Matt Mountain

President, Association of Universities for Research in Astronomy

Testimony before the Committee on Science, Space and Technology, Subcommittee on Space

NASA's Next Four Large Telescopes

December 6, 2017

Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to testify about the revolutionary changes under way in Space Science that have the potential to answer the profound question that has haunted humanity for millennia, for as long as we have looked up into a clear night sky and wondered: Are we alone in the Universe?

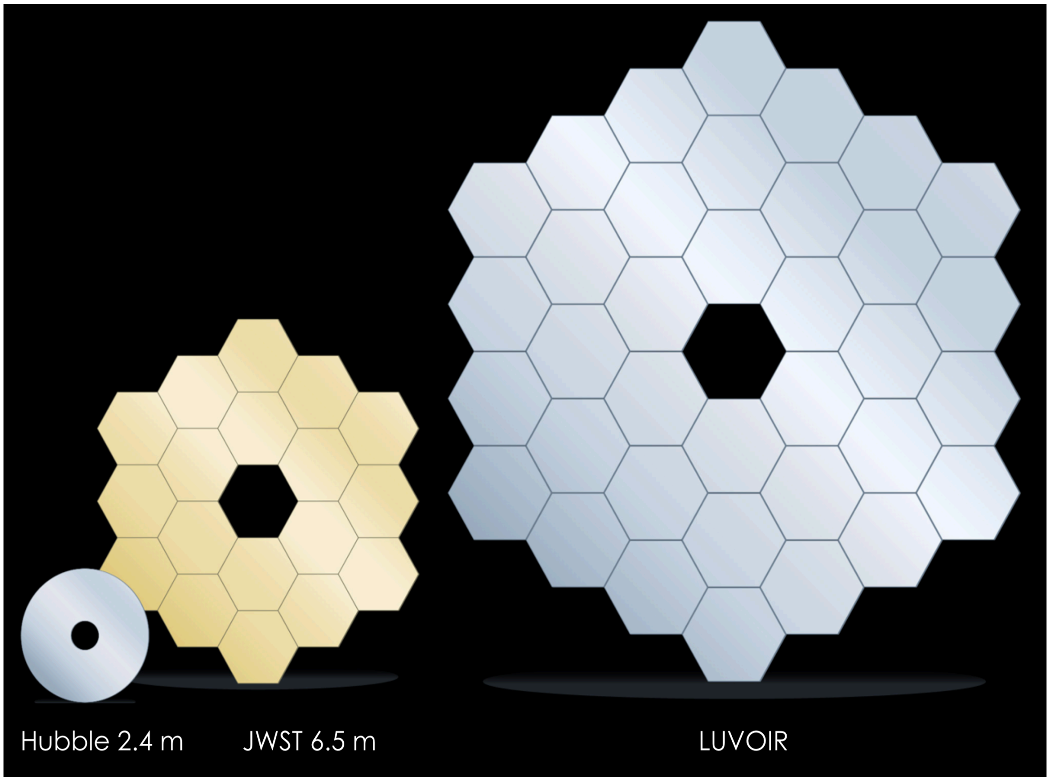
Had I sat before you a mere seven years ago, I could not have told you the sky is full of planets. Now, because of early observations with the Hubble Space Telescope (HST), the transformational observations of a small piece of the sky with NASA's Kepler mission, and ground-based observatories, we now know almost every observable star has a planetary system. With NASA's upcoming Transiting Exoplanet Survey Satellite (TESS), we will be able to refine this view to map out stars in our solar neighborhood that have planets in a habitable zone, perhaps even find some with Earth-sized planets.

If I had sat before you just seven years ago I could not have told you NASA was capable of building the world's largest and most ambitious space telescope, the James Webb Space Telescope (JWST). Today, after staying within budget for the last seven years, even maintaining its cryogenic test program at the Johnson Space Center (JSC) through hurricane Harvey, we now know the complex segmented 21-foot JWST mirror can work in the conditions of deep space. Building the JWST mirror has been an amazing technological accomplishment, and a critical precedent for future space telescopes. Today, because of JWST, we have new mirror technologies that will enable us to build future space telescopes capable of looking deeper and sharper than ever before and, for the first time, of gathering the faint fingerprint of life imprinted on the atmospheres of Earth-like planets around other stars.

