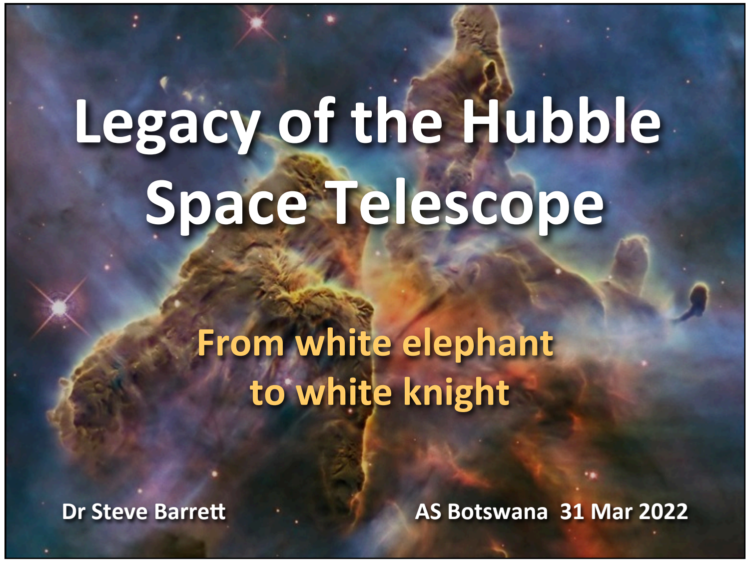

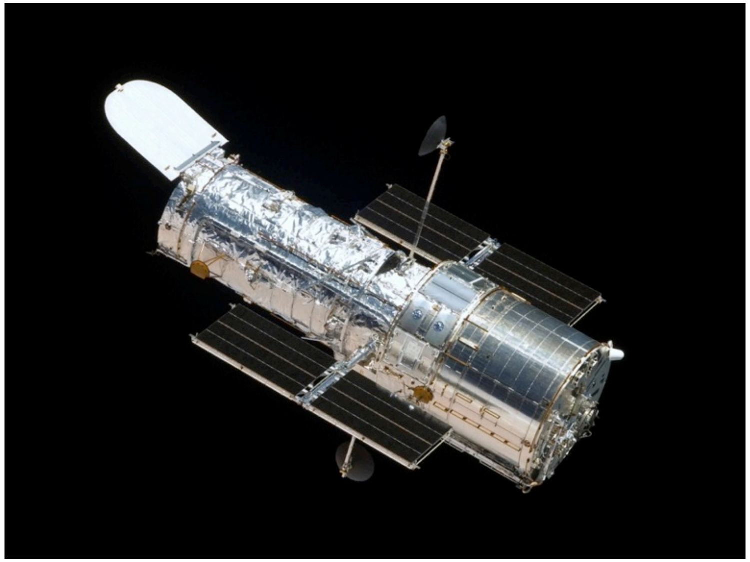

Contents

Introduction — Need for a space telescope; Ground-based alternatives

History — Why the mirror was flawed; How the optics were fixed

Legacy — Extending our understanding; Touching the public consciousness

Future — Need for a space telescope; Ground-based alternatives

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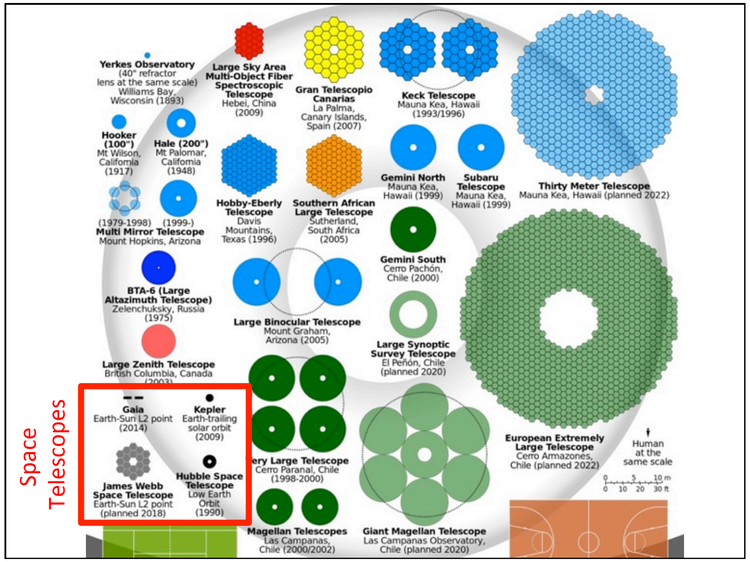
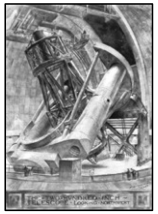
3



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.



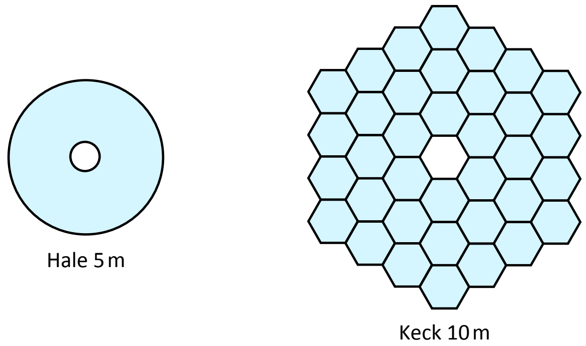
The quest for telescopes with larger mirrors is driven by two mirror characteristics that improve with size. Larger mirrors …

… collect more light ➔ see ***fainter*** objects

… have higher resolution ➔ see ***smaller*** or more ***distant*** objects

Introduction

In the latter part of the last century large telescopes have used multi-segment mirrors due to the difficulty of making monolithic mirrors over ~8 m in diameter.



