

UNVEILING THE UNIVERSE WITH THE HUBBLE SPACE TELESCOPE

Dr. Glenn Schneider
Steward Observatory
Department of Astronomy
The University of Arizona
Tucson, Arizona 85721 USA



INSTRUMENT SCIENTIST
Near Infrared Camera
and Multi-Object
Spectrometer (NICMOS)

PRINCIPAL INVESTIGATOR
Exoplanetary Circumstellar
Environments and Disk
Explorer (EXCEDE)

Nassau Academy of Law
Dean's Discussion Lecture Series
Invited Talk
Monday, 29 October 2018
Mineola, New York



gschneider@as.arizona.edu
<http://nicmosis.as.arizona.edu:8000>

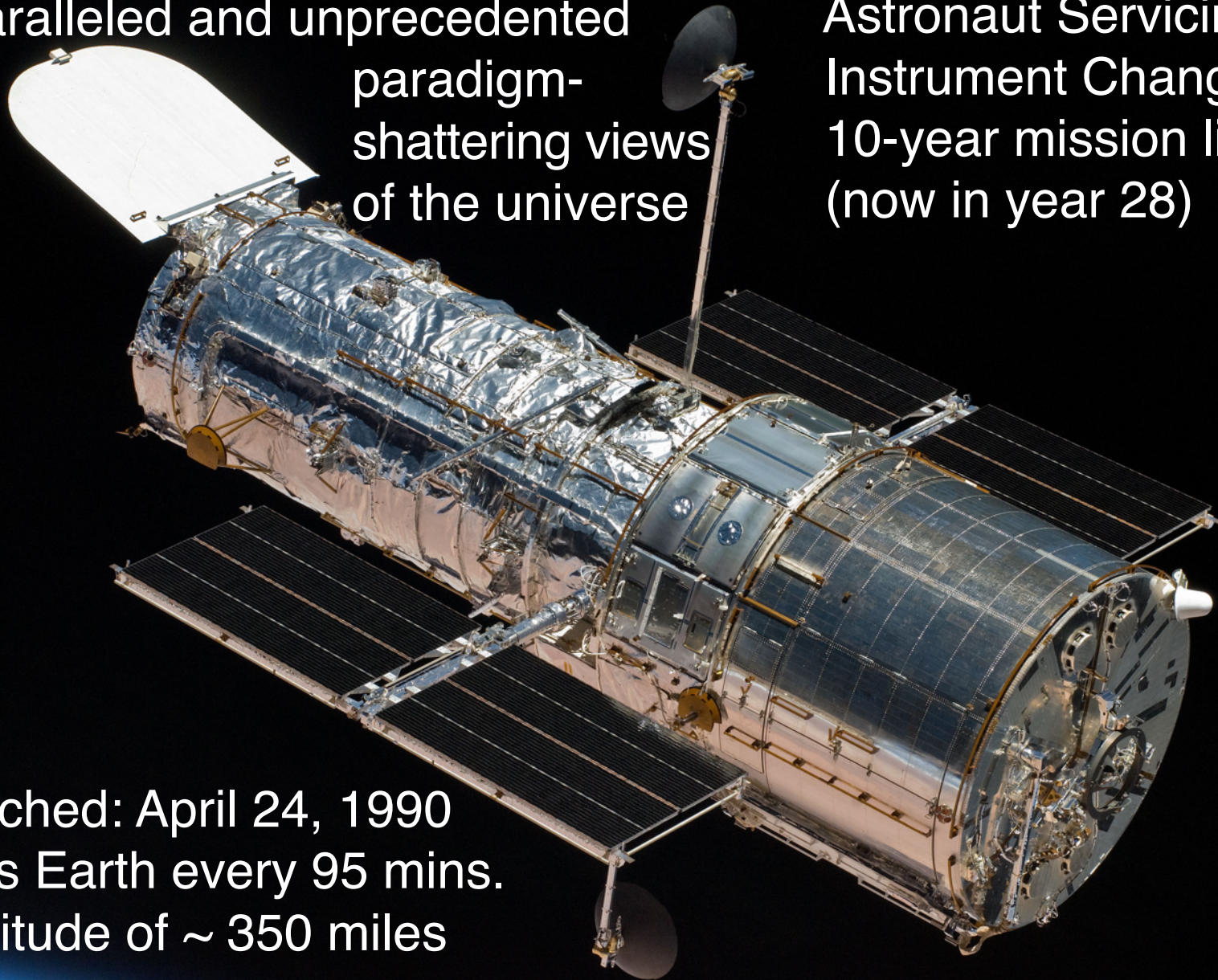
The HUBBLE SPACE TELESCOPE

Unparalleled and unprecedented
paradigm-
shattering views
of the universe

Designed for:
Astronaut Servicing &
Instrument Changeouts
10-year mission life goal
(now in year 28)

Launched: April 24, 1990
Orbits Earth every 95 mins.
At altitude of ~ 350 miles

Much more than a telescope: an orbiting robotic observatory



The HUBBLE SPACE TELESCOPE – 28 Years On-Orbit

With Increasingly Powerful Instruments and Observatory Upgrades

1990 (Launch)

Wide Field/Planetary Camera
Faint Object Camera
High Resolution Spectrograph
Faint Object Spectrograph
High Speed Photometer

1993 (SM1)

Wide Field/Planetary Camera 2

1997 (SM2)

S. T. Imaging Spectrograph
Near-Infrared Camera and
Multi-Object Spectrometer

2002 (SM3B)

Advanced Camera for Survey

2009 (SM4)

Cosmic Origins Spectrograph
Wide Field Camera 3

HOW DID WE GET HERE?



IN THIS TALK...

- Historical Motivation:
The Quest for Cosmic Vision



- The Rocky Road to the Hubble Space Telescope
Trials & Tribulations → Victory and Success
with a focus on the *Near-INFRARED*

- HST-Enabled New Views on the Universe

- What Next?: HST → JWST

- And (in closing) Changing Gears,
a brief discussion on something
“completely different”...

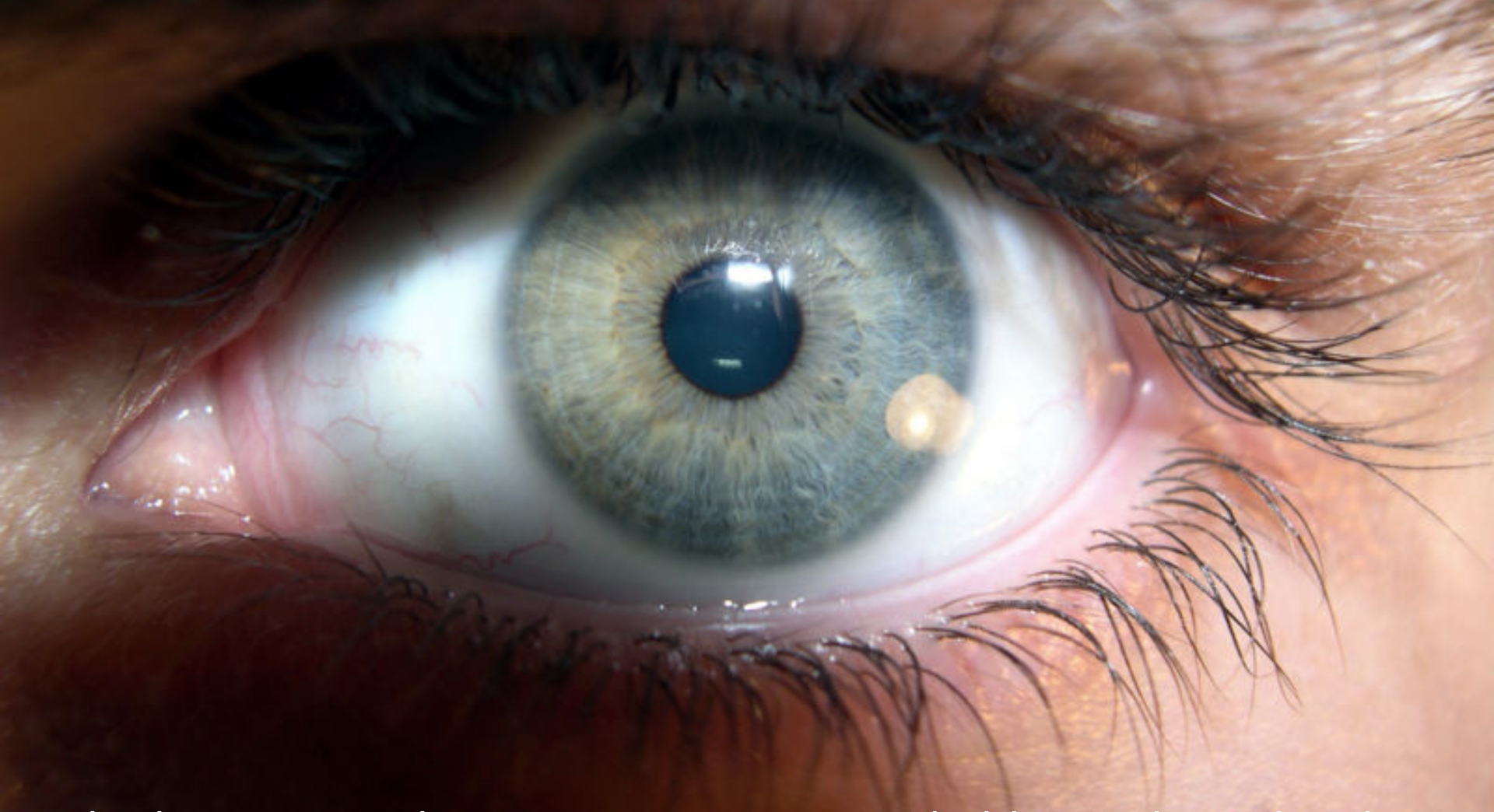


For millennia, preceding the invention of the telescope...



Early cosmologies were built upon what our eyes alone could perceive.

Observational astronomy informed our concepts and our understanding of the make-up, physical properties, and processes of the universe of which we are a part.

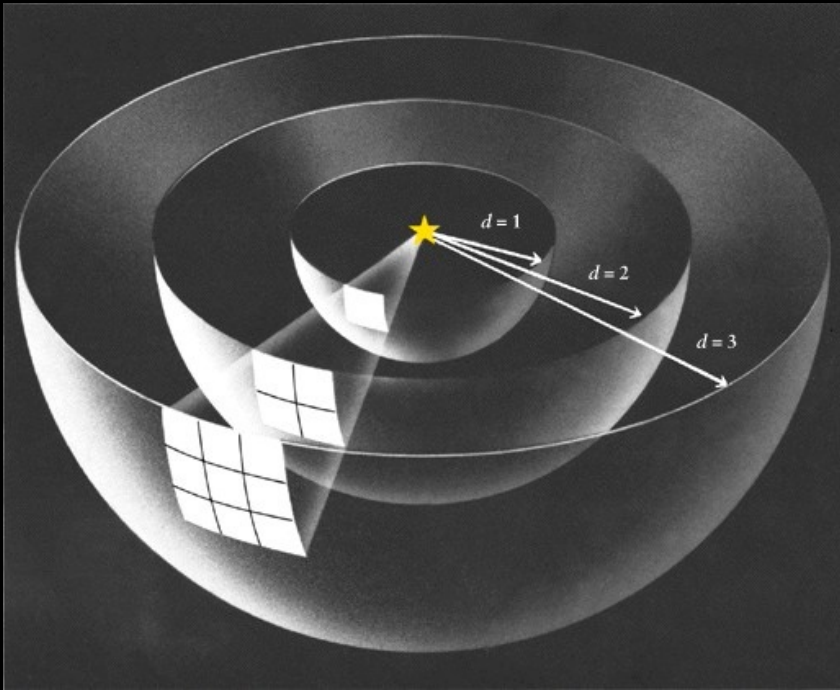


The human eye/brain system is a remarkable machine, but has physiological limitations... mitigatable by modern technologies.

Observational astronomy informed our concepts and our understanding of the make-up, physical properties, and processes of the universe of which we are a part.

THREE VISION-LIMITED OBSERVATIONAL DOMAINS

1 — BRIGHT (and “near”) vs. FAINT (and far)



The “1 over r-squared”
attenuation of star/galaxy light



Some of the most distant galaxies in
the observable universe (with HST)

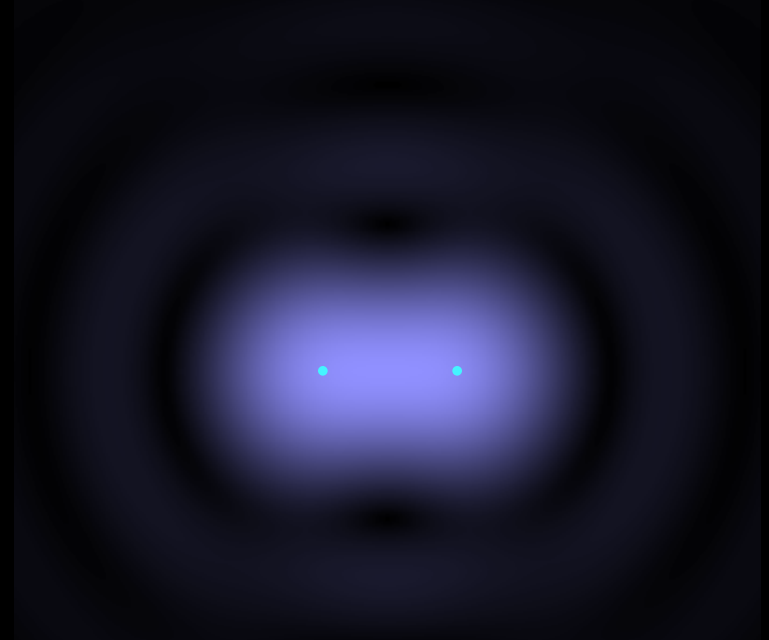
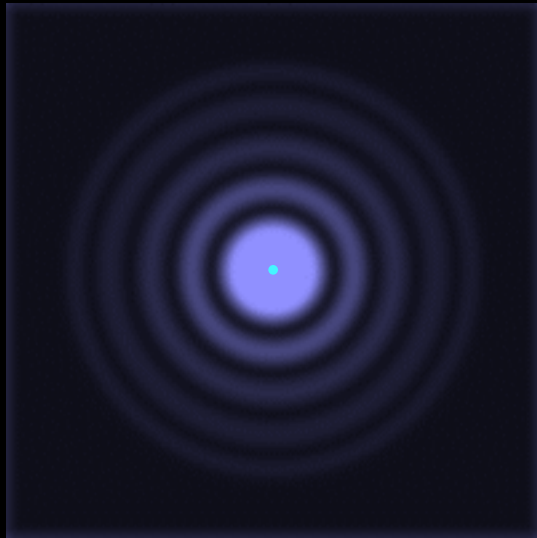
(1) Our vision is limited by the feebleness of faint signals
of astronomical origin diminishing in brightness as $1/r^2$.

Observational astronomy informed our concepts and our understanding of the make-up, physical properties, and processes of the universe of which we are a part.

THREE VISION-LIMITED OBSERVATIONAL DOMAINS

2 — SPATIAL (ANGULAR) RESOLUTION: “Blurry” vision

“Point Spread Function”
Diffraction for a circular aperture



Angular Resolution (radians) = $1.22 \times \text{Wavelength} / \text{Aperture Diameter}$
Perfect (“20/20”) human vision: 1 arcminute = 1/30 full moon diameter

(2) Our vision is limited in its ability to spatially “resolve” (separate) objects that are in close angular proximity

Our vision is *ALSO* CONTRAST-limited: Unable to detect faint objects in the glare of brightly-luminous ones in close proximity.

Seeing a lit match in a dark room is easy.



Seeing the same match adjacent high-beam headlights is impossible.

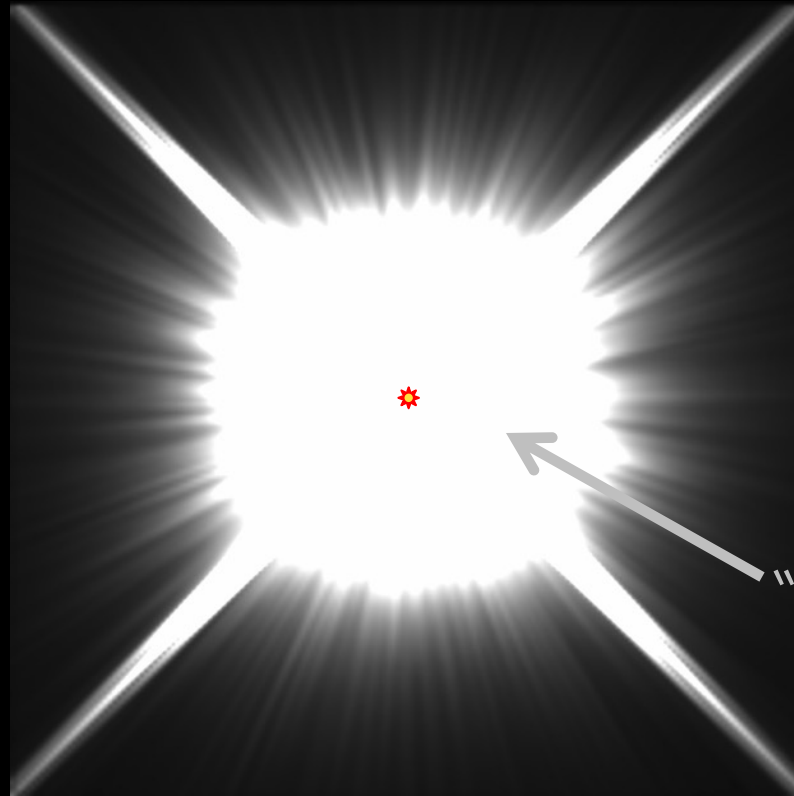


car headlight $\sim 20,000$ x brighter than a match

Earth-like planets are a billion times fainter than the Sun-like stars they orbit

Observational astronomy informed our concepts and our understanding of the make-up, physical properties, and processes of the universe of which we are a part.

THREE VISION-LIMITED OBSERVATIONAL DOMAINS 3 – DYNAMIC RANGE (CONTRAST)



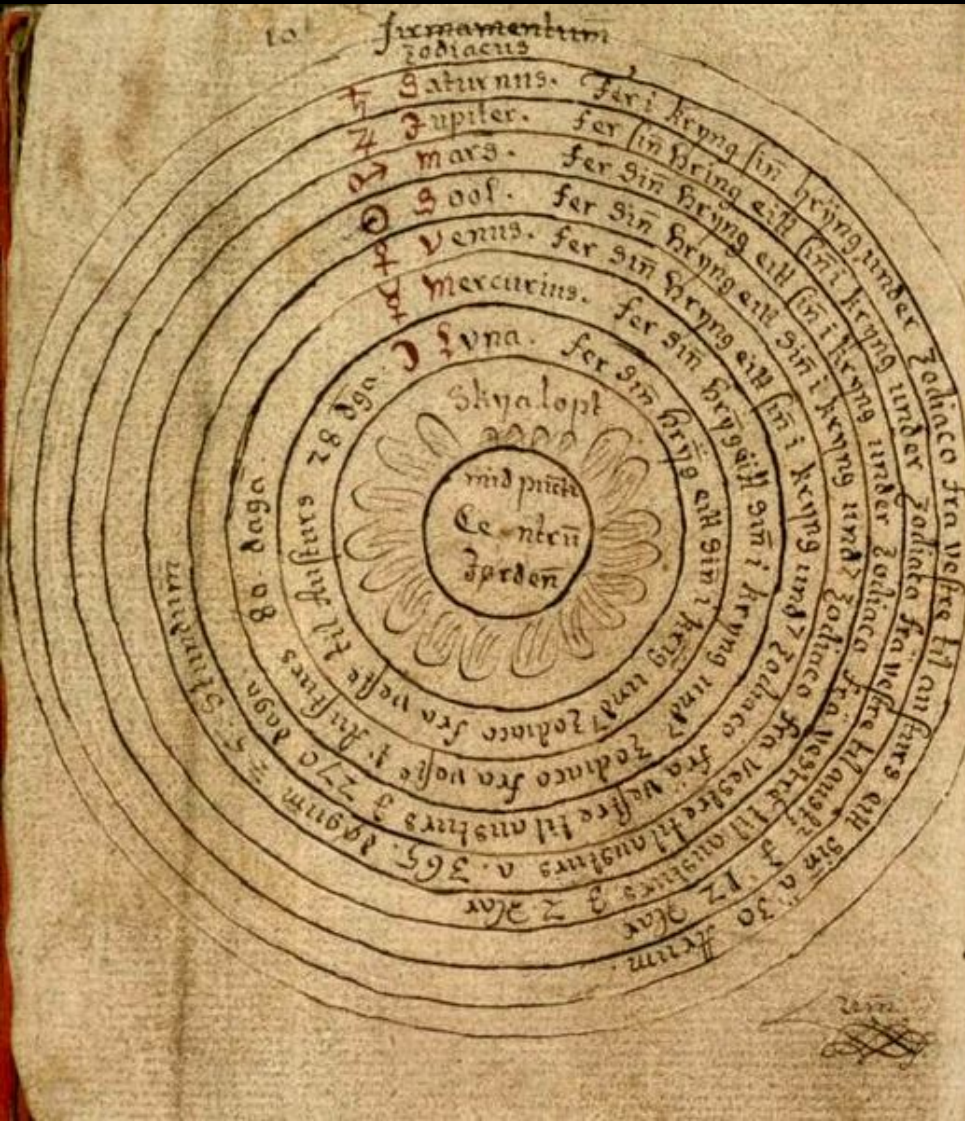
“here be dragons...”

(3) Our vision is contrast-limited by its ability to see faint objects hidden in the glare of nearby bright objects

From what ancient eyes alone informed
of the Sun, Moon, and Stars,
early cosmologies emerged...

The Ptolemaic “Universe” – GEOCENTRICISM

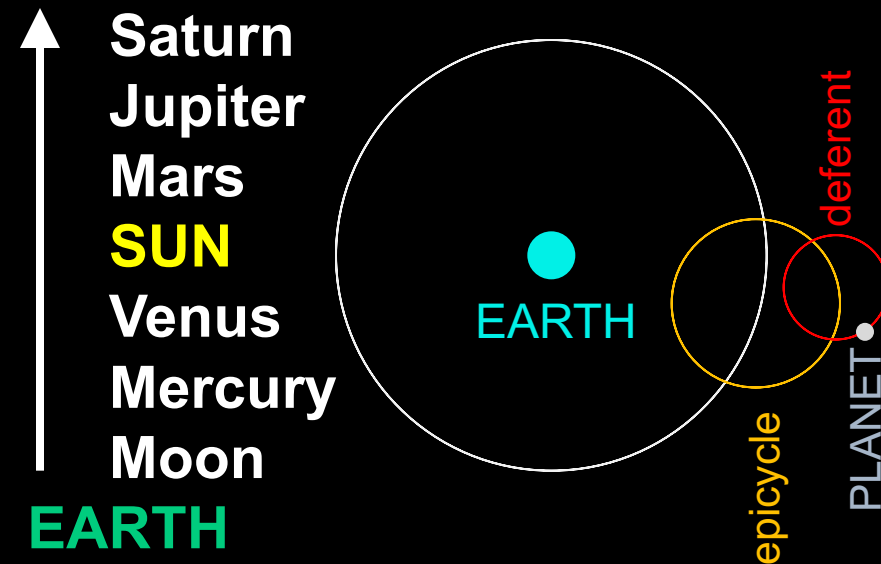
EARTH-centered crystalline spheres with celestial objects “attached”
(with “epicycles” and “deferents” to ‘explain’ retrograde motions)



Claudius Ptolemais

(140 AD) 14 Vol. “Almagest”
The *Geocentric* cosmology

The *Firmament*: Celestial
Sphere of “fixed” STARS



Greek Concept,
Church Adopted Doctrine

The Copernican “Universe” - HELIOCENTRIC

Dethroning Earth as the Center of the Universe

Nicolaus Copernicus “*De Revolutionibus*”, 1543

(On the Revolutions of the Heavenly Spheres)

Published the year of his Death

“Fixed” STARS

↑ Saturn
Jupiter
Mars
EARTH/Moon
Venus
Mercury

SUN

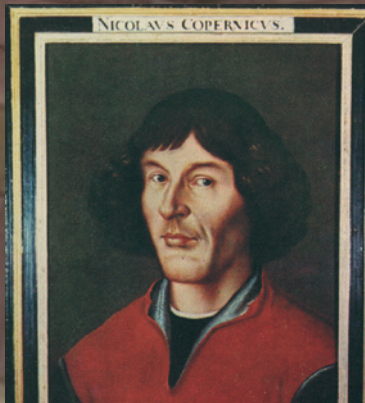
NICOLAI
COPERNICITOT-
RINENSIS DE REVOLVTIONIBUS
orbium coelestium,
Libri VI.