Only seven years ago, I could not have told you we would master the complex technologies required to suppress starlight to directly image planets in orbit around their parental stars, and use these coronagraphic technologies on actual working telescopes. Today, because of investments made by the National Science Foundation in the Gemini Observatory telescopes, and by NASA at JPL and elsewhere, we now know coronagraphs work on real telescopes. They are taking real images of nearby solar systems, and studying individual planets with precisions of one part in a million. With JWST we will soon see coronagraphic data of a quality never seen before. And we plan to fly the first truly advanced coronagraph in space on NASA's Wide Field Infrared Survey Telescope (WFIRST) mission, complete with adaptive optics and active wavefront control required to precisely image some of the faintest objects ever observed. This will herald in a new era of high-performance space coronagraphy, giving a further 100 times improvement in our ability to distinguish the faint glow of planets in the presence of their bright host stars. With WFIRST we will be laying the technical foundation for imaging Earth 2.0 around another star.

What is so exciting today is that we have the very real potential to bring these incredible advances together: the latest science discoveries on exoplanets, the technologies of large segmented telescopes, and our ability to fly and operate high-performance coronagraphs in space, with NASA's unique new capabilities to launch a space telescope with the ability to detect signs of life on an exoplanet, nearly 200 trillion miles away!

Imagine a telescope that has the ability to directly image and characterize hundreds of planets outside our solar system – one that can tell us with great certainty whether there are other worlds capable of supporting life as we know it. This is within our reach for the first time in human history. This is where NASA's audacious space science program is leading us, to a telescope that can provide a definitive answer to the question: *Are we alone*?

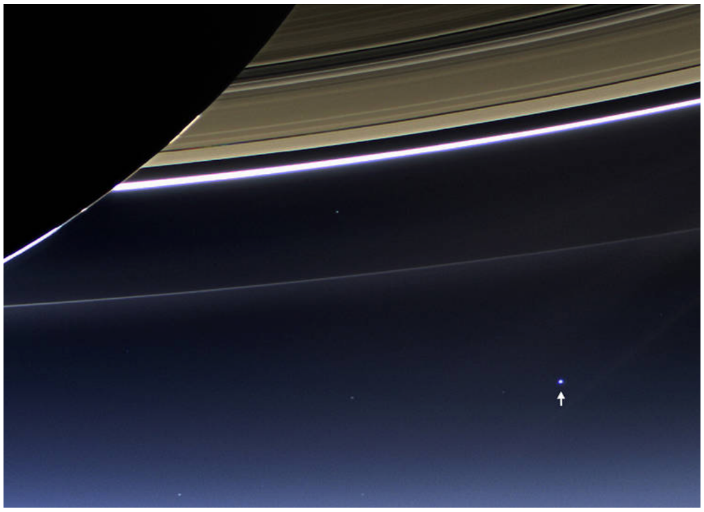


Such a transformative tool is not one of science fiction or even the distant future. NASA, in one of its four studies for future advanced space observatories is looking at a Large Ultraviolet/Optical/Infrared (LUVOIR) Telescope, which with the right commitment, could be ready for launch by the early 2030s. Each of NASA's Great Observatories had a transformational Mission. Hubble's was to understand the age and size of our Universe. JWST is designed to explore our Origins: the origins of Galaxies, of Stars buried in their placental clouds, and the origins of planetary systems like our own. Building on the scientific discoveries and advanced technologies developed for HST, JWST, and, WFIRST, the Mission for this new, Large Ultra-Violet/Optical/Infrared "Great Observatory" would be to complete our long journey, to discover if we are alone in the universe. And, along the way, observe the Universe in unprecedented "high-definition." In the words of Noble Laureate Riccardo Giacconi, for the first time to observationally tackle *"the evolution of the Universe in order to relate causally the physical condition during the Big Bang to the development of RNA and DNA."*

NASA's great observatories have shown us that it is not enough just to wonder – we have to go out and observe; we have to go and explore the Universe with tools only NASA can provide.

Why is such an ambitious telescope, with a mirror almost three times larger than JWST's mirror, required?