Introduction

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

Larger mirrors do indeed collect more light than smaller ones but their higher resolution is compromised by the turbulence of the Earth's atmosphere.

Putting a telescope in Earth orbit, above the atmosphere, means that the telescope's resolution can be exploited to the full.

For the HST, the resolution is more than 10 times better. The 2.4 m diameter mirror in the HST was a result of the restriction that the entire telescope had to fit inside the cargo bay of the space shuttle.

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

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

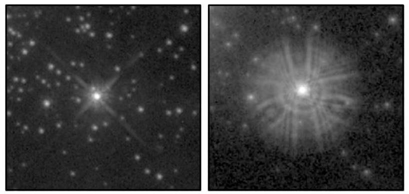
Design

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 at Mount Palomar which has a 5 m (200") mirror.

The Mirror

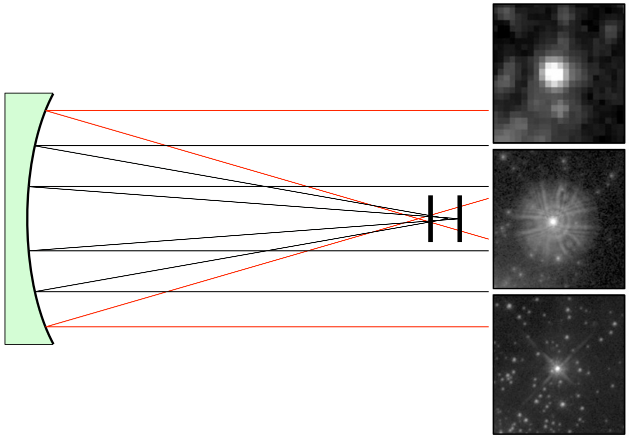
Only when in orbit did the horror slowly dawn on those responsible for commissioning the telescope. ***It would not focus***.



Expected Observed

Eventually it was admitted that mirror has spherical aberration.

Spherical Aberration



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 ~2 µm.

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.

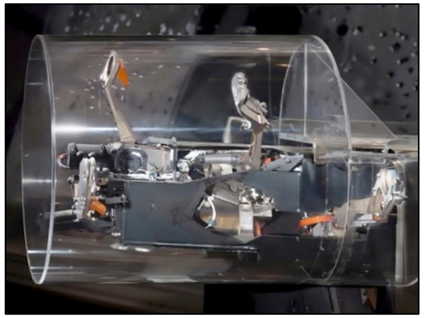
Many alternatives were considered, even the option of bringing it back in the shuttle and replacing the primary mirror with the Kodak backup.

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

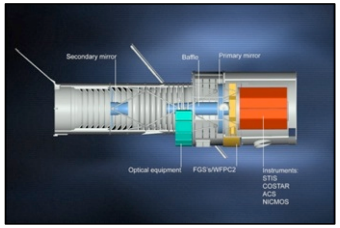
For all the other instruments, a complex set of corrective optics (COSTAR) would be inserted into one of the instrument bays by sacrificing one of the instruments.



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.



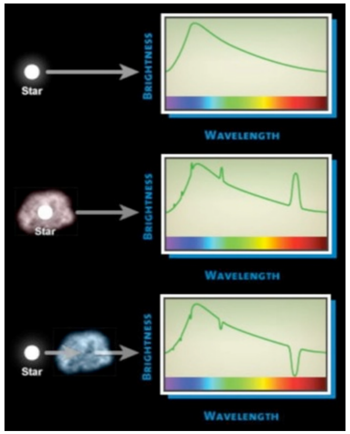
The cameras are labelled 'wide-angle' or 'high-resolution' depending on the effective focal length at which they are used (HST nominal FL ~ 58 m).

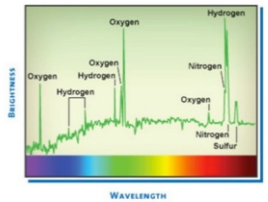
Spectroscopy

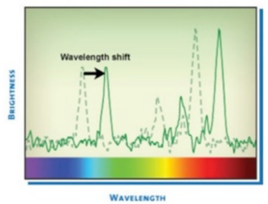
The cameras have of course been responsible for all of the incredible images that the HST has produced.

However, the spectroscopy instrumentation has been just as important from a scientific viewpoint, providing data that has augmented the image data and aided the interpretation of the images.

