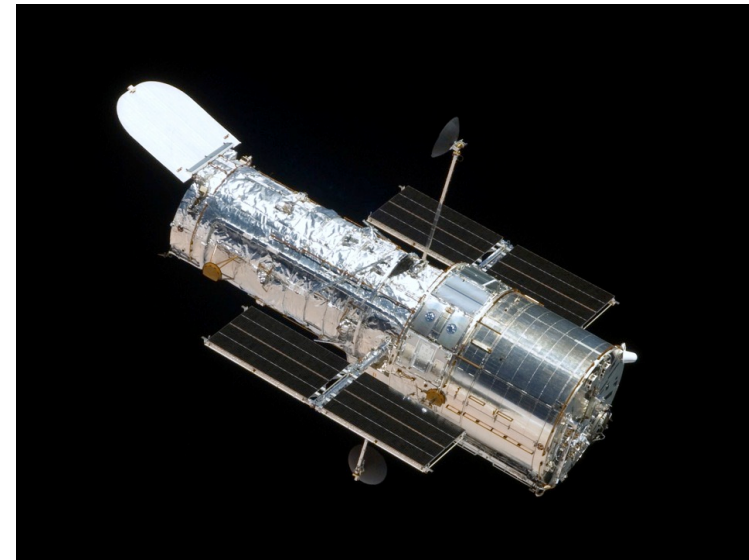


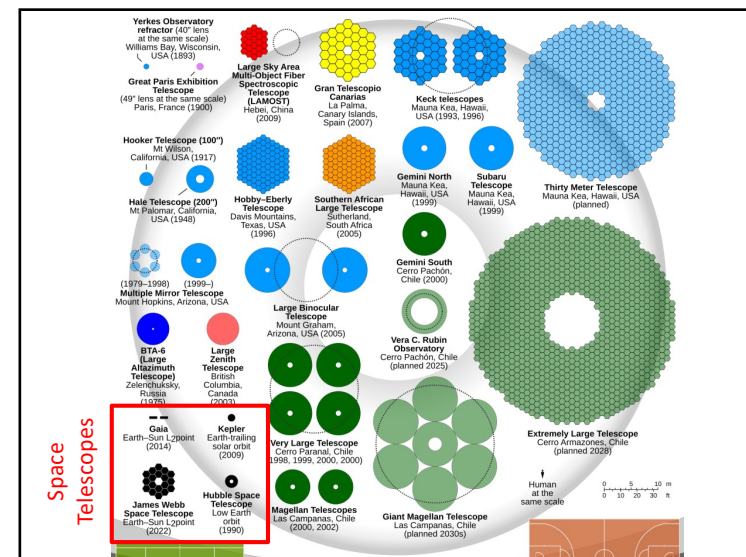
Legacy of the Hubble Space Telescope



Contents	
Introduction	Need for a space telescope Ground-based alternatives
History	Why the mirror was flawed How the optics were fixed
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Future	Need for a space telescope Ground-based alternatives

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Legacy of the Hubble Space Telescope

Introduction



Telescopes have come a long way in the 400 years since Galileo.

Refractors (using lenses) gave way to reflectors (using mirrors) over a century ago as lenses larger than ~1 m in diameter are impractical.



The quest for telescopes with larger mirrors is driven by two mirror characteristics that improve with size. Larger mirrors ...

- ... collect more light → see *fainter* objects
- ... have higher resolution → see *smaller* or more *distant* objects

Introduction

So if we have (large) telescopes on the ground, why put a (small) telescope in Earth orbit?



For the HST, the resolution is more than 10 times better in orbit compared to a similar telescope on the ground.

History

- 1970 NASA started planning for a large space telescope (LST)
- 1974 Congress withdrew all funding
 - National Academy of Sciences lobbied senators
 - National letter-writing campaign
 - Senate agreed to (reduced) funding
 - Funding problems led to collaboration with ESA
- 1978 Congress funded LST project



- Spacecraft construction → Lockheed
- Optical Telescope Assembly → Perkin-Elmer

History

- 1979 Construction of primary mirror begins



- 1981 Polishing of mirror complete
- 1981 Work on back-up mirror (made by Kodak) halted

Legacy of the Hubble Space Telescope

History

- 1983 Originally planned launch date
LST named the Hubble Space Telescope (HST)