First, we have to realize how faint another Earth orbiting a neighborhood star would be.



NASA's Cassini Spacecraft took this image our planet while orbiting Saturn. Already at this distance, some 900 million miles all we see is a small pale blue dot. Now imagine you are looking for this same blue dot, but now from a 222 thousand times further away, a distance of 200 trillion miles, the distance to our nearest stars.

At a distance of over 200 trillion miles (or just over 30 light-years), an earth-like planet, the same color and brightness as our Earth is an incredibly faint object: in fact fainter than the faintest galaxy in the Hubble Deep Field. It will take a large telescope, far larger than the Hubble Space Telescope to collect and analyze the faint photons from another earth. Even with a 15m space telescope we would only get one photon per second from such another Earth: over the course of this testimony such a space telescope two and half times larger than JWST, would only collect 300 extra-terrestrial photons. And unfortunately, at this distance, an Earth 2.0 is incredibly close to its Sun 2.0, as seen from here on Earth 1.0, less than the width of a human hair held at arm's length…..if your arm is two football fields long. Only with something as large as LUVOIR can we have both the photon gathering power **and** the spatial resolution to pull this this observation off.

And then we have to understand, what are we looking for?

With all of these discoveries and with 10^{23} stars in the universe, it would seem statistically very likely that life exists in some of these alien planetary systems. Indeed, in June of last year, *The New York Times* acknowledged this new perspective with an optimistic piece titled, "Yes, There Have Been Aliens."

But not so fast. These optimistic statistics and promising discoveries can't tell us *for sure* that we aren't alone. The only place we *know* life exists is here on Earth. And yes, here on our planet life is tenacious: thriving 20,000 feet down, where strange organisms flourish on deep-sea vents without sunlight or oxygen; and 20,000 feet up, where cacti and insects have found a niche in the Atacama Desert. And yes, it is also resilient, adapting to ponds as corrosive as battery acid and feeding off radioactive waste in Chernobyl. And yet, we don't know how life actually *began* here on Earth. Modern DNA analysis tells us that complex life, anything beyond a single cell organism, resulted from a random "event" in which two cells came together to form eukaryotes (cells with a nucleus) – something that apparently happened only once in the 4.5- billion-year history of our planet. Every worm on a deep-sea vent, or cactus eking out an existence in the high Andes, every human who hunted on the plains or stood on the moon, all owe their existence to a single chance meeting of two cells that learned to get along.

There may be billions of Earth-like planets out there that are abundant with all the elements for life, but that doesn't mean that there is life, let alone *complex* life on any of them. Today we can't calculate how likely Life might be, the only way to determine how unique we are is to go see for ourselves, and this is exactly what NASA now has the capability to do

We know, for example, from experience with the currently hostile environments of Venus and Mars that not all Earth-sized planets orbiting in the habitable zones of their stars are equally hospitable to life. Determining whether an exoplanet is habitable requires careful, and rather detailed analysis of the planet's atmosphere.