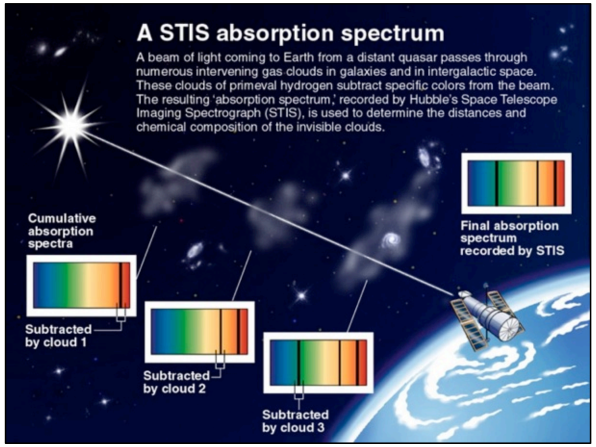
Spectroscopy







Spectroscopy



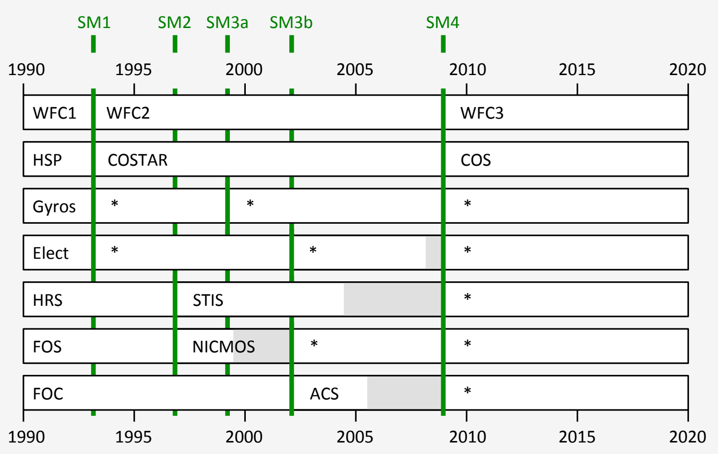
HST Service Missions

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



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 in the fields of:

- Cepheid distances
- Exoplanets
- Star birth and star death
- Galaxy formation and evolution
- Supernovae and the age of the universe

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Cepheids

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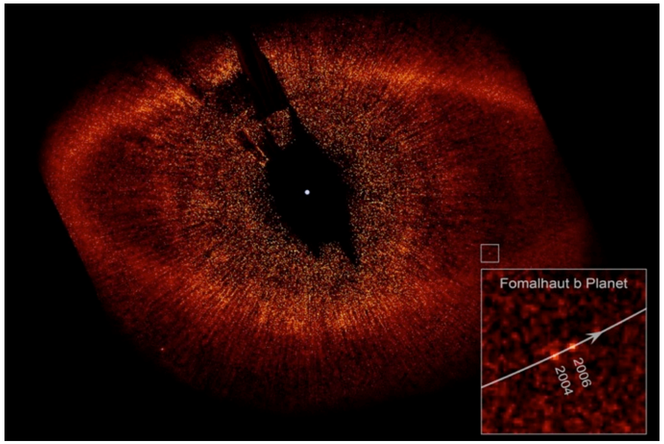
Exoplanets



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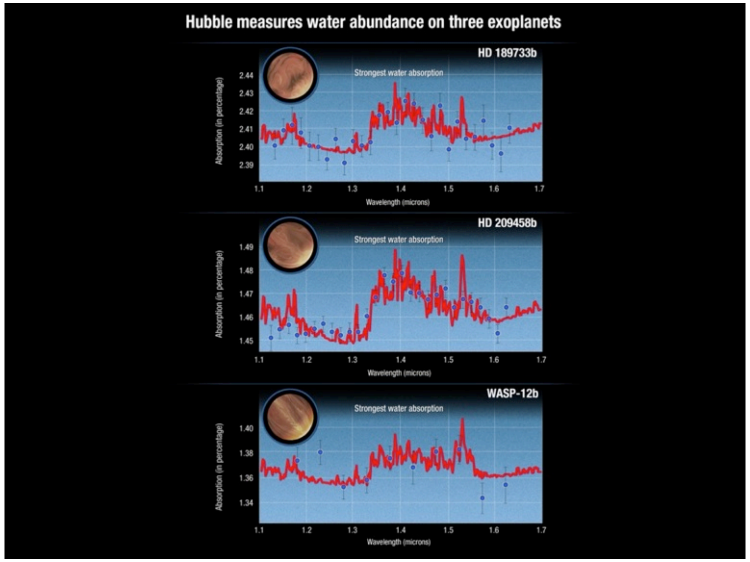
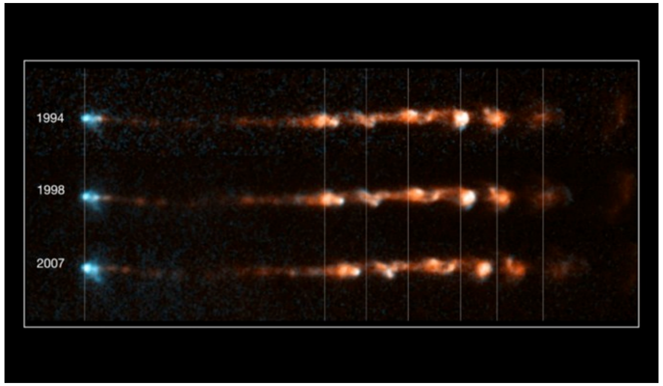