- 1984 Launch date put back due to Perkin-Elmer schedule slips
- 1985 Launch date put back due to Perkin-Elmer and Lockheed slips
- 1986 Budget exceeds \$1 billion and still rising
- 1986 Challenger disaster
- 1990 HST finally launched into Earth orbit

Total construction costs
estimated to be ~\$2.5 billion



Design

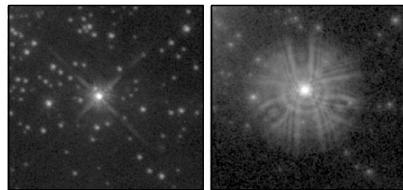
The HST is a Ritchey-Chrétien design – the primary mirror is **hyperbolic**.

The last big telescope to have a **parabolic** mirror is the Hale Telescope on Palomar Mountain which has a 5 m (200") mirror.



The Mirror

Only when in orbit did the horror slowly dawn on those responsible for commissioning the telescope. **It would not focus.**

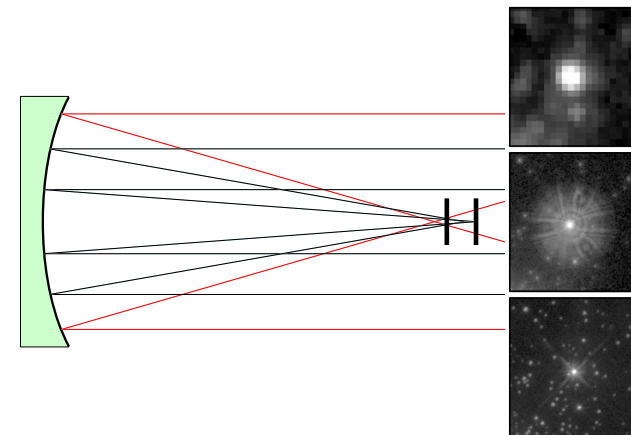


Expected

Observed

Eventually it was admitted that mirror has spherical aberration.

Spherical Aberration

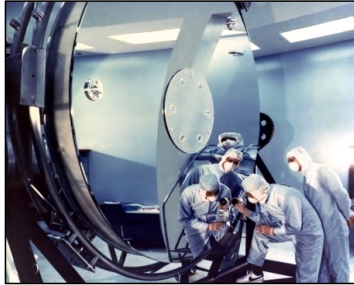


Legacy of the Hubble Space Telescope

The Mirror

How could such a mistake be made?

Tests carried out during construction indicated that it was the most precisely figured mirror ever made – a surface roughness of ~ 10 nm.



For some perspective on that value, that's equivalent to a roughness of ~ 30 mm on an object the size of the Earth!

Unfortunately, the mirror was not the correct *shape*.

It was wrong by $\sim 2 \mu\text{m}$.

The Mirror

Because the mirror is hyperbolic, it requires a 'null corrector' to be used as part of the optics used in the test rig.

A lens in the null corrector was misplaced in the Perkin-Elmer test rig because a washer was placed on a bolt where it should not have been.

A simpler test would have revealed the fault but was deemed 'unnecessary' by Perkin-Elmer.

The backup mirror was made, and tested, independently by Kodak and so did not suffer from the same error. However, it was on the ground!



Saving Hubble

One thing saved the HST from a scientific and public relations disaster – it was designed from the outset to be serviced by shuttle astronauts.

Many alternatives were considered, even the option of bringing it back in the shuttle and replacing the primary mirror with the Kodak backup.

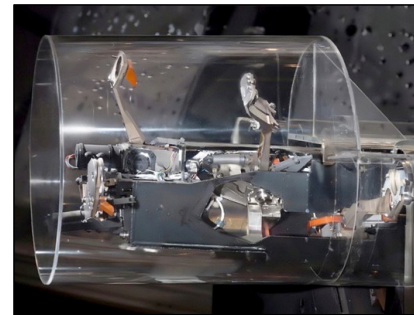
The final solution was a combination of luck and ingenuity.

A second camera (WFC2) was an identical 'non-flight' copy of the one in the HST and was sitting in the Jet Propulsion Laboratory. It would be fitted with corrective optics and sent up to replace the original WFC1.



Saving Hubble

For all the other instruments, a complex set of corrective optics (COSTAR) would be inserted into one of the instrument bays by sacrificing one of the instruments.