IN QVIBVS STELLARVM ET FIXARVM ET ERRATICARVM MOTVS, EX VETERIBUS atq; recentibus obseruationibus, restituit hic autor. Præterea tabulas expeditas luculentasq; addidit, ex quibus eisdem motus ad quoduis tempus Mathematicum studiosus facillime calculare poterit.

ITEM, DE LIBRIS REVOLVTIONVM NICOLAI COPERNICI Narratio prima, per M. Georgium Ioachim Rheticum ad D. Ioan. Schönerm scripta.



Cum Gratia & Privilegio Car. Maiest.
BASILEÆ, EX OFFICINA
HENRICI PETRINI.



NICOLAI COPERNICI
net, in quo terram cum orbem lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum deniq; locum Mercurius tenet, octuaginta dierum spacio circū currens. In medio uero omnium residet Sol. Quis enim in hoc



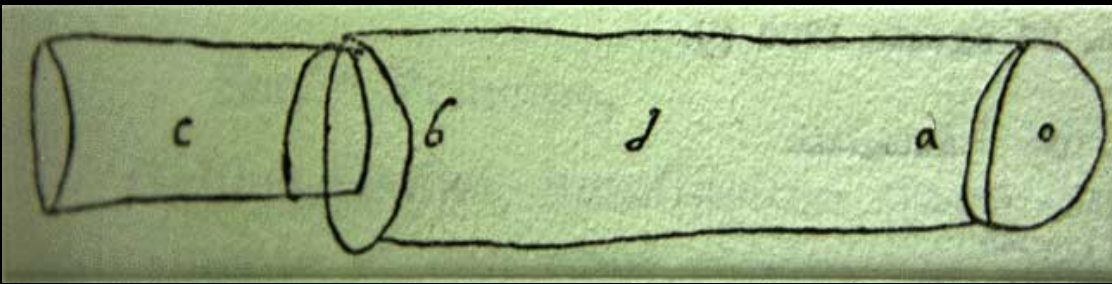
pulcherrimo templo lampadem hanc in alio uel meliori loco poneret, quam unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegitus uisibilem Deum, Sophoclis Electra intuentē omnia. Ita profecto tanquam in folio regali Sol residens circum agentem gubernat Astroorum familiam. Tellus quoque minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximam Luna cum terra cognitionē habet. Cōcipit iterea à Sole terra, & impregnatur anno partu. Inuenimus igitur sub hac

1609 - The Year the Universe “Changed”

Prelude, October 1608 The Hague, Netherlands

National Government Discusses

Patent Application by Hans Lippershey
and Jacob Metius for a device for
“seeing far-away things as though nearby”



Earliest known sketch of the
“Optik Tube” (telescope)
Giambattista della Porta (1609)



1609 - The Year the Universe “Changed”

The Galilean Revolution in Observational Astronomy

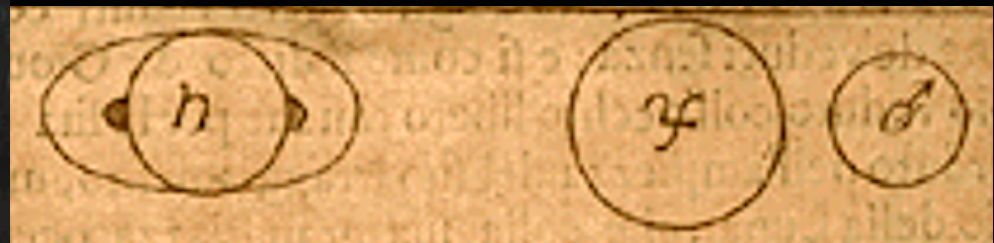


Phases of Venus



Explained by HELIO-CENTRIC Theory
("Eppur si muove!")

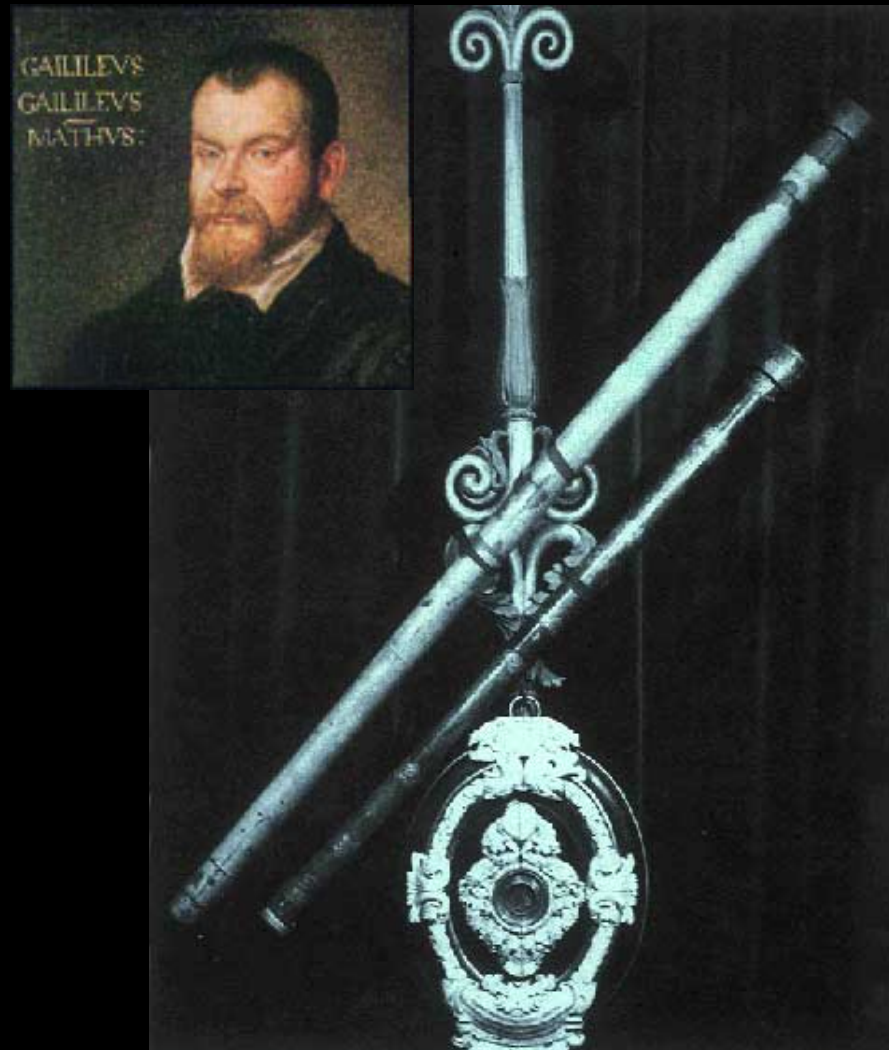
PLANETS Not Just Points of Light



Saturn **Jupiter** **Mars**
with Ears/Bulges & Circular Disks

1609 - The Year the Universe “Changed”

The Galilean Revolution in Observational Astronomy



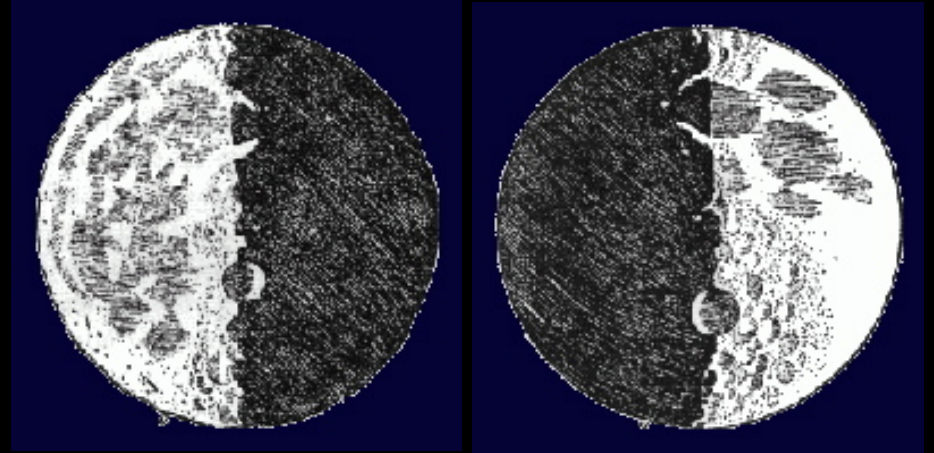
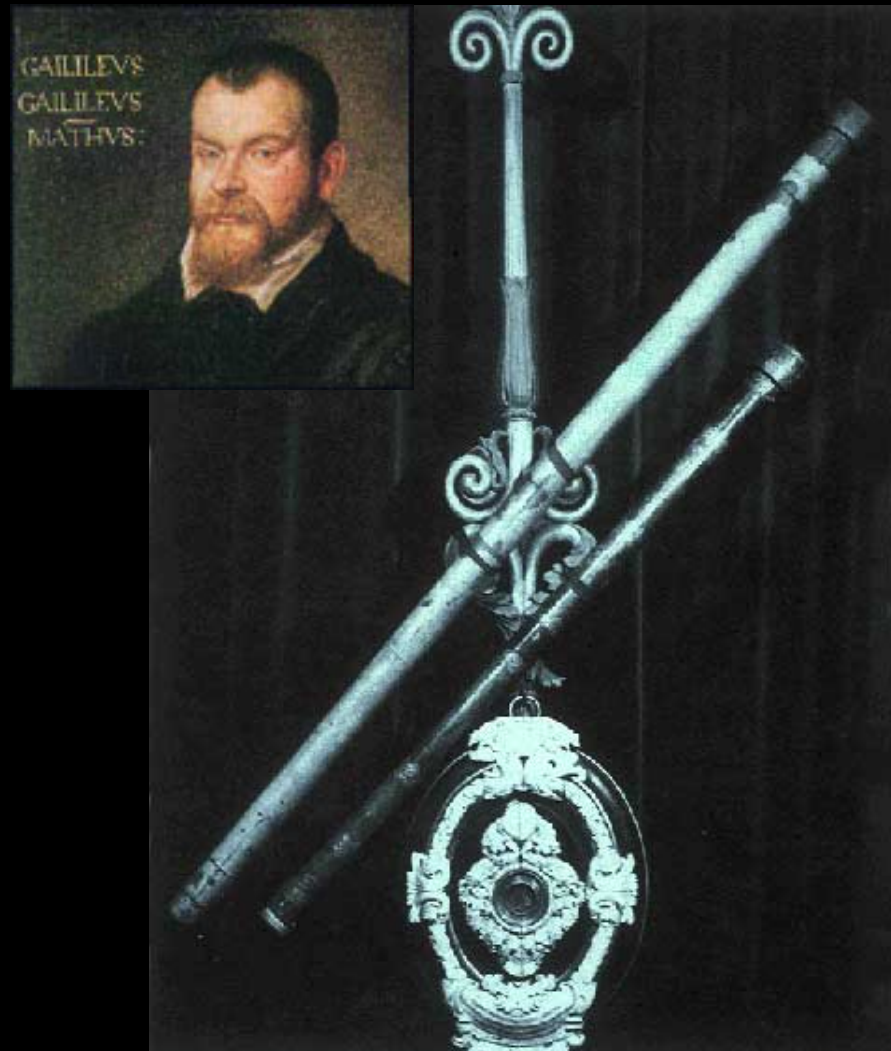
Observations Jovianae
1610

2. Jovis. mand. H. 12.	○ **
30. mand.	** ○ *
2. Jovis.	○ ** *
3. mand.	○ * *
3. Ho. 5.	* ○ *
7. mand.	* ○ **
6. mand.	** ○ *
8. mand. H. 17.	* * * ○
10. mand.	* * * ○ *
11.	* * ○ *
12. H. 4. reg.	* ○ *
13. mand.	* * ○ *
14. Cassi.	* * * ○ *

“... our own eyes show us **four planets which wander around Jupiter** as does the Moon around the Earth, while all together trace out a grand revolution about the Sun... four planets never seen from the creation of the world up to our own time...”

1609 - The Year the Universe “Changed”

The Galilean Revolution in Observational Astronomy

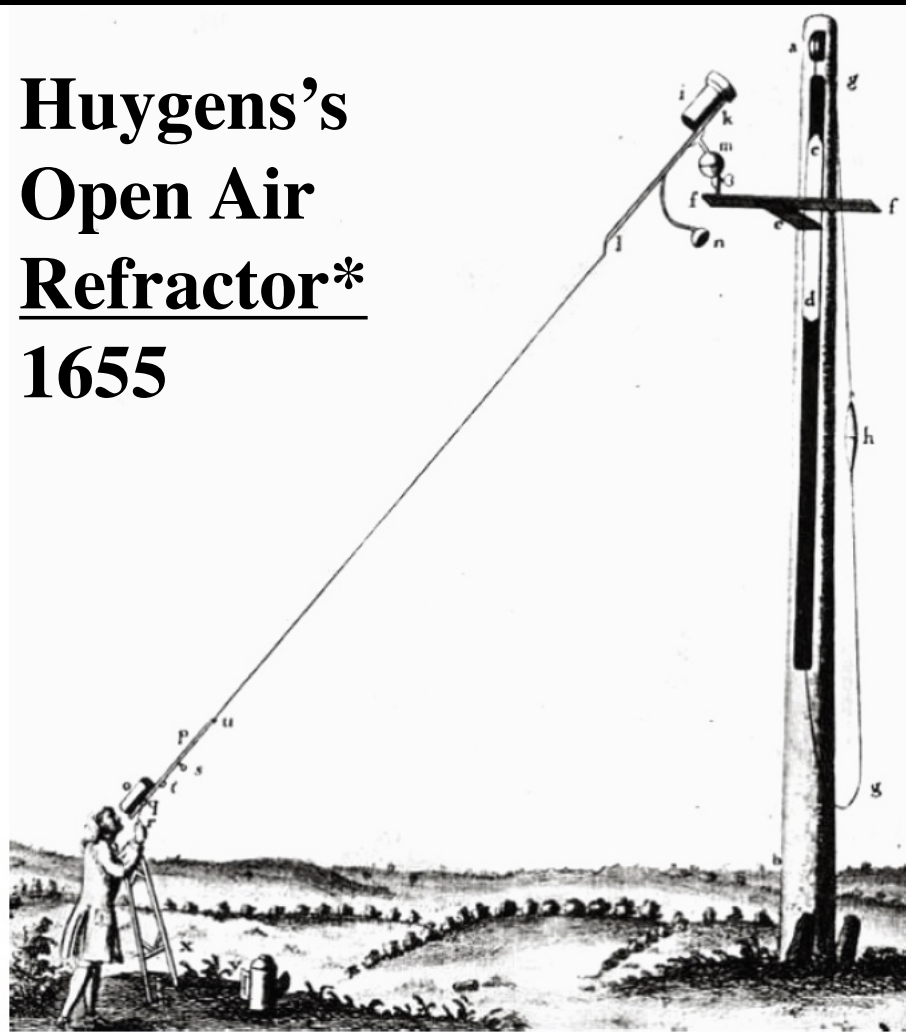


“The surface of the Moon is **not smooth, uniform, nor precisely spherical**... but is uneven, rough, and full of cavities... **not unlike the face of the Earth**, relieved by chains of mountains and deep valleys.”

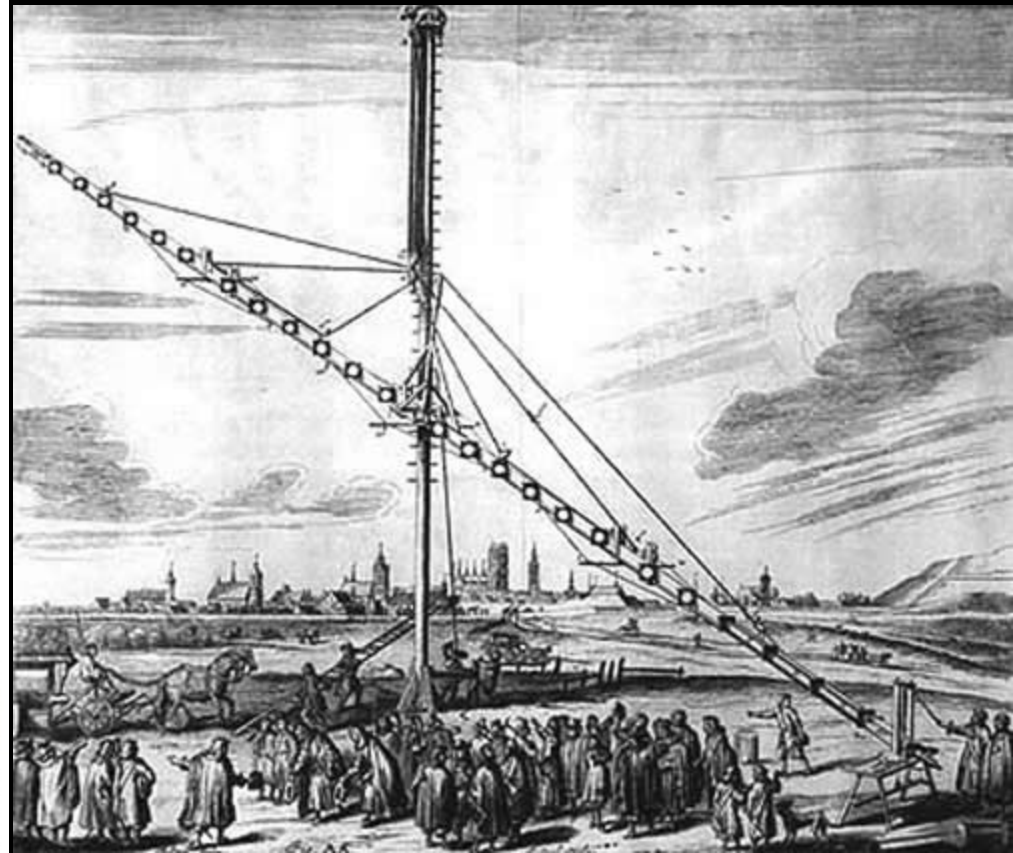
The Evolution of the Telescope

LONGER focal lengths -- more magnification

**Huygens's
Open Air
Refractor***
1655



Helvetius 150 ft Refractor*
(1673)



*Simple, single-lens, Galilean telescopes of the Lippershay design

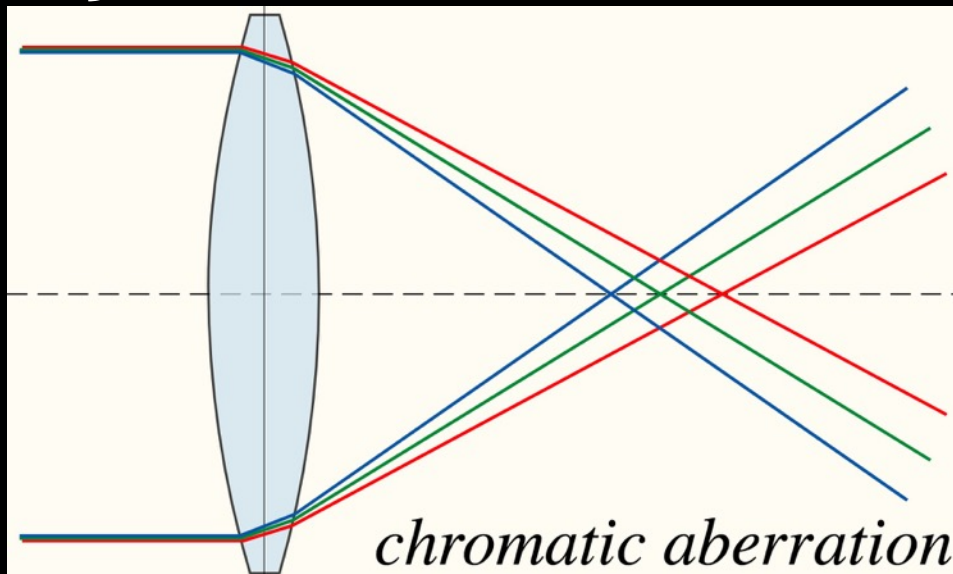
The Evolution of the Telescope

LONGER focal lengths -- more magnification

But, in addition to being very cumbersome and difficult to use, such “refracting” telescopes, using a simple imaging lens, suffered from “*chromatic aberration*”

Resulting in blurry images

Light of different colors



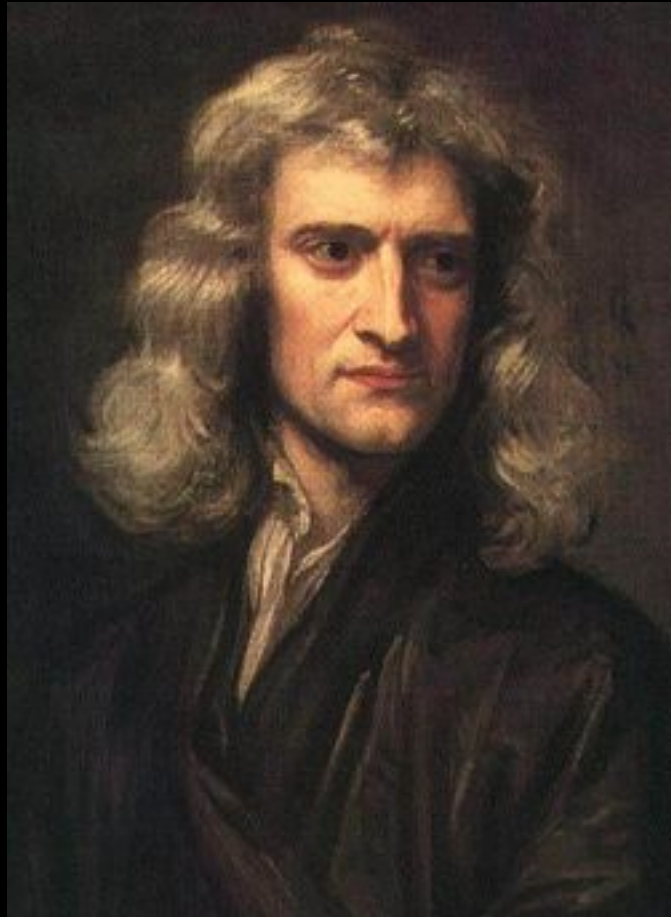
Focus at different distances



(A “refractive” optical problem not solved until the 1830’s)

The Evolution of the Telescope ***REFLECTING Mirror -- no “Chromatism”***

Isaac Newton's Speculum Metal Mirror Telescope (1668)

