I thank Chairman Cruz, Ranking Member Markey and other committee members for the opportunity to testify on scientific opportunities and NASA space science. My name is David Spergel. I am Charles Young Professor of Astronomy on the Class of 1897 Foundation at Princeton University and Managing Director of the Flatiron Institute, a new Institute funded by the Simons Foundation to conduct basic research in computational sciences. I am also the immediate past chair of the NAS Space Studies Board, serve on the JPL advisory board, and am currently co-chair of the WFIRST Formulation Science Working Group. I am a MacArthur Fellow, member of the National Academy of Science and the American Academy of Arts and Sciences. I shared this year's Breakthrough Prize for our work using NASA's WMAP satellite, one of its Explorer missions, to establish the current standard model of cosmology.

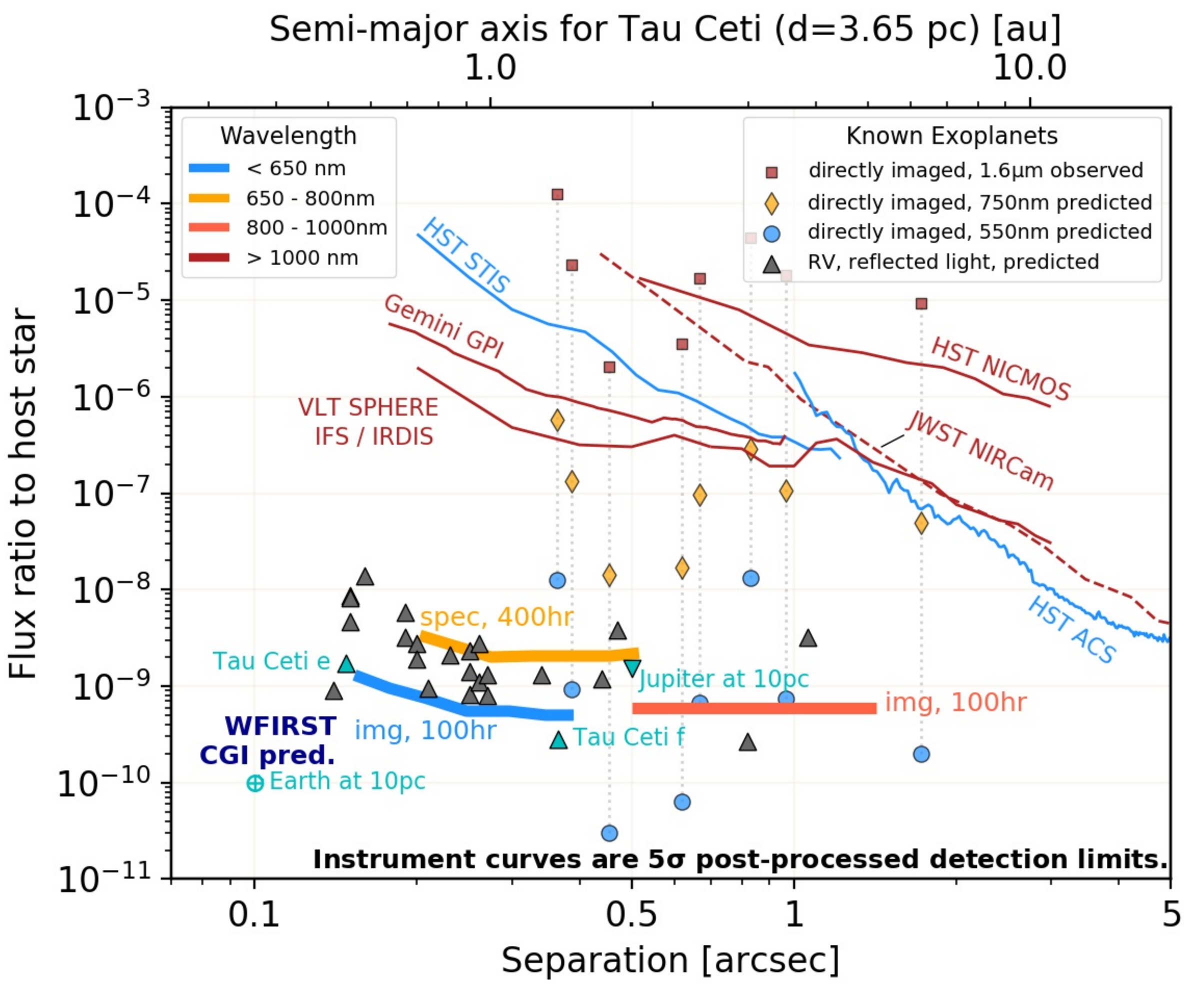
Our multi-generational program of exploring and studying space is the modern version of the construction of the great medieval cathedrals of Europe. Many of NASA's most important activities from sending humans to Mars to the study of extrasolar planets to understanding the cosmos are century-long projects.