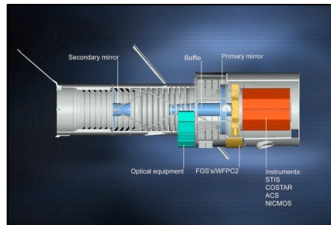


Legacy of the Hubble Space Telescope

Instrumentation

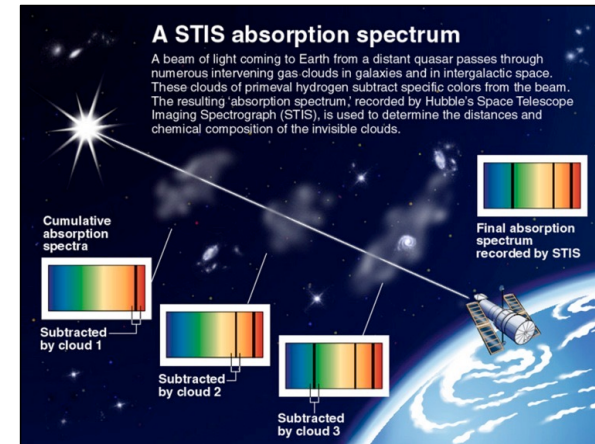
It should be remembered that the HST is not simply a telescope with a CCD camera bolted on the back end.

At any given time the HST has had at least **two** cameras and **two** spectrographs on board – these have been swapped out and upgraded during the various service missions spread over 16 years.



The cameras are labelled 'wide-angle' or 'high-resolution' depending on the effective focal length at which they are used (HST nominal FL ~58m).

Spectroscopy



HST Service Missions

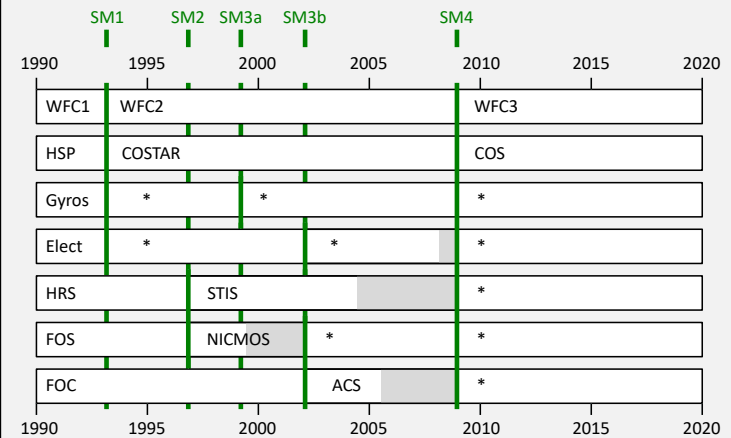
The five service missions have resulted in a confusing number of swaps and upgrades of the instrumentation, and the power (solar panels) and guidance (gyro) systems have also had major upgrades and servicing.

The need for power may be obvious, but remember that without a set of gyros, the HST would not be able to point at its target with an accuracy of *milli* arc seconds and so the advantages of the HST over ground-based telescopes would be compromised. Ultimately, the gyros may be the components that determine how long the HST continues to function.

The five service missions comprised 23 spacewalks totalling 166 hours.



HST Service Missions



Legacy of the Hubble Space Telescope

Instrumentation

Prior to Service Mission 1 the HST was still able to carry out some observations, including imaging of bright objects or spectroscopy, neither of which were affected too badly by the flawed focussing.

However, it wasn't until after the successful installation of WFC2 and COSTAR during SM1 that the HST was ready to deliver on the promises first made twenty years earlier.

Disaster was averted and NASA gave a corporate sigh of relief.

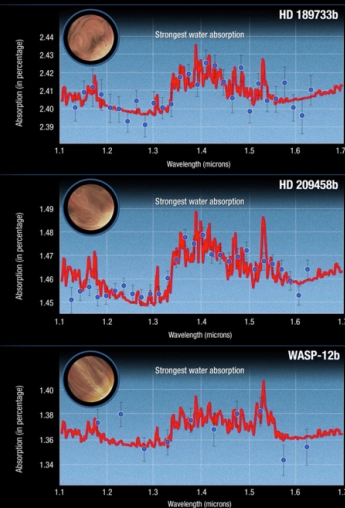
So much for history. What about the legacy?

