EXOPLANETS:
A Tale of Two Suns
PAGE 34

TELESCOPE DIY:
Make Your Own Mirror
PAGE 58

ASTRO OUTREACH:
From Street to Streaming
PAGE 84

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WILDS OF THE SOLAR SYSTEM by Christopher Crockett

The Elusive Planet X

CALTECH / R. HURT (IPAC)

IS THERE A WORLD OUT THERE? Artist's concept of a distant mini-Neptune, looking back on the Sun. If Planet X exists, its average distance from the Sun is perhaps 10 times larger than Neptune's is.

Some astronomers suspect that a ninth planet lurks in the most distant reaches of the solar system. *Does it really exist?*

Of everything we know about our solar system, the number of planets orbiting the Sun might seem like one thing that we should have nailed down.

And yet, there have been rumors of another world, lurking beyond Neptune. This is no dwarf planet like Ceres or Pluto, but a world with some heft, possibly five to 10 times as massive as Earth. The primary hints of its existence come from a paltry number of diminutive icy objects whose orbits all appear to be bunched up in one quadrant of the solar system (*S&T:* Oct. 2017, p. 16).

For the past six or so years, Konstantin Batygin (Caltech) has been at the forefront of the hunt for this elusive world, dubbed by some as Planet X, by others as Planet Nine (sorry, Pluto).

"Here's the update," he says. "We haven't found it yet."

That's not for lack of trying. Planet sleuths have been hunting in various ways — searching through old telescope images for a possible glimpse of this phantom planet; looking for more of those tiny objects, to see if they're bunched up as well; poring over data on the small bodies we do know about, to see what other secrets they hold; and running computer simulations to better understand how an extra planet might interfere with the motions of things that orbit far from the Sun.

Despite all that effort, we're no closer to a clear answer. Some say the evidence is shaky. Some say it's a slam dunk. Everyone says we need more data, with a lot of hope pinned on the upcoming Vera C. Rubin Observatory, which could settle the debate once and for all.

"It is the way science works," says Scott Sheppard (Carnegie Institution for Science), one half of the duo who first proposed that this planet might exist. "At some point, the data reach a tipping point where the hypothesis is either ruled out or it becomes much, much stronger. And we just haven't reached that yet."

Hypothesis Testing

Astronomers have been predicting the existence of additional planets for more than 170 years. Irregularities in the orbit of Uranus led to the discovery of Neptune in 1846. Further apparent orbital oddities in those planets and in some comets sparked many suggestions of additional planets throughout the late 19th and early 20th centuries. One of those proposals triggered the search that, by chance, found Pluto.

So, when Sheppard and Chad Trujillo (now at Northern Arizona University) suggested in 2014 that there may be a planet hiding far from the Sun, they became part of a long legacy. The pair had been surveying the sky for small icy bodies beyond Neptune and the ring of frozen relics in the main Kuiper Belt. They noticed that all objects beyond a certain distance from the Sun made their closest approach to our star near where their orbits crossed the *ecliptic*, or the midplane of the solar system.

That was odd, because subtle yet persistent tugs from the known giant planets should make those orbits drift. Over the age of the solar system, they should have slowly arranged themselves in random orientations — unless something was corralling them. And these orbits didn't appear to be strongly influenced by the known giant planets. Perhaps, Sheppard and Trujillo suggested, there was another planet out there, holding these orbits in place.

Two years later, Batygin and Mike Brown (Caltech) took a closer look. Zeroing in on a handful of "extreme" objects — those that are far enough from the Sun to keep well clear of Neptune — they not only confirmed what Sheppard and Trujillo saw but also reported that the orbits were physically aligned, all stretching out roughly in the same direction away from the Sun. They agreed that the probable culprit was a planet, roughly 10 times as massive as Earth, with an average distance from the Sun of several hundred astronomical units (a.u.) — about 10 to 30 times farther out than Neptune.

In the years since, this possibility has kept some planetary scientists busy examining and reexamining the evidence. "There've been three themes through which the Planet Nine hypothesis has progressed," Batygin says. "Data analysis, theory, and actual observations."

Analysis of available data has produced the most controversy. "There are a lot of observational biases in discoveries of the outer solar system," says Samantha Lawler (University of Regina, Canada). If those biases aren't accounted for, she adds, "you can find some really weird things, like it looks like there's clustering when there's not."