In cosmology, we have learned that our universe is both remarkably simple and remarkably strange. Nearly a century ago, Dr. Edwin Hubble's work at Mount Wilson observatory began our program of measuring the size and shape of our universe. Today, the Hubble Space Telescope and measurements of the microwave background continue this program. Over the past two decades we have learned that a simple model with only five parameters (the age of the universe, the density of atoms, the density of matter and the properties of the initial fluctuations), describes all of the basic properties of the observed universe. While successful, this model implies that atoms make up only 5% of the universe. Most of the universe is in the form of *dark matter* and *dark energy*.

Understanding the nature of dark energy is one of the most compelling problems in physics. Both Europe and China are leading missions to study dark energy. When I was in Beijing last year, I was impressed by China's plans to launch a large space telescope off of its new space station with a primary focus on studying dark energy. This telescope will have the world's largest space camera and use Chinese military technology to construct a large off-axis telescope. Fortunately, NASA is moving forward with the premier dark energy mission, WFIRST, the top ranked large space project in the 2010 astronomy decadal survey. It will measure the expansion rate of the universe and the growth of structure to unprecedented precision. WFIRST is meeting all of its technical requirements and is on track for a 2025 launch.

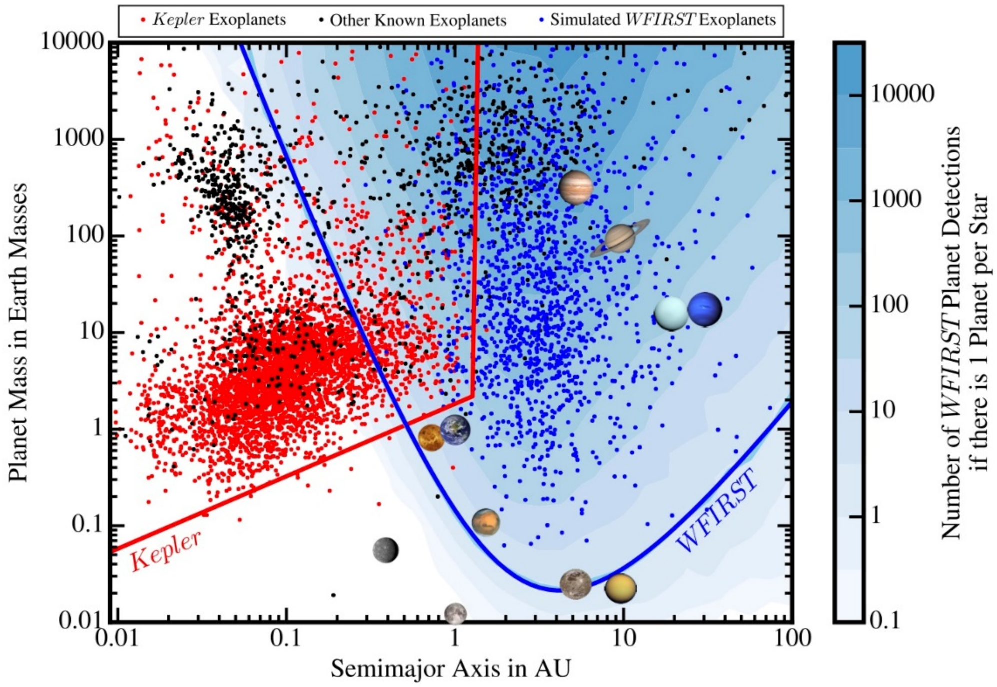
Astronomers have also learned that the solar system is far from unique. Using observations from the Kepler spacecraft and ground-based observatories, they have discovered thousands of exoplanets revealing a diversity of planetary architectures and a diversity of planetary properties. Shakespeare's line, "There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy" is perhaps our best guide as we contemplate whether there is life elsewhere in the Milky Way.