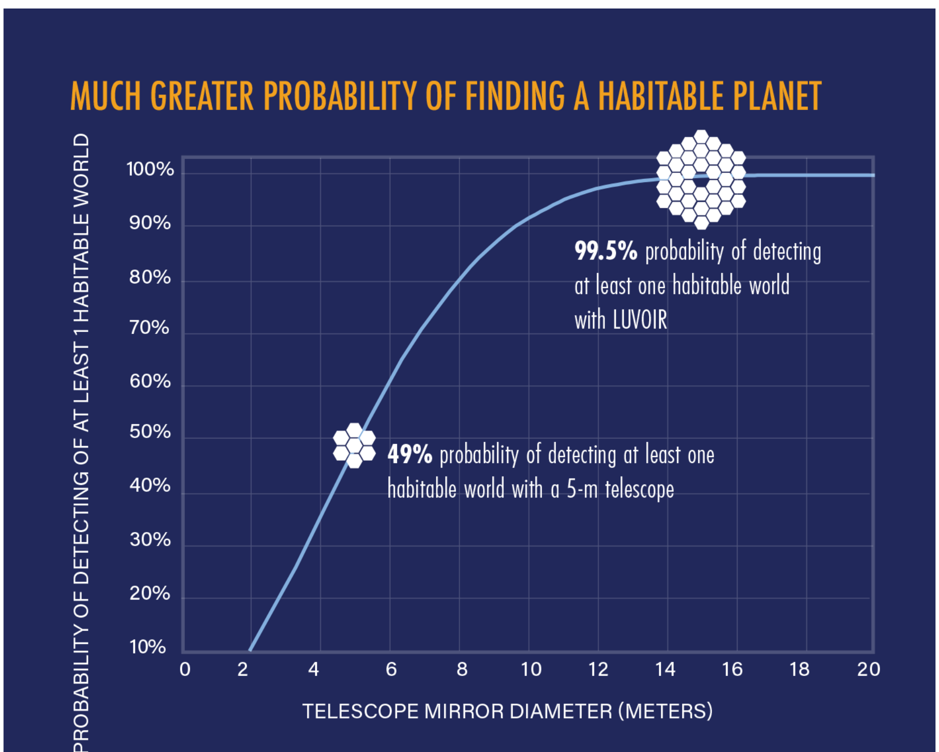
LUVOIR, with its large segmented mirror, powerful light-blocking coronagraph, and precision spectroscopic instrumentation, will be uniquely outfitted to measure and monitor changes in the atmospheric compositions of dozens of Earth-sized exoplanets, revealing the presence—or absence—of molecules like water, carbon dioxide, ozone, and oxygen, which are known to support life on Earth.

This is the first time in human history that we have all the tools to go and see – to find an answer.

But finding one Earth-like planet will not be enough.

When designing a mission to detect life outside our solar system, we must assume that only a small fraction of exoplanets are actually habitable. Detecting life—or ruling it out— with confidence requires sampling hundreds of planetary systems, a feat possible only with a large telescope like LUVOIR.

Examining hundreds of exoplanets allows us to put important constraints on how common life is in the universe. If there are habitable planets orbiting around stars near a Sun, LUVOIR is almost certain to find at least one. If LUVOIR does not detect any signs of habitability, we will know that life, as it exists on our home planet is, as biologists' think, probably extremely rare. This too would be a profound discovery for humanity.