In the case of Planet X, there appear to a bunch of objects whose perihelia are near the ecliptic. But observers are biased toward finding things when they are near perihelion — because that's when they're closest to the Sun and therefore brightest — and they tend to search along the ecliptic, because that's where most solar system stuff resides.

There are more subtle biases as well, Lawler notes. Seasonal weather patterns in Hawai'i and Chile — where many planetary surveys are conducted — mean certain parts of the sky have better telescope coverage than others, which could make it look like some extreme Kuiper Belt objects are crowding up on one side of the solar system.

Accounting for these biases is tricky. It requires knowing everything about the observations, including where the telescope pointed (including where it didn't find anything) and how faint an object it could have seen. Unfortunately, for many Kuiper Belt finds, much of that info is lost.

"What the community has been trying to do for a few years now is not only try to find objects but try to understand what objects a given survey can find," says Pedro Bernardinelli (University of Washington). This type of work involves limiting analyses to just the Kuiper Belt objects found by a single survey — one which has a good grasp of all its biases — and seeing if the orbital clustering shows up there in some statistically meaningful way.

These analyses keep saying there's no evidence for an extra planet.

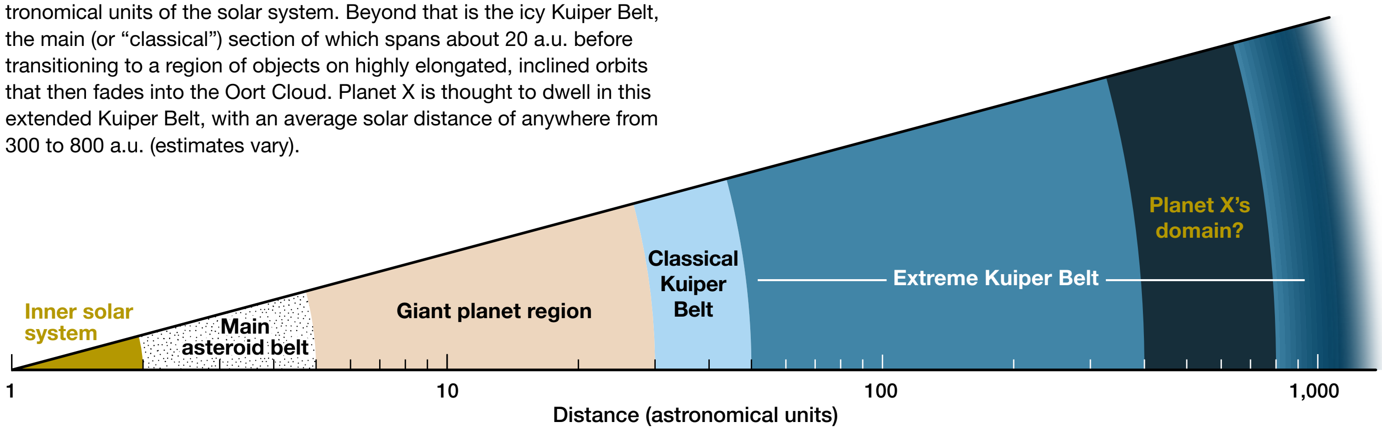
The Outer Solar System Origins Survey, or OSSOS, spent four years focusing on two regions of sky near the ecliptic. During that time, the project tallied more than 830 new Kuiper Belt objects, four to eight of which fit some definition of "extreme" — that is, some combo of perihelion distance and orbit size that keeps them mostly detached from the gravitational sway of Neptune. Based on computer simulations of what OSSOS could find, these extreme objects could be part of a larger, unseen population spread uniformly around the Sun, the team reported in 2017.

"We can't say Planet Nine doesn't exist," Lawler says. "But we don't have evidence in favor of the reason for it existing."

Recently, two other teams came to similar conclusions.

The Dark Energy Survey (DES) wasn't designed to look for things in the solar system. It spent six years scanning

▼ **DISTANT NEIGHBOR?** The known planets inhabit the inner 30 astronomical units of the solar system. Beyond that is the icy Kuiper Belt, the main (or "classical") section of which spans about 20 a.u. before transitioning to a region of objects on highly elongated, inclined orbits that then fades into the Oort Cloud. Planet X is thought to dwell in this extended Kuiper Belt, with an average solar distance of anywhere from 300 to 800 a.u. (estimates vary).



