HOW TO VIEW THIS MONTH'S **LUNAR ECLIPSE** p. 46

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HOW WE CAN VISIT ANOTHER STAR

Breakthrough Starshot plans robotic craft to Proxima Centauri p. 16

Explore gems of the deep southern sky p. 48

» **PLUS**

See Apollo 14 in 3D p. 40

Celestron's StarSense scope reviewed p. 54

Bob Berman on astrophysical food fights p. 13

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BONUS ONLINE CONTENT CODE p. 4

Vol. 49 • Issue 5

Breakthrough

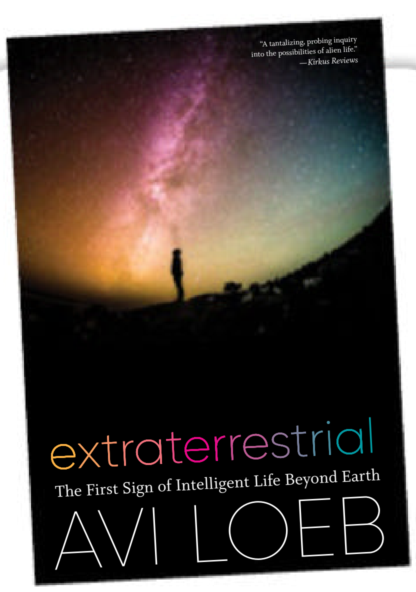
A voyage to the stars

Using laser-propelled lightsails, tiny spacecraft could venture to the Sun's nearest neighbor in just a few decades. **BY JAKE PARKS**

On Nov. 6, 2018, as millions of Americans cast their votes in a hotly contested midterm election, astrophysicist Avi Loeb sat in his office surrounded by four television crews. Loeb, chair of Harvard University's Department of Astronomy and author of the new book *Extraterrestrial* (Houghton Mifflin Harcourt, 2021), was not being targeted for his political insight. Instead, the media attention was due to his recent eye-catching paper exploring whether the interstellar space rock 'Oumuamua was really a piece of alien technology that's sailing on sunlight.

Loeb first pondered the possibility that the solar system's first known interstellar interloper was an extraterrestrial craft back in late 2017, shortly after astronomers discovered the object (formally known as 1I/2017 U1) using the Pan-STARRS telescope at Haleakalā Observatory in Hawaii. But it wasn't until he began exploring what he himself describes in his book as "an exotic hypothesis, without question" that he began to take it seriously — if only as a thought experiment.

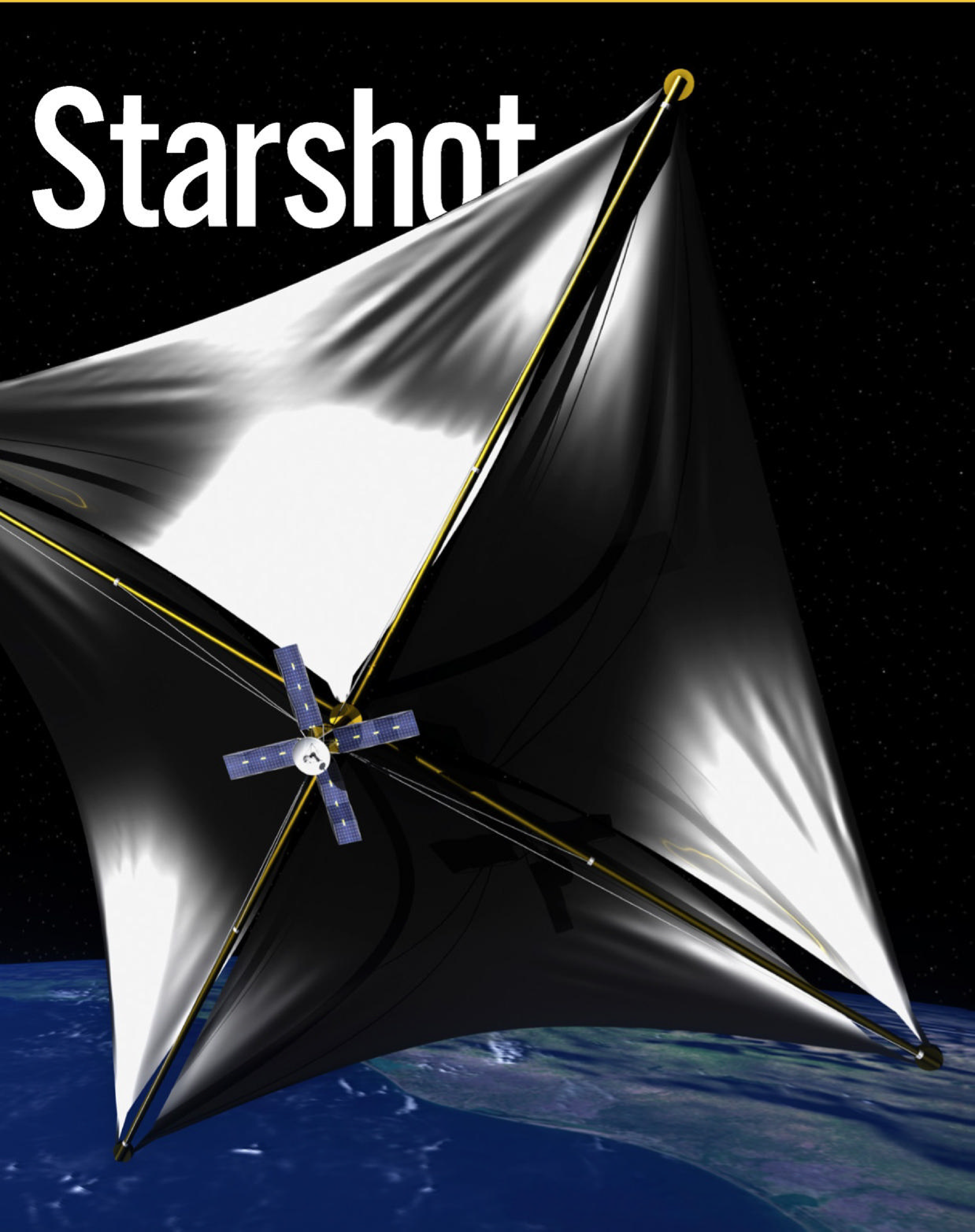
He drew his 'Oumuamua hypothesis from what was fresh in his mind. At that point, Loeb had spent the previous few years working with some of the world's brightest and most ambitious people to develop an audacious interstellar mission that would use lightsails to venture to a nearby star. The moonshot project, fittingly called Breakthrough Starshot, aims to create a tiny spacecraft equipped with a sail that will catch a brief burst of powerful laser light, propelling it to some 20 percent the speed of light. At that rate, such a craft would arrive at the nearby star Proxima Centauri within about 20 years of launch.