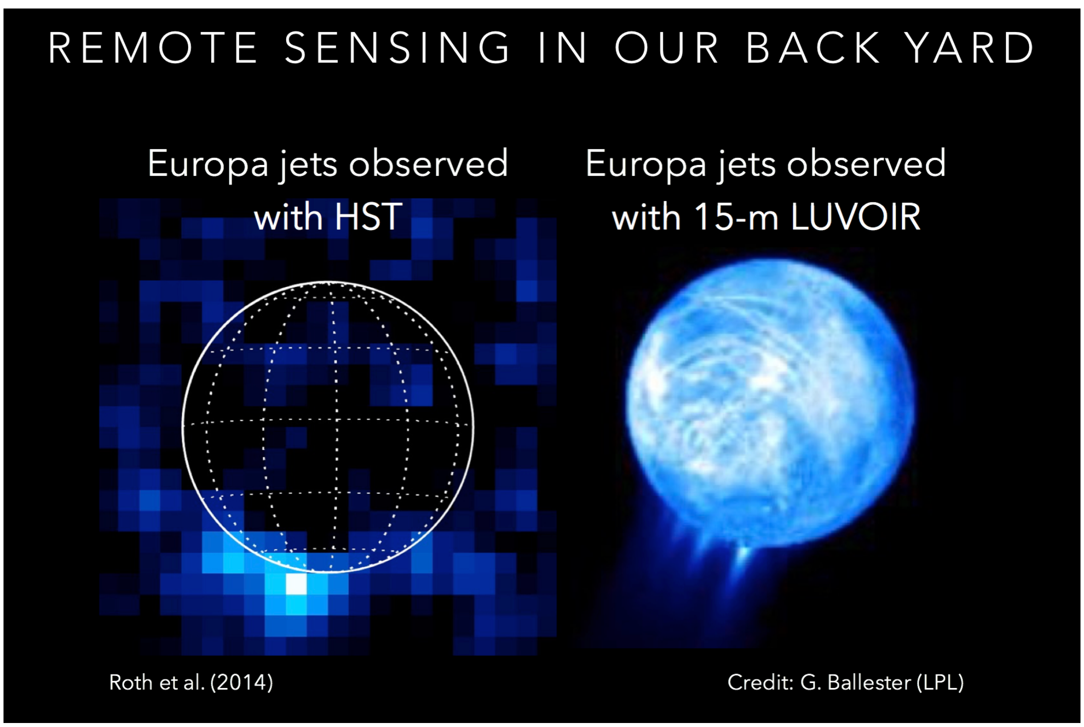


Probability of finding at least one habitable planet, assuming 10% of candidate planets are habitable: The larger the mirror, the more likely we are to detect signs of life outside the solar system.

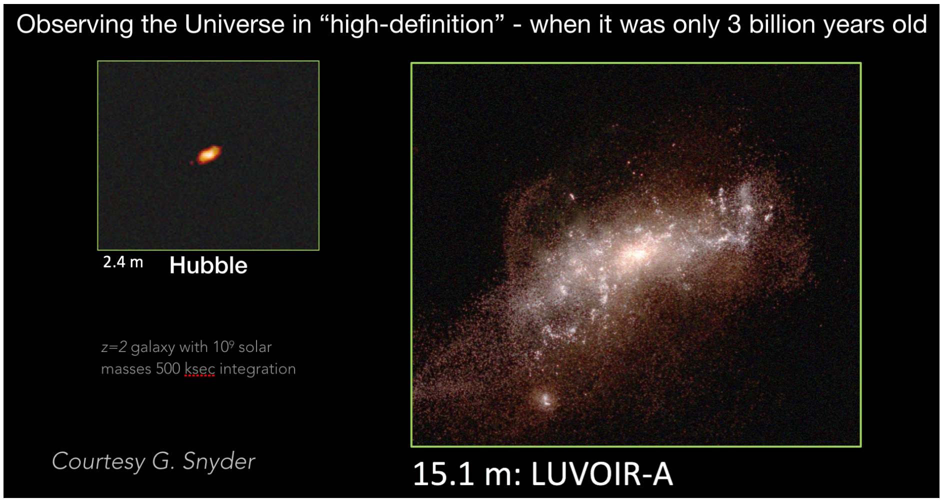
As my colleague Ken Sembach articulated in an article for Space News, titled, "In Searching for Life, Go Big or Stay Home": "*We could build a smaller telescope and hope we detect a handful of potentially Earth-like planets and hope that one is habitable. But hope is not a strategy.*"

A transformative tool for Space Astronomy.

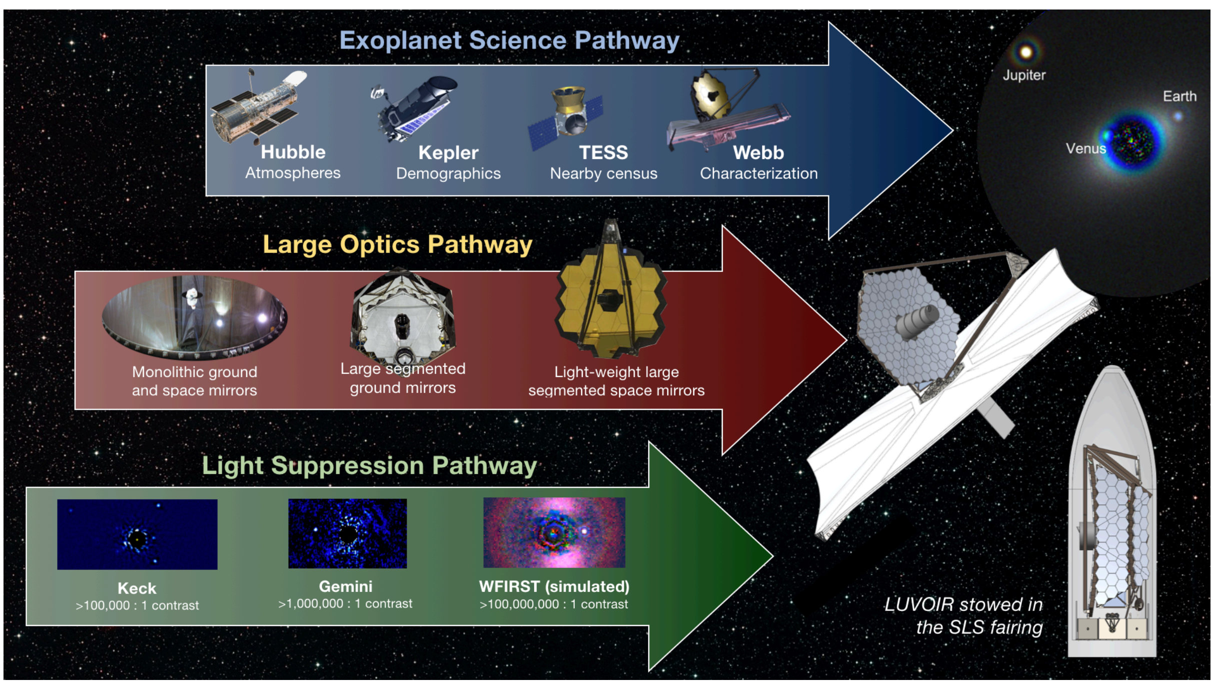
Though the focus of this testimony has been on the future of exo-planet research, quite crucially the LUVOIR mission is envisioned as a Great Observatory in the era beyond Hubble and JWST. At this point on the ground we will have at least one enormous 39m ground-based telescope, maybe even three. With its optical diffraction limited 10m -16m aperture, and unparalleled UV sensitivity, which is possible only from space, a LUVOIR will still outperform even the largest ground based telescopes, retaining US leadership in observational astronomy.