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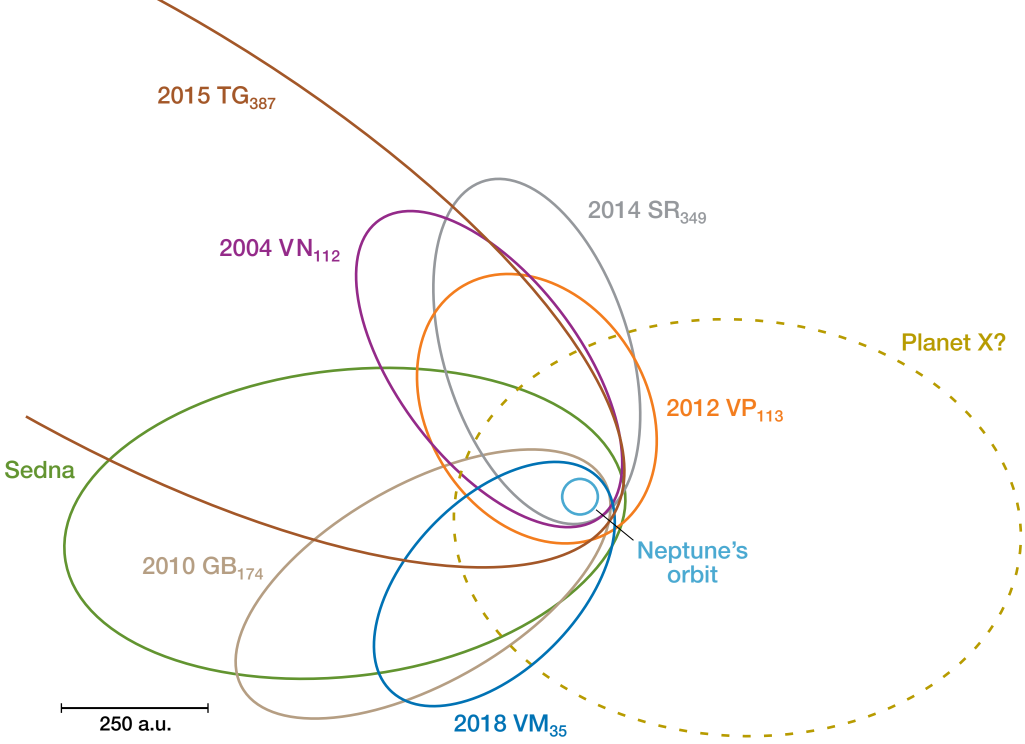


STRANGE CLUSTERING Several objects in the extreme regions of the Kuiper Belt follow stable orbits that are notably aligned, suggesting the presence of a shepherding planet. Astronomers have found additional objects on unstable orbits in these regions that show weaker signs of clustering behavior, but they're omitted here for clarity.

GREGG DINDERMAN / *S&T*, SOURCE: WORLDWIDE TELESCOPE AND K. BATYGIN & M. E. BROWN / *ASTROPHYSICAL JOURNAL LETTERS* 2021

a wide swath of southern sky for supernovae and patterns in large-scale cosmic structure. But plenty of locals have photobombed the survey, including 812 small bodies beyond Neptune, 458 of which had never been seen before.

Of the nine most extreme objects they saw — those which should be most sensitive to the proposed planet — they didn't find evidence of orbital clustering, the team reported in February 2022. "We can't really differentiate between a clustering effect caused by Planet Nine . . . and just having things everywhere," says Bernardinelli, a DES team member. "In other words, we're finding things where we're looking for things."

Going further, a team led by Kevin Napier (University of Michigan) combined data from OSSOS, DES, and an ongoing survey led by Sheppard and Trujillo. Those data also show no clear evidence of clustering, the team reported in April 2021.

All of this might seem like bad news for Planet Nine. But the pro–Planet Nine crew thinks these analyses, while well done, also miss the mark. Each survey on its own has found relatively few of these extreme objects, Batygin says, and small numbers can lead to wonky statistics.

These surveys also aren't great for testing the Planet Nine hypothesis, Sheppard says. The Dark Energy Survey overlapped with only one stretch of the ecliptic, while OSSOS focused on two relatively small patches. "It's hard to . . . get rid of observational biases if you haven't looked in other places," he says. Scanning along the whole ecliptic, for example, could clarify whether extreme objects are actually hanging out in one part of the sky, or if it just appears that way because that's where astronomers keep looking.