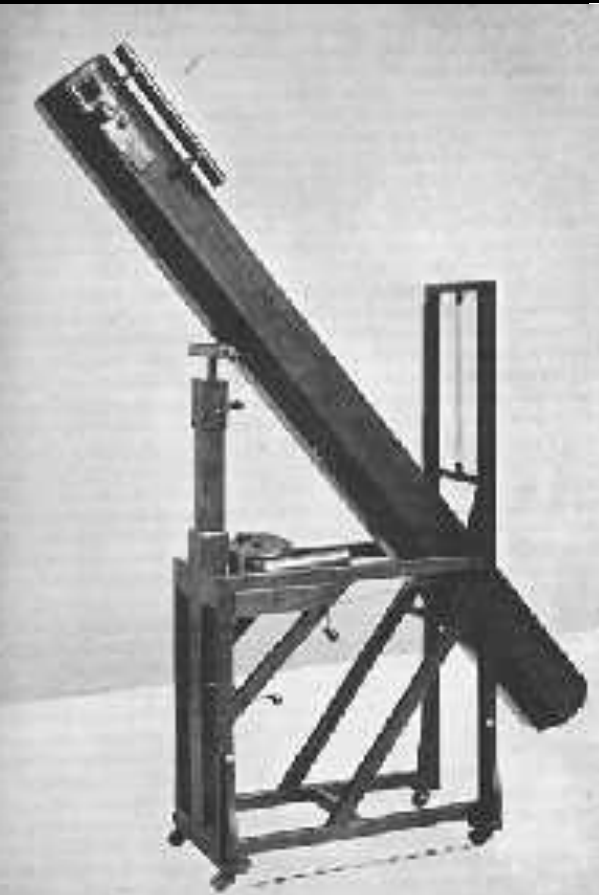


The Evolution of the Telescope *Larger Diameter - Brighter & Sharper*

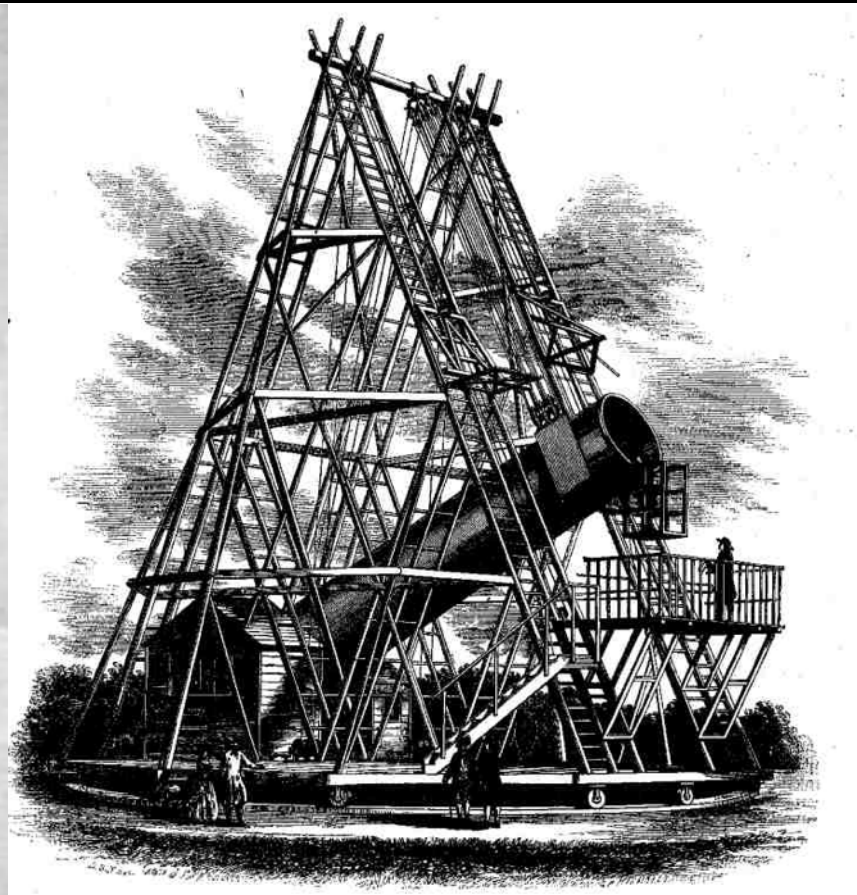
William Herschel's 400 Telescopes...



7', 6.5" mirror (1744)



40', 49.5" mirror (1788)



- Binary Stars:
Universality of Kepler's Laws
- Stellar Proper Motions:
Solar system motion through space
- Milky Way:
Disk Structure
- Extensive
Nebulae Catalog

The Evolution of the Telescope

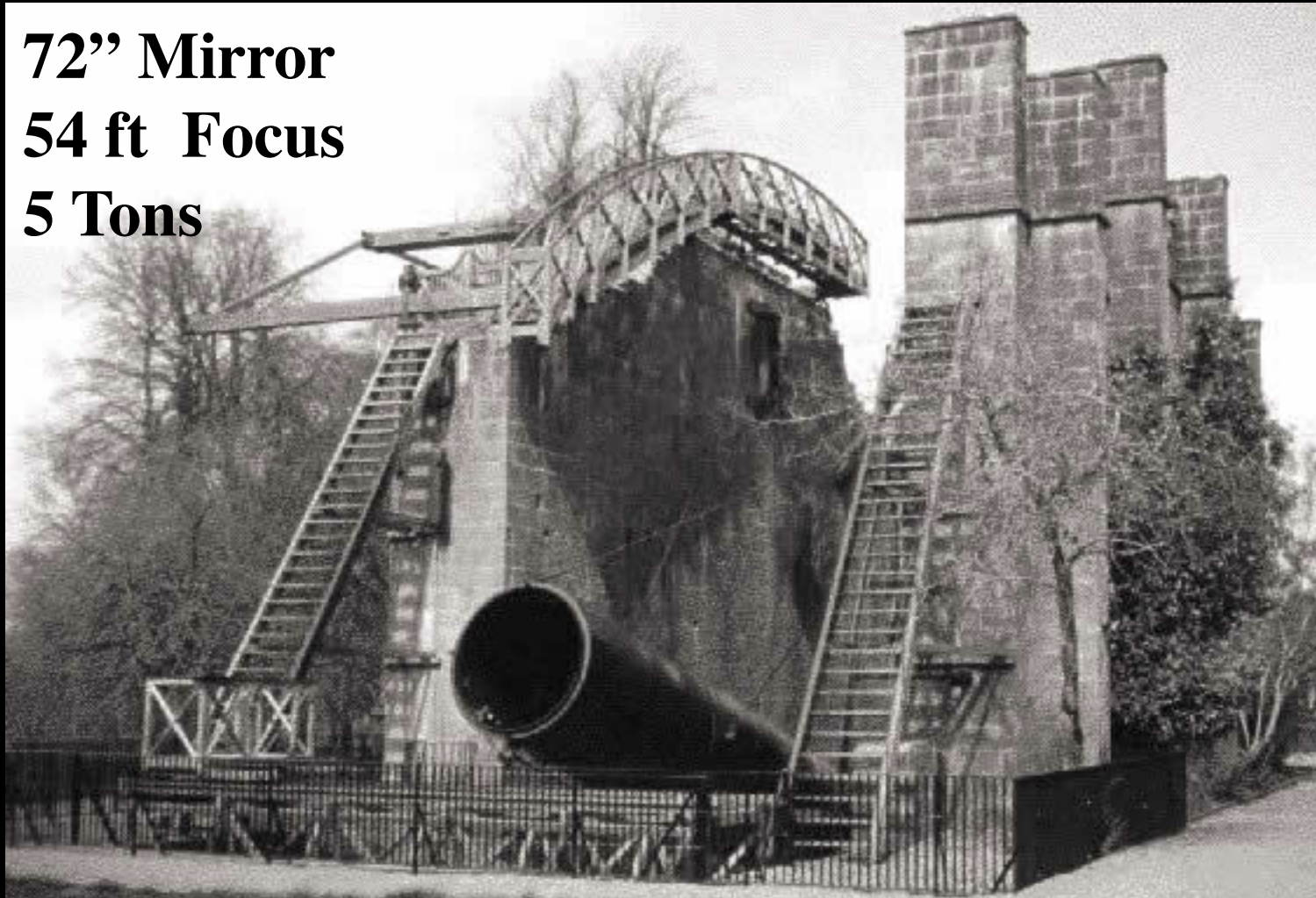
Larger Diameter - Brighter & Sharper

William Parson's (3rd Earl of Ross) "Leviathan of Parsonstown" (1845)

72" Mirror

54 ft Focus

5 Tons



World's largest telescope prior to the 20th century

The Evolution of the Telescope

Larger Diameter - Brighter & Sharper

Parson's Drawing of the
M51 "Spiral Nebula" (1845)



Hubble Space Telescope
Image (2005)



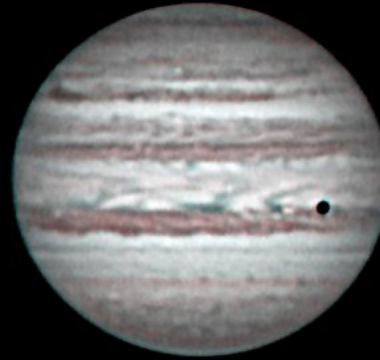
The Evolution of the Telescope

“Big” Tracking Achromatic Refractors

Asaph Hall



U.S. Naval Observatory
26” f/15 Clark Refractor
(1873, \$50,000)

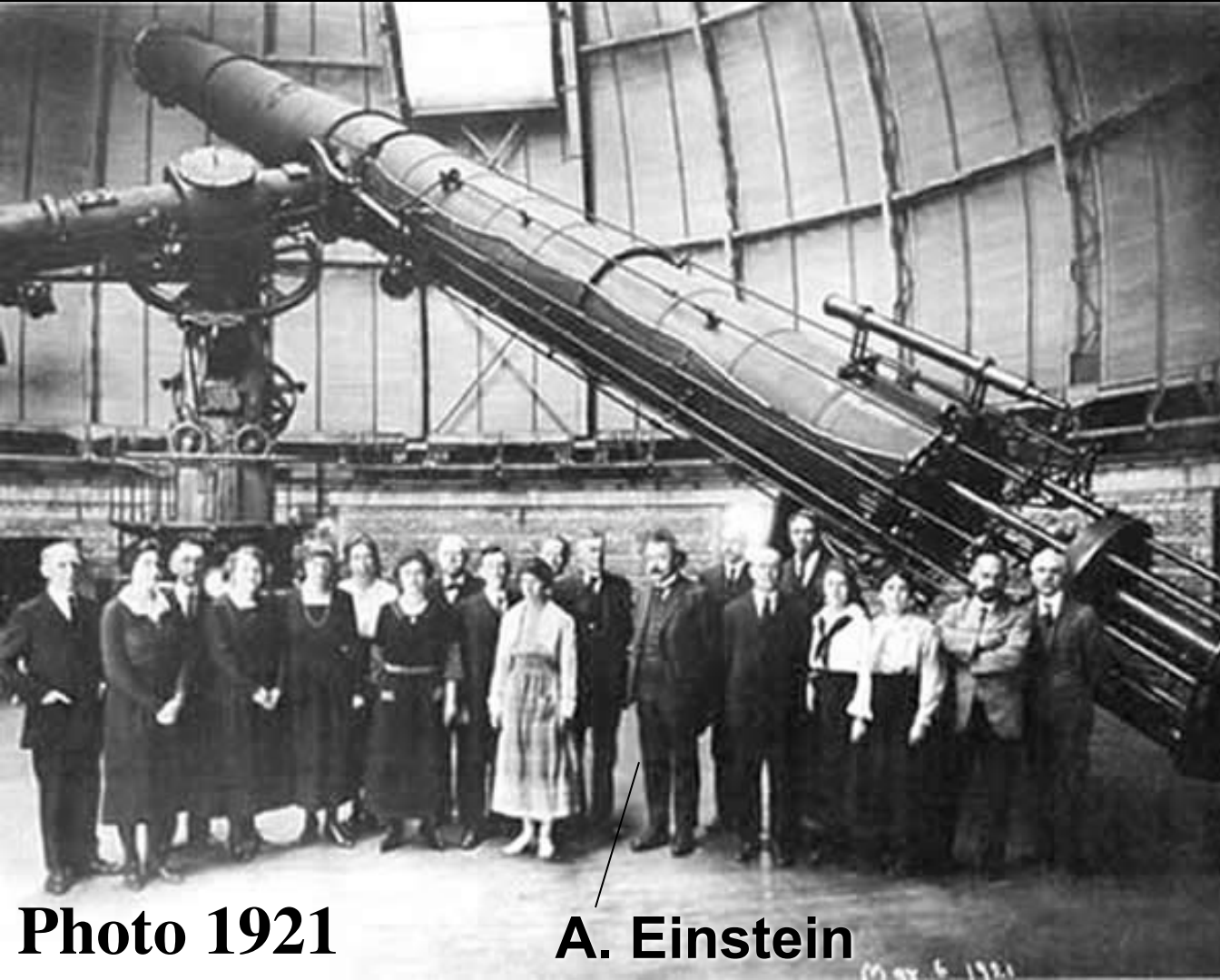


Unlike the “Leviathan”, on a tracking
mount with precision clock drive

The Evolution of the Telescope

“Big” Tracking Achromatic Refractors

Yerkes Observatory 40” Refractor (1895)



Chicago tycoon Charles Tyson Yerkes, convicted embezzler with a reputation for dishonest deals, financed the telescope. He liked the idea of his name being attached to a famous telescope and agreed to pay whatever it took, but insisted repeatedly that it had to be the biggest in the world.

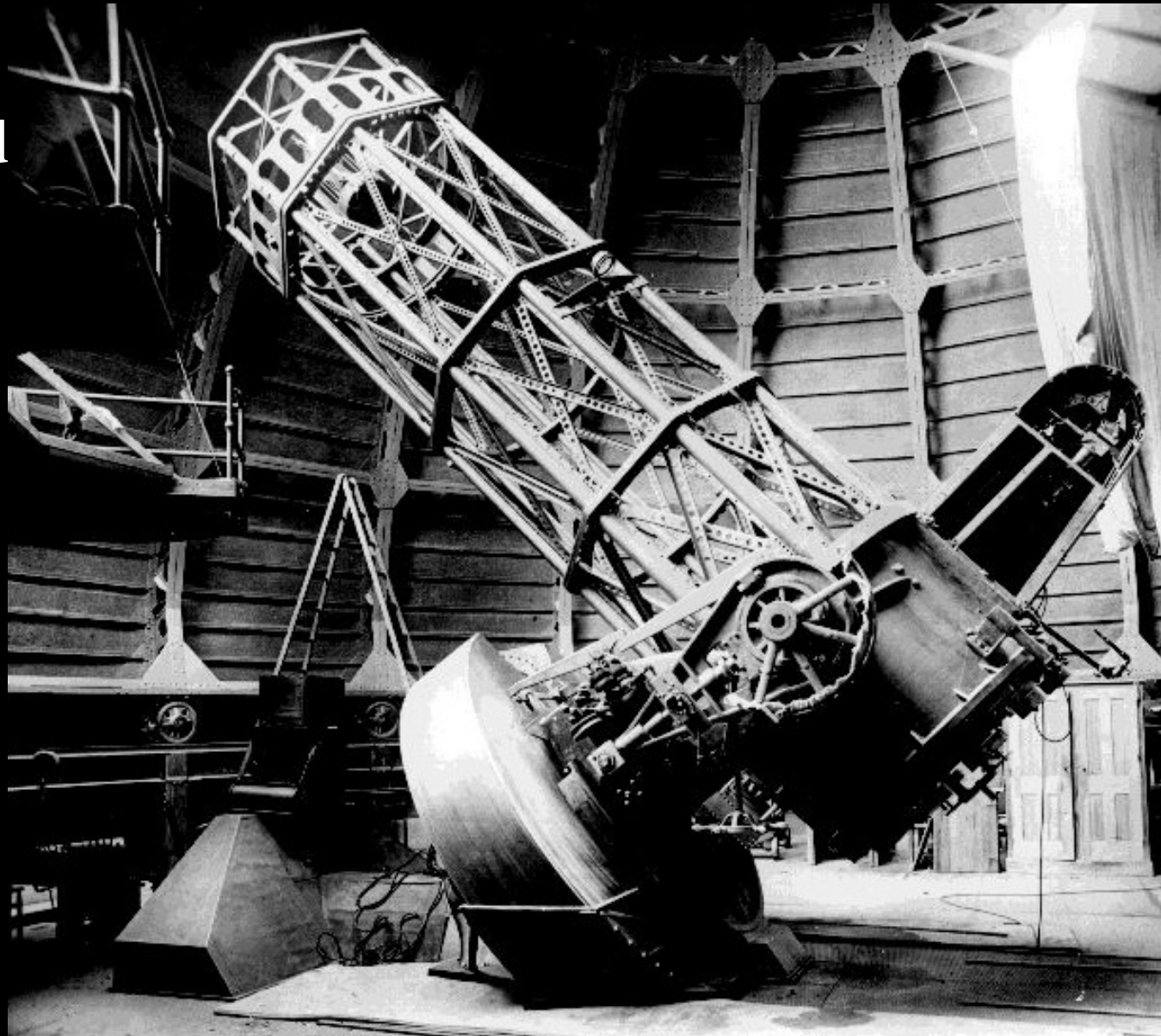
Photo 1921

A. Einstein

The Evolution of the Telescope

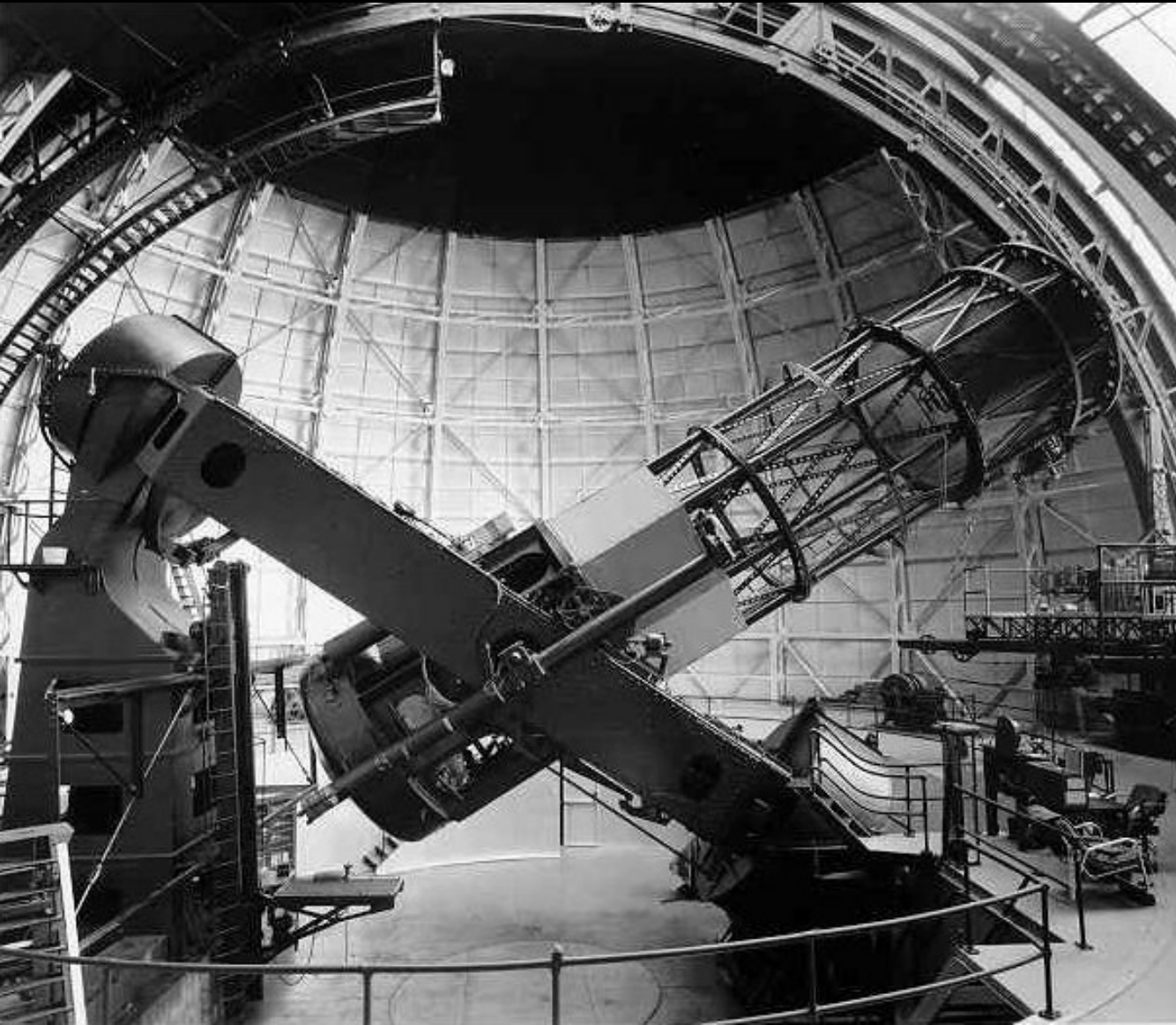
“Big” Tracking Precision Reflectors

**Mount Wilson
60” Silver Coated
Glass Mirror
Equatorial
Telescope
(1905)**



And in 1929 the Universe “Changed” Again!

Mount Wilson 100” Telescope (1917)



Edwin Hubble

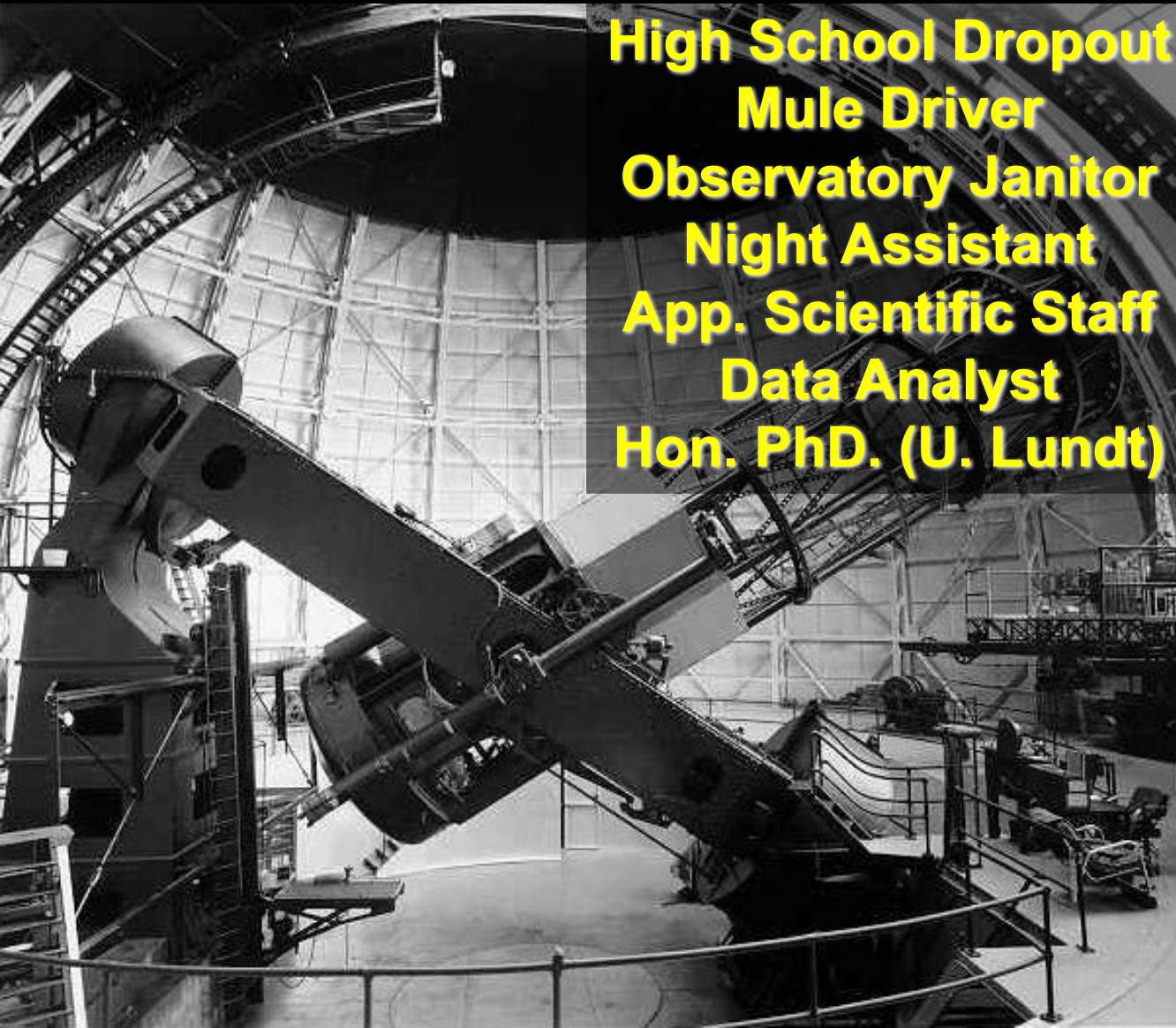


And in 1929 the Universe “Changed” Again!