Legacy

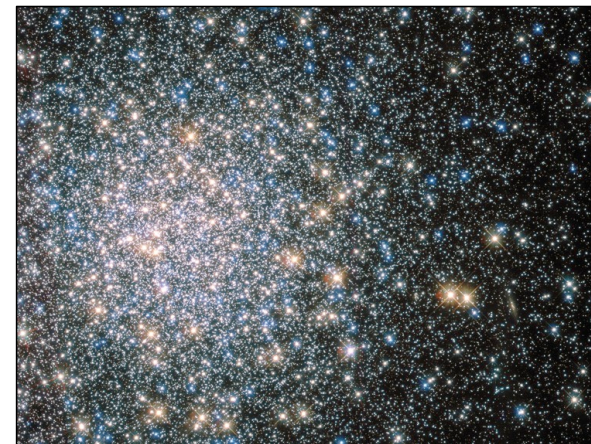
How has the HST contributed to extending our understanding of the structure and evolution of the Universe?

Examples are legion, but here I select just a few...

Hubble measures water abundance on three exoplanets



Stellar Evolution



Legacy of the Hubble Space Telescope

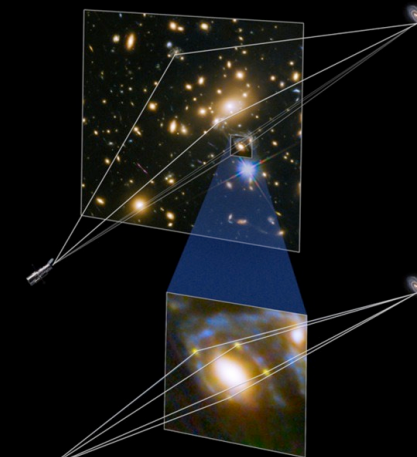
Galaxy Formation



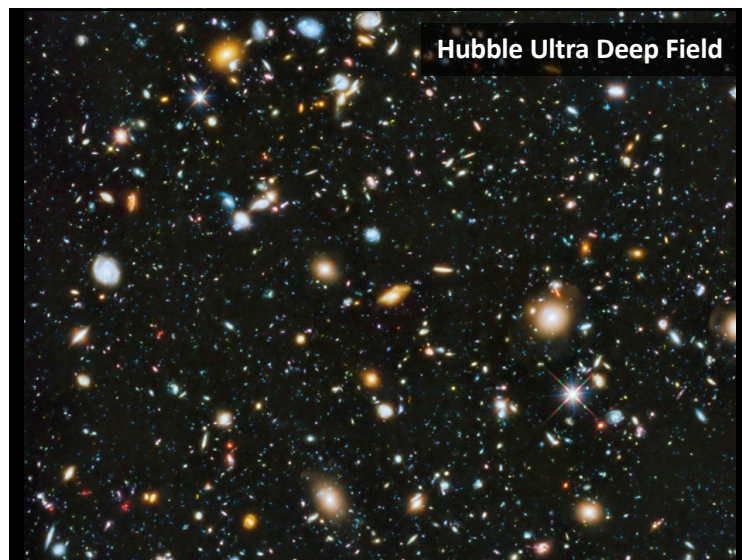
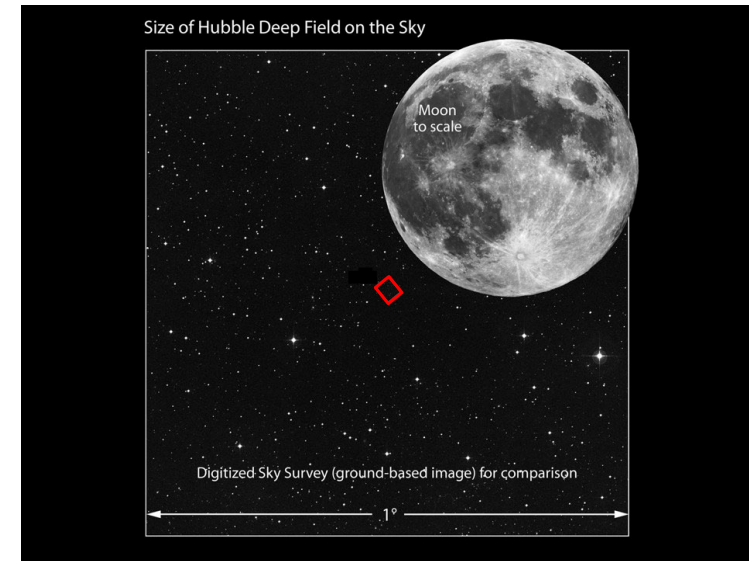
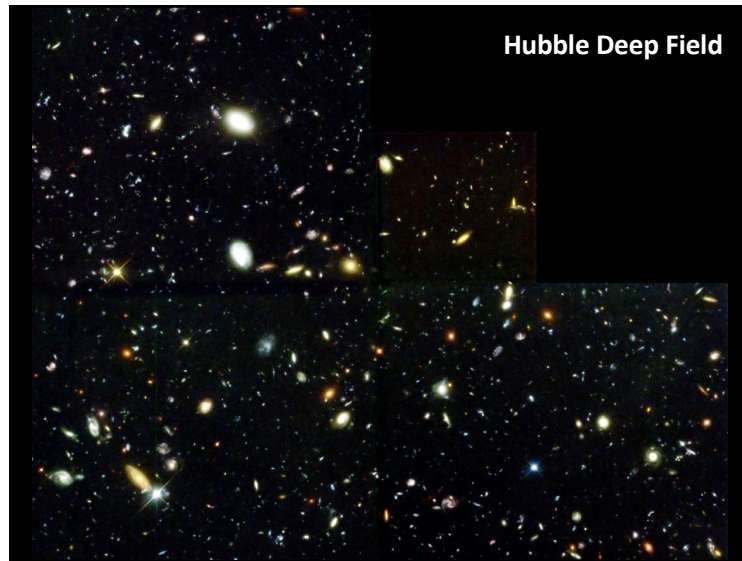
Galaxy Formation