COURTESY OF HOUGHTON MIFFLIN HARCOURT/AVI LOEB

A tiny nanocraft attached to a large lightsail might be humanity's best bet for reaching another star within a generation. BREAKTHROUGH INITIATIVES

Starshot

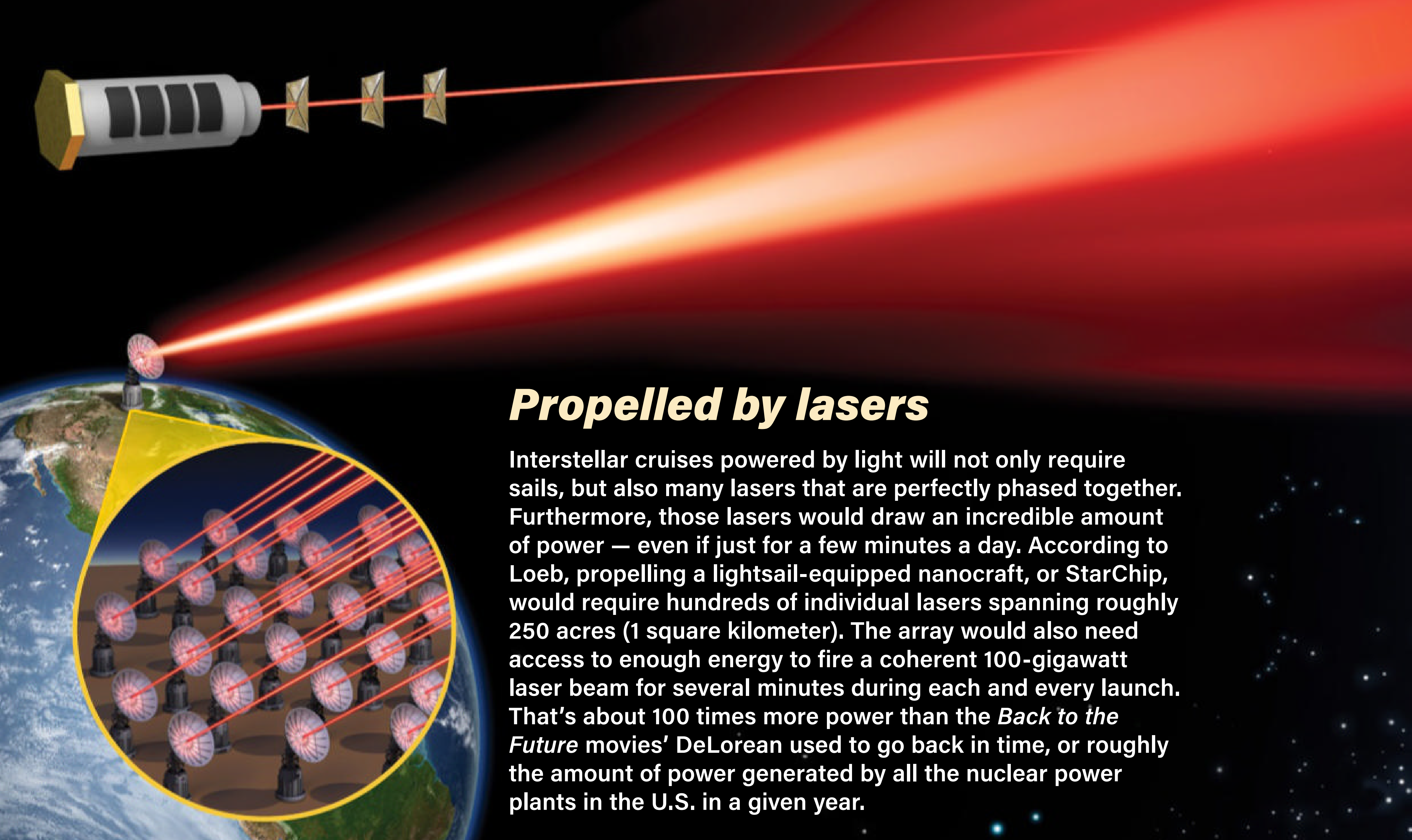


How to speed to a nearby star

Sailing on light

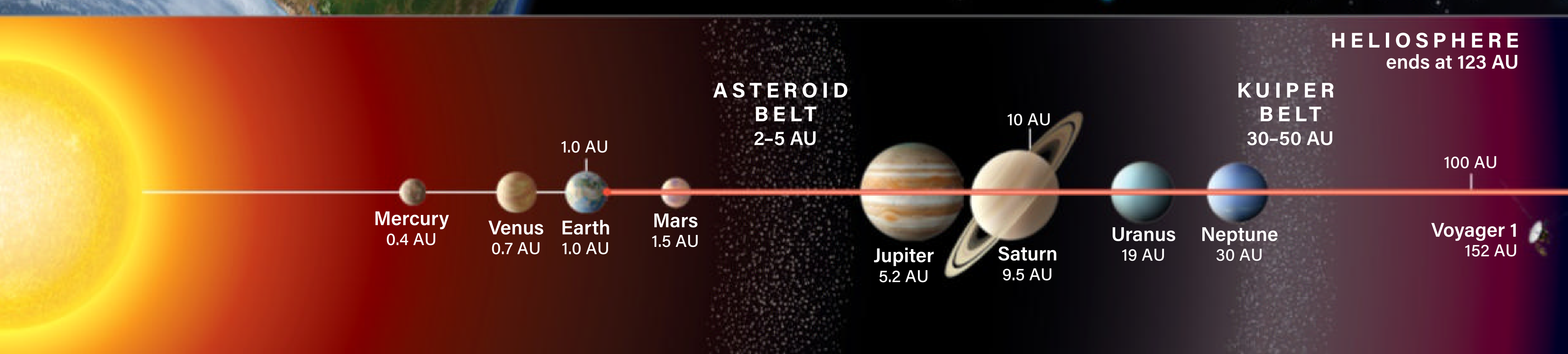
One fundamental property of electromagnetic radiation, or light, is that it has momentum. This means that despite having no mass, particles of light can transfer their momentum to macroscopic objects. And one way to harness that momentum is to mimic how sailboats harness the momentum of rushing air molecules.