Mount Wilson 100” Telescope (1917)

**High School Dropout
Mule Driver
Observatory Janitor
Night Assistant
App. Scientific Staff
Data Analyst
Hon. PhD. (U. Lundt)**

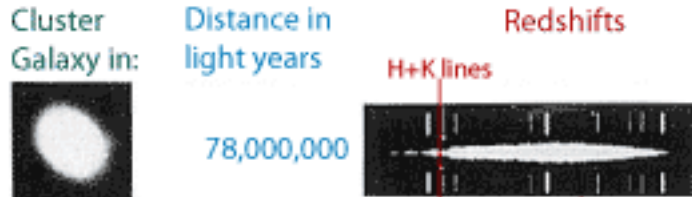
**Assisted by
Milton Humason**



The Evolution of the Universe

Hubble's Observations

Relation Between Redshift and Distance
for Distant Galaxies



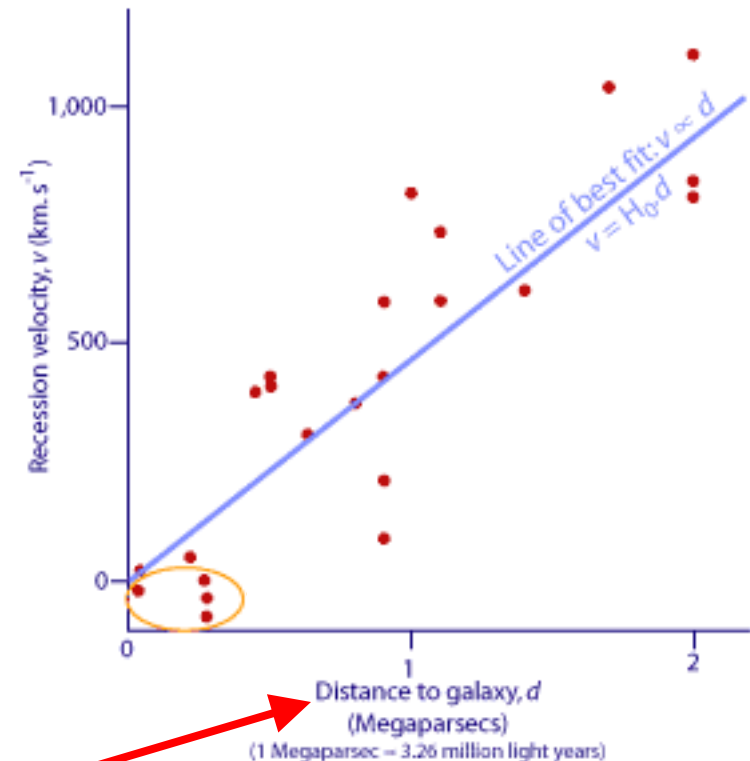
not moving
("rest frame")



moving away
("red shifted")

The Hubble's Law Relation

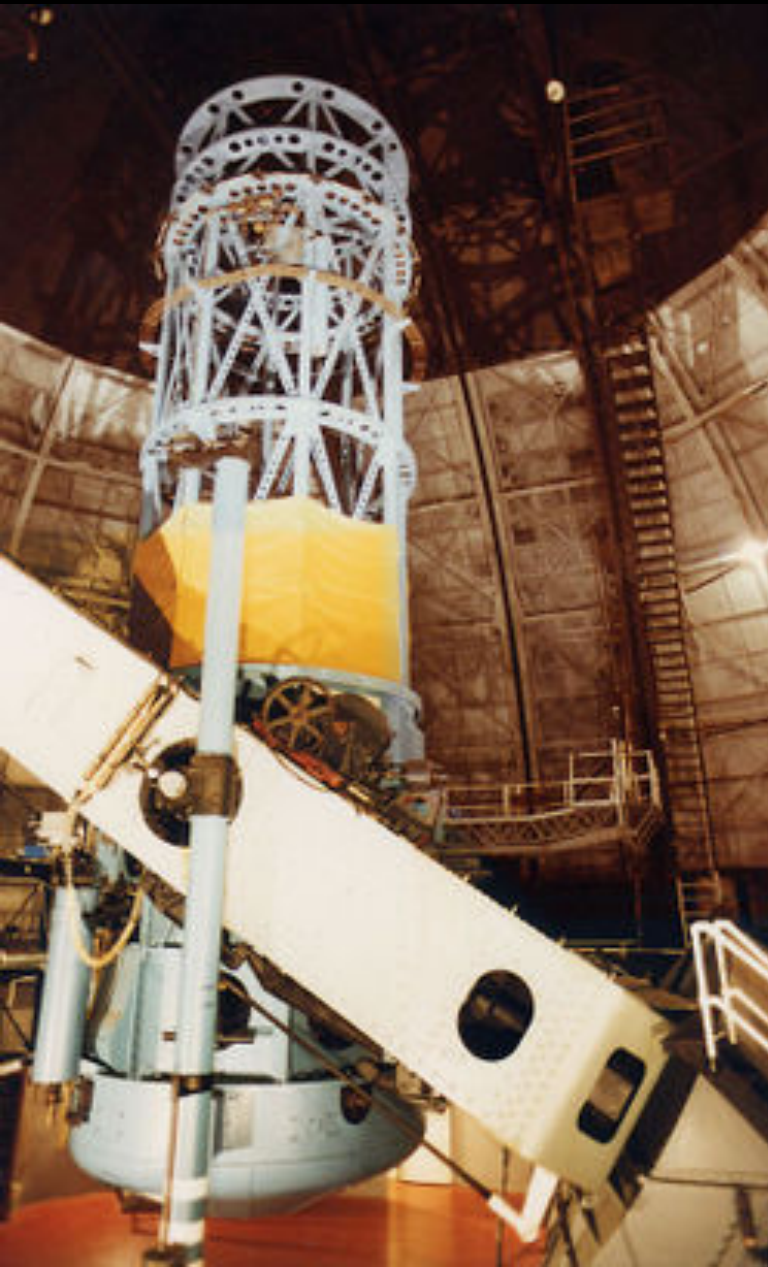
Hubble's Plot of Galaxy Velocity & Distance



But, the extra-galactic distance
scale was off by a factor of 6.

$$V = H_0 d \quad ; \quad H_0 == \text{Hubble Constant}$$
$$1/H_0 \rightarrow \text{age of the universe!}$$

The Evolution of the Universe



Using the 100" telescope Edwin Hubble found:

- The “spiral nebulae” are tremendously distant, not part of or within our galaxy, until then thought to be the whole of Universe.
- The Universe is vastly larger than had ever been imagined.
- All the distant galaxies are flying away from each other, the further the faster.
- The universe as a whole is expanding.



To explore the most distant reaches of the observable universe at the earliest stages in cosmic time...

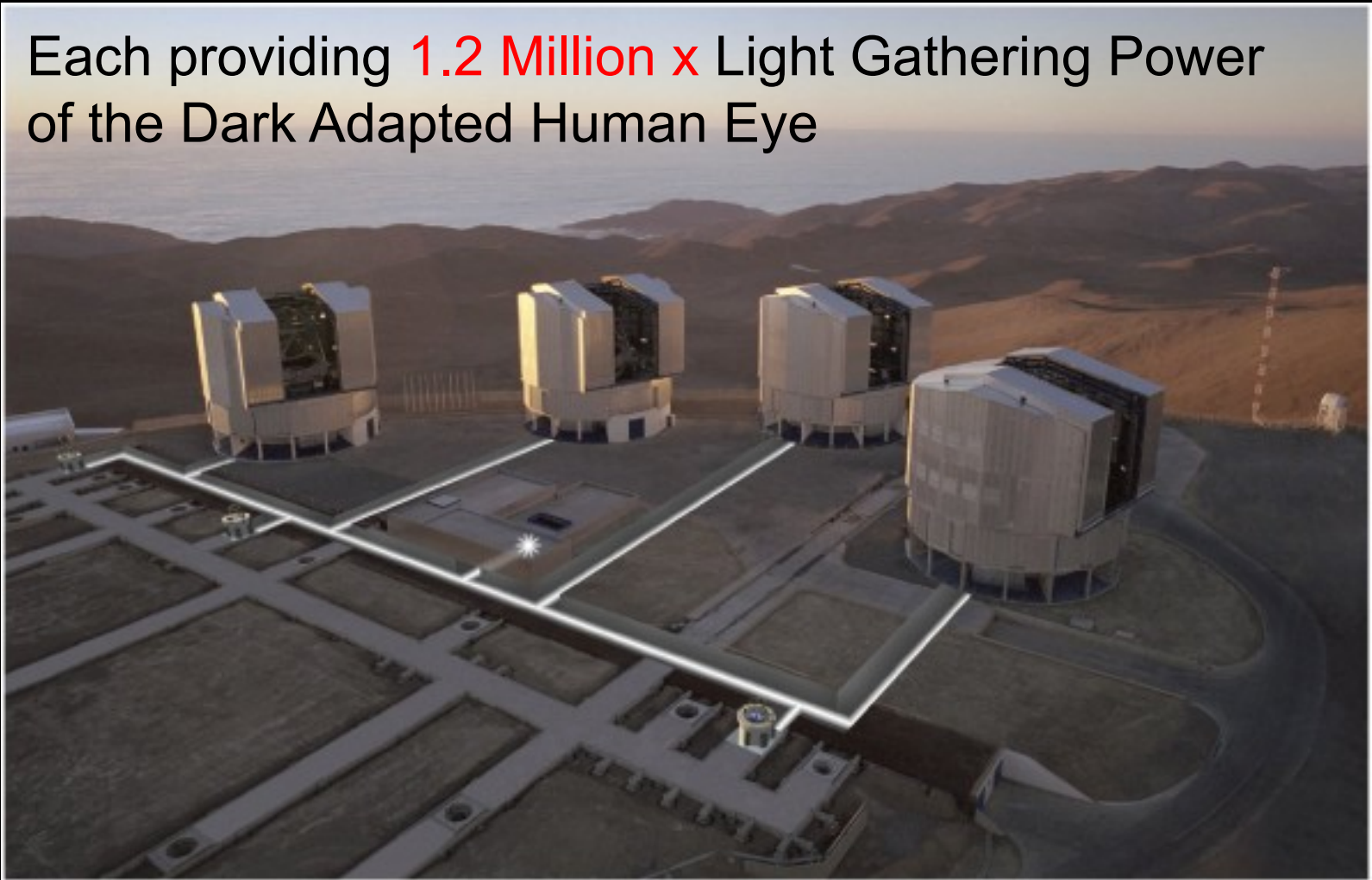
The Quest for Ever Larger Telescopes Continues.

Today →

Ever-bigger telescopes more deeply address the “photon-starved” (faint object) observational domain.

VLT Observatory. Four – 8.2 meter diameter telescopes.

Each providing **1.2 Million x** Light Gathering Power of the Dark Adapted Human Eye



Today's Largest (Mirror Diameter) Telescopes

Ever-bigger telescopes more deeply address the “photon-starved”
(faint object) observational domain.

Keck Observatory. “Twin” 10 meter diameter telescopes.

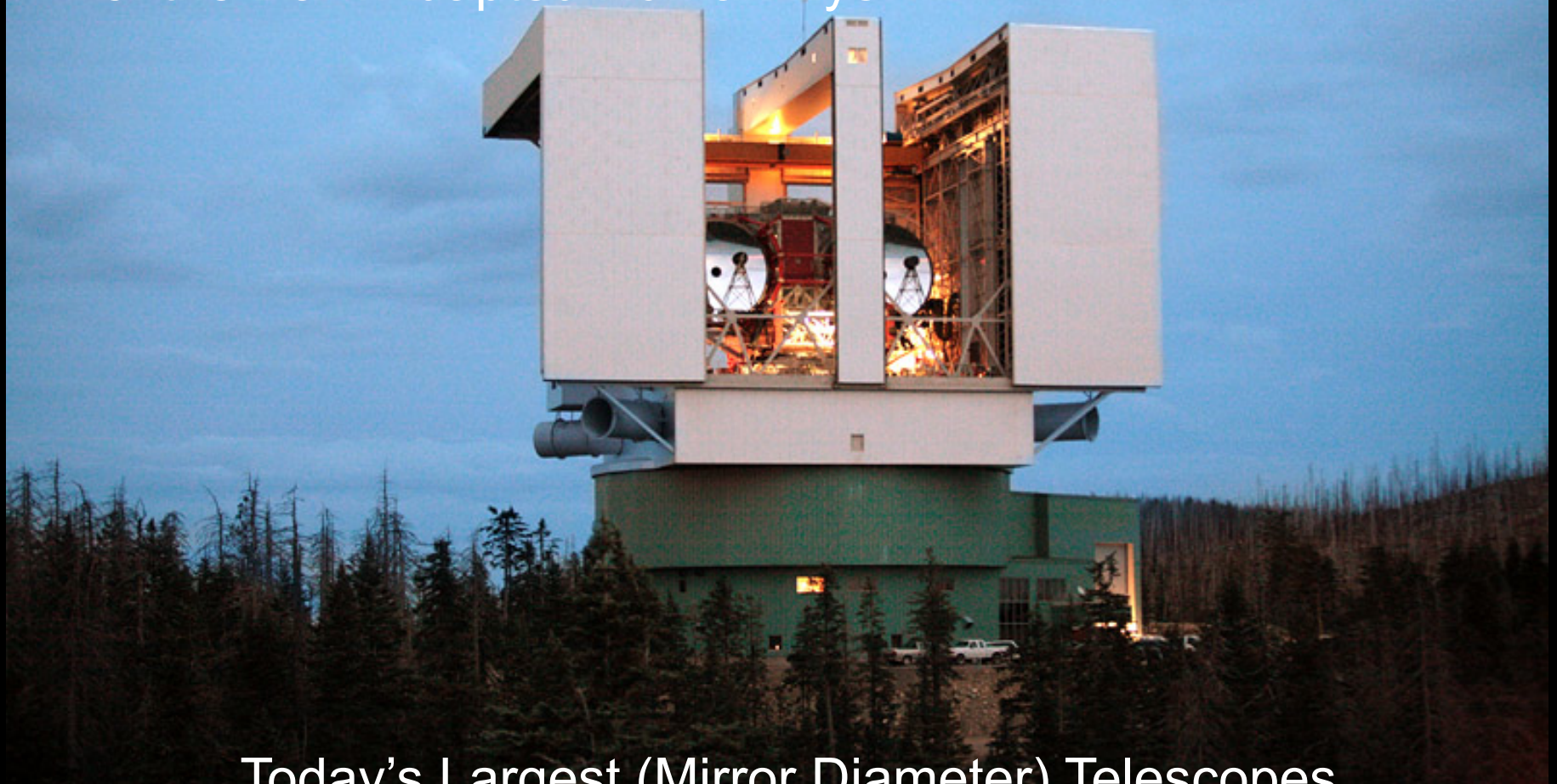
Each providing **1.8 Million x** Light Gathering Power
of the Dark Adapted Human Eye



Today's Largest (Mirror Diameter) Telescopes

Ever-bigger telescopes more deeply address the “photon-starved” (faint object) observational domain.

Large Binocular Telescope. Two 8.2 meter diameter telescopes with beam combining capability.
Together providing **2.4 Million x** Light Gathering Power of the Dark Adapted Human Eye

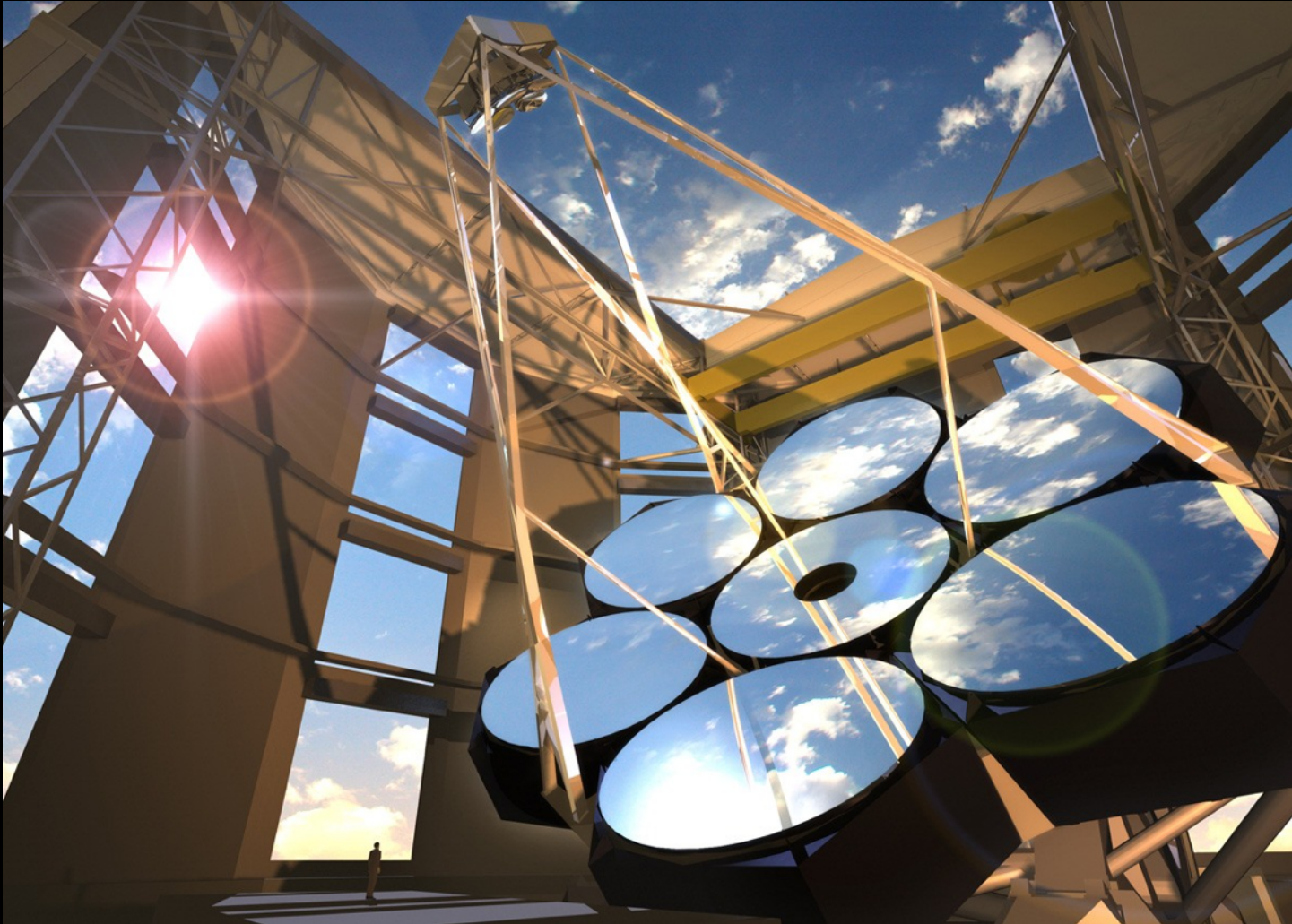


Today's Largest (Mirror Diameter) Telescopes

Ever-bigger telescopes more deeply address the “photon-starved”
(faint object) observational domain.

Giant Magellan Telescope – 20 meter diameter telescope

7.1 Million x Light Gathering Power of the Dark Adapted Human Eye



Under Construction

Ever-bigger telescopes more deeply address the “photon-starved”
(faint object) observational domain.

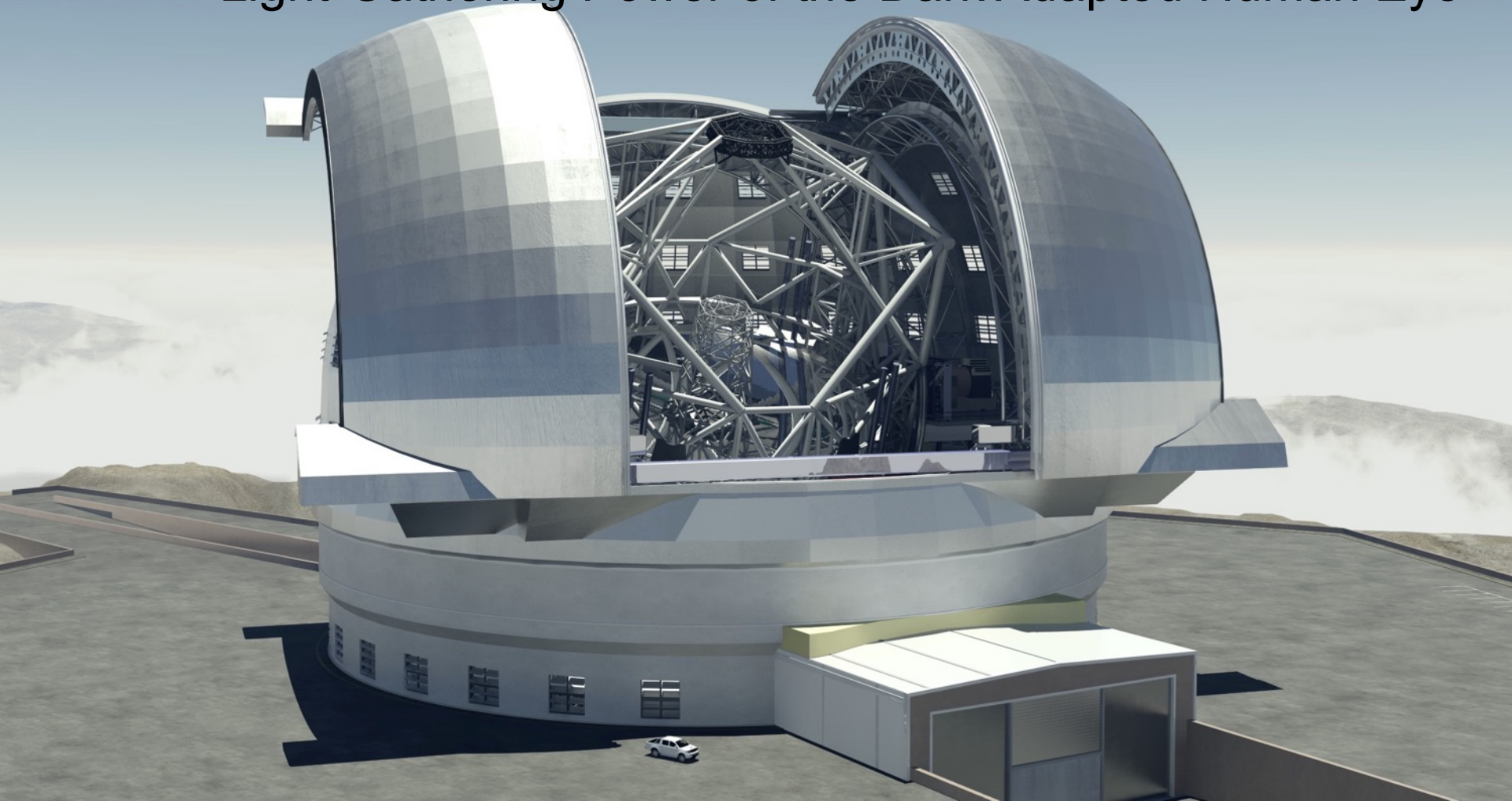
Thirty-Meter Telescope - Providing **16 Million x** Light Gathering
Power of the Dark
Adapted Human Eye



Proposed (site permitting in progress)

Ever-bigger telescopes more deeply address the “photon-starved”
(faint object) observational domain.