To maximize the number of objects, Batygin and Brown have repeatedly turned to the Minor Planet Center (MPC), a database that records when and where every Kuiper Belt object, or KBO, was discovered. "The full census of KBOs that are discovered on the night sky provides you with a map of where people have looked," Batygin explains. (Others counter, however, that the MPC doesn't record where past teams have looked and not found anything worth reporting.)

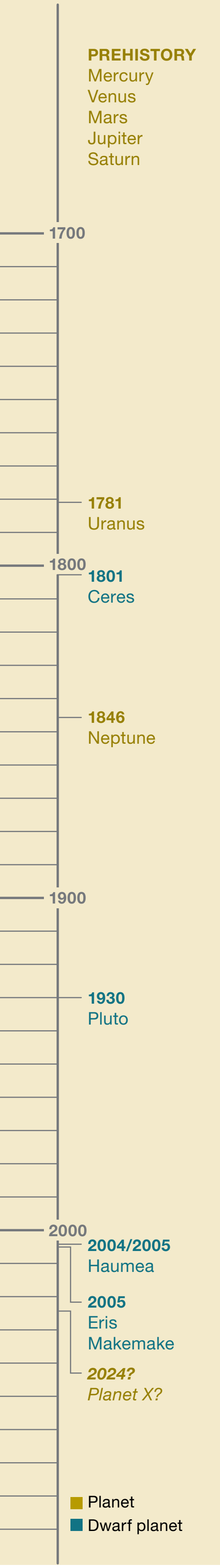
By using the orbits and brightnesses of known KBOs, Batygin and Brown simulated a "synthetic" population whose elliptical orbits are orientated uniformly around the Sun. For each known KBO, they calculated which members of this synthetic population should have been spotted in the same patch of sky, if they existed. Using that info, Batygin and Brown estimated which orbit orientations have historically been more likely to be seen than others.

And, of course, past observations *are* biased. But not in a way that is likely to produce the observed clustering patterns, Brown reported in 2017 and, with Batygin, again in 2019. They calculate that the odds that all the clustering is just a coincidence is about 0.2%. "I'm not a gambling man, but that's pretty good," Batygin says.

Part of the trouble in reconciling all these results is that every group has focused on a different cache of objects in the extended part of the Kuiper Belt. "No one agrees on the definition of 'extreme,'" Bernardinelli says.

And muddled definitions lead to muddled results. "The question 'Is the population overall clustered?' is not the right question," Batygin says. "The right question is whether the *stable* Kuiper Belt objects in the distant solar system are clustered." Here, stable refers to bodies that — in the absence of an extra planet — are never sharply redirected by the gravity of Neptune.

But the bigger issue may be that both sides of the debate are trying to wring a definitive story out of too few characters. "I



◀ **DISCOVERY TIMELINE** Excluding Earth, astronomers currently know of seven major planets and at least five dwarf planets in the solar system. (There are six additional dwarf planet contenders in the Kuiper Belt awaiting official approval, with the prospect of dozens more.) Could there be another planet lurking out there somewhere — and will we soon find it?

talk to certain groups, they say, 'This planet doesn't exist, it's not possible, almost zero percent,'" Sheppard says. "You talk to other groups, and they're saying it's 100 percent. Both of those groups, I would say, have rose-colored goggles on." He puts himself more in the middle. "I would say it's more likely than not that there's a planet out there . . . but we're just not using that many objects."

Getting a Better Picture

One way to settle the debate would be to see the planet directly. "Lots of predictions of Planet X are that it's pretty bright," says David Trilling (Northern Arizona University). By "bright," he means roughly magnitude 24; Pluto is 10,000 times brighter right now, at magnitude 14. "You just need to be looking in the right place."

And that's the rub. The solar system is big, and telescopes see only a sliver of it at a time. Planet Nine's proposed orbit is rife with uncertainty. And even if it were better constrained, there is zero intel about where along that orbit the planet might be.

That hasn't stopped people from trying. Over the past several years, many researchers have combed through archival images from telescopes in space and on the ground, in visible and infrared light, to see if the planet ever wandered into some past survey's field of view. Even a group studying the cosmic microwave background got into the game, looking through seven years of data from the Atacama Cosmology Telescope for possible thermal emissions from a remote planet. If Planet Nine is out there, it has eluded our gaze so far.

Better odds lie with building up a larger census of these extreme KBOs.