Enter the lightsail: an ultra-thin, incredibly reflective sheet of material. As light hits a lightsail, it bounces backward, imparting its forward momentum to the sail itself. This can propel a spacecraft through space. But unlike water slowing ships in the ocean, there isn't much material in space that a sailing craft must push through. So, a cosmic vessel will continue accelerating as long as it's being pushed by light. That means lightsail-equipped spacecraft (deployed by a mothership and targeted by lasers) could theoretically reach a significant fraction of the speed of light in just a few minutes.



Propelled by lasers

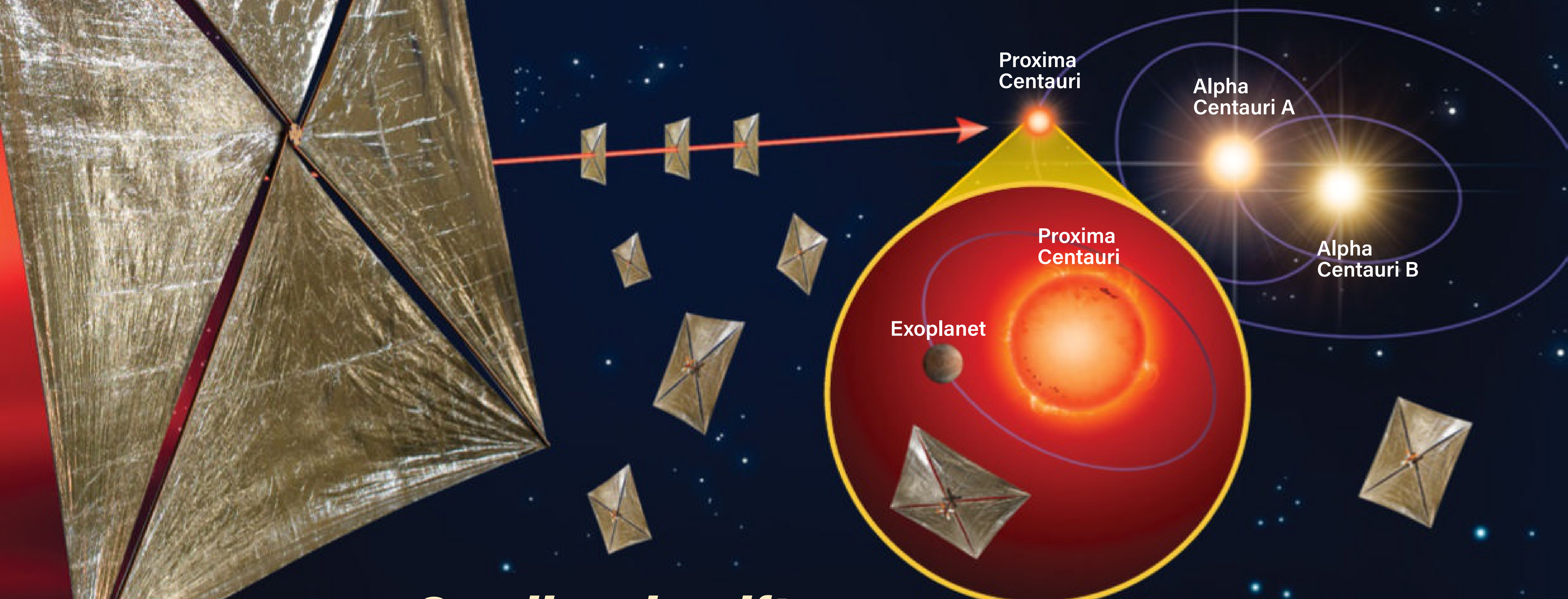
Interstellar cruises powered by light will not only require sails, but also many lasers that are perfectly phased together. Furthermore, those lasers would draw an incredible amount of power — even if just for a few minutes a day. According to Loeb, propelling a lightsail-equipped nanocraft, or StarChip, would require hundreds of individual lasers spanning roughly 250 acres (1 square kilometer). The array would also need access to enough energy to fire a coherent 100-gigawatt laser beam for several minutes during each and every launch. That's about 100 times more power than the *Back to the Future* movies' DeLorean used to go back in time, or roughly the amount of power generated by all the nuclear power plants in the U.S. in a given year.



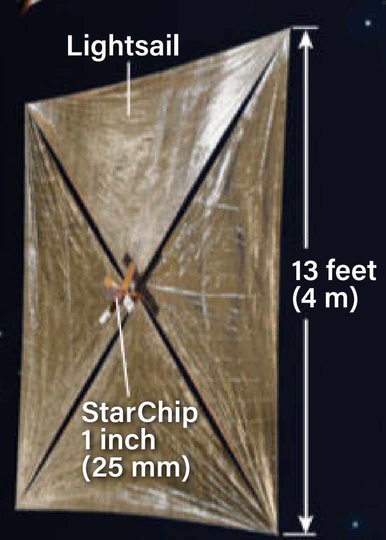
Taking a closer look

When a StarChip (or a fleet of them) finally reaches Proxima Centauri, its navigation system will likely orient the craft using four built-in photon thrusters, each capable of firing a roughly 1-watt diode laser. This would allow the StarChip's various onboard devices — such as cameras or magnetometers — to gather scientific data on specific targets as they unstoppably zip by.