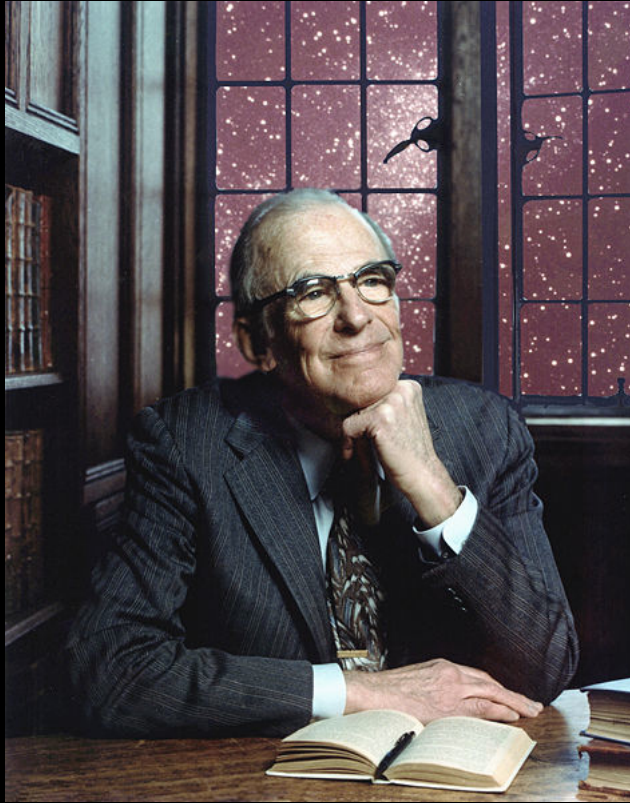
(E)ELT - Thirty-Nine Meter Telescope - Providing **31 Million x** the
Light-Gathering Power of the Dark Adapted Human Eye



Proposed (site development started)

A Earlier Inspiration – Put A Telescope Into Space!

Lyman Spitzer, Jr.



1914 - 1997

“Father of the Hubble Space Telescope”

1946

**Conceived Telescopes in
Space Concept***

1965

**Chaired National Academy of
Science Committee to Study a
Proposed “Large Space
Telescope (LST)”**

1975

NASA/ESA begin (LST) project

1977

Congress Approves Full Funding

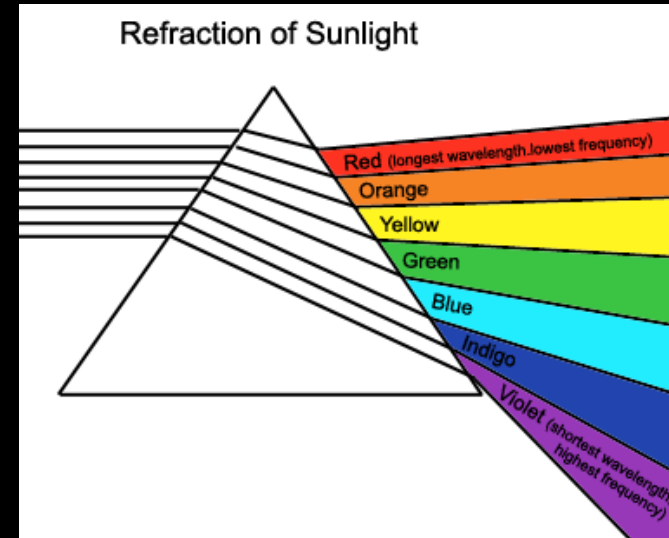
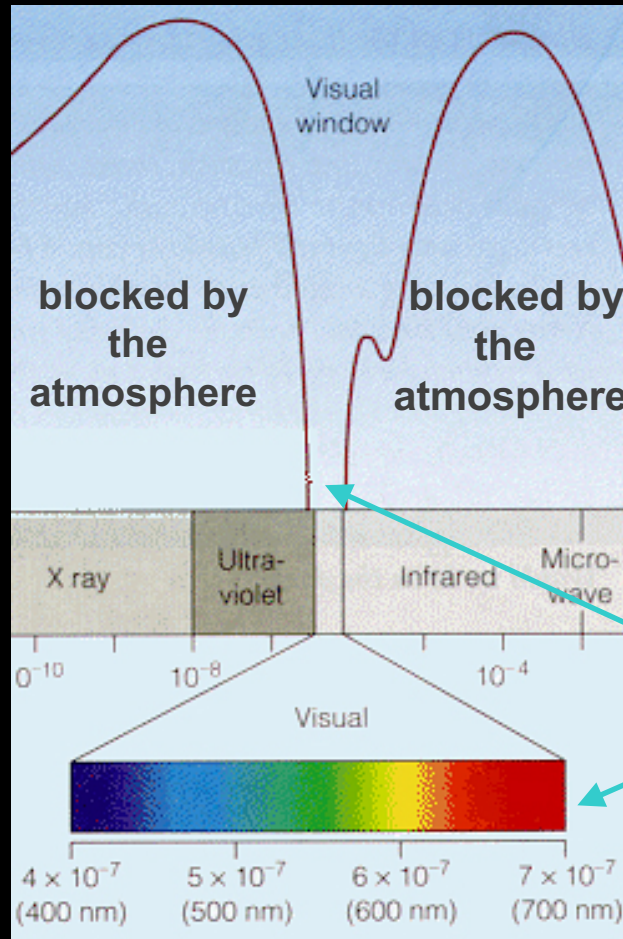
**“Astronomical advantages of an
extra-terrestrial observatory”*

Why Put An Telescope Into Space?

Not Limited by the Earth's Atmosphere:

TRANSMISSION

Unfettered Spectral Access from the **Ultra-Violet** to the **Infrared**



**Spectral Range of
Atmospheric
Transmission
and of Human
Visual Perception**

Visible-light is just a small part of the electro-magnetic spectrum

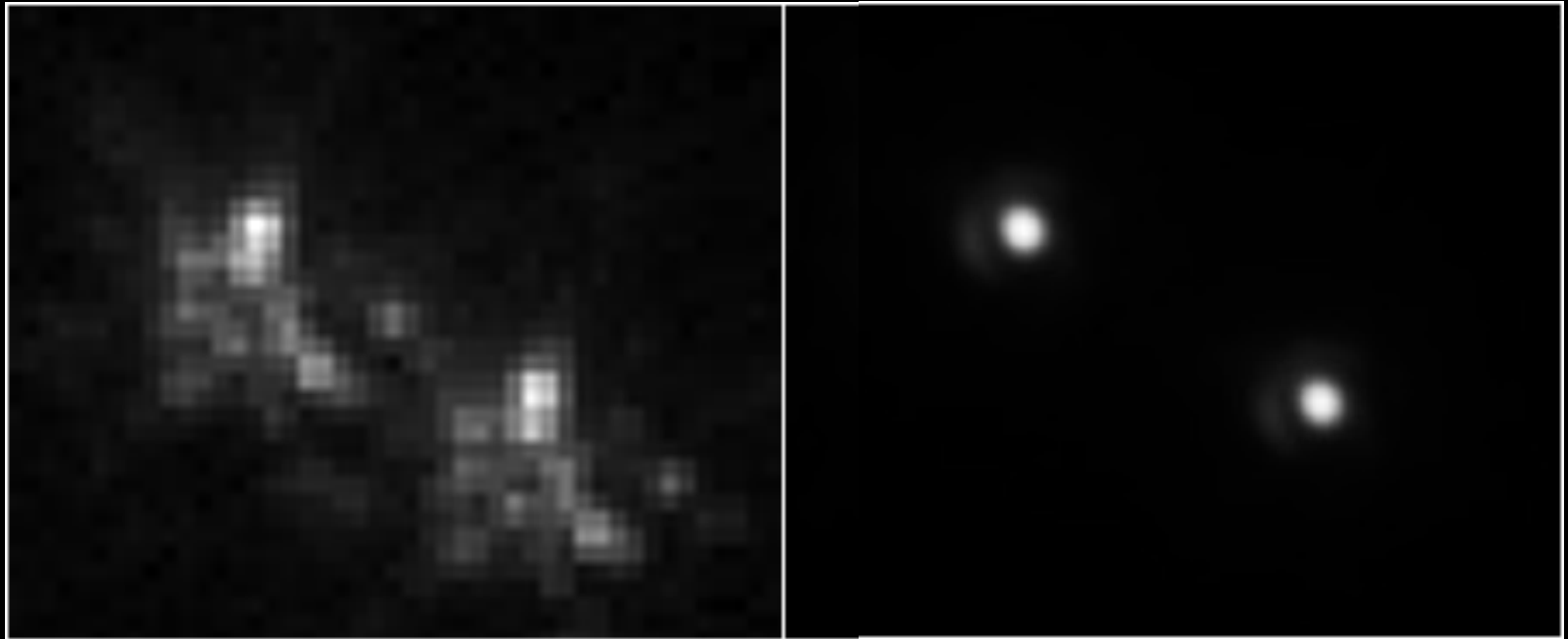
Why Put An Telescope Into Space?

Not Limited by the Earth's Atmosphere:

IMAGE CLARITY (“SEEING”)

No Blurring Due to Atmospheric Turbulence

Images of the Double Star Zeta Lepus



From the Ground

From Space

Why Put An Telescope Into Space?

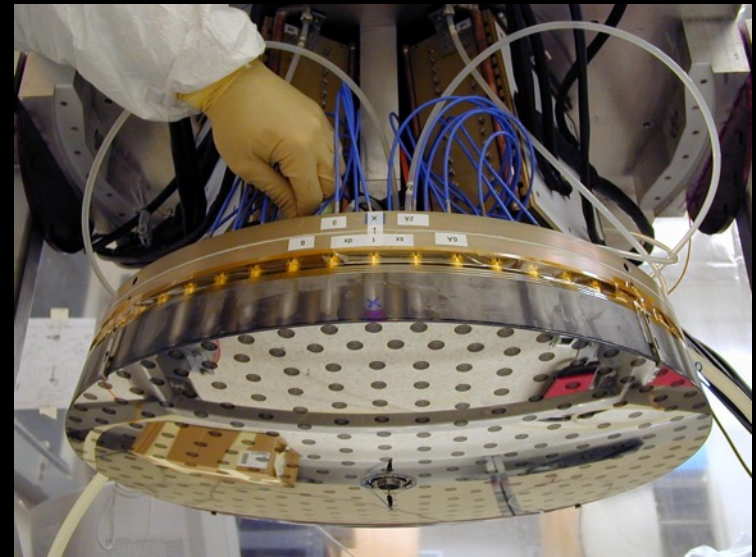
Not Limited by the Earth's Atmosphere:

IMAGE CLARITY (“SEEING”)

No Blurring Due to Atmospheric Turbulence

Today's large ground-based telescopes with *Adaptive Optics*:

- **Work best at near-IR and longer wavelengths (not VIS or UV light)**
- **Provide only partial corrections to atmospheric disturbances (e.g. “Strehl ratio”)**
- **Have only very narrow field-angle correction capability (iso-planatic angle)**



**The University of Arizona's
MMT adaptive secondary mirror
(before shell reflective coating)**

Why Put An Telescope Into Space?

Not Limited by the Earth's Atmosphere:

IMAGE RESOLUTION (Diffraction Limited)

Set by the size of the telescope mirror (HST: 94-inch diameter)

With **Ultra-Violet** to **near-IR** sensitive instruments:

→ “Diffraction Limited” Seeing = **50 milli-arcsec in “visible”**
10 milli-arcsec in the UV*
(= 0.000003°)

*Resolution: 50 feet at the distance
of the Moon @ 1000 Å

ALSO:

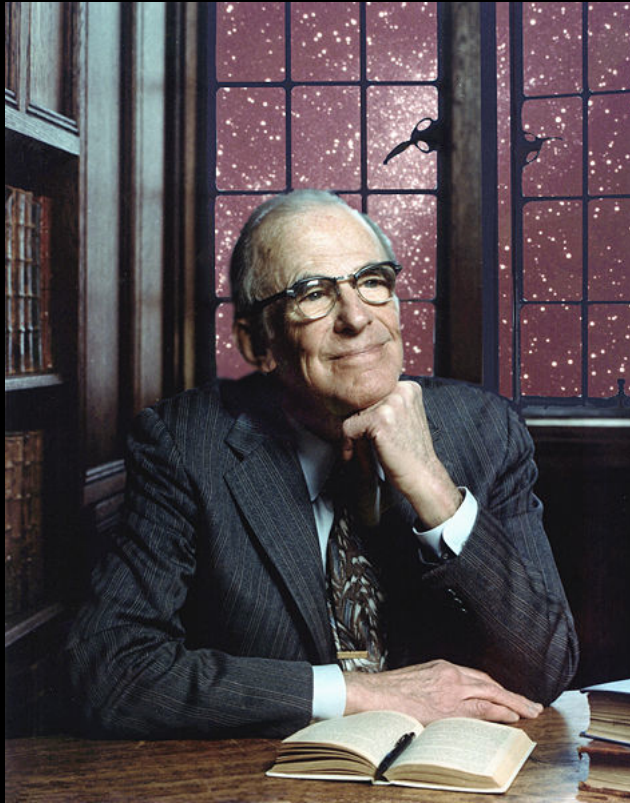
- *Very Dark Sky Background*

**Sensitivity: Can detect a lit match at
the distance of the Moon**



Why Put An Telescope Into Space?

Lyman Spitzer, Jr.



1914 - 1997

“Father of the Hubble Space Telescope”

**The Hubble Space Telescope
Key Project on the
Extragalactic Distance Scale**

**To Determine the
Hubble Constant, H_0
to an accuracy of
10% (or better)**

**Thus to measure the
Age of the Universe...**

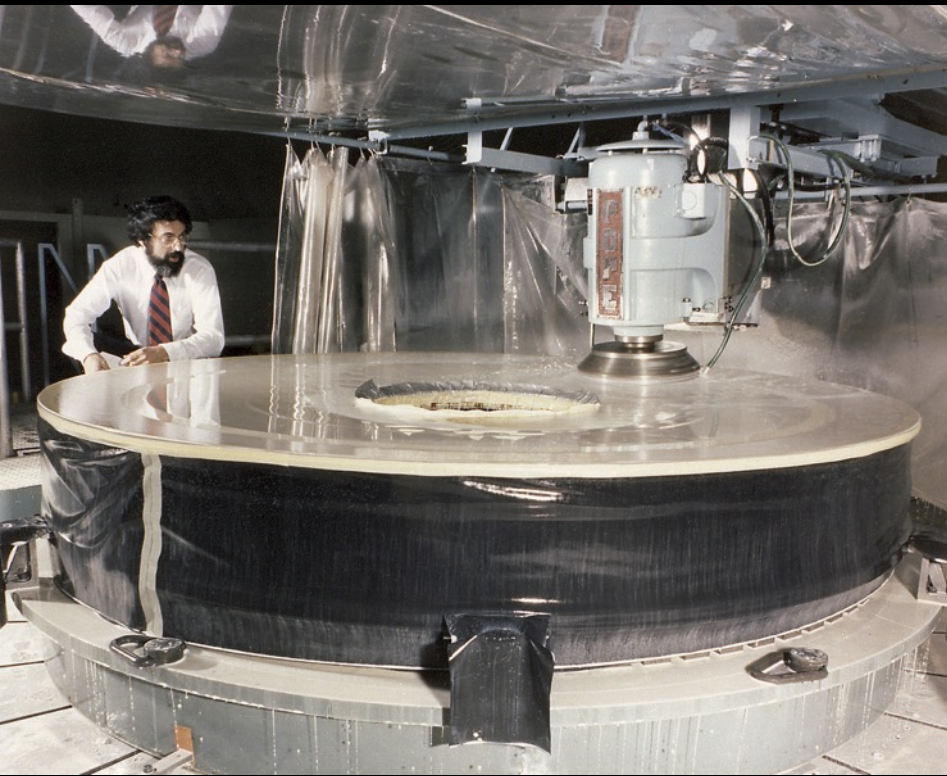
1977

**Congress Approves Full
Funding for “LST*”**

***LST “married” to the Shuttle program as the ticket to space.**

Hubble Space Telescope (HST)

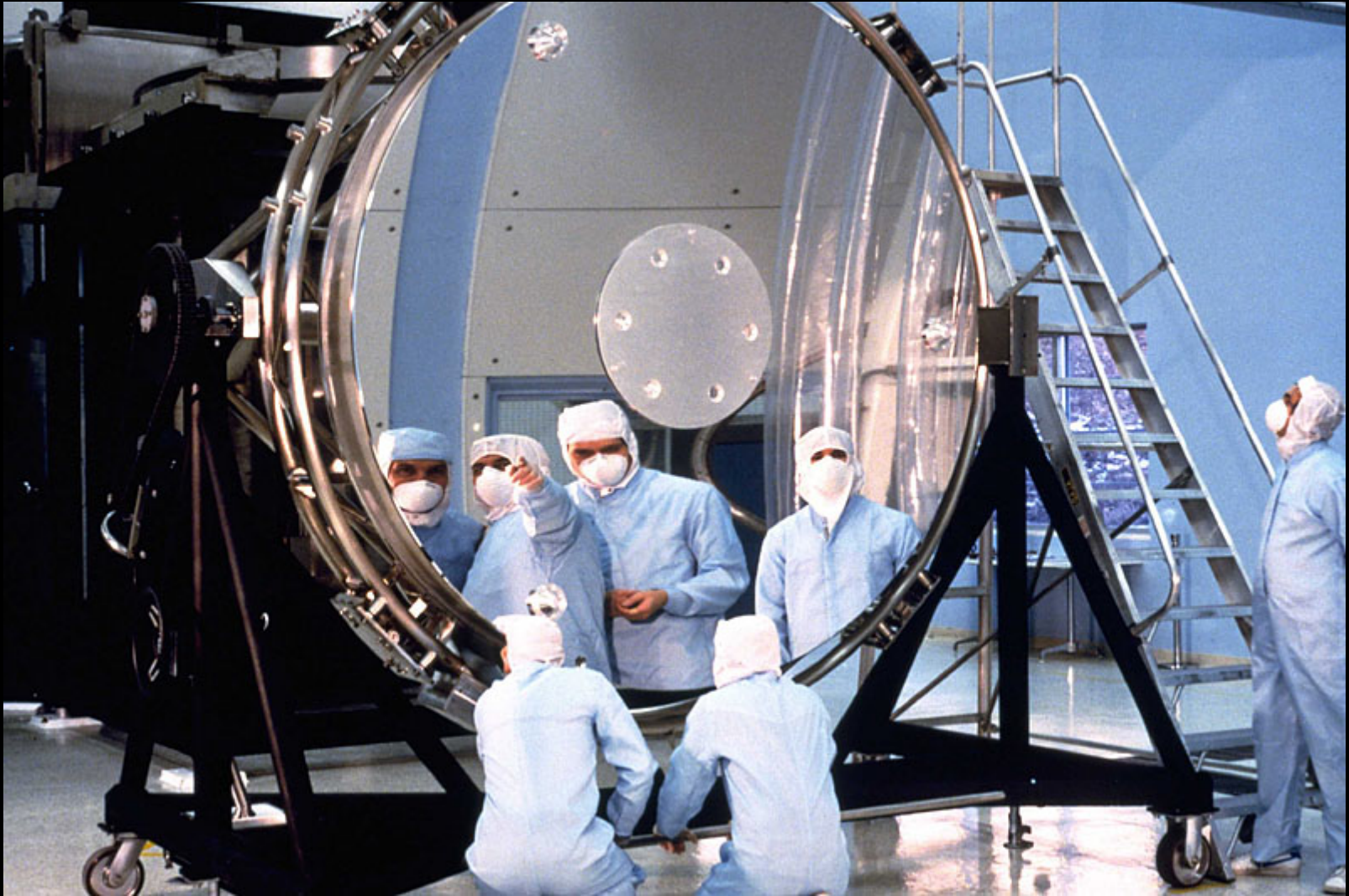
94-inch Diameter Primary Mirror Fabrication at Perkin-Elmer Corp.



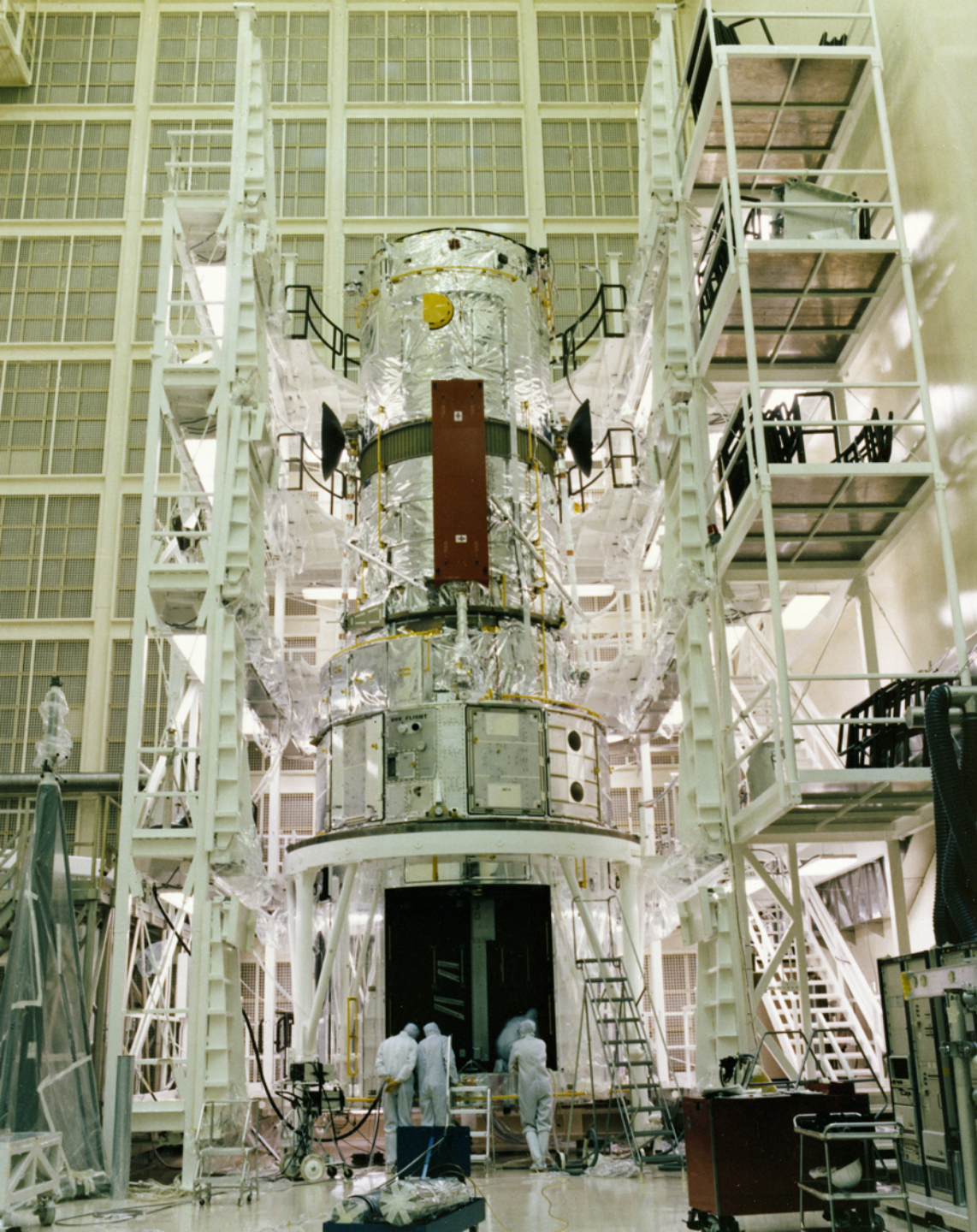
**1979 – 1981: Grinding and Polishing the HST Primary Mirror
(The “Heart of Hubble”)**

Hubble Space Telescope (HST)

94-inch Diameter Primary Mirror Inspection at Perkin-Elmer Corp.