Hubble Sees Distant Supernova
Multiply Imaged by Foreground Galaxy Cluster



Legacy of the Hubble Space Telescope



Legacy

In addition to its scientific legacy, the HST has managed to do what most scientific instruments have failed to do — it has touched the public consciousness.

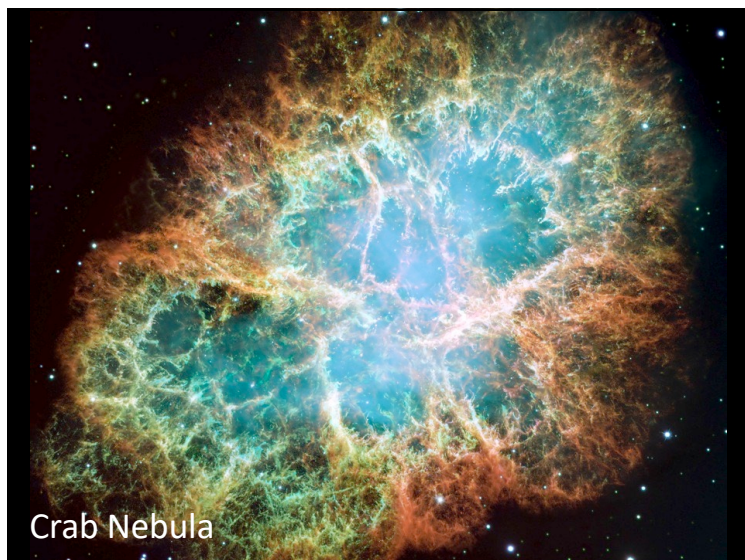
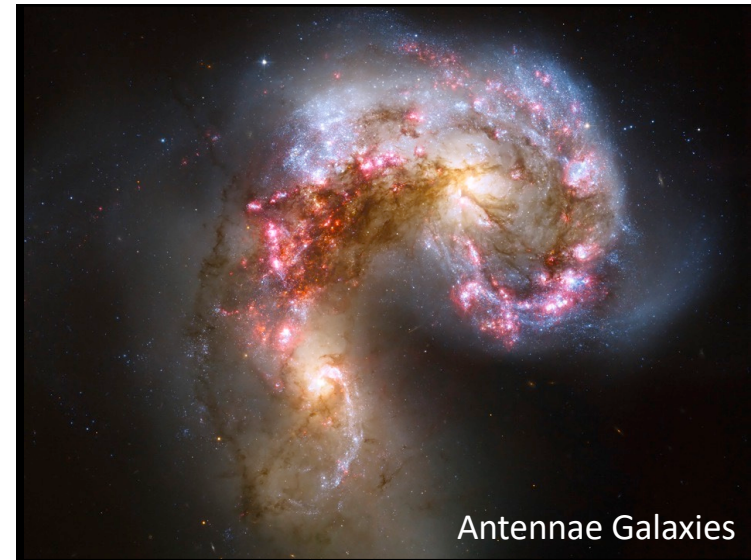
"The laws of physics have created these incredible structures, and Hubble has revealed them."