Stellar Evolution

29

Stellar Evolution



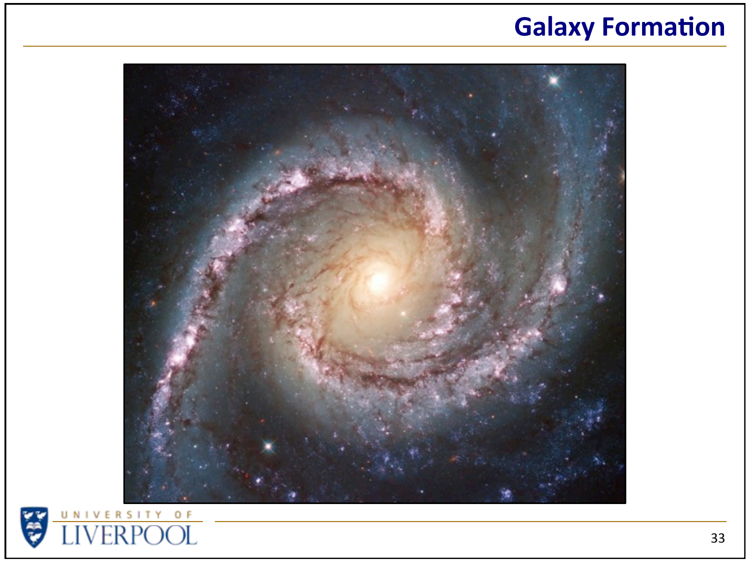
30

Stellar Evolution

31

Galaxy Formation

32


Galaxy Formation
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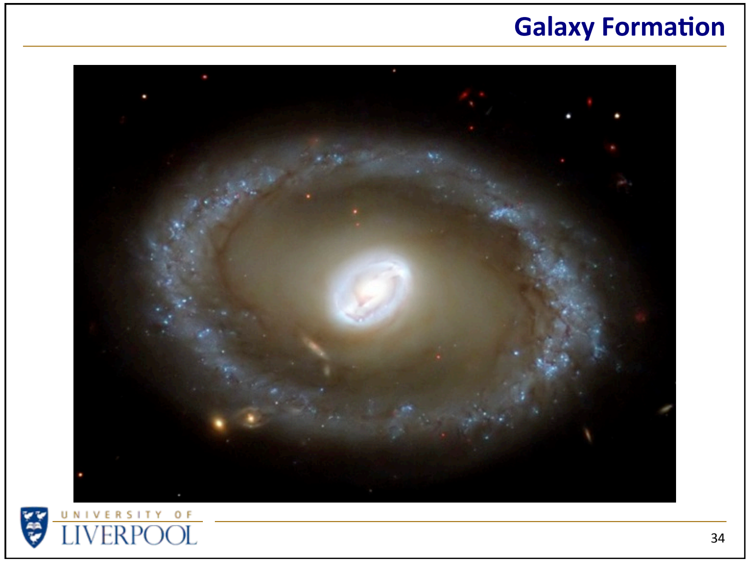
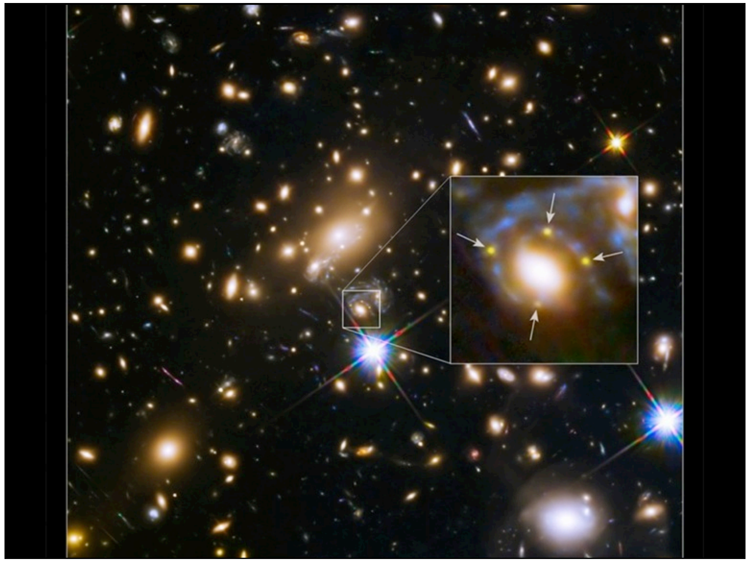
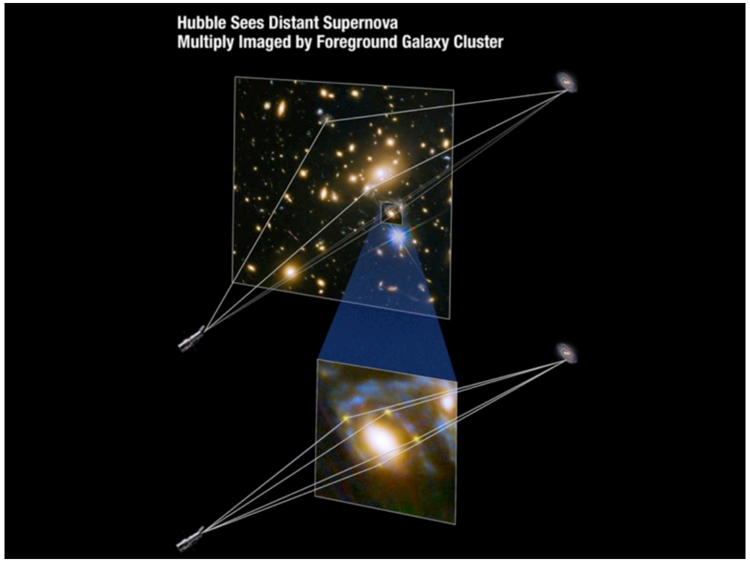
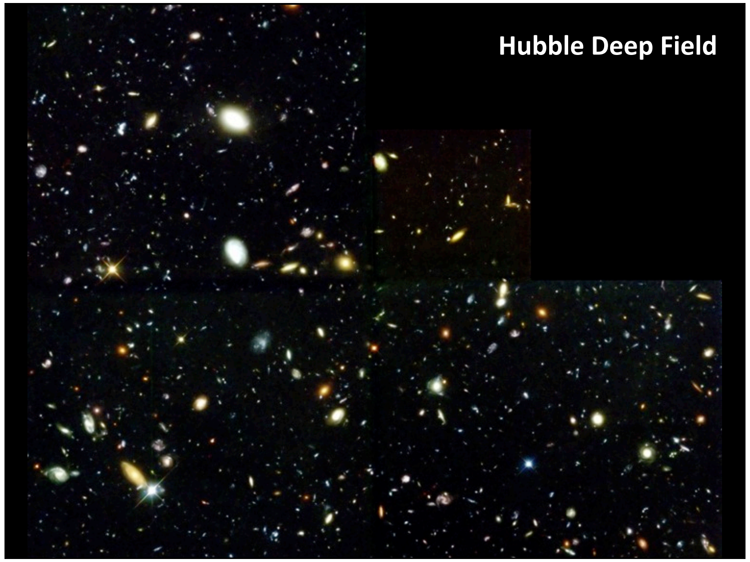
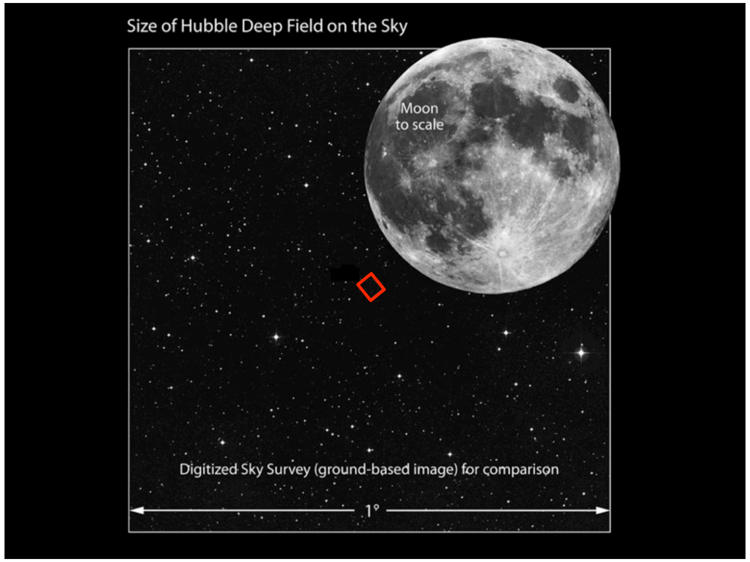
33