Just as the exploration of the cosmos has driven telescope design for the past century, the study of exoplanets and the search for life beyond our solar system will likely shape the telescopes of the coming century. NASA's TESS mission, which was launched in April and just entered science operations, should soon reveal many new nearby transiting planets. When launched, the James Webb Space Telescope will be able to characterize the atmospheres of some of these planets. This is one of the powers of a flagship mission: JWST was not designed for transit spectroscopy but its enormous sensitivity in the infrared will enable it to make potential transformative measurements of planetary atmospheres. WFIRST's coronagraph is poised to be the next step in exoplanet characterization. The coronagraph should be more than 1000 times more sensitive than previous coronagraphs aboard Hubble and JWST. It will not only be able to image massive planets around nearby stars but will be the stepping stone for developing technologies for the next generation of great observatories. One of the possible highest priorities for the upcoming decadal survey are large telescopes likely launched in the 2030s that will be capable of characterizing extrasolar planets. Even these telescopes will likely be stepstones to even more sensitive telescopes that we will develop in the 2050s that will enable detailed characterization of planetary atmospheres.



This figure shows the sensitivity of the WFIRST coronagraph. Note that WFIRST's coronagraph should be a significant improvement over HST, JWST and ground-based instruments (GEMINI and VLT sphere). WFIRST should be a significant step towards Earth-like planets

Understanding planet formation requires use a wide range of observational approaches. Within our own solar systems, comets and asteroids are fossils of the early solar system. Radio and infrared observations reveal extrasolar planetary system in formation. WFIRST will complete the census begun by Kepler and TESS with its microlensing observations. These should reveal thousands of planets in the outer regions of their solar systems.



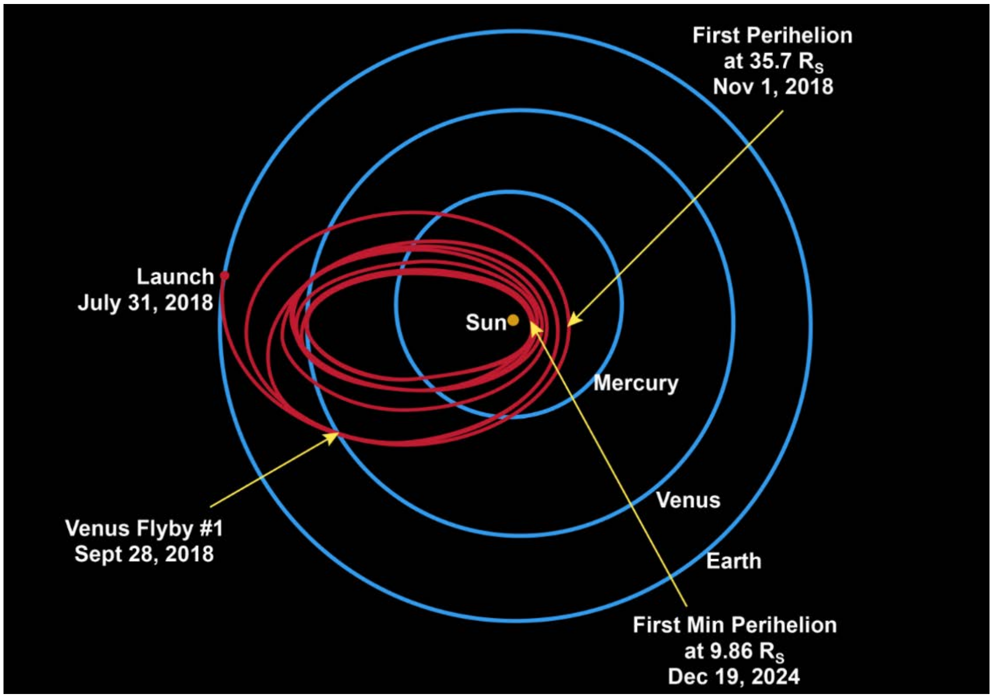
This figure shows the discovery space for the Kepler and WFIRST mission as a plot of distance from the host star (measured in astronomical units (AU)) and planet mass. The Earth distance from the Sun is 1 AU. The plot also shows the planets of our own Solar system. The black points in the plot are the planets discovered by ground-based measurements of stellar radial velocities.

Within our own solar system, we have learned that water, the most essential ingredient for life is seemingly ubiquitous in our solar system. Comets have brought water to burning hot Mercury and the seemingly barren Moon. Mars had not only a wet past but as recent observations reveal has liquid water. Outer planet moons such as Europa host vast oceans. Did any of these systems once host life? Do they still host life today?