One way forward might be to find more *high-inclination objects*. One prediction is that Planet Nine's gravity could lift some extreme KBOs into orbits that are highly tilted relative to the rest of the solar system. In 2018, Juliette Becker (now Caltech) and colleagues reported finding the first of such a cohort. "In the known solar system, you really can't produce an object like this," Becker says. Locating a few more could clarify whether this one was just an oddball or part of a larger, undiscovered family.

Others are trying to figure out if the orbits of the extreme bodies are truly bunched up. Partly to that end, Sheppard and Trujillo, along with David Tholen (University of Hawai'i), have been continuing their survey of the outer solar system, ongoing since 2012. "The main goal of our survey is to make sure we get rid of those observational biases or make them pretty much minimal," Sheppard says. "To do that, you need to observe very uniformly."

Using the Subaru telescope in Hawai'i and the Víctor M. Blanco telescope in Chile, the team has been observing a wide band straddling the entire ecliptic at all times of year, sweeping the gaze of these two telescopes in a full circle around the Sun to tally up extreme KBOs in all quadrants of the solar system, not just the one whether they seem to show up. The hope is to triple the number of known objects on these distant orbits.

However, they've been coming up a bit short. "We're finding fewer of them than we thought we'd find," Sheppard says.

To Sheppard, that suggests that the orbital clustering might be real. The spot on the sky where these objects bunch together was covered early on in their survey. If the distant KBOs truly are hanging out in one quadrant of the solar system, then observing elsewhere won't turn up many more.

"Right now, the statistics are still borderline," Sheppard says. "The stats are a little better than or similar to what we saw a few years ago."

Another survey, the DECam Ecliptic Exploration Project (DEEP), is using a large camera on the Blanco telescope to scan four patches of sky along the ecliptic, going wider and fainter than other similar projects. Entering its third year, the survey will hopefully find between 5,000 and 10,000 new objects beyond Neptune, says project lead Trilling, substantially increasing the known census.

In particular, the survey could find more of these very distant objects that have been at the heart of the Planet Nine debate, Trilling says. Though it's not yet clear, he cautions, if the calculated orbits will be refined enough to put better constraints on the planet's trajectory.

But what most in the community are waiting for is the Vera Rubin Observatory.

Scheduled to start science operations in 2024, the Rubin Observatory in northern Chile will spend at least 10 years sweeping all the sky it can see every few days, providing an unprecedented view of anything that changes — including the motions of tiny things in the outer solar system.

Researchers expect the tally of objects seen orbiting past Neptune to increase by about a factor of 10. "Today we know of only about 4,000," says Megan Schwamb (Queen's University Belfast), cochair of the project's Solar System Science Collaboration. After Rubin, "it's going to be about 40,000."

Crucially, astronomers will have a good handle on Rubin's observing biases. For the Planet Nine hypothesis, "I feel like

TERRI DUBÉ / *S&T*

that's going to say the answer: yes or no," Schwamb says. "We're going to find so many Kuiper Belt objects, if there's any influence of a distant planet on that disk [of objects], we might start seeing that in more subtle ways."

What's more, Rubin has a good shot at directly seeing the planet. Based on available estimates about the planet's orbit and size, the world might be bright enough to show up in the observatory's camera and could be seen along much of its orbit, Trilling and colleagues calculated in 2018.

"It will not reach all of the necessary parts of the sky to have the final word on Planet Nine," Batygin says. "But if Vera Rubin doesn't discover Planet Nine, at least it should discover these stable, long-period Kuiper Belt objects."

Even Rubin's persistent gaze may not be enough to settle the debate, though, as the project may not be optimized to see lots of objects distant enough to be swayed by an extra planet, Sheppard cautions. "It will definitely find more of these. . . . The question is, how many more?"

