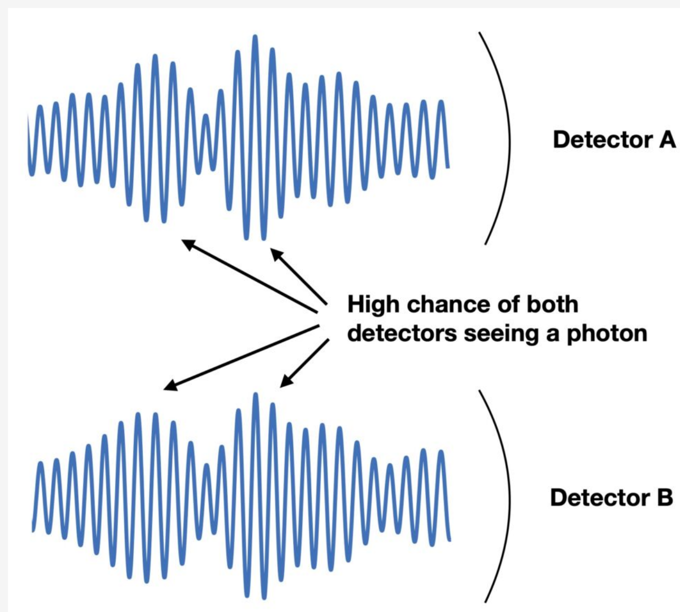
If we go back to our beach and watch the waves as they roll in, we notice that the ripples from all the pebbles will occasionally add up to give an unusually high peak—a kind of mini 'rogue wave'. With light, the height of the wave is related to the chance that we will see a photon—a big peak is when we are most likely to have a photon arrive. Since the waves look nearly the same at positions near each other on the beach, two nearby locations will be more likely to see a photon at the same time.

In 1956 Robert Hanbury Brown and Richard Twiss exploited this in a brilliant measurement of the size of the star Sirius. The British engineers took two searchlights left over from WWII and converted them into crude but sensitive light detectors. Due to the poor quality of the searchlights, atmospheric distortions, and the primitive nature of electronics in 1956, there was no way they could align the waves from the searchlight detectors to the precision needed to build an interferometric telescope.

What they could do is see when they detected photons simultaneously in the two detectors.



The original detectors built by Hanbury Brown and Twiss using modified searchlights. [credit: SPIE]



When the detectors are close together, they see very similar waves. When the waves are unusually tall, both telescopes are likely to see simultaneous photons from the distant star. [credit: Miguel Morales]

Effectively they were looking for the high peaks from the photon waves. When the searchlight detectors were close together, both detectors see the same wave shape. So when one detector sees a high wave peak the other will too—there is an enhanced probability of the detectors simultaneously seeing photons. But when the searchlight detectors are moved farther apart, the detectors see different waves and the correlation between photon arrivals disappears.

By determining how far apart the detectors needed to be for the correlation in photon arrivals to go away, Hanbury Brown and Twiss could infer the size of the star Sirius—they were pacing off what the waves looked like on the beach. They had achieved the resolution of an interferometric telescope without the troublesome alignment problem.

Hanbury Brown and Twiss did not intend to start a revolution—they just had a clever way to measure the size of a star with some inexpensive equipment that was lying around. But physicists were flummoxed by their result. It took *years* for the physics community to accept that the arrival of photons in different detectors would be correlated.

Partly this is due to misplaced pride (the two British engineers must surely be confused), and partly due to the subtlety of the associated quantum mechanics. Eventually, this became known as the "HBT effect" and led to the field of quantum optics. It is now understood that this correlation is a hallmark of quantum mechanics, and is a spatial extension of the photon bunching we saw in the last article.

Today, the mirror alignment problem can usually be solved; interferometric telescopes have become much more sensitive than the correlation technique Hanbury Brown and Twiss invented. For light, the photon correlation technique is crude overkill, leading Hanbury Brown to describe their work as "building a steam roller to crack a nut."