Whether from observing Proxima Centauri, its exoplanets, or intriguing asteroids and comets that are circling the red dwarf, the data would then be beamed back to Earth via a transmitter. (The Breakthrough Starshot team is also considering using the lightsail itself as a primary reflector for the transmitter.) Four years later, scientists would finally receive and analyze the StarChips' data — that is, assuming they have built the roughly 30-meter-diameter receiving telescope needed to pick up the signal on Earth.



Small and swift

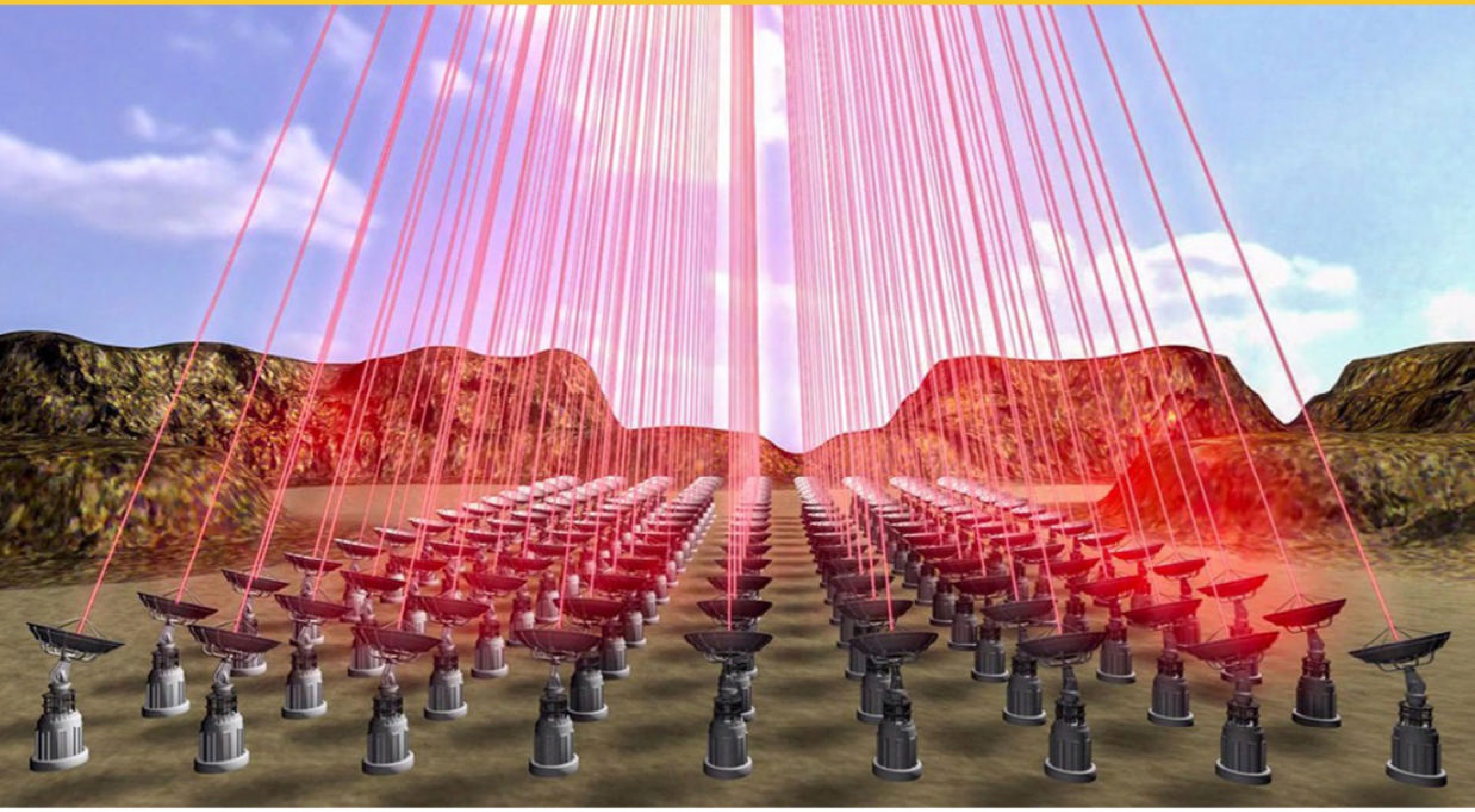


A necessary requirement for the Breakthrough Starshot mission is keeping the mass of each sail-equipped StarChip to just a few tenths of an ounce. But thanks to dramatic decreases in the size of microelectronics over the years, the mission team is confident their gram-scale craft will be able to include an onboard power supply (likely an atomic battery powered by radioactive decay), navigation and communication equipment, and even tiny thrusters to adjust its orientation as it approaches its target.

Likewise, the solar sail itself, which is expected to span up to around 13 feet (4 meters), will need to weigh in at less than about 0.035 ounce (1 gram). It will also need to be extremely thin, as otherwise the sail would absorb far too much heat and be vaporized by the barrage of laser light. Fortunately, rapid advances in microfabrication are leading to increasingly lightweight and ultrathin materials that could potentially fit the bill, including graphene. — *J.P.*

ASTRONOMY: ROEN KELLY

Logarithmic scale; planet and star sizes are not to scale
Astronomical unit (AU) = 92,955,807 miles (149,597,871 km)



An array of lasers, seen in an artist's concept, would create a roughly 100-gigawatt beam to propel each StarChip to 20 percent the speed of light in just minutes. BREAKTHROUGH INITIATIVES