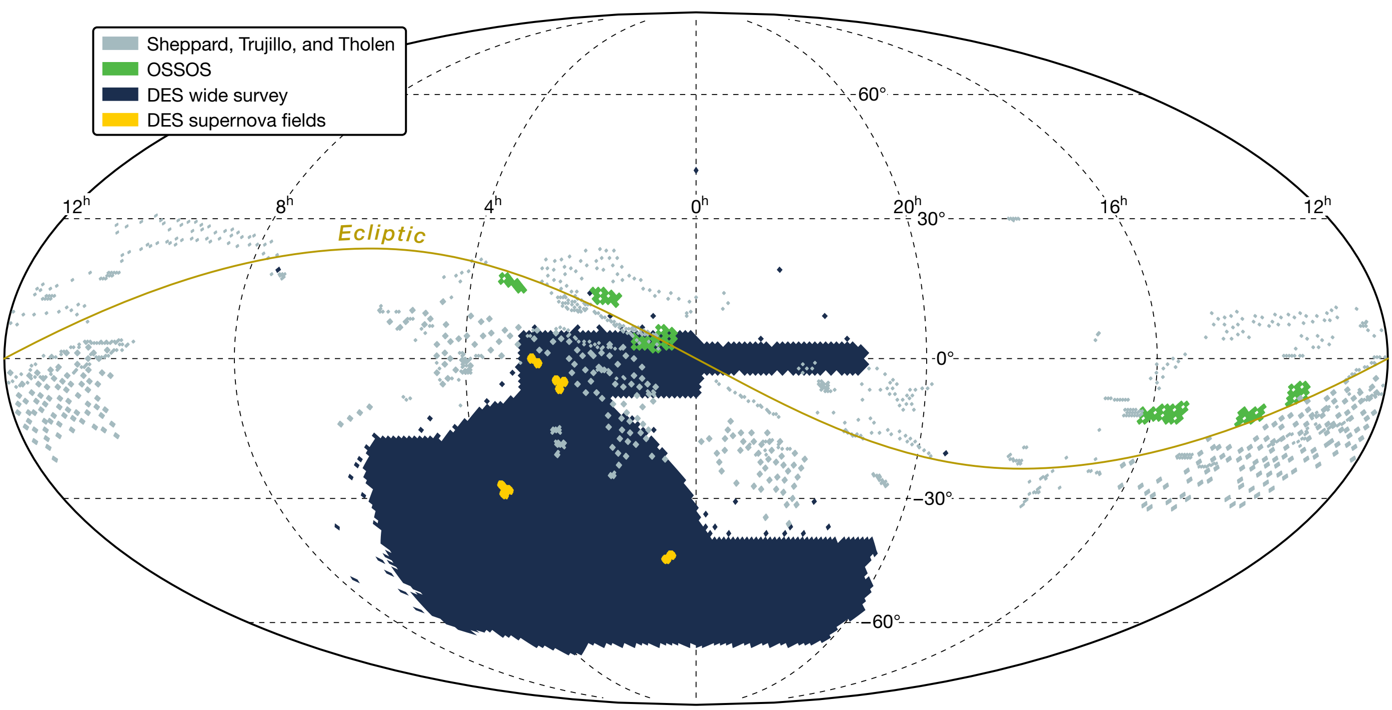
If it turns out Planet Nine doesn't exist, that doesn't mean the search was in vain. "This whole Planet Nine debate has basically made people care a lot more about the outer solar system," Bernardinelli says. "If we find Planet Nine, that will be amazing. If not, then we have a lot of explaining to do. But in the end, it only matters that we've learned things either way."

Planet Nine, if nothing else, has helped sharpen focus on the tiny, remote, frozen residents of our solar system. Far removed from the gravitational influence of the known giant planets, the motions of these icy denizens preserve a tale about how the planets formed and jockeyed for position, and about the neighborhood in which our Sun was born some 4.6 billion years ago.

"The solar system has been mapped out pretty well out to Pluto. But it has not been mapped out well beyond that," Sheppard says. "And we don't know what's out there."

▲ **UNDER CONSTRUCTION** The Vera C. Rubin Observatory, seen here at twilight on Chile's Cerro Pachón in April 2021, will discover many thousands of distant Kuiper Belt objects. Science operations will begin no sooner than December 2023.

■ **CHRISTOPHER CROCKETT** has a PhD in astronomy and is now an award-winning science journalist based in Arlington, Virginia. He looks forward to the next Planet Nine update, whenever that may be.



▲ **NOT ALL SURVEYS ARE THE SAME** Shown here are the coverage maps for the three major sky surveys of the region beyond Neptune: the Dark Energy Survey, the Outer Solar System Origins Survey, and the ongoing survey by Sheppard and company. The latter two follow the ecliptic, where solar system objects tend to lie. DES has a notably different footprint because it's a cosmological survey.

RUBIN OBSERVATORY: RUBIN OBSERVATORY / NSF / AURA; MAP: K. J. NAPIER ET AL. / *PLANETARY SCIENCE JOURNAL* 2021