From being able to continuously observe planets within our own solar-system in unprecedented detail, to exploring how galaxies like our own built up over Cosmic time – LUVOIR would be a transformative Great Observatory.



NASA has laid the scientific and technological foundations for this next Great Observatory over the course of its incredible 50-year history of scientific discovery. Without the "jewel" of the Science Mission Directorate in NASA's portfolio, none of the discoveries we have made to date, with mission like Hubble or Kepler, or to be made in our audacious future, would be possible.



The evolutionary path to a 10m - 16m UV/Optical/IR space telescope capable of providing a transformational tool for Astrophyscis, and capable of characterizing sufficient exo-Earths to confirm the null hypothesis: we are alone*

** Requirement from the Kavli IAU Meeting on Global Coordination: Future Space-Based Ultraviolet-Optical-Infrared Telescopes*

How can such an ambitious space telescope be affordable?

"Affordability" begins with concerted technology investments, which of course have already begun with missions like JWST, WFIRST, and investments by some of our aerospace partners. Astronomers are not alone in wanting large optical imaging systems in space. However, it's important not to fall into the tempting trap of assuming the cost of space telescopes scale simply with telescope diameter.

Several factors drive, and have driven, the actual costs of space missions like HST, JWST or even WFIRST.

First, numerous studies have shown that many more factors than the size of the telescope mirror drive the costs of a space telescope. For example, an ananlysis of the cost of JWST and its subsystems (figure below) shows the cryogenic 6.5 mirror diameter mirror (the Optical Telescope Element, or OTE) contributed only 17% of the cost of JWST. The flight systems required for an L2 orbit, and cooling the entire spacecraft to – 400° F and JWST's instrument package (ISIM) together represented over 50% of the total cost.