Visiting Proxima Centauri

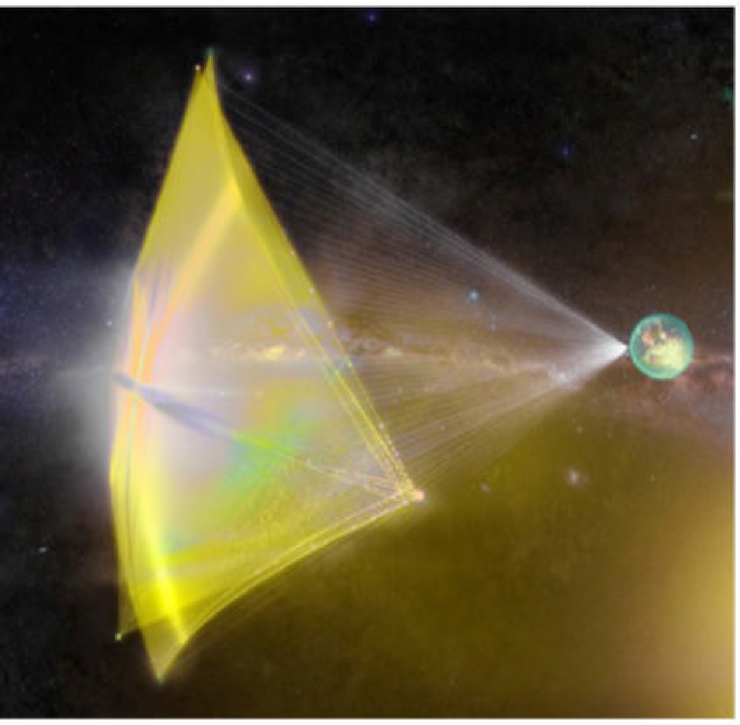
Exploring the world and universe around us is one of humanity's most instinctual traits. And although this exploration is often difficult and dangerous, the potential rewards tend to justify the risks. Humans are willing to sacrifice a lot to learn what lies beyond the horizon. And now, for the first time in history, humanity seems to be on the precipice of literally reaching out and touching the stars.

It's not going to be easy, though. The closest star to Earth after the Sun is Proxima Centauri — a red dwarf with just over one-tenth the mass of our star located some 4.24 light-years away in the Alpha Centauri system. Given our Milky Way is some 100,000 light-years across, 4.2 light-years might seem like a stone's throw. But it's not. At that distance, which is equivalent to about 25 trillion miles (40 trillion kilometers), it would take our swiftest modern spacecraft about 100,000 years to reach our nearest neighbor. After all, it takes light — the Usain Bolt of the universe — more than four years to run the same race.

The reason? Mass. Mass is the bane of accelerating objects to great speeds. To significantly increase the velocity of a heavy object takes a tremendous amount of energy. So, if the goal is to reach a distant star in a reasonable amount of time, say, within a generation, a spacecraft must be extremely tiny and, therefore, robotic. Plus, it still requires an insanely energetic boost to get up to speed.

That's the basic premise of Breakthrough Starshot: Design a lightsail-equipped nanocraft (named StarChip), give it a powerful push, and let it zip off to Proxima Centauri at more than 130 million mph (216 million km/h). Oh, and while we're at it, we might as well send a fleet of hundreds or thousands of StarChips to ensure at least some succeed.

Simple, right? In theory, yes. In reality, it's going to take a huge amount of work, many technological breakthroughs, and, of course, a ton of money. But what better time than the present to start such a humanity-defining mission?



Each lightsail would be limited to about one-thirtieth of an ounce (less than 1 gram) while still being incredibly reflective. KEVIN GILL

Setting sail in space

To quickly travel to another star, it's clear a spacecraft must be small. But it also needs a strong push to get started. One possible way to do that is borrow a tool pirates used to help them plunder the seven seas: sails. However, instead of catching wind, StarChip's sails would catch powerful beams of laser light.

Loeb, chair of Breakthrough Starshot's advisor board, is quick to note that the first mention of cruising through the cosmos on celestial winds dates back to a 1610 letter from astronomer

Johannes Kepler to his friend Galileo Galilei. In it, Kepler writes, "With ships or sails built for heavenly winds, some will venture into that great vastness." However, the true potential of using sunlight to sail through space wasn't fully recognized until the work of Soviet rocket pioneers Friedrich Sander and Konstantin Tsiolkovsky in 1924. Then, in the 1960s, Hungarian astrophysicist György Marx pushed the idea further by pondering whether a directed beam of energy, rather than sunlight, could be used to propel such a spacecraft.

American physicist and science-fiction writer Robert Forward took the lead in the 1970s, further developing the lightsail concept. By 1984, Forward's work led him to publish a paper in the *Journal of Spacecraft and Rockets* titled "Roundtrip Interstellar Travel Using Laser-Pushed Lightsails." In it, he outlined how the laws of physics did not forbid using lightsails to venture to other stars. However, Forward also noted that "whether it can be engineered and is financially or politically feasible is left for future generations to determine."

Despite the daunting, multipronged challenge of interstellar travel, in 1985, Forward created actual plans for an ultra-light interstellar probe powered by microwave lasers, or masers. He called it Starwisp and, in the 1990s, NASA Glenn Research Center scientist Geoffrey Landis jumped into the fray to elaborate on Forward's basic design. But Starwisp never took flight. In 2005, the Planetary Society launched its own solar sail, Cosmos-1, but it failed to reach orbit.

Finally, in 2010, nearly a century after the notion of sailing on sunlight was first outlined in detail, the Japan Aerospace Exploration Agency (JAXA) successfully launched a solar sail named Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS), which hitched a ride to Venus with the climate orbiter Akatsuki. Once in position, IKAROS cleverly spun at some 25 revolutions per minute to unfurl its 46-foot-wide (14 m) sail, which was just 0.0003 inch (7.5 micrometers) thick — or about one-third the width of a human hair. Within a month, JAXA reported photons from the Sun were indeed accelerating IKAROS as planned, boosting its speed by a relatively modest 890 mph (1,430 km/h). And by utilizing adjustable LCD panels embedded near the edges of its sail, the spacecraft was even able to adjust the force pushing against it, changing its orientation at will.