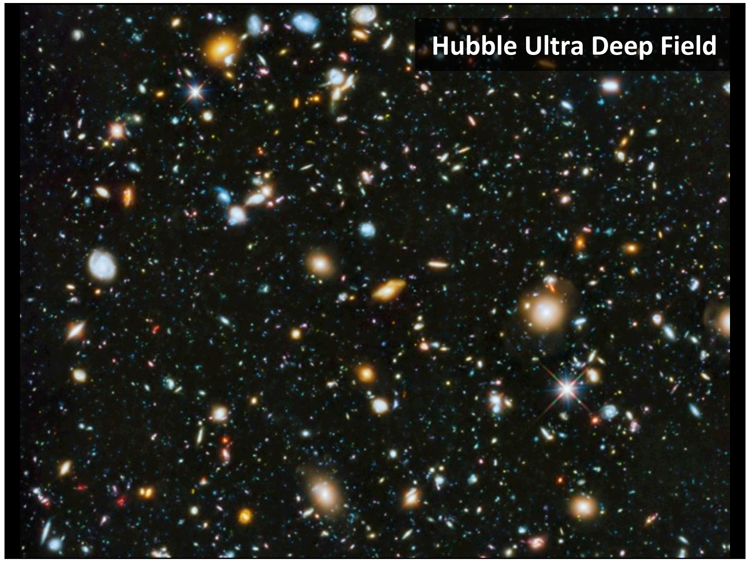

Galaxy Formation
UNIVERSITY OF
LIVERPOOL
34




Hubble Sees Distant Supernova
Multiply Imaged by Foreground Galaxy Cluster







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 …

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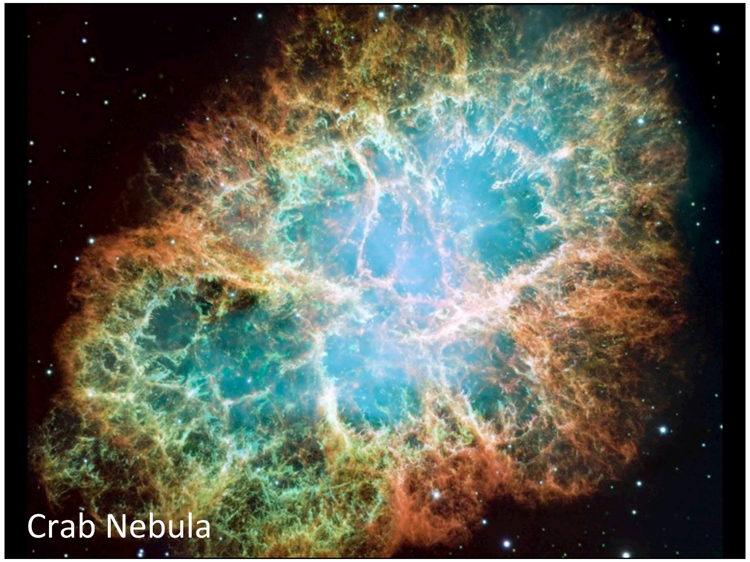
Legacy of the Hubble Space Telescope