The exploration of Mars is another one of humanity's multi-generational challenges. The Mars 2020 mission is the next step in this program that should continue with the return of carefully selected samples. As the NAS report "Vision and Planetary Sciences in the Decade 2013-2022" recommends:

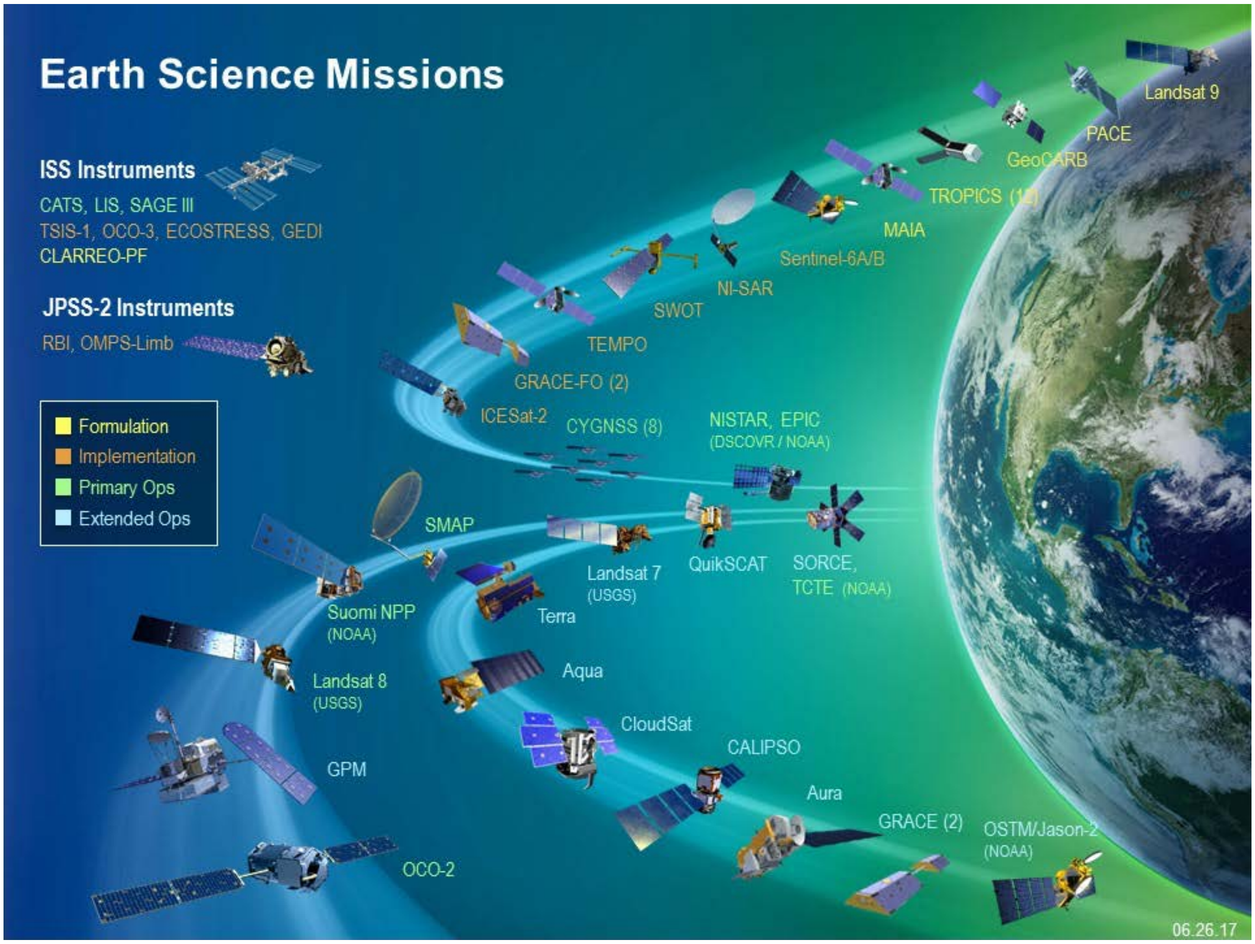
> Mars is unique among the planets in having experienced processes comparable to those on Earth during its formation and evolution. Crucially, the martian surface preserves a record of earliest solar system history, on a planet with conditions that may have been similar to those on Earth when life emerged. It is now possible to select a site on Mars from which to collect samples that will address the question of whether the planet was ever an abode of life.

Besides the enormous scientific value of the samples, the process of sample return should be an important step towards NASA's horizon goal of sending humans to Mars and returning them safely to Earth.



The Parker Solar Probe will launch this summer. It will pass far closer to the Sun than any other satellite. Parker Solar Probe will study the origin of the Sun's activity.