"Through all the research, Hubble has brought the public along for the ride. It has taken the excitement that scientists feel with new discoveries and brought it to non-scientists."

Astronomy (April 2015)

Let us take a few minutes to remind ourselves with just a few of the breath-taking images that the HST has produced ...

Legacy of the Hubble Space Telescope



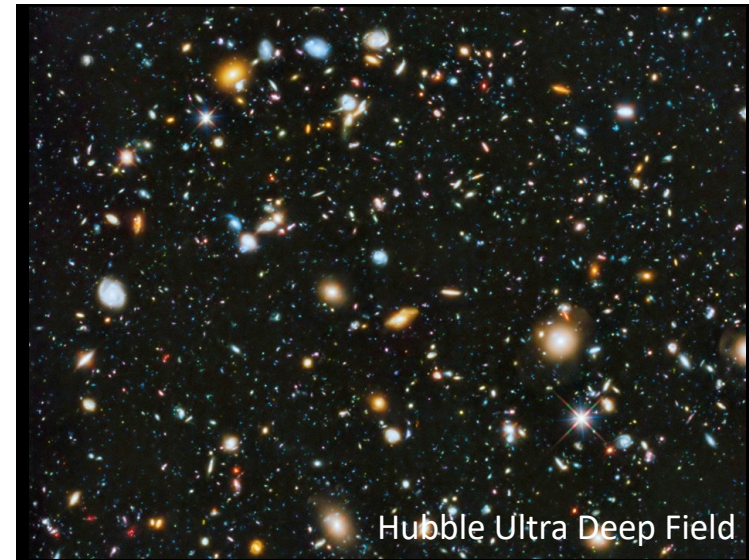
Legacy of the Hubble Space Telescope



Legacy of the Hubble Space Telescope



Legacy of the Hubble Space Telescope



Beyond Hubble

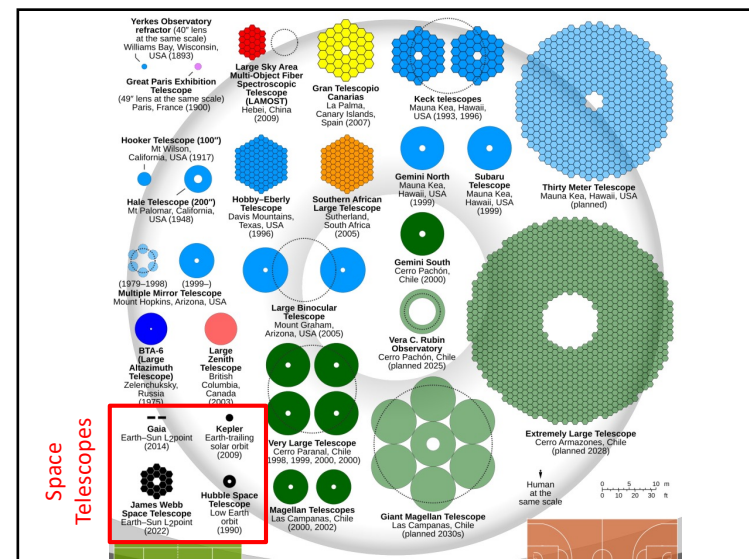
So what lies beyond Hubble?



Ground-based telescopes now have adaptive optics that can compensate for the Earth's turbulent atmosphere, so is there a need any more for space telescopes?

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Legacy of the Hubble Space Telescope

Beyond Hubble

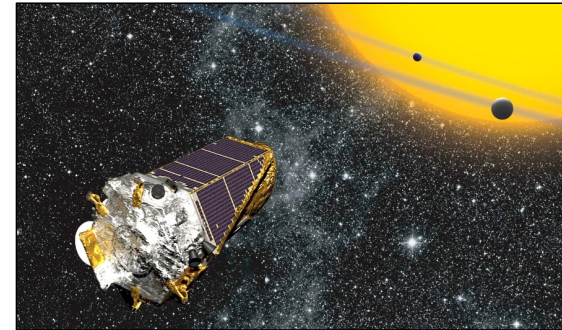
Even with adaptive optics, ground-based telescopes can only achieve high resolution over a limited field of view.