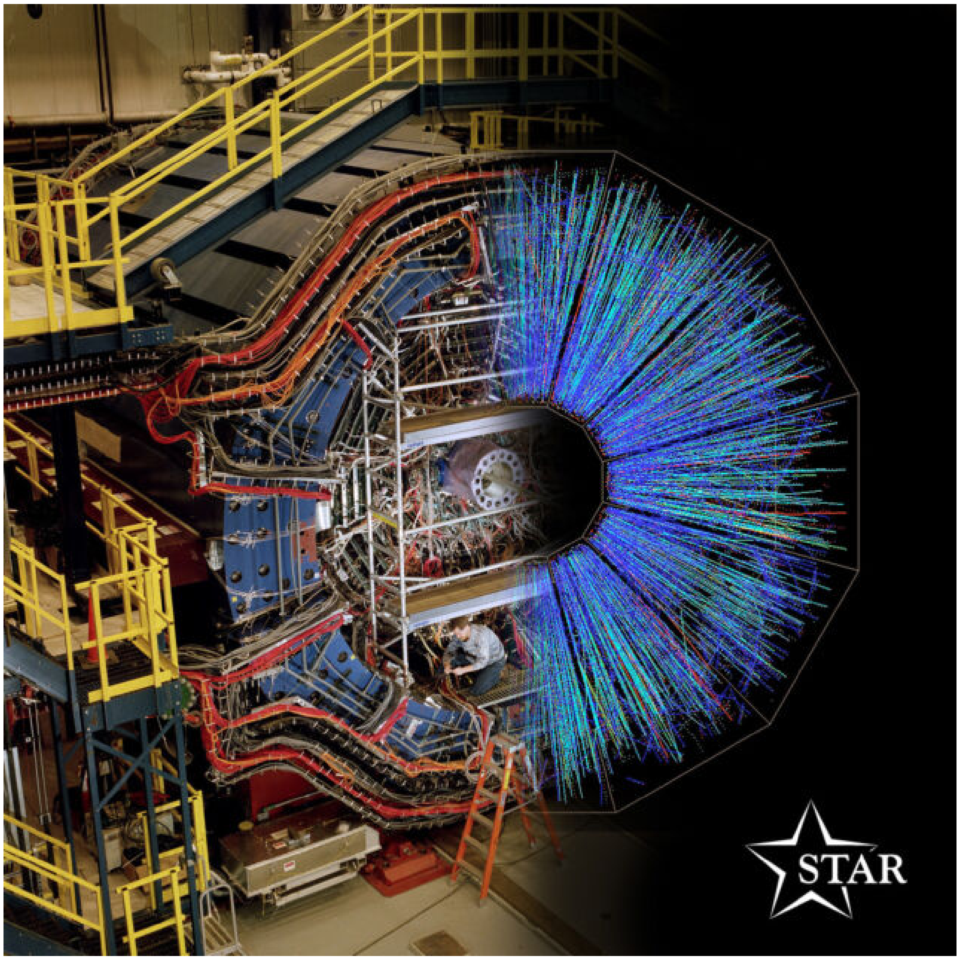
But sometimes you need heavy machinery.

One of the frontiers of particle physics is to recreate the conditions of the Universe just after the Big Bang. When you collide two gold nuclei traveling at nearly the speed of light head on, the nuclei not only collide, they melt into a quark-gluon plasma that mimics the conditions when the Universe was too hot for protons and neutrons to form. In many ways, this little quark-gluon fireball looks like a tiny star, but instead of radiating photons of light it radiates huge numbers of particles called *pions*.

Pions are exotic particles that are very different from photons. They are made of two quarks, are heavy, and quickly decay. We don't know how to make mirrors and lenses for pions, and without mirrors or lenses it is impossible to make a conventional image of the quark-gluon fireball.

But in quantum mechanics *all particles* move like waves. Both pions and photons are bosons (extroverts that like to travel together, as explored in last week's article). As they travel together, the pion particle ripples will overlap and mix, occasionally creating a high peak—just like the photons when Hanbury Brown and Twiss looked at Sirius.

So when one detector sees a pion, there is an enhanced probability that a nearby detector will simultaneously see a pion. By surrounding our little quark-gluon fireball with hundreds of detectors and measuring how far apart the detectors must be for this correlation to go away, we can measure the size of our quark-gluon fireball. Done carefully from all angles, this makes a movie of the quark-gluon plasma as it expands.



Enlarge / The STAR detector at the Relativistic Heavy Ion Collider makes images using pions.
Brookhaven National Lab.

And the results are surprising. The quark-gluon fireball is more spherical than initially expected (the quark-gluon plasma has high effective surface tension), and the fireball is somewhat translucent—you can see about a 1/3 of the way through it. By studying how this fireball expands and moves, we are gaining insight into how our early Universe evolved, and learning more about some of the fundamentals of quantum chromo-dynamics (the strong nuclear force).

But to make this movie, we had to utilize the insight of Hanbury Brown and Twiss, and use the wave-like nature of particles and how they mix together. We've turned an odd aspect of quantum mechanics into a tool.