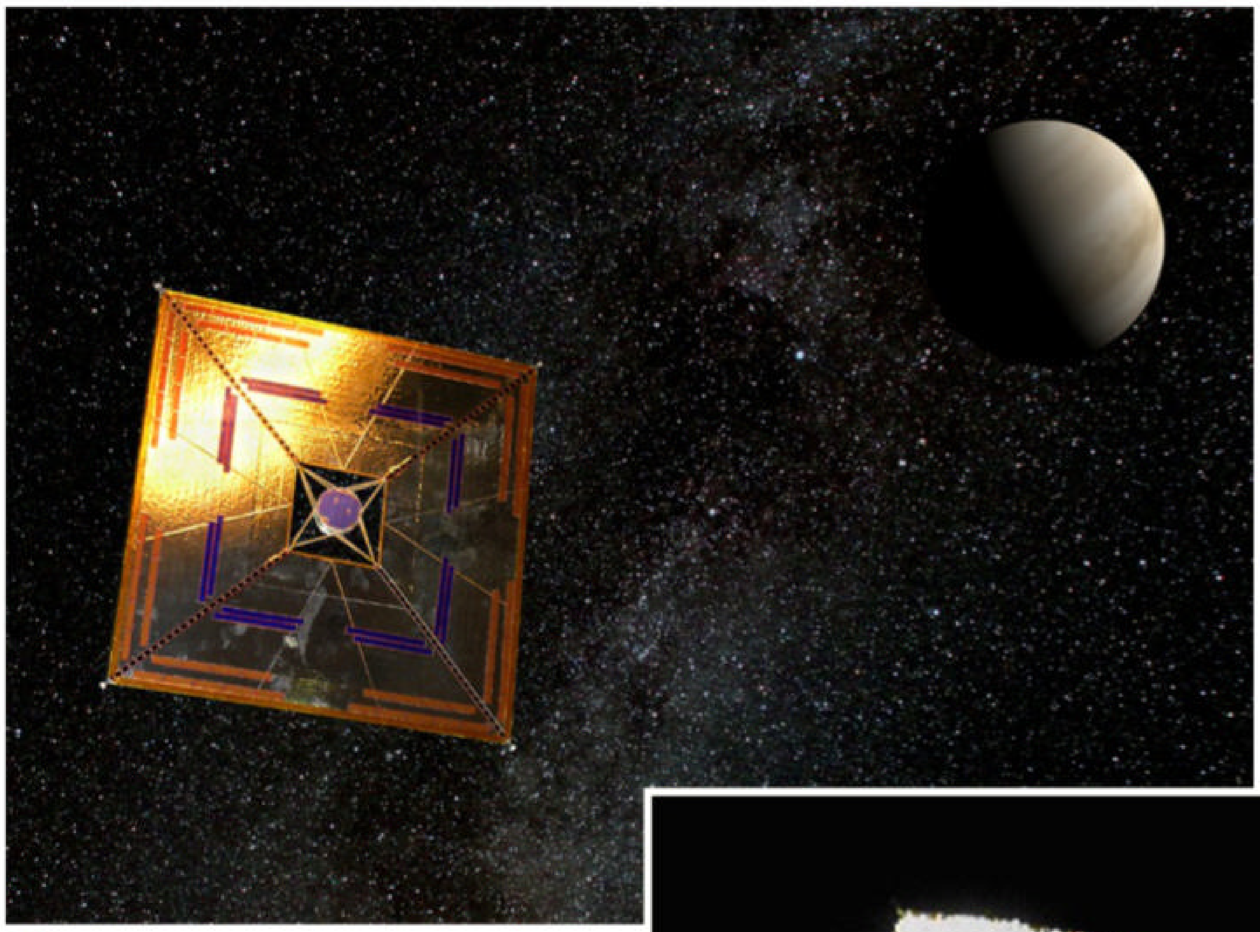
With the technology behind lightsails finally proven to work in space, Russian billionaire Yuri Milner picked up the ball a few years later. In May 2015, Loeb says, Milner nonchalantly asked him to look into the idea of interstellar spacecraft that could sail on light. The task took the eternally inquisitive Loeb and his team some six months to exhaustively research.

By early 2016, Milner was convinced an interstellar mission was feasible — or at least soon would be if technology continued to sprint forward. He officially kicked off the Breakthrough Starshot project by contributing $100 million of his own money to fund proof-of-concept research and development not just for lightsails, but also for the other advanced technology required to send a craft to another star within a generation. Ever since, dedicated scientists and engineers have been tirelessly working to make this ambitious dream a reality, taking advantage of additional funding from multiple NASA grants.

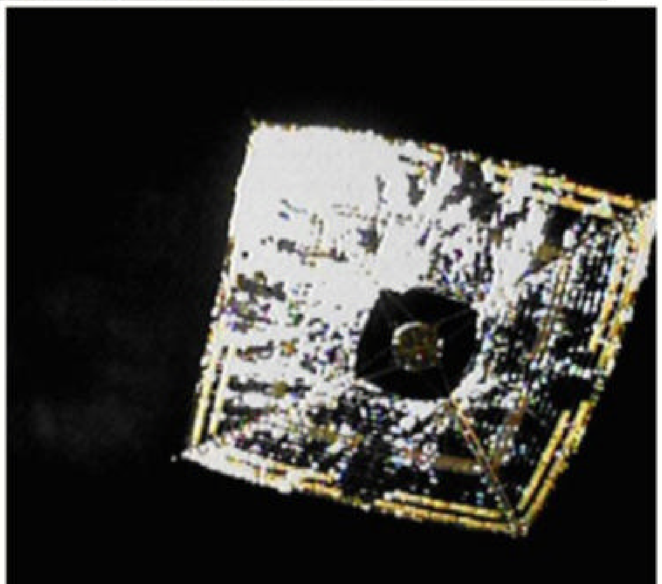
"With ships or sails built for heavenly winds, some will venture into that great vastness." *—Johannes Kepler, 1610*