Legacy of the Hubble Space Telescope

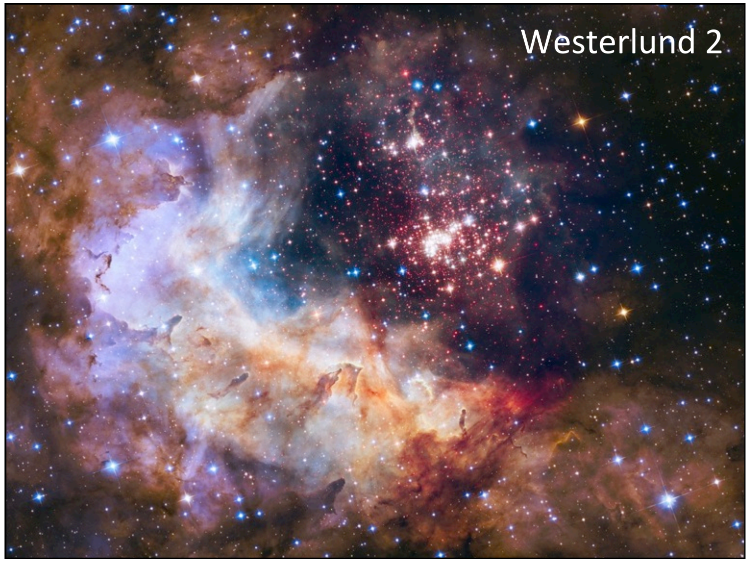

Mystic Mountain

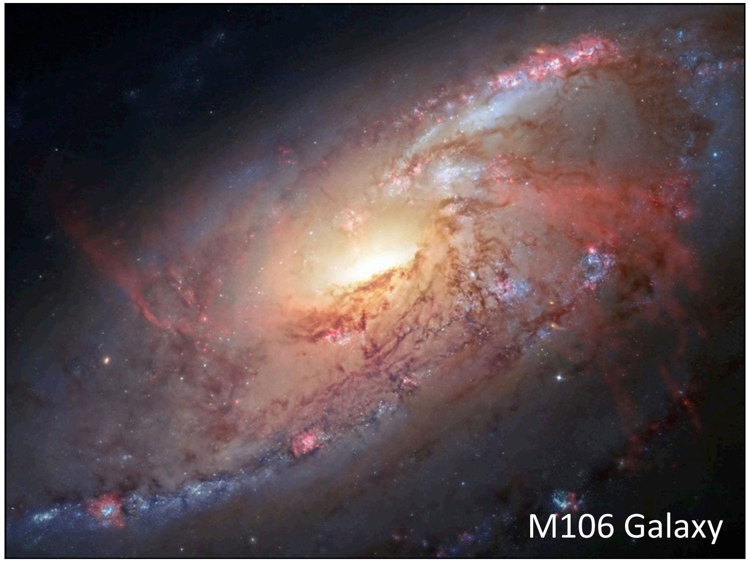

Sombrero Galaxy

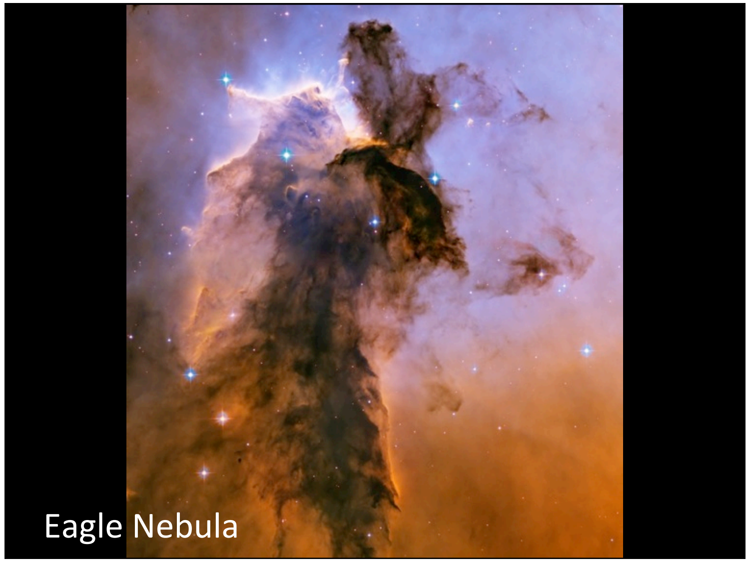

M5 Globular Cluster

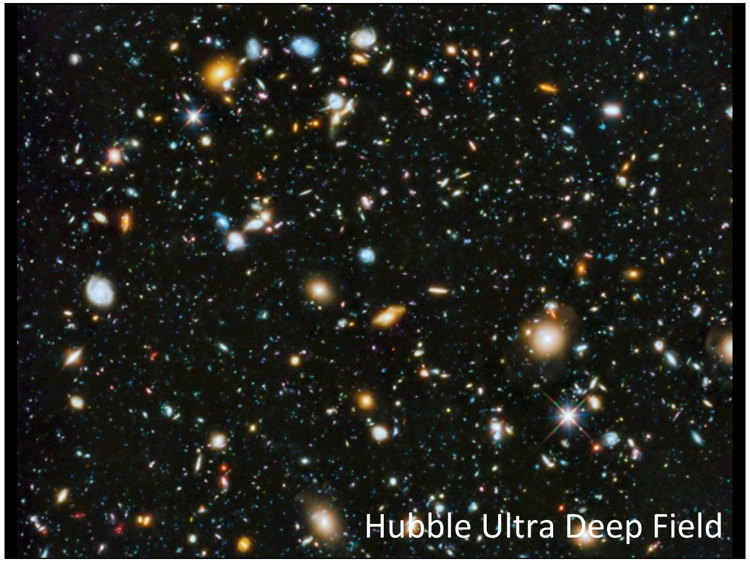

Barred Spiral Galaxy

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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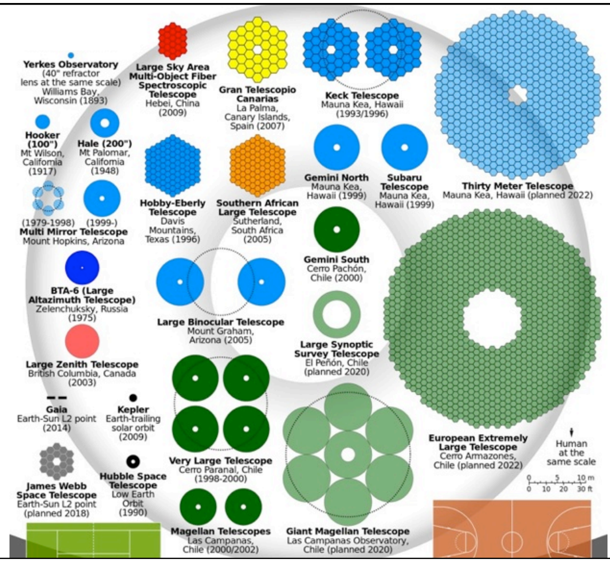
55

Space Telescopes



Beyond Hubble

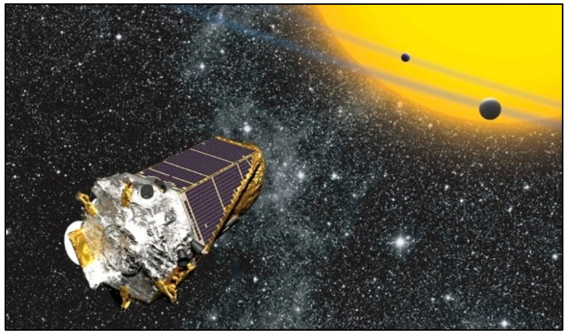
Even with adaptive optics, ground-based telescopes can only achieve high resolution over a limited field of view.

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, telescopes are already in orbit.

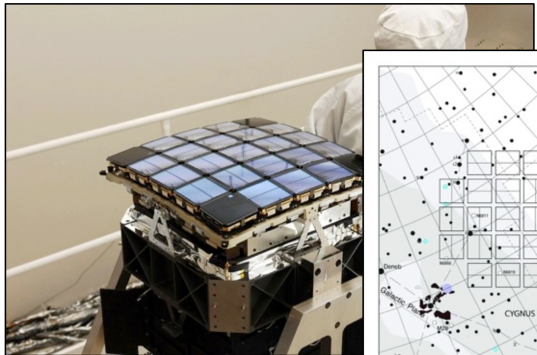
Kepler

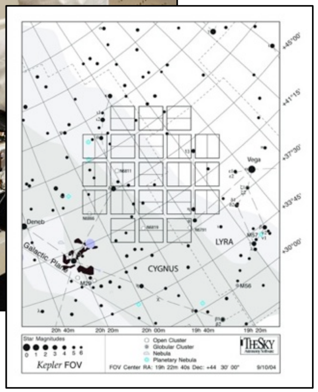
Kepler had a very specific mission …



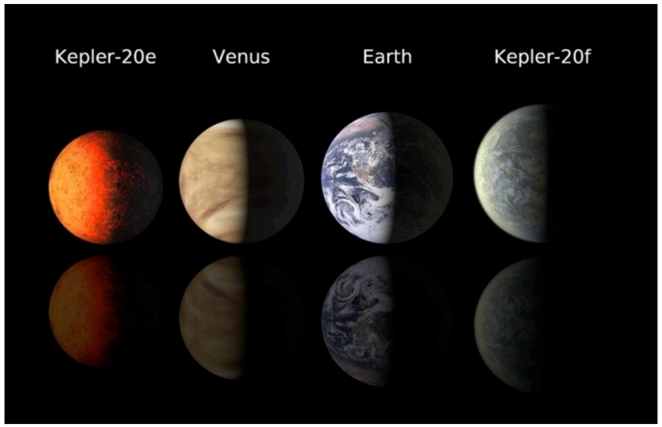