Understanding the physics of our Sun and the many ways that it affects the space environment and the Earth itself is another one of NASA grand challenges. What is the origin of the Sun's activity? How does this affect the space environment, the solar system and the Earth itself? These questions are not only profound physics questions but have important economic consequences as space weather could devastate our technological society. Hopefully, later this month NASA will launch the Parker Solar probe, an ambitious mission that will effectively touch the Sun and directly probe the origin of Solar activity. NASA has also just announced that my Princeton colleague Dave McCommas will lead the Interstellar Mapping and Acceleration Probe (IMAP) mission. IMAP will help researchers better understand the boundary of the heliosphere, the magnetic bubble surrounding and protecting our solar system. The DRIVE initiative is an important complement to these major missions: a combination of cubesats, small sats, and theoretical work.



Earth scientists utilize a large constellation of current and planned missions to monitor the changing planet.

Understanding our rapidly changing planet is perhaps NASA's greatest scientific challenge and a pressing societal need. As the recent NAS report, "Thriving on a Changing Planet: A Decadal Strategy for Earth Observation from Space" finds:

> Space-based Earth observations provide a global perspective of Earth that has over the last 60 years, transformed our *scientific understanding* of the planet, revealing it to be an integrated system of dynamic interactions between the atmosphere, ocean, land, ice, and human society across a range of spatial and temporal scales, irrespective of geographic, political, or disciplinary boundaries. In the past decade in particular, enabled *societal applications* that provide tremendous value to individuals, businesses, the nation, and the world. Such applications are growing in breadth and depth, becoming an essential information infrastructure element for society as they are integrated into people's daily lives.

Monitoring the Earth from space requires a robust, resilient and appropriately balanced constellation of satellites that will provide the observational capacity to address our most profound problems.

Let me now turn to JWST. These large projects are challenging and require perseverance. Back in 1917, the state-of-the art mirror at the Mt. Wilson observatory had to be recast multiple times as human error led to breakage. Today, we are faced with delays and overruns in the construction of the James Webb Space Telescope, today's cutting edge facility. The delays are even more frustrating as they are due to human mistakes during integration and testing at Northrup Grumman. The Independent Review Board chaired by Tom Young concluded that a combination of human errors, poor schedule performance, embedded problems, system complexity and the novelty of sunshield has led to the delay of nearly two years and overruns of close to $1 billion dollars. While painful, I believe that JWST will not only be a transformative astronomical observatory but will be a flagship for all of NASA and the eventual success of this incredibly complex engineering project will become a source of national pride and a symbol of US technical prowess. Since JWST is an agency-wide priority, these new costs should be spread across the agency, perhaps supplemented by new resources for NASA. If they are borne entirely by the astrophysics directorate, they will have devastating effects on its future missions and its scientific program.

Given the challenges in building complex missions like JWST, it is easy to question the role of flagship missions in the NASA program. Flagship missions like JWST and WFIRST not only carry out their core science program but enable a very rich program of general astrophysics. Similarly, flagship missions in other areas of space science help drive their entire fields. I want to echo the recent NAS report, "Powering Science: Large Strategic Science Missions":

> NASA's large strategic missions like the Hubble Space Telescope, the Curiosity rover on Mars, and the Terra Earth observation satellite are essential to maintaining the United States' global leadership in space exploration and should continue to be a primary component of a balanced space science program that includes large, medium, and smaller missions.

I also agree with the report's finding that "It is not possible for NASA to abandon large strategic missions simply because they can be challenging and still maintain world leadership in space".

When contemplating our leadership role, it is important to consider the growing role of other nations in space science. European-led missions, often with significant US contributions, now produce some of the most exciting results in space science. Our partnerships with Europe, Canada and Japan both enhance our own missions and enable our partners to launch more capable scientific probes. We need to continue to work to strengthen these opportunities. The emerging role of China in space science is a more complex situation. China is making major investments in space science and is embarking on its own ambitious program. I have visited China several times to observe their program and meet with my colleagues. I have been impressed by their rapid rate of progress. For example, China is building its own dark energy mission, the Chinese Space Satellite Optical Survey, that makes use of its own technologies and aims to launch before WFIRST. The United States should strive to maintain its leadership role in space science and other areas of space exploration.

While NASA does face immediate challenges like JWST, this is an incredibly exciting time in space science. NASA satellites have enabled the discovery of 1000s of exoplanets, are detecting the optical counterparts of merging neutrons stars whose gravitational waves have travelled for billions of light years, and are tracing the large scale distribution of dark matter and dark energy. It is launching a satellite that will literally touch the Sun. NASA exploration of our solar system is revealing new insights into the origin of the solar system and perhaps even of life itself. Its satellites are deepening our understanding of the rapidly changing Earth. Most importantly, each of these discoveries raises new questions that future satellite missions will address in the years to come.