Starshot progress so far

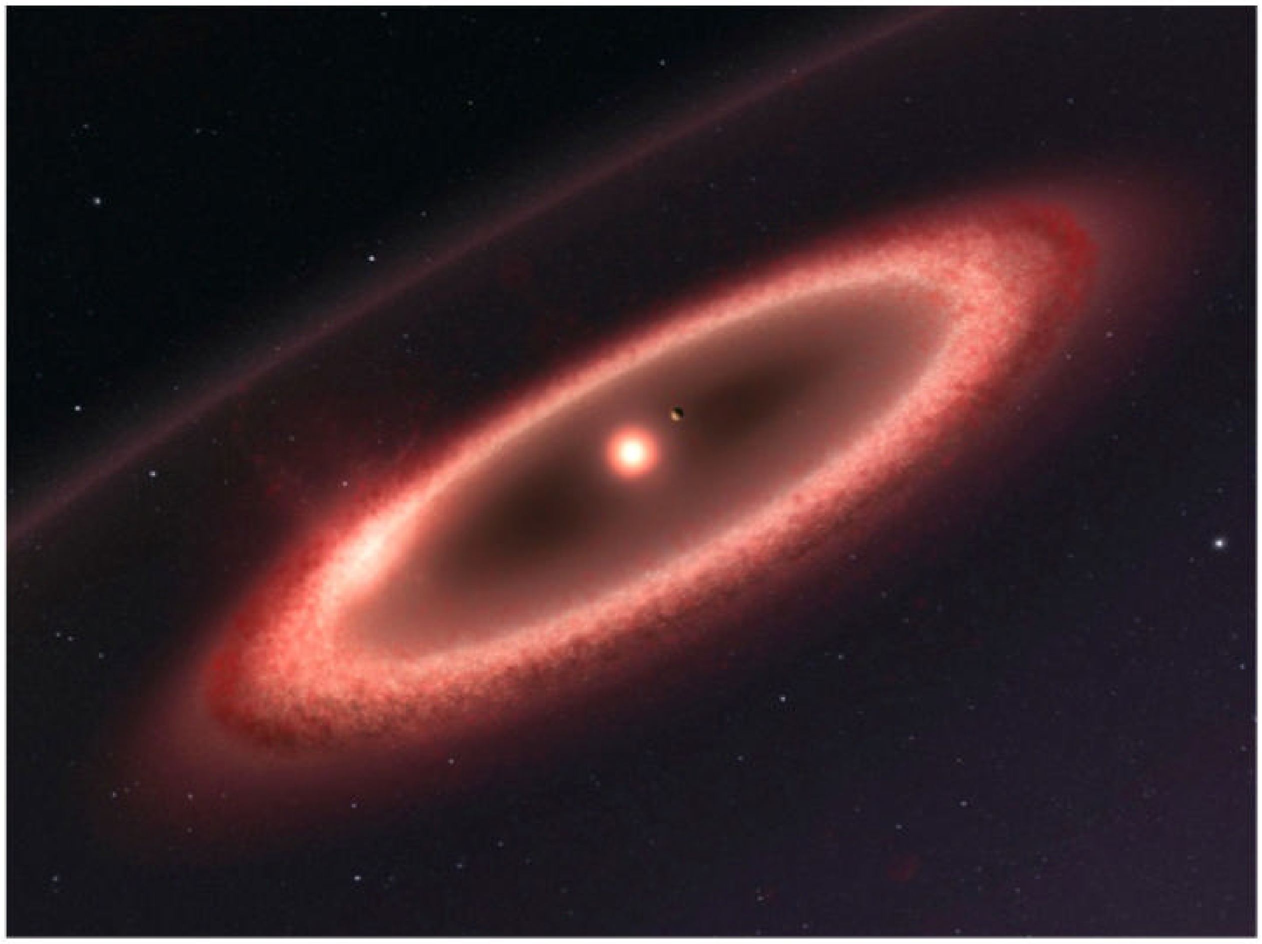
It's important to remember that Breakthrough Starshot is still in its early infancy. The initiative has made some impressive strides, but there's still a long way to go. For instance, if Breakthrough Starshot is really going to accelerate a spacecraft to 20 percent the speed of light, that craft will need to be roughly 1/1,000 the mass of IKAROS, which weighed in at about 4.4 pounds (2.2 kilograms). That means Starshot will



IKAROS, seen in this artist's concept, proved solar sails work in space by harnessing sunlight to boost its speed by 890 mph (1,430 km/h). ANDRZEJ MIRECKI/WIKIMEDIA COMMONS



This real image of IKAROS was taken after it deployed its sails on June 14, 2010. The proof-of-concept mission tagged along to Venus with JAXA's climate orbiter Akatsuki. JAXA