**1982 – The World's “Most Perfect” Telescope Mirror
8 ft diameter, 1820 lbs.**



Hubble Space Telescope (HST)

*In Assembly at LMSC
Sunnyvale, CA*

01 Jan 1986

Length: 43 ft 6 in

Diameter: 14 ft

Weight: 25, 500 lbs



Tragic Loss of Space Shuttle Challenger STS-51L

28 Jan 1986

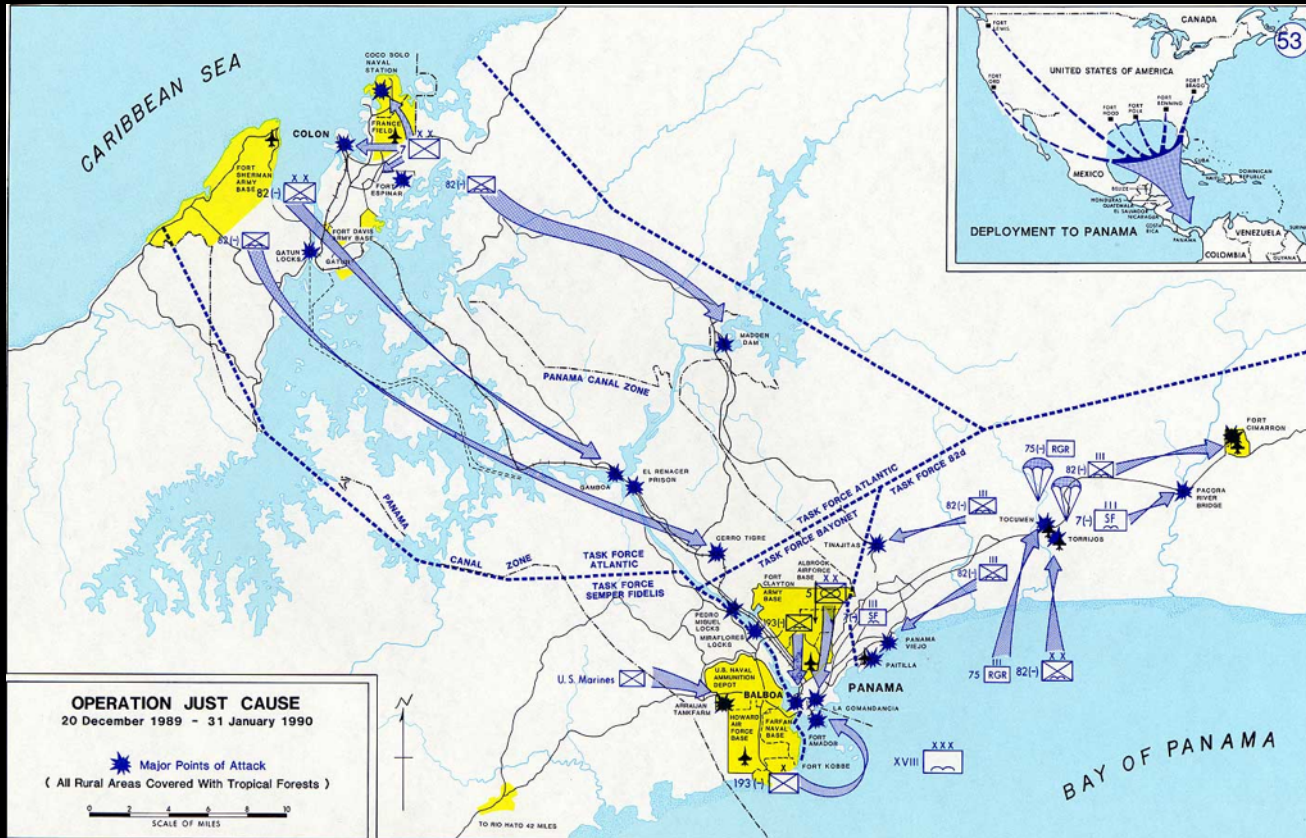
**Causes
Hubble launch
delay to 1990**





Hubble Space Telescope (HST)

Original Plan was to Barge Through Panama Canal, Dec. 1989, but...



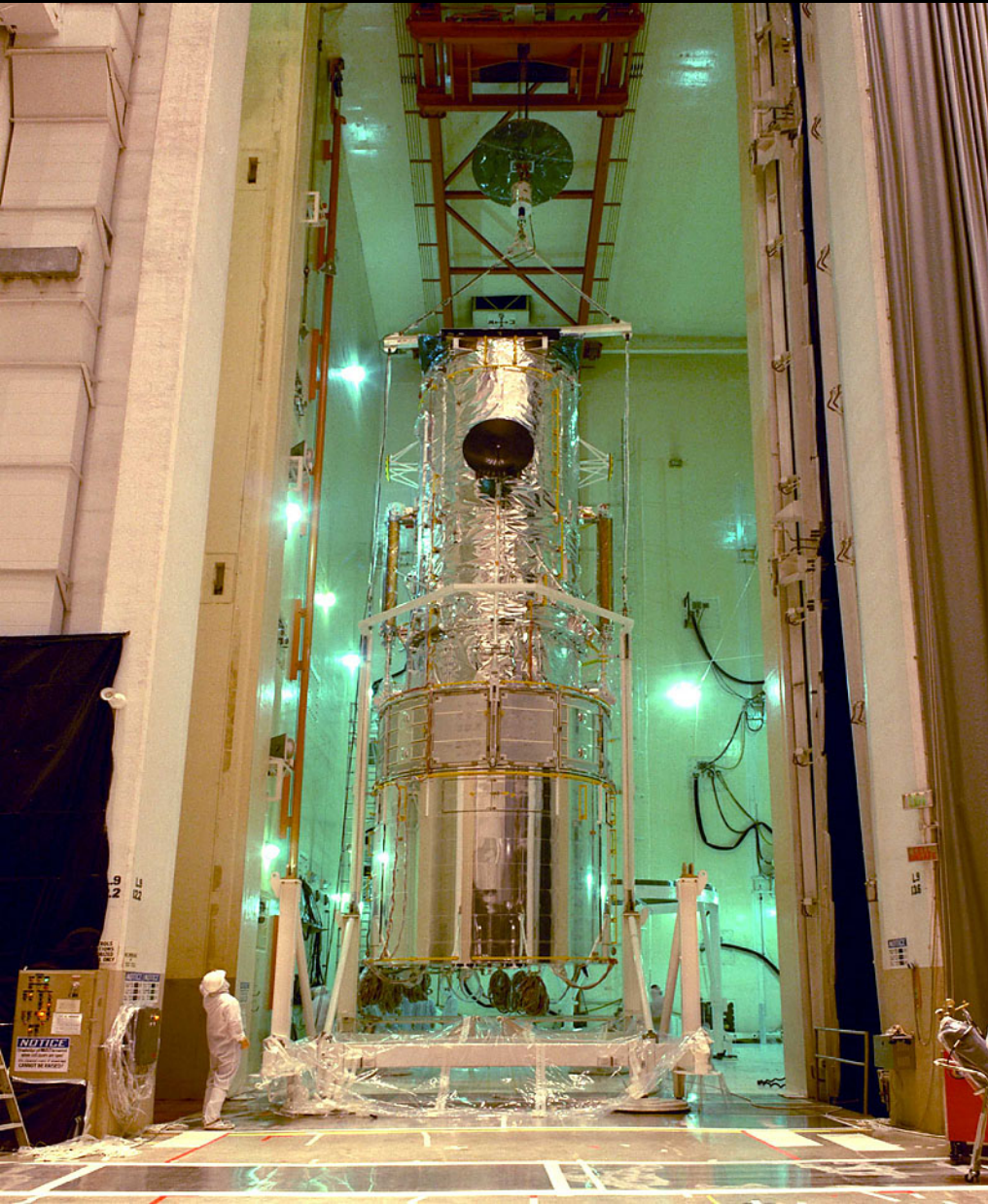
Hubble Space Telescope (HST)

Plan B: Getting a Ride to KSC in NASA's "Super Guppy"



Hubble Space Telescope (HST)

Fully Assembled at Kennedy Space Center



**In the
Vertical Processing Facility
in preparation for launch
aboard the Space Shuttle
Discovery**

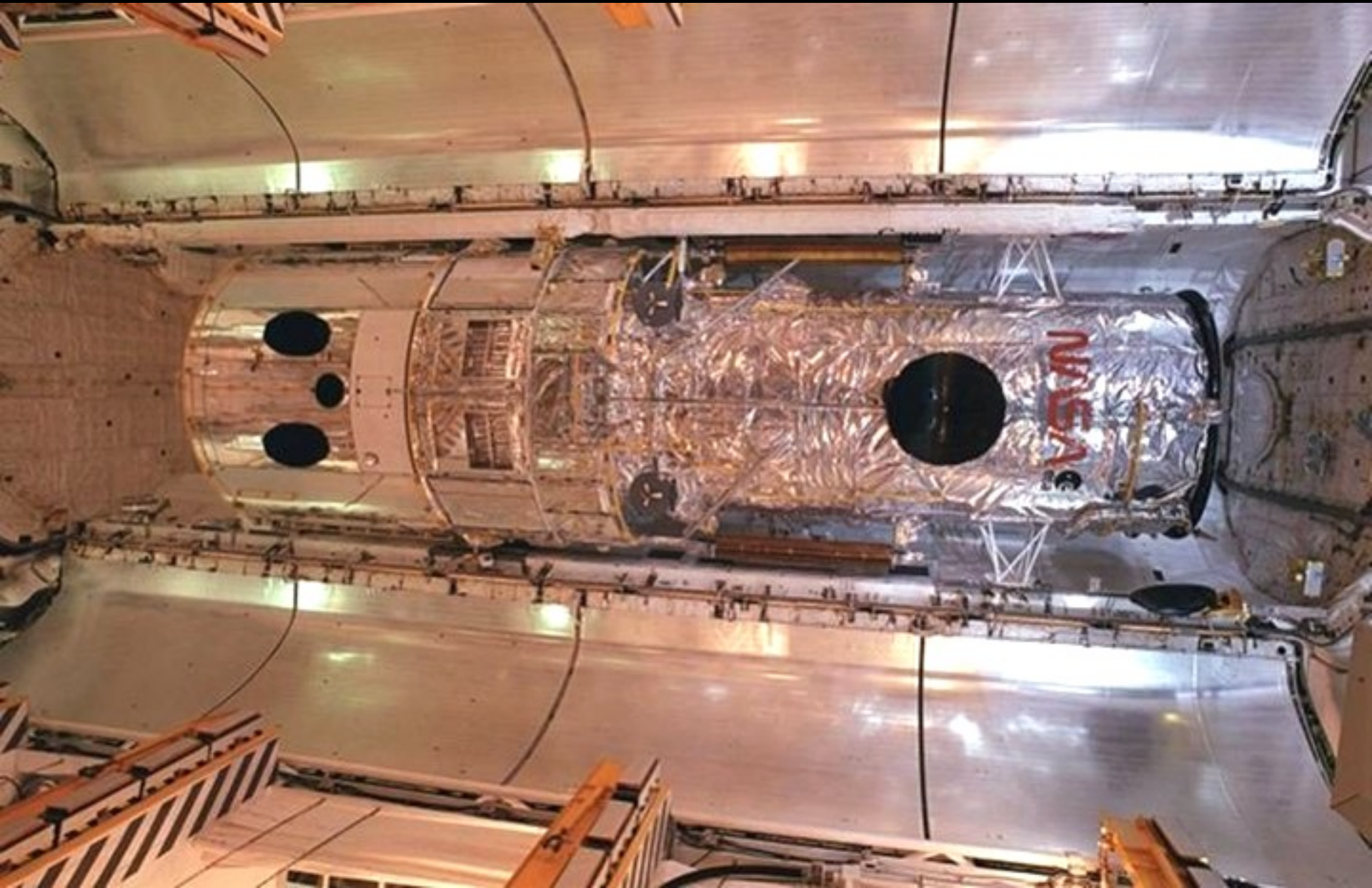
Original (5+) Science Instruments

- **Wide-Field/Planetary Camera**
- **Faint Object Camera**
- **High Resolution Spectrograph**
- **Faint Object Spectrograph**
- **High Speed Photometer**
- + **Fine Guidance Sensors**

Imaging: morphology/structure,
Spectroscopy: composition/velocity,
Photometry: brightness/variability,
Astrometry: relative position/motions

Hubble Space Telescope (HST)

“Just Fits” in the Space Shuttle Cargo Bay



Hubble Space Telescope (HST)

T+12 seconds!

LIFTOFF!

April 24, 1990

HST rides to orbit

(44 years after conception)



Hubble Space Telescope (HST)

“Hello World!”

R. Giacconi E. Schrier G. Schneider R. Doxsey

**“ALIVENESS
TEST”**

**1:42 AM EST
25 APRIL 1990**

**STScI,
Baltimore, MD**



Hubble Space Telescope (HST)

Deployment -- The Hubble Space Telescope is “Born”

Release

**From the Shuttle
Cargo Bay.**

**“Ungrapple”
with the
Remote
Manipulator
Arm**



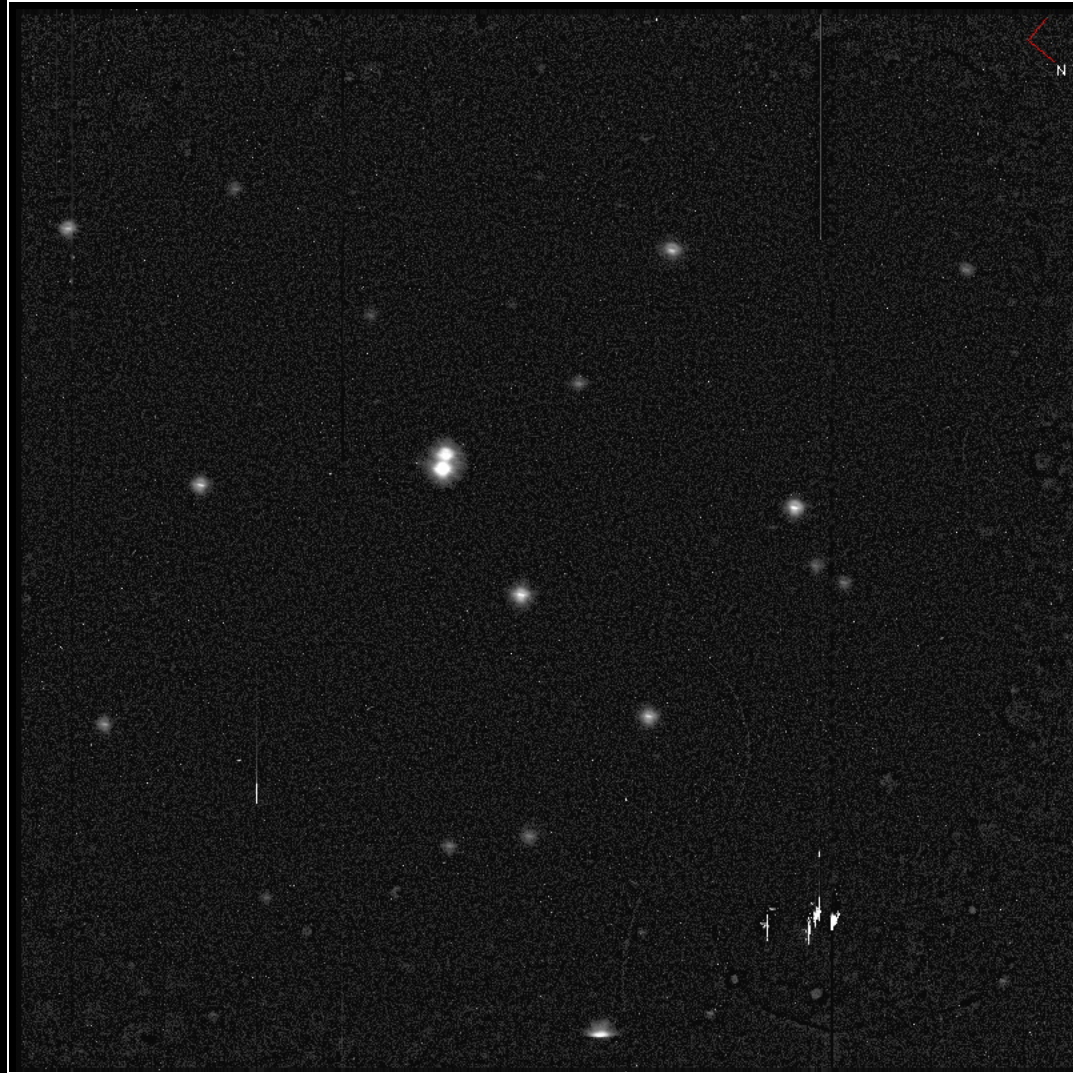
Hubble Space Telescope (HST)

20 May 1990 — Wide-Field/Planetary Camera

“1st Light” Image



**cross-check with
“deeper”
imaging in the
Faint-Object Camera**

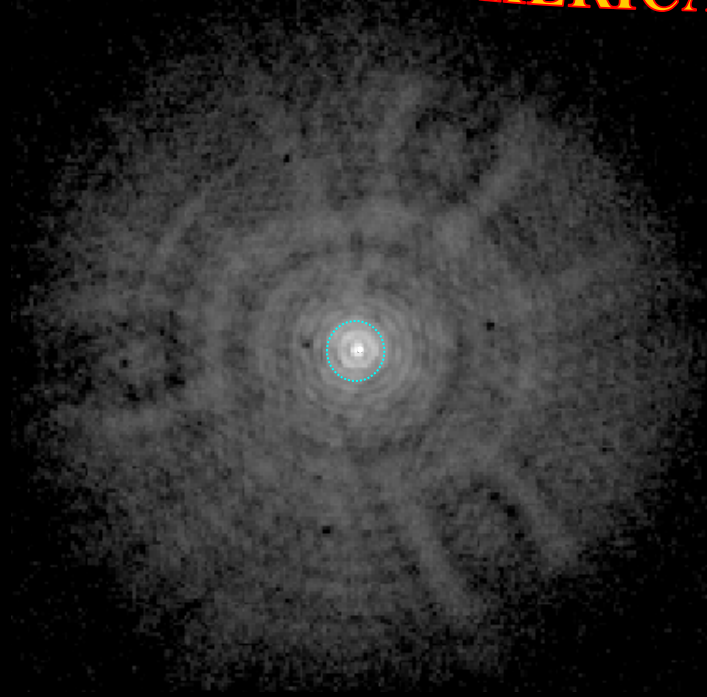


Hubble Space Telescope (HST)

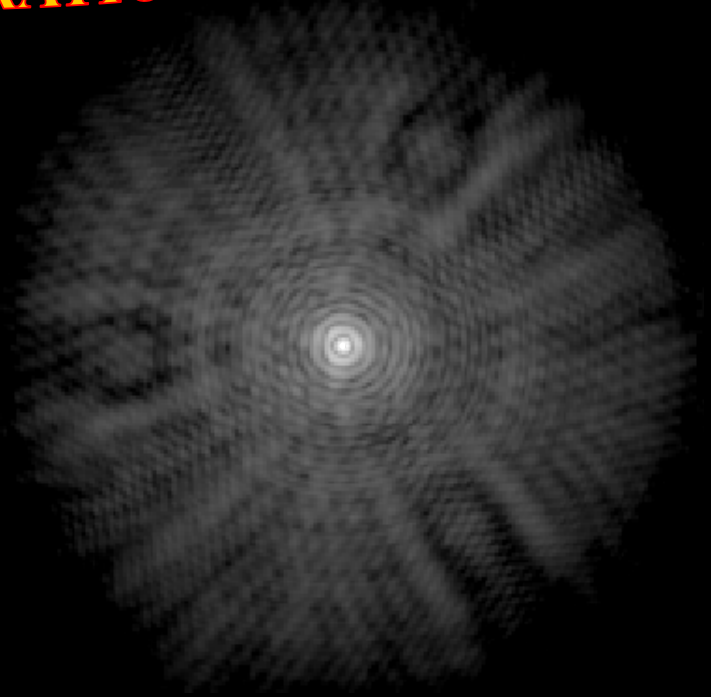
*A Nearly-Perfect
Mirror...*

SPHERICAL ABERRATION

*Ground to the
Wrong Shape!*



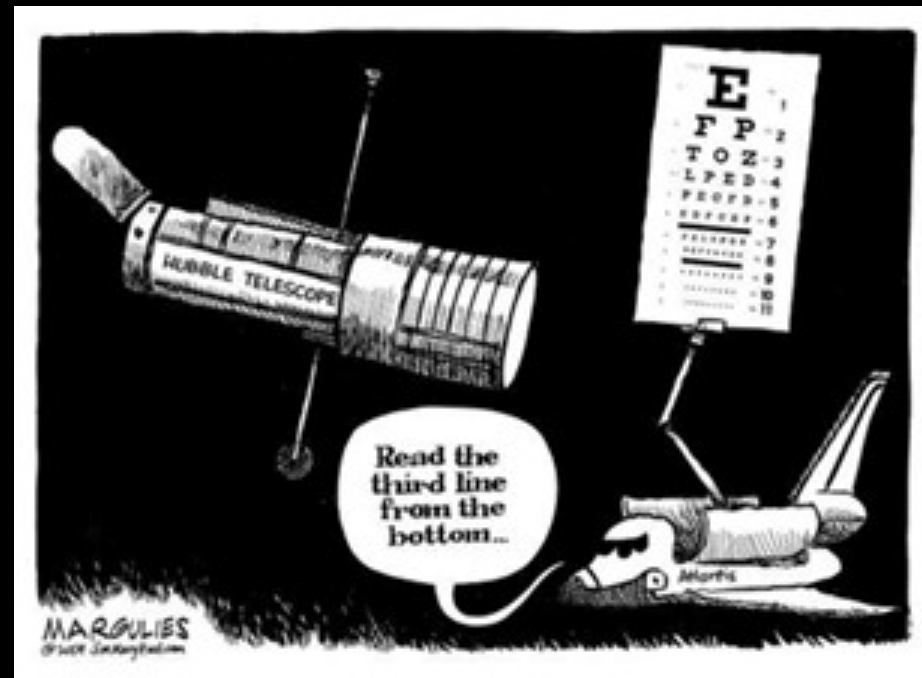
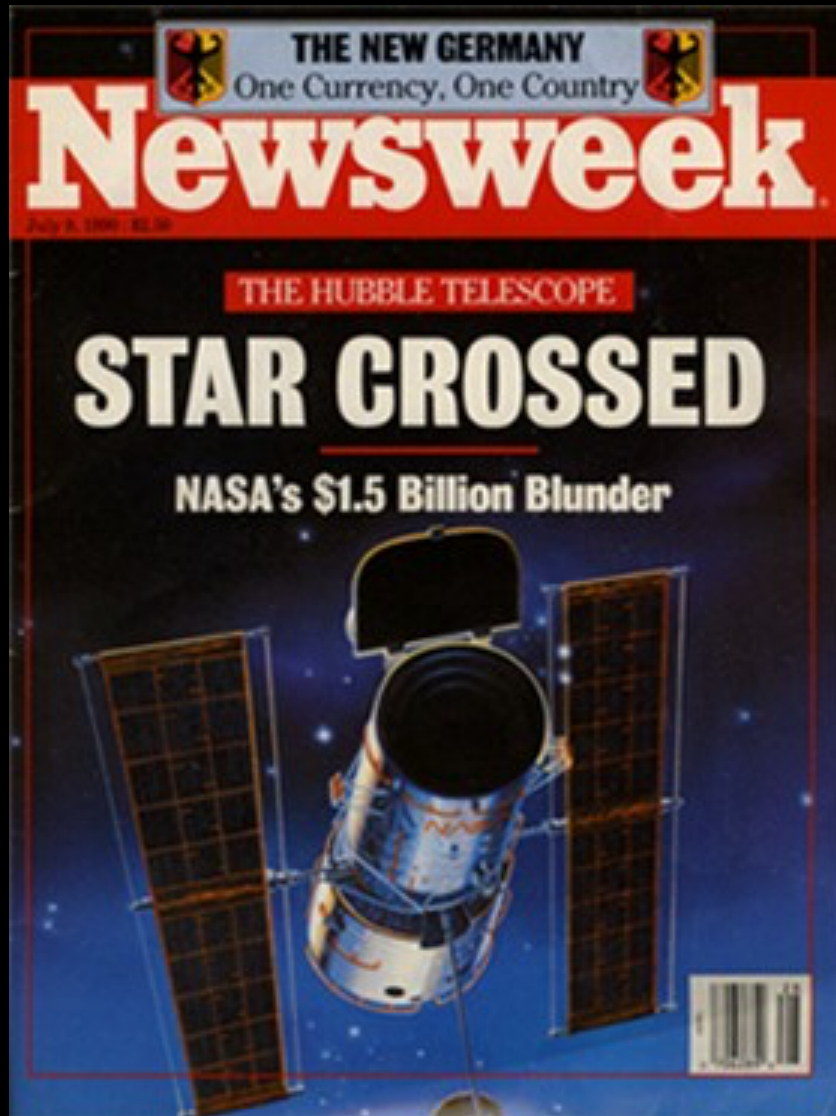
FOC OBSERVED