Space telescopes can achieve their specified resolution over the entire field of view covered by their detectors (the CCD chips).

Other, perhaps less well-known, space telescopes ...

Kepler

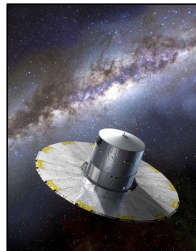
Kepler had a very specific mission ...



... to find earth-like planets orbiting other stars.

Gaia

Gaia was an ESA mission with a number of very ambitious aims:



- To measure the positions of ~ 1 *billion* stars
- To measure to an accuracy down to ~ 10 *micro* arc seconds
- To perform spectral and photometric measurements
- To derive star velocities in the Milky Way
- To use this data to create a 3D structural map of the Milky Way

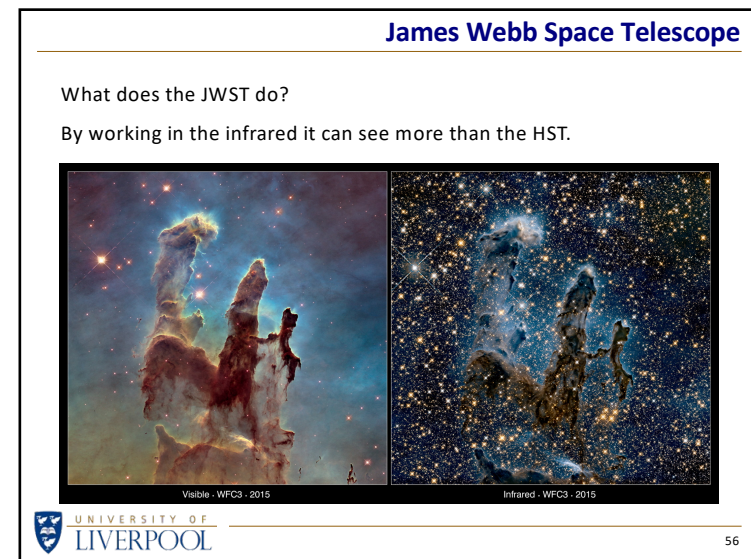
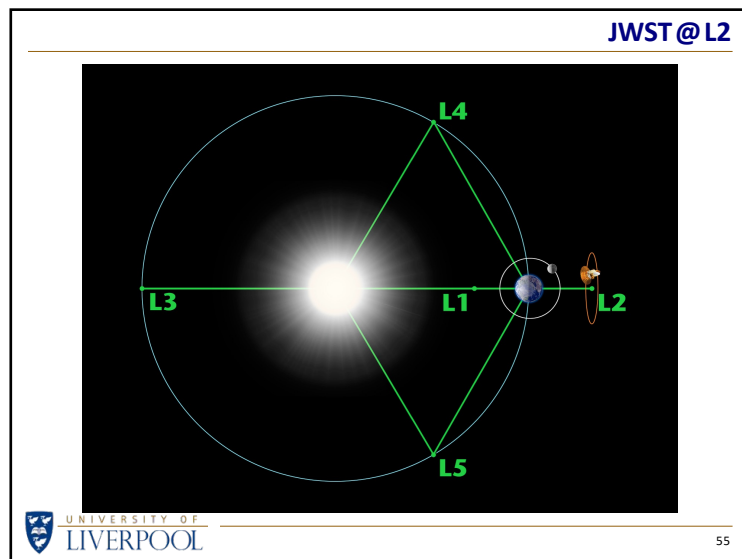
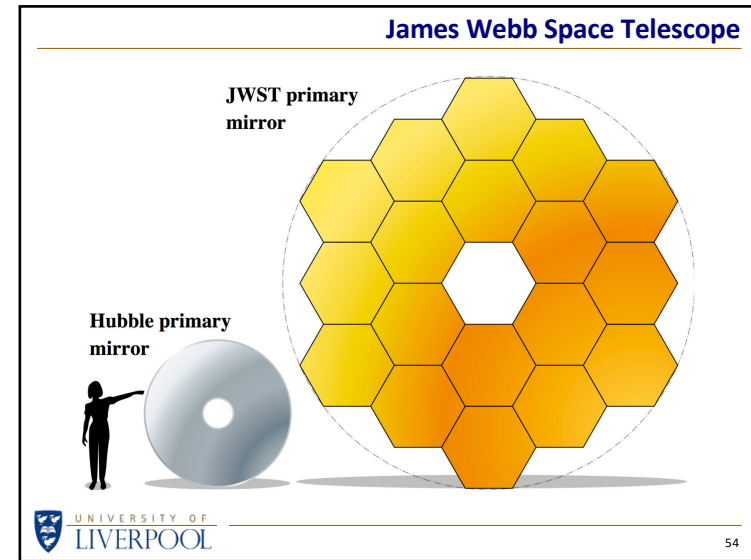
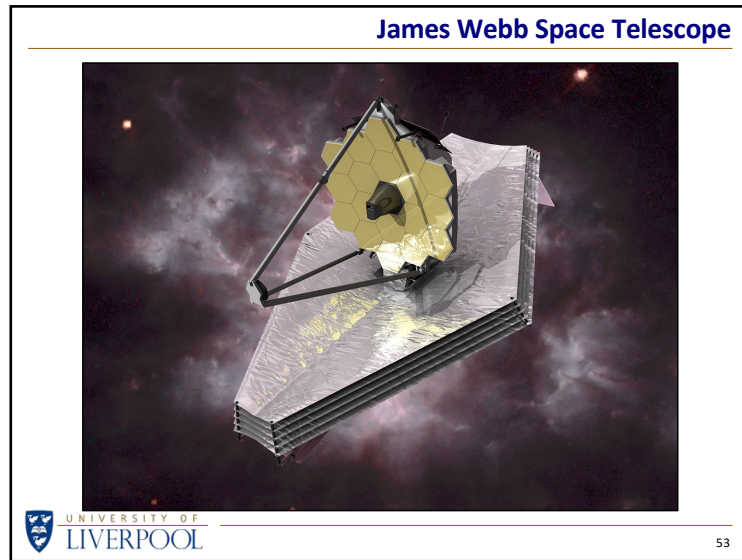
Beyond Hubble