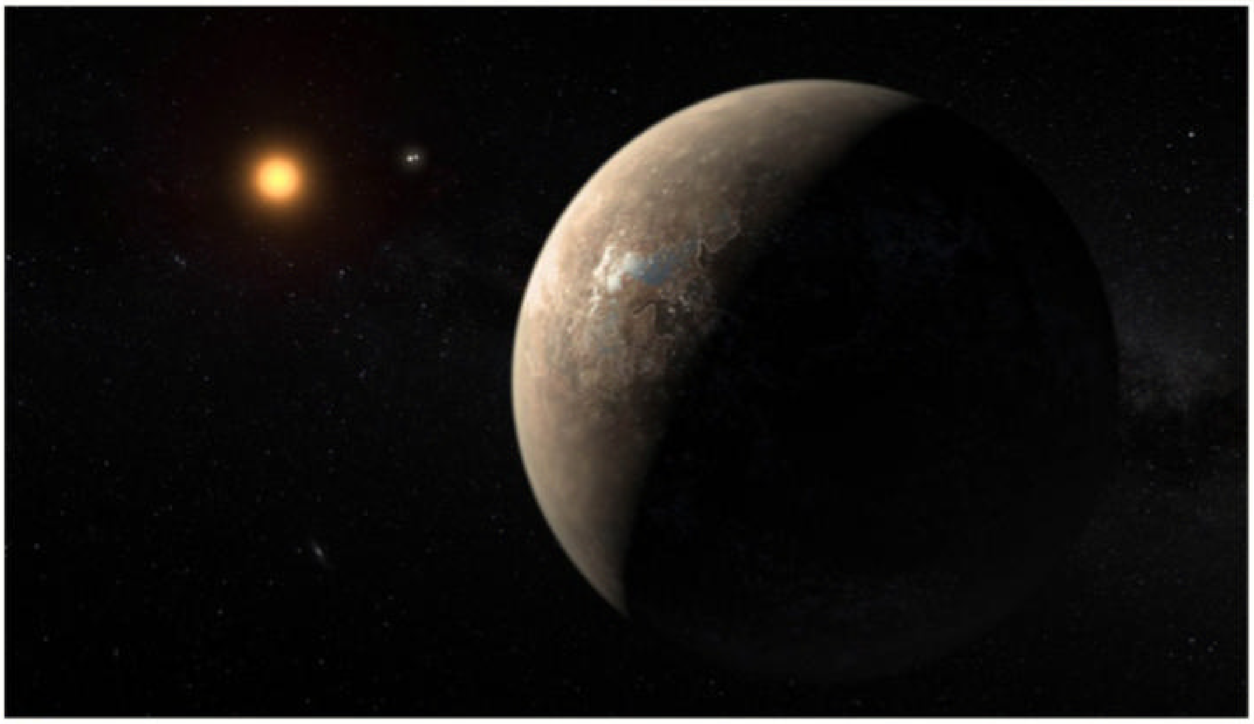


Using the Atacama Large Millimeter/submillimeter Array, astronomers detected evidence of a dust belt around the nearby red dwarf Proxima Centauri, seen here in an artist's concept. ESO/M. KORNMESSER

have to pack everything it needs for a four-year interstellar trip into a suitcase no heavier than a few paperclips.

Fortunately, thanks to Moore's law — which predicts a biennial doubling in the number of transistors that can fit on a microchip, enabling smaller, more powerful devices — that challenge is quickly becoming less of an issue. Tiny electronics already exist that are capable of some pretty amazing things. For instance, engineers have developed affordable cameras that weigh around a gram and are able to capture resolutions of at least 200 by 200 pixels. That's not much by today's smartphone standards, but it's still sharp enough that one mounted to a StarChip could resolve exoplanetary continents and oceans as it zips by. And the Breakthrough Starshot team has their bar set even higher: They are counting on technological improvements in upcoming years that will allow for ultralight cameras capable of snapping roughly 20-megapixel pics.

The sail itself also needs to be extremely light. Fortunately, the cost of manufacturing high-quality, nanoscale materials is constantly dropping. Unfortunately, weight isn't the only issue when it comes to lightsails. According to Loeb, to avoid being vaporized by



The star Proxima Centauri is orbited by at least two exoplanets: Proxima Centauri b (seen in the foreground of this artist's concept) and Proxima Centauri c (not pictured). The red dwarf star is also part of the Alpha Centauri triple-star system. ESO/M. KORNMESSER

100 gigawatts of laser light, a sail must only absorb (rather than reflect) about 1 out of every 100,000 photons that strike it. From a material standpoint, that's a major challenge. Loeb says the team is looking into building such a sail out of graphene, but so far, they haven't yet been able to create an ideal prototype.

However, the Starshot team has successfully launched other prototype craft in recent years, testing various aspects of their design and technology. For instance, in 2017, researchers sent six tiny craft, each weighing about 0.14 ounce (4 grams), into low Earth orbit. Dubbed Sprites, these chips included solar panels, computers, sensors, and communication equipment on a square frame just 1.4 inches (3.5 cm) wide. And though the researchers never established communication with most of the Sprites, they did get a signal from at least one, proving such miniaturized communication and power systems can function in space.

Then in 2019, the initiative sent another tiny prototype some 100,000 feet

Proxima Centauri b is an Earth-sized exoplanet around the nearest star after the Sun. Even a quick flyby by a fleet of StarChips could reveal a lot about its surface, which is seen here in an artist's impression.
RON MILLER

In the likely best-case scenario, Breakthrough Starshot might begin launching StarChips to Proxima Centauri by the mid-2030s.

(30,500 m) above Earth to snap pictures of our planet's surface. The test captured some 4,000 shots during its flight, spawning much discussion about what equivalent images of the two known exoplanets around Proxima Centauri might look like.

A long way to go

With more than $100 million in funding so far, Breakthrough Starshot is already off to a strong start, but it will inevitably cost billions to become a reality. However, according to Loeb, that puts it right in line with some of the world's other most ambitious (and expensive) science projects, such as the Large Hadron Collider and the upcoming James Webb Space Telescope, which cost about $5 billion and $10 billion, respectively. Fortunately, as technology matures, the team expects the cost of each launch to fall to a few hundred thousand dollars. That's still a lot of money, but obtaining up-close views of our nearest exoplanetary neighbors borders on invaluable.

In the likely best-case scenario, Breakthrough Starshot might begin launching StarChips to Proxima Centauri by the mid-2030s. Factoring in 20 years of travel time and four more years of waiting for the data to make it back to Earth, researchers wouldn't get the first up-close and personal views of a star and planets beyond our solar system until at least 2060. And Milner said in a 2016 interview that it will likely take closer to a generation (perhaps 25 to 35 years) before the first trip is underway.

Supporting and funding a project that, optimistically, doesn't launch until 2060 might seem like a frivolous venture to some — especially considering the slew of pressing events that have unfolded on Earth so far this decade. But as award-winning *Cosmos* writer and producer Ann Druyan, a member of the Breakthrough Starshot advisory board, said during a 2016 press conference announcing the initiative: "Science thinks in timescales of billions of years. And yet, we live in a society that only thinks in terms of, generally, the balance sheet of the next quarter or the next election. … So, this kind of thinking that looks at a horizon that's 35 years away — possibly 20, possibly 50 — is exactly what's called for now, because it's this kind of multigenerational enterprise that nets us such great results."

Loeb shares that same sentiment but puts it more succinctly by quoting Oscar Wilde: "We are all in the gutter, but some of us are looking at the stars."

Jake Parks, *associate editor at* Astronomy, *calculated it would take him approximately 190 billion years to reach Proxima Centauri when traveling at his fastest sprint speed.*