FOC MODEL

*Outer-Edge of 8 ft dia. mirror too flat
by 0.00008 inches
(~ 1/50 width of a human hair)*

SPHERICAL ABERRATION



Hubble Space Telescope (HST)

94-inch Telescope in “Low” Earth Orbit - Launched in April 1990

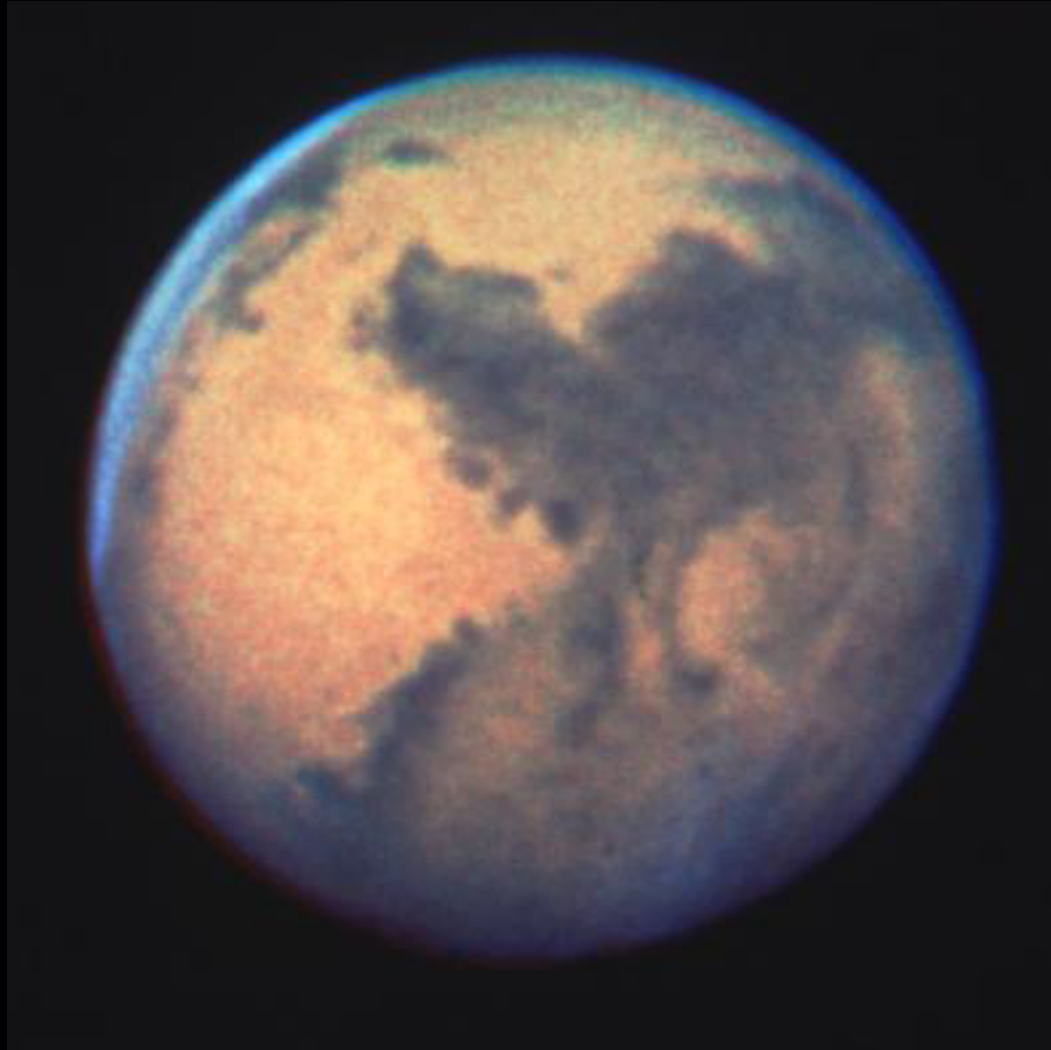
EVEN SO (1990-1993)...

[in parallel with working the problem]



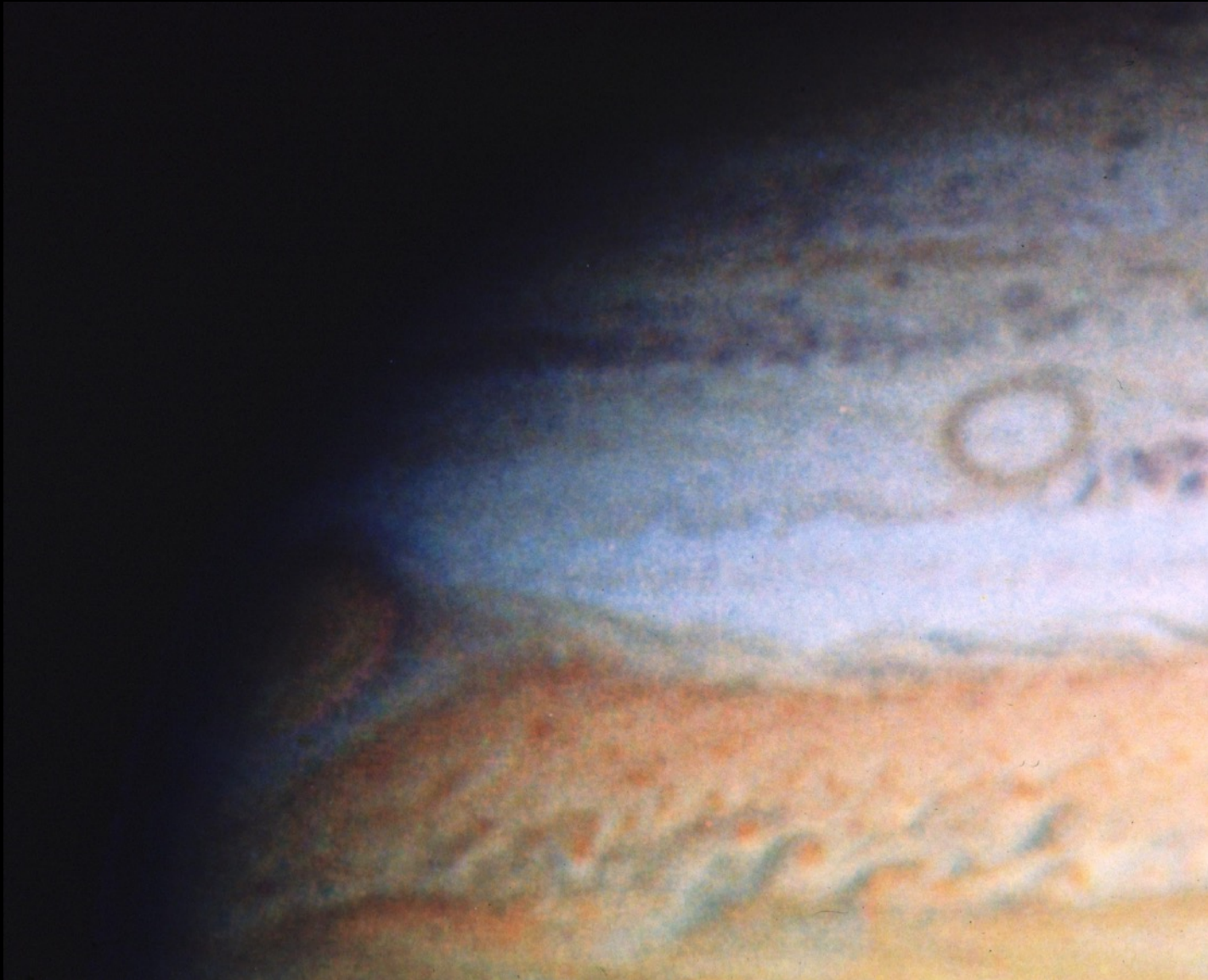
Hubble Space Telescope (HST)

Mars at Opposition



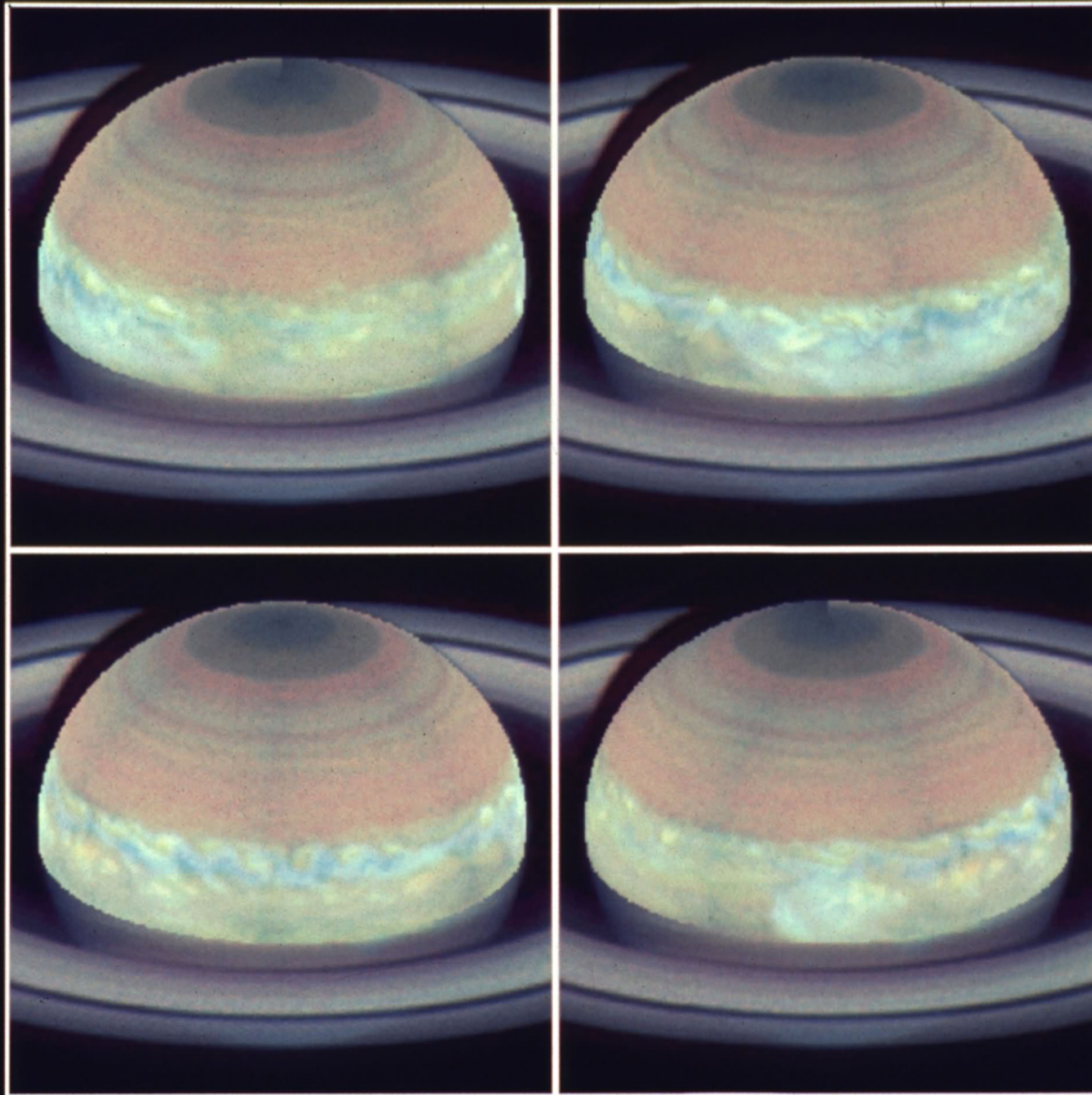
Hubble Space Telescope (HST)

1st Look at Jupiter



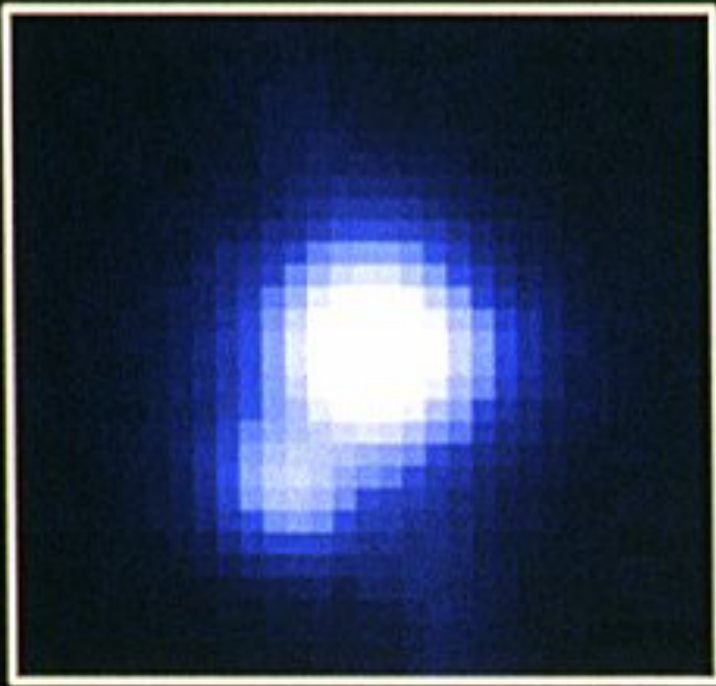
Hubble Space Telescope (HST)

Saturn's North Polar Region and Equatorial Storm

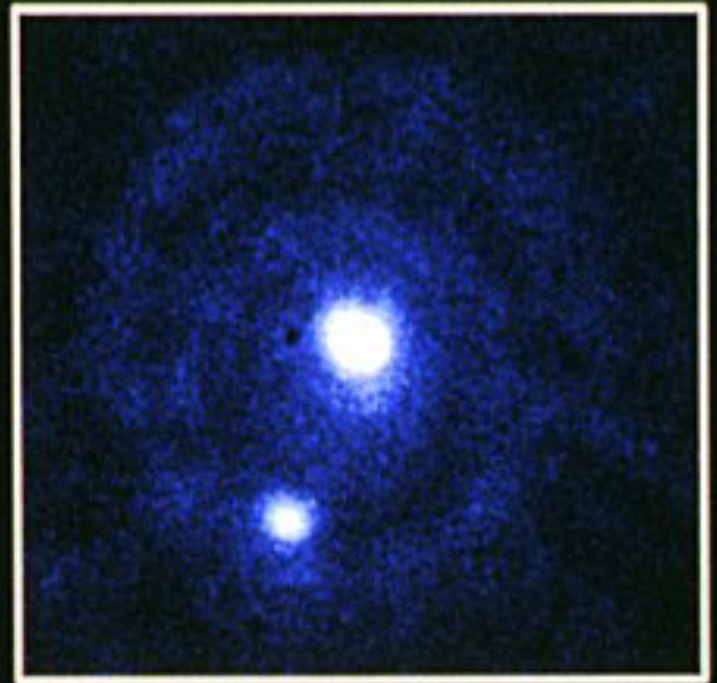


Hubble Space Telescope (HST)

Pluto (when it was still a planet) / Charon



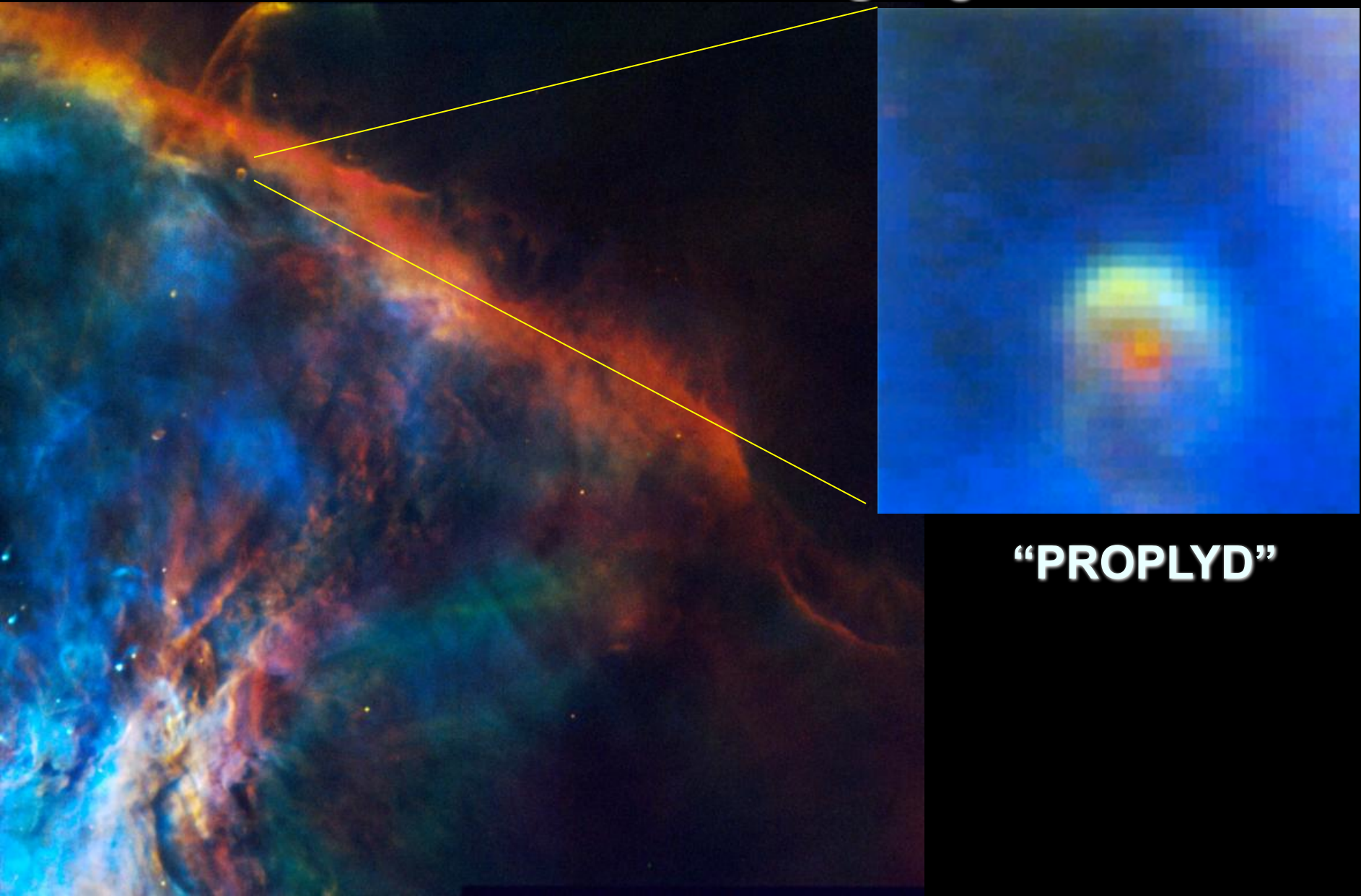
Ground Based



HST/FOC

Hubble Space Telescope (HST)

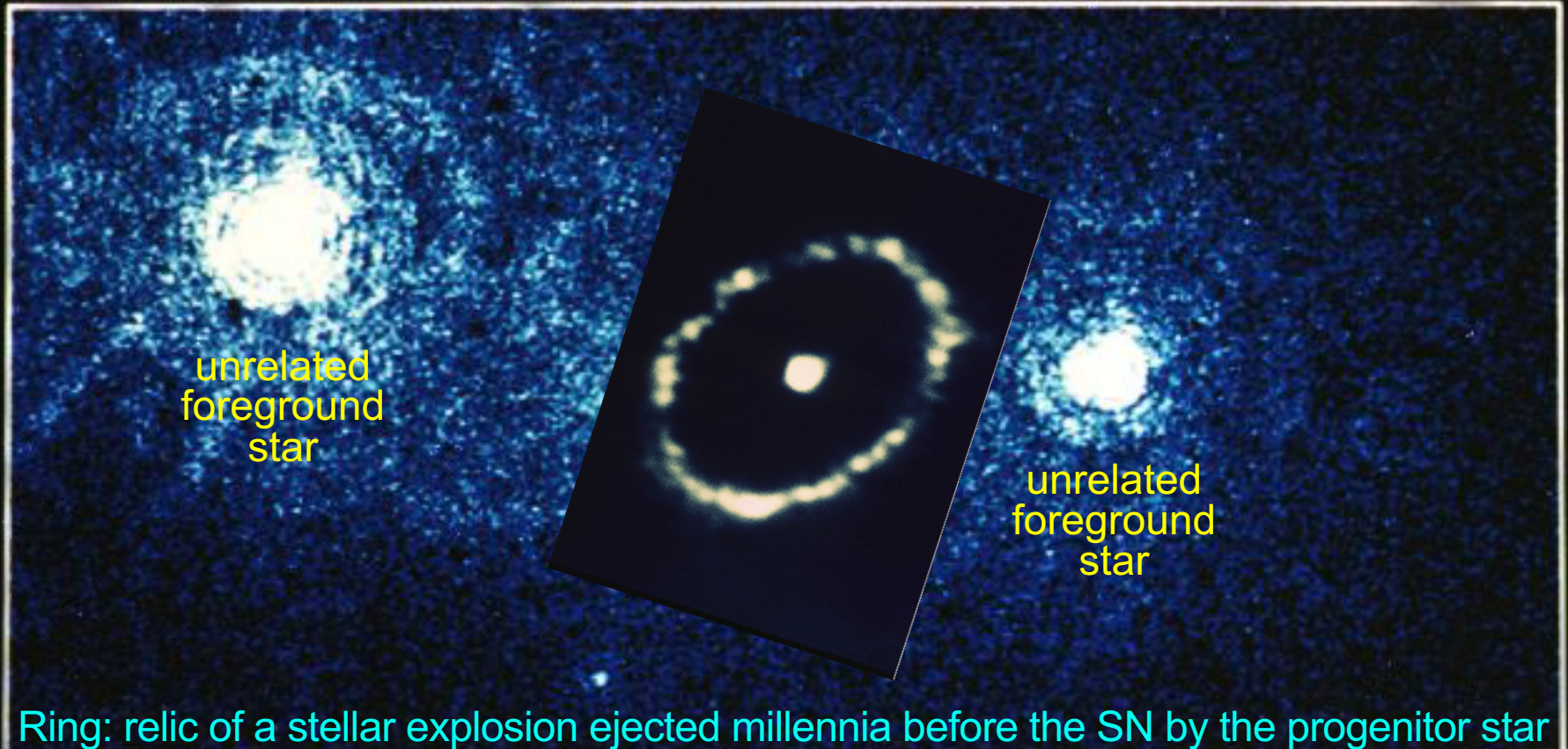
Orion Nebula - Star Forming Region



“PROPLYD”

Hubble Space Telescope (HST)

Super-Nova 1987a in the LMC



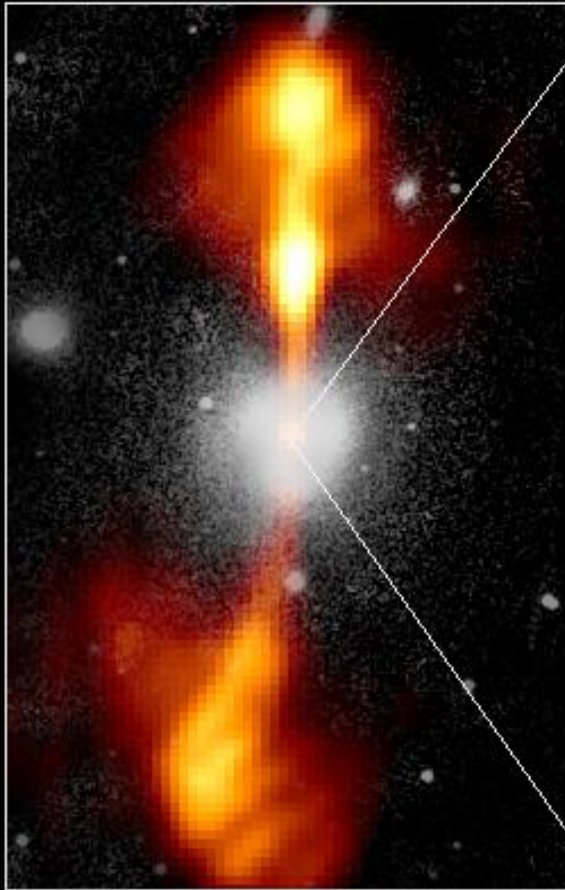
A supernova in the nearby (168,000 ly) satellite galaxy to our Milky Way, the Large Magellanic Cloud. The closest SN to Earth observed since 1604 (before the invention of the telescope)! HST continue to monitor...