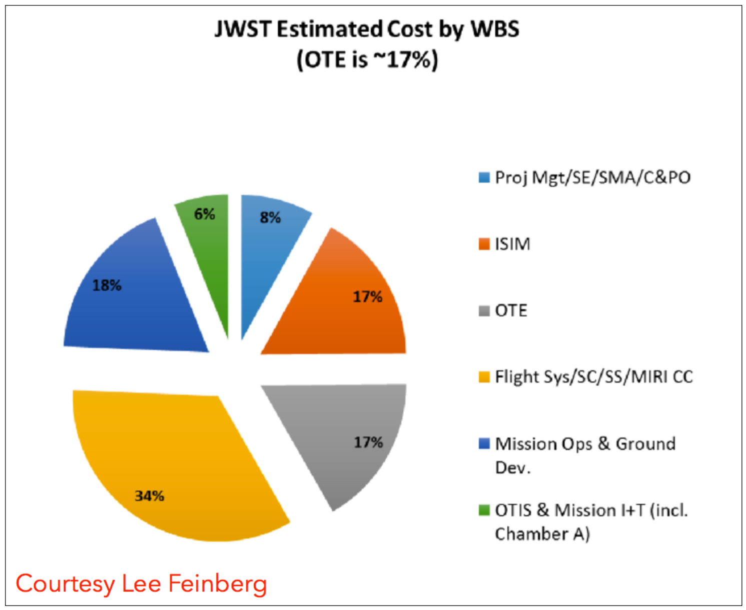


Figure showing the breakdown of NASA's JWST costs by Work Break Down Structure (WBS) element.

The cost of JWST's mirror, described by the Optical Telescope Element (OTE), the accounts for only 17% the cost of JWST.

The Instruments (ISIM) and Flight Systems (Sys/SC/SS/MIRI CC) account for over 50% of the cost of JWST.

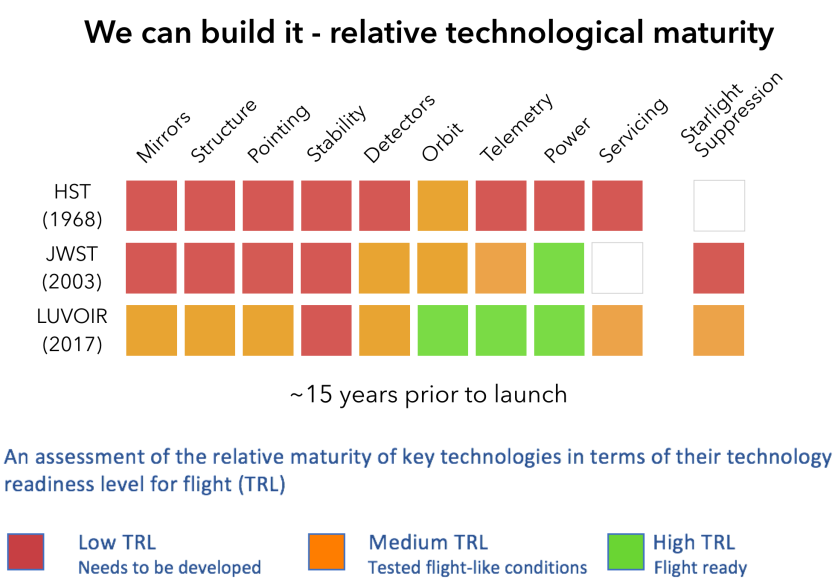
Second, as was the case for JWST whose early funding was artificially constrained in the crucial early years of technology and design development, without an optimal funding profile costs will be increase. Once an optimal funding profile was finally agreed for JWST, it has remained inside its cost-envelope for the last seven years.

A point re-iterated in fact by the WFIRST Independent External Technical/Management/Cost Review (WIETR) that a factor in this missions cost growth was a less-than-optimal funding profile.

Consequently there is no engineering or technology basis for the statement, "building a telescope three times larger than JWST will cost at least three times more than JWST". *This scaling didn't work extrapolating the costs from HST to JWST.*

As my colleague Martin Frederick (from Northrop Grumman) has pointed out, the first step in comparing the cost of missions across the decades is to appreciate the compounding effects of simple inflation. Thirty years ago, in late-1980 dollars (assuming NASA full cost accounting) HST cost NASA approximately $3B. Taking that same mindset ("back in the day, this would have cost $3B"), and simply indexing the HST $3B profile to 2007 dollars, the year JWST was first costed, that same profile would have cost $8.4B. This is comparable to the cost of JWST today, but JWST has a mirror diameter almost three times larger than HST, and will have infrared capabilities 100 times more sensitive than HST.

The key to JWST's tremendous capabilities as compared to HST is that in order to build the cryogenically cooled 6.5m JWST, NASA had to "invent" ten new technologies. For a warm (or non-cryogenic) telescope like LUVOIR, as I have discussed above with JWST and WFIRST as technology demonstrators, NASA is already building up considerable heritage in the key technologies. It is interesting to qualitatively compare the relative maturity of HST, JWST and a potential LUVOIR.