… to find earth-like planets orbiting other stars.

Kepler



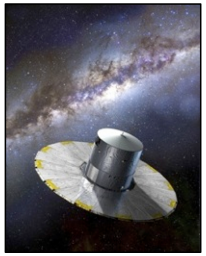


Kepler



Gaia

Gaia is 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 ~ 25 *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

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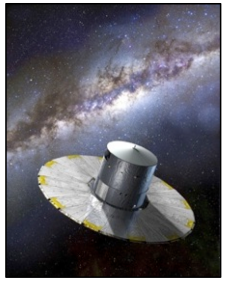
Gaia

In addition, almost as a 'by-product' of its attempt to determine the positions of stars to incredible precision, Gaia will also:

- Detect and classify thousands of extra-solar planetary systems
- Survey the huge numbers of minor bodies in our Solar System
- Survey neighbouring galaxies
- Survey distant quasars (quasi-stellar objects)



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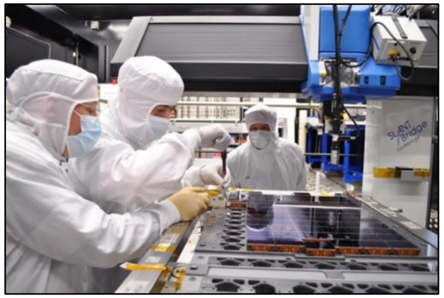
Gaia

How does Gaia achieve such precision with, like the HST, mirrors of a very modest size?

The answer lies with its gigapixel CCD detector array.