Reflecting on the Hubble Space Telescope ...



What are its successors?

Legacy of the Hubble Space Telescope

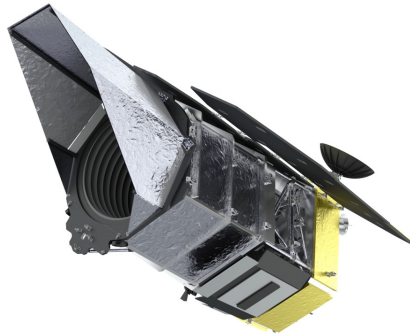


Legacy of the Hubble Space Telescope

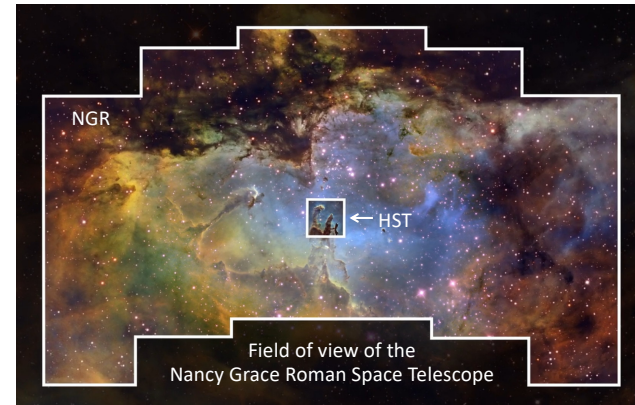
Nancy Grace Roman Space Telescope

Launched in Aug 2026, the NGRST will also work in the infrared.

It will survey billions of distant galaxies to gain a better understanding of dark energy.



Nancy Grace Roman Space Telescope



Summary

Introduction	Need for a space telescope Ground-based alternatives
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Legacy	Extending our understanding Touching the public consciousness
Future	Need for a space telescope Ground-based alternatives

Legacy of the Hubble Space Telescope

www.liverpool.ac.uk/~sdb/Talks

Dr Steve Barrett

RCC 25 Sep 2026