The fundamental point is that the only credible approach to estimating the cost of a mission of the scale of LUVOIR is to invest in the appropriate technologies ahead of time, undertake comprehensive analysis of all the systems required for a telescope to be launched around 2030, and then, ***crucially***, undertake to fund the mission with an optimal funding profile.

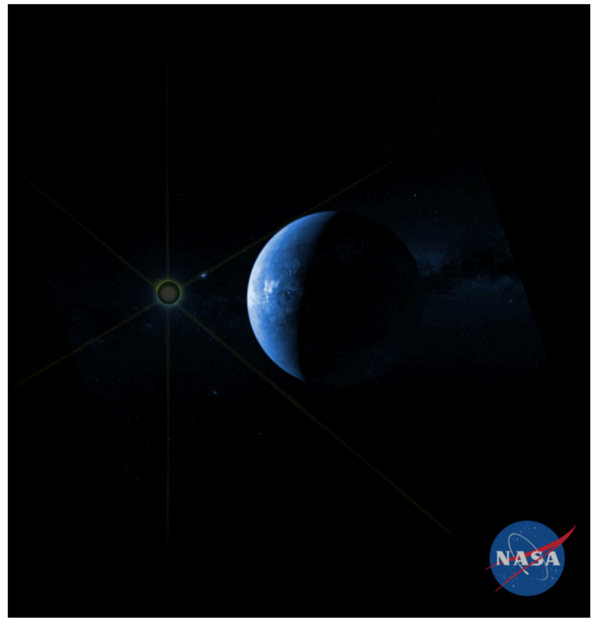
In this time frame, we also have to take into account the capabilities of NASA's Space Launch System (SLS). The SLS has the potential to change the paradigm for ambitious space science missions. For example, the SLS provides the means for launching deployable telescopes three to four times larger than JWST. SLS will be able to lift as much as 130 metric tons of payload to low Earth orbit. This means that more conventional materials could be used in the spacecraft and observatory design. Ultra-lightweight components could be replaced with heavier and more rigid structures. This can greatly simplify design and testing, and significantly reduce the cost of such space telescopes.

The discovery of extra-terrestrial life would have as profound an impact on the twenty-first century as Neil Armstrong's first step on Moon walk had in the twentieth century.

Answering the question" Are we alone in the Universe?" is the space science challenge of the 21st century. And this is a quest only NASA is uniquely capable of undertaking. In 1969, NASA inspired the world with Neil Armstrong's foot print on the Moon. The author Yuval Noah Harari wrote in his best-selling book on the history of our species, Sapiens: *"This was not merely a historical achievement, but an evolutionary and even cosmic feat."*

This year Congress and the administration passed the NASA Authorization Act. In this bill, this sub-Committee and subsequently Congress added a momentous phrase to the agency's mission: **"the search for life's origins, evolution, distribution, and future in the universe."** It's a short phrase, but a visionary one. It acknowledges at this threshold of the 21st century that NASA, and this nation, once again have the opportunity to "change the world."

20th Century NASA



21st Century NASA

Let me end with two images. On the left the iconic view of our world taken on Christmas by the Apollo 8 Astronauts, signaling to the world, the United States was on its way to “a cosmic feat.” On the right is an imaginary image taken with a far future NASA spacecraft visiting another blue planet, Earth 2.0, first discovered with a large LUVOIR-like space telescope launched as a follow-on to JWST and WFIRST.

As Carl Sagan so eloquently said: *“when our far descendants perhaps centuries, even millennia in the future, look back from their new home planets, they will wonder how humble and fragile were our beginnings, how many rivers we had to cross before we found our way.”* Our science points the way to satisfy humanity’s insatiable curiosity; we have the technologies to build and launch telescopes like LUVOIR; now we must determine if we have the will as a nation to take our first, tentative steps to crossing that first interstellar river, to find our way to the first Earth 2.0.

For decades, the United States was an established world leader in space science and the exploration of the Universe. An ambitious but affordable mission to answer the grand question of the cosmos will continue to keep us at the forefront of science and technology for decades to come.

Mr. Chairman, thank you for your support, and that of this Subcommittee. I would be pleased to respond to any questions you or the other members of the Subcommittee may have.