Hubble Space Telescope (HST)

The CORE of NGC 4261

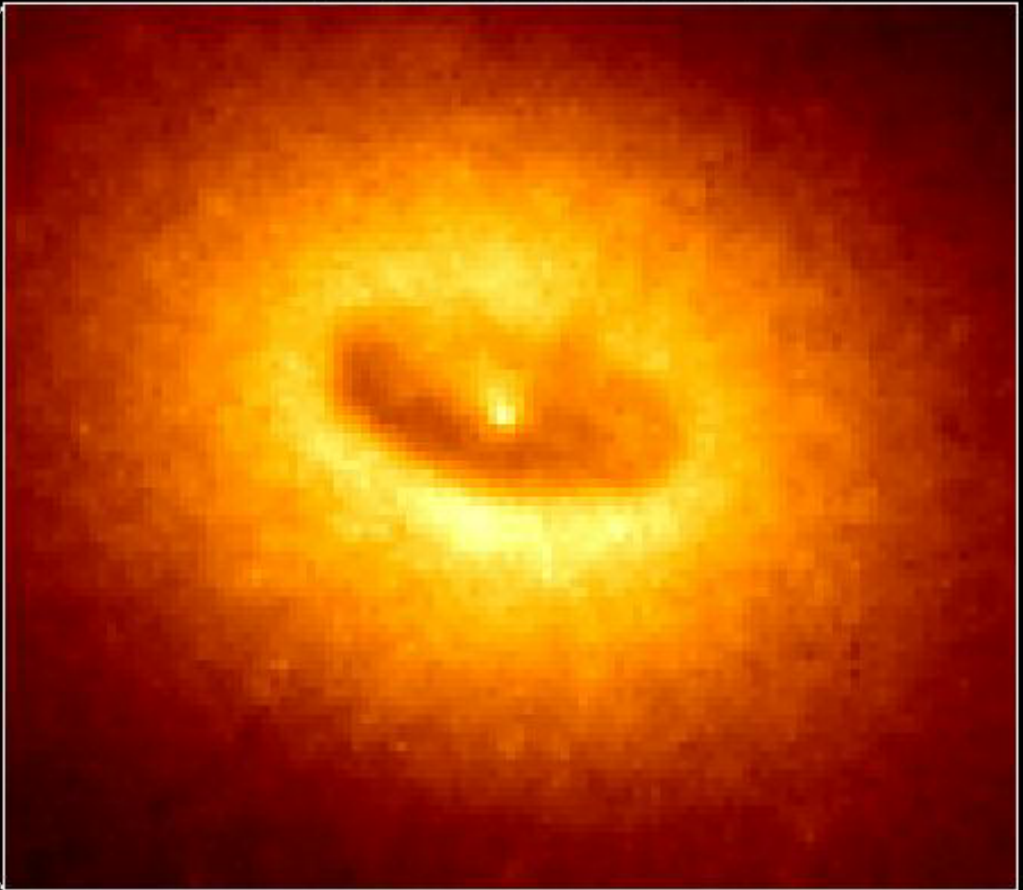
Circum-Nuclear Dust Disk Fueling a Black Hole

Ground-Based Optical/Radio Image



380 Arc Seconds
88,000 LIGHT-YEARS

HST Image of a Gas and Dust Disk

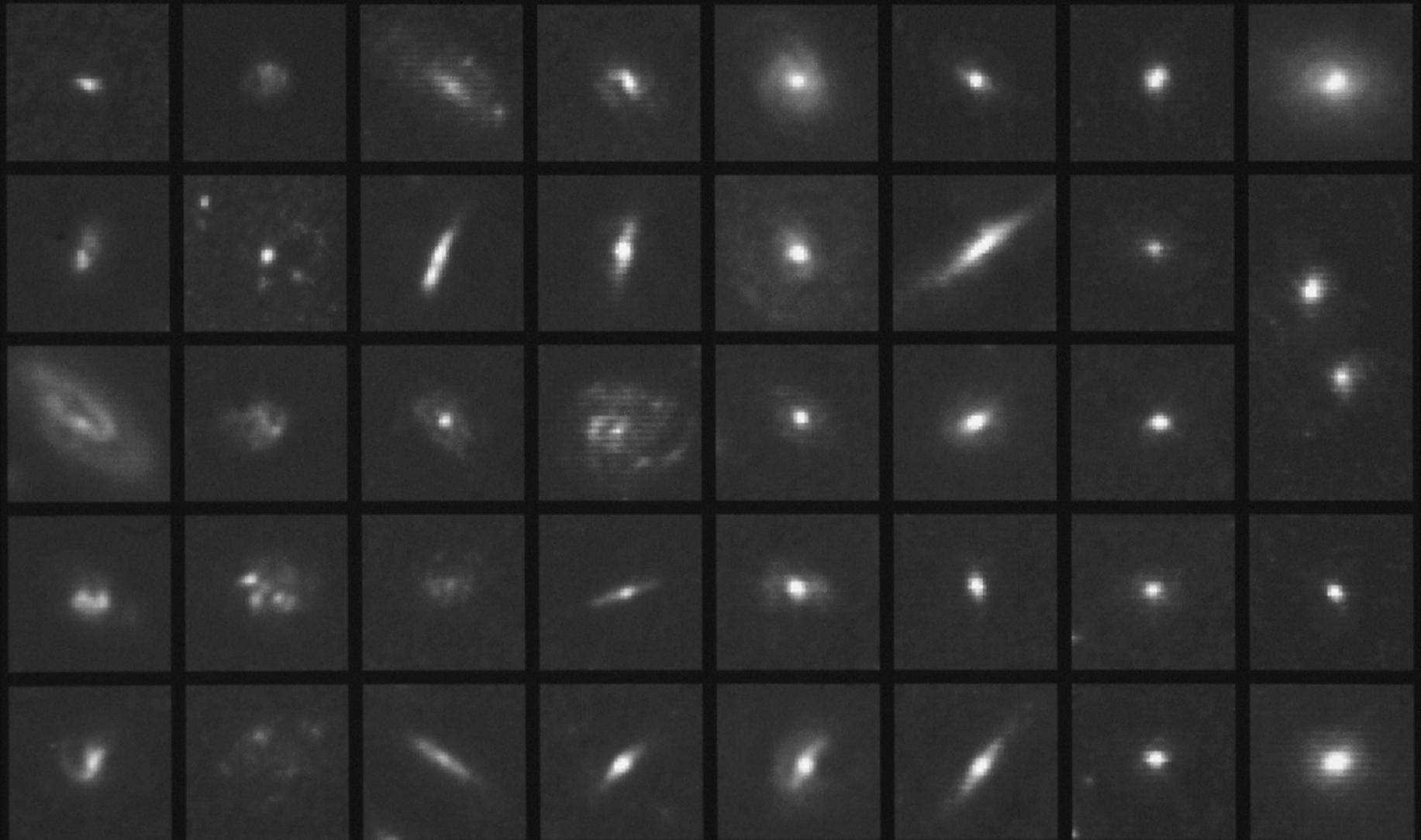


17 Arc Seconds
400 LIGHT-YEARS

Confirmation of predicted accretion disk driving polar jets seen at radio wavelengths

Hubble Space Telescope (HST)

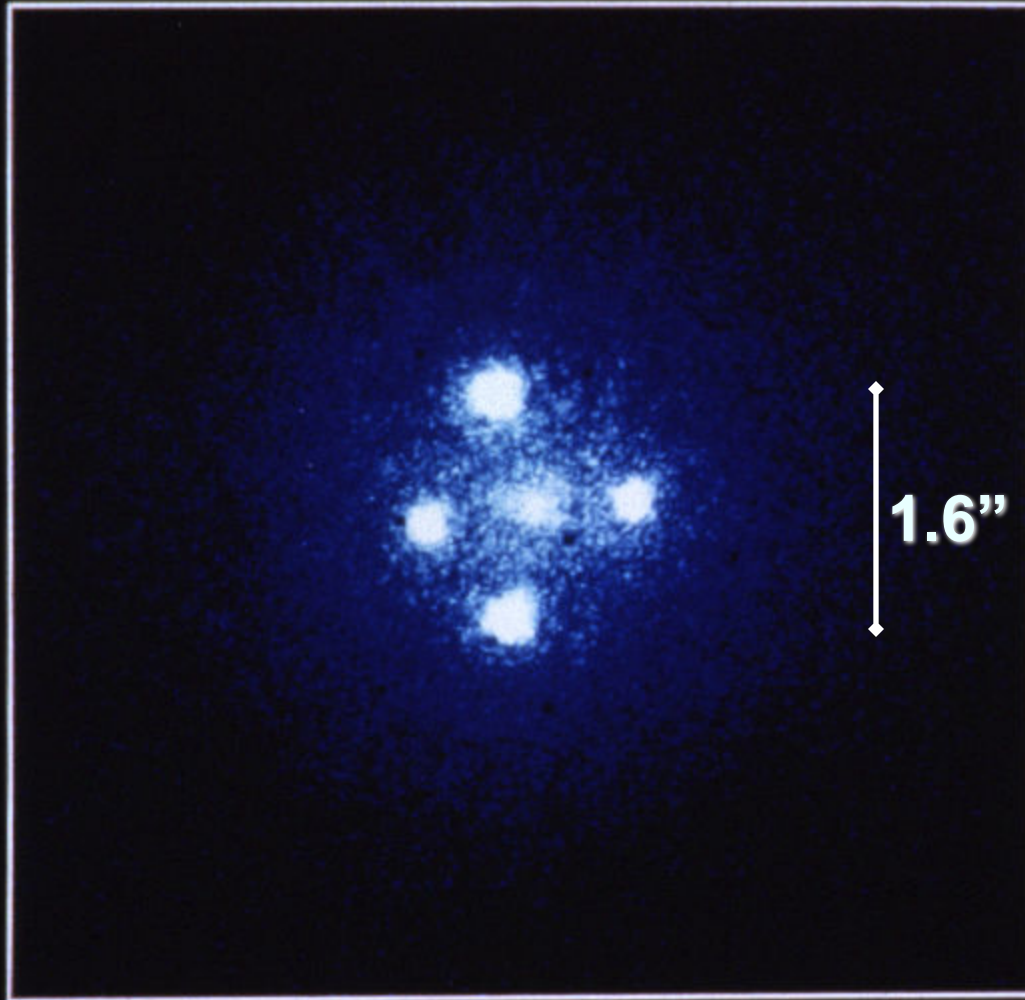
An “Atlas” of Galaxies in CL 0939+4713 @ 4B ly from Earth



Diversity in galaxy structure & morphology in a common environment

Hubble Space Telescope (HST)

Gravitational Lens G2237+0305 — The “Einstein Cross”



Foreground galaxy: 400M ly, "Lensed" Quasar: 8B ly

SPHERICAL ABERRATION

BUT...

→ HST OPTICS WERE (FAR)
OUT OF SPEC TO ACHIEVE
KEYS SCIENCE GOALS

FORTUNATELY...

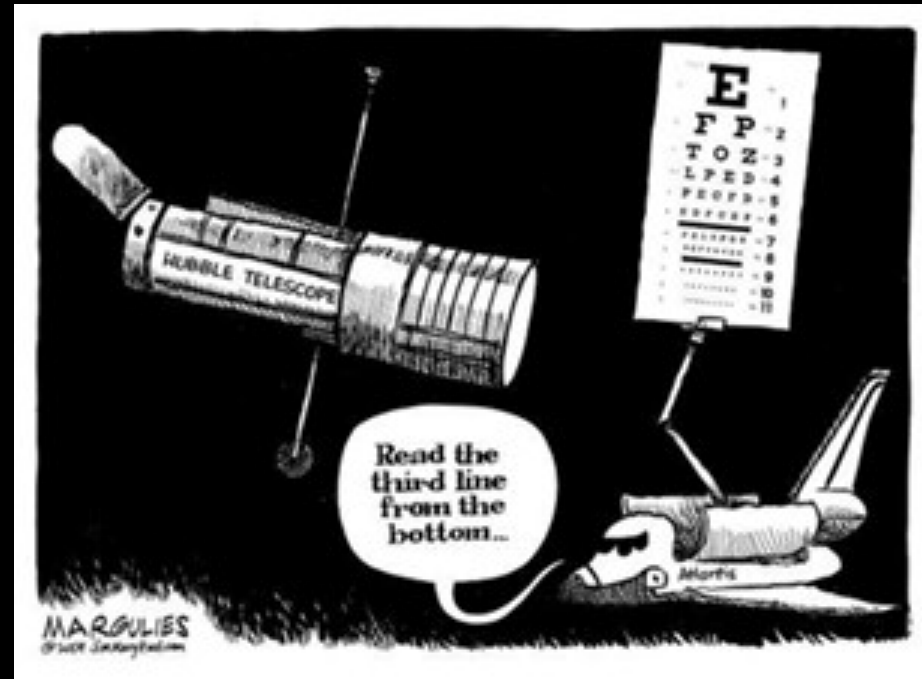
→ WE KNEW THE EXACT
CORRECTIONS NEEDED

AND...

→ IN PRINCIPLE, OPTICALLY
NOT DIFFICULT

BUT...

→ IN PRACTICE, *HOW?*...

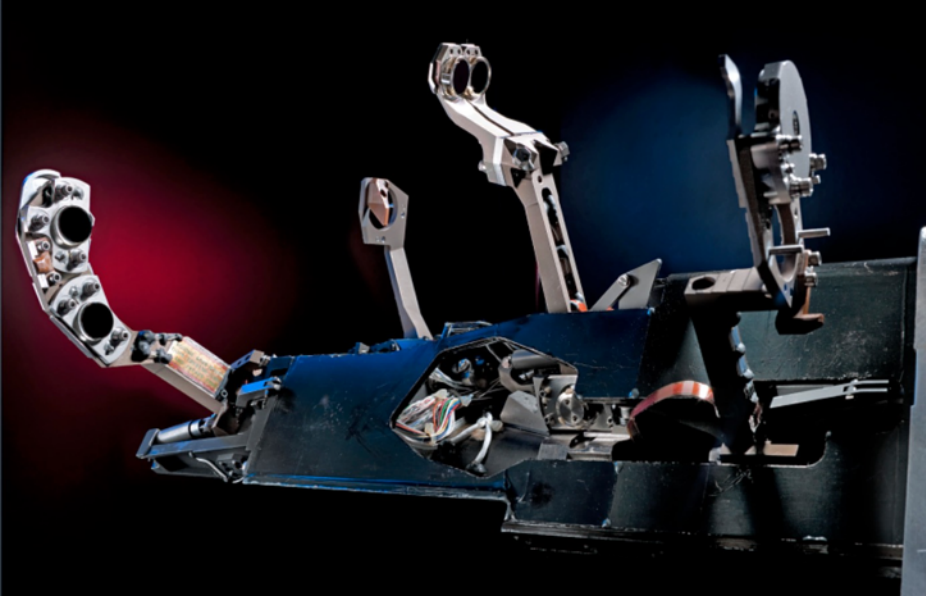


Hubble Space Telescope (HST)

THE FIX

Corrective Optics Space Telescope Axial Replacement (COSTAR)

EXTERNAL 2-Optic per instrument Fix for FOC, FOS and GHRS



Wide Field/Planetary Camera-2

Astronaut Serviceable

INTERNAL corrective optics with planned (augmented) instrument changeout

Future Hubble Instruments

All with INTERNAL corrective optics (similar to WF/PC-2)



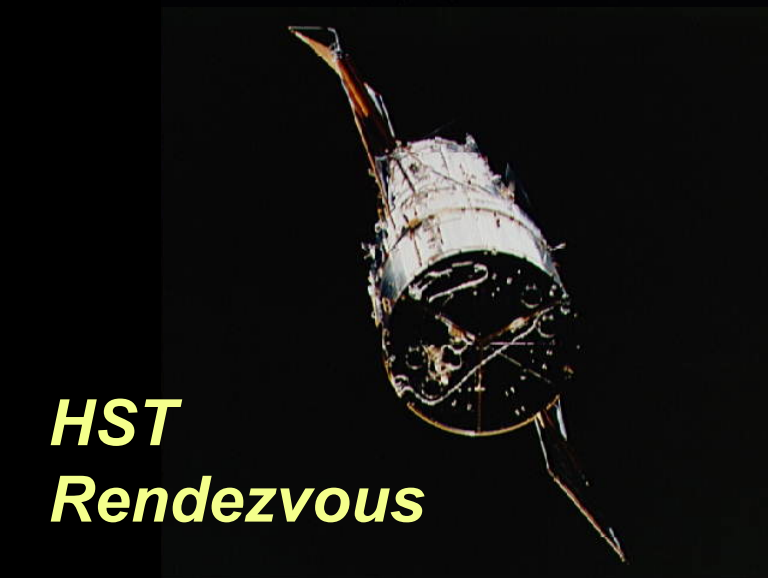
Hubble Space Telescope (HST)

First Servicing Mission, December 1993

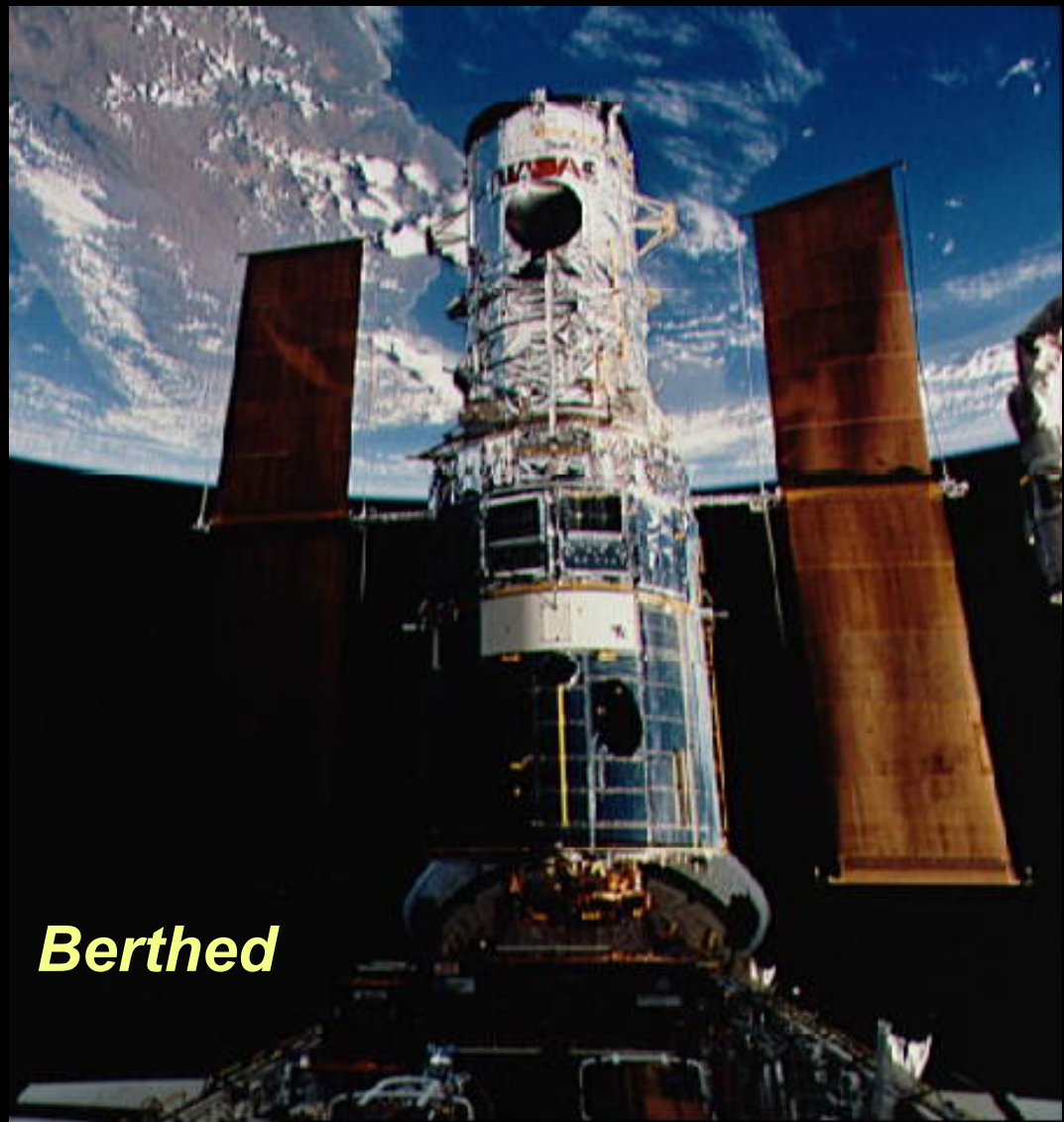
SM1



STS-61 Launch



**HST
Rendezvous**



Berthed

HUBBLE SPACE TELESCOPE DEPLOY, SERVICING & TEST SHUTTLE MISSIONS

LAUNCH (1990) [STS-31]