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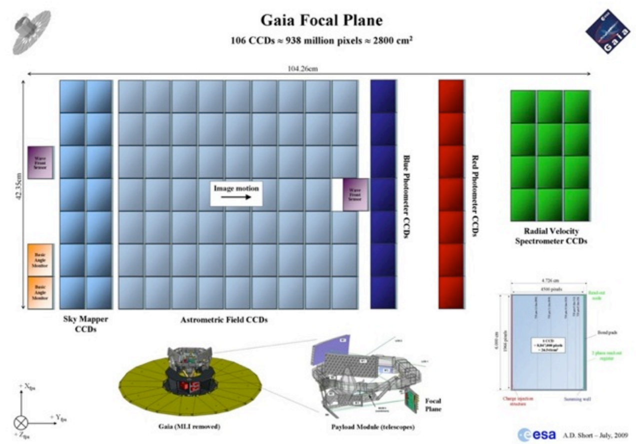
Gaia



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Beyond Hubble

Reflecting on the Hubble Space Telescope ...

Is there a successor waiting in the wings?

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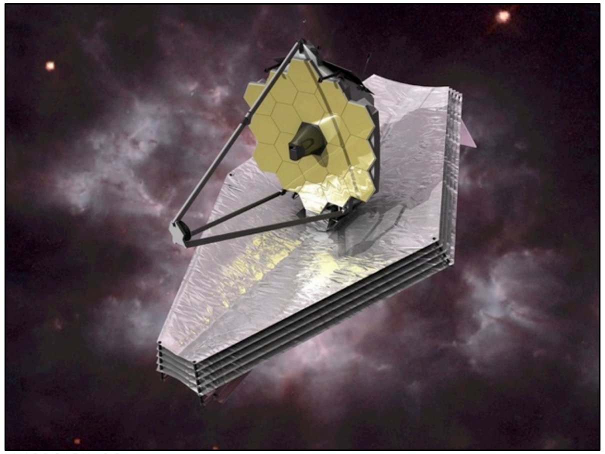
James Webb Space Telescope



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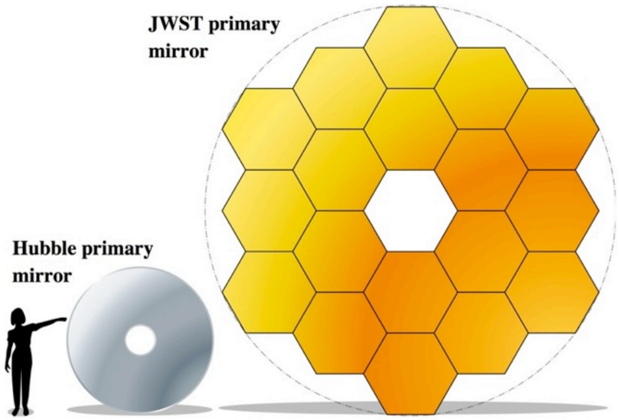
James Webb Space Telescope



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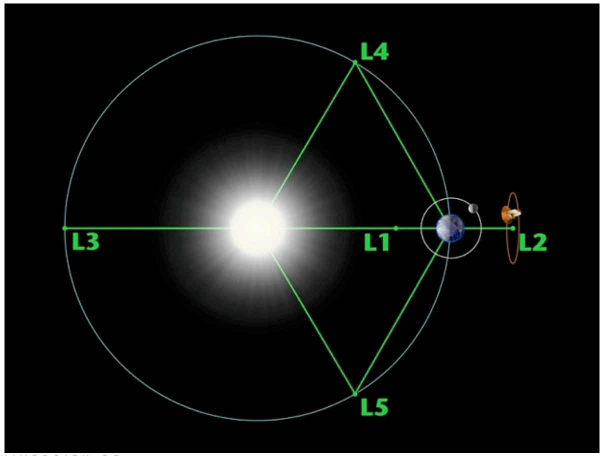
JWST @ L2



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James Webb Space Telescope

What will the JWST do?

By working in the infrared it will be able to see more than the HST.

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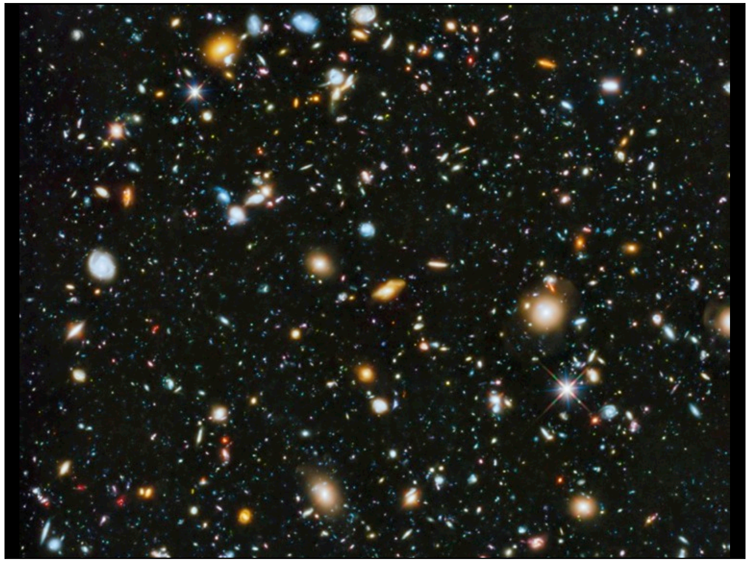
69



Summary

Introduction	Need for a space telescope Ground-based alternatives
History	Why the mirror was flawed How the optics were fixed
Legacy	Extending our understanding Touching the public consciousness
Future	Need for a space telescope Ground-based alternatives

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71