Back at the Visitor's Center

As I mentioned earlier, interferometers are used everywhere. But it is still stunning the precision that can regularly be achieved with modern interferometric telescopes.

When I was a postdoc visiting the Haystack radio telescope in northern Massachusetts, I remember seeing an old yellowed piece of paper taped to the wall of the control room with a desiccated bit of masking tape. Plotted on the paper was the distance between the radio telescope in Massachusetts and another radio telescope at Jodrell Bank in England, in centimeters, measured over the course of 15 years. On the plot, you could clearly see the telescopes floating away from each other due to plate tectonics! By combining the two telescopes into one virtual mirror, they could easily measure the plates moving apart. (With precision GPS, it is now fairly easy to watch the tectonic plates float around, bend, and twist. UNAVCO is a neat place to start. Amateurs with a good GPS can even measure how their home is moved around by the plates.)

Another remarkable application is the International Earth Rotation and Reference Systems Rapid Service/Prediction Center, run by the US Naval Observatory. In introductory physics classes, we always discuss how when you jump from a boat, the boat moves backwards—it's an application of equal and opposite forces (Newton's third law). The question always comes up, "Does the Earth move backwards when I jump forward?"

While the answer is yes, the motion is currently unmeasurable—the Earth is much heavier than you are. But if a major storm system forms and much of the air above North America starts moving 40 mph East, the storm is a heavy enough jumper that we can see the Earth's rotation slow down as the storm forms. We can later watch it speed back up as the storm blows itself out.

Every Thursday the US Naval Observatory publishes what the Earth's actual rotation was each day for the past week, to millimeter precision as measured by radio interferometric telescopes observing distant galaxies. If you are trying to measure gravity waves with pulsars or guide spacecraft to distant Kuiper Belt objects, you need to know where you are *very* precisely, and this is published as a free service by the US Navy.

Quantum mechanics is not limited to the microscopic world—it applies to particles traveling astronomical distances. This necessitates that particle waves are very broad, which we can exploit with interferometric telescopes to make measurements of mind-boggling precision. We live in a world where we can watch the tectonic plates float around and the Earth speed up and slow down due to storms, and these measurements are enabled by the waviness of particles in motion.

Next week

I hope you enjoyed seeing quantum mechanics go big. Next week, we are going to head in the opposite direction and go small. Most people think small when they think quantum mechanics, so we'll have a close look at electron waves trapped in atoms and how they lead to the spectra of stars and enhance the color of your TV.

FAQ

Why is the US Navy measuring the rotation of the Earth every day? There is a long association between precision time keeping, astronomy, and maritime navigation. In the late 1700s, the first precision ocean-going clocks were built to enable ships to determine their longitude, and the local time in each port was determined by astronomic observations of when stars transited. The falling of the New Year's ball is an echo of this: historically a ball was lowered from the astronomy observatory at noon every day so the ships in the harbor could set their clocks.

In the US, making the astronomical observations to set the master harbor clocks was the job of the US Naval Observatory. The GPS satellites were designed and launched by the US military largely for maritime navigation, and are based on precision atomic timekeeping and astronomical observations by the Naval Observatory. Measuring the Earth's rotation to correct the official time, and freely publishing those observations, is part of a long tradition for the US Naval Observatory.

In the Hanbury Brown Twiss experiment, how can a single photon be detected in both detectors? This is an extension of one of the more illuminating mis-critiques of the HBT effect. Critics would point out that if a light source emits a single photon, and there are two detectors, there are only three possible outcomes: it is seen in detector A, it is seen in detector B, or it is detected in neither (it hit somewhere else). It is not possible to emit *one* photon and detect *two* of them.

And if you do this experiment, this is exactly what you will see. A photon may appear in one detector or the other, but never both.

But it turns out this is a mis-analogy with what Hanbury Brown and Twiss were observing. The star emitted bajillions of photons; it is only because we are very far away that their arrival rate is so low. If there is only one photon emitted, then you can only detect only one photon. But if we are detecting a small fraction of a bajillion, sometimes we see two (or more) photons arrive at once. The average number of photons arriving will still be very low, but the number arriving will fluctuate around.

Due to the bunching of photons in space and time, they like to arrive together. An interesting corollary is that it is impossible to associate one detected photon with one particular emitted photon. Lots of photons left the star and, because their ripples overlap, their identities get shuffled. When we detect a photon with a small telescope, we can't tell where on the star it started, *even in principle*. This indistinguishability is a core feature of quantum mechanics.

Miguel F. Morales is a professor of physics at the University of Washington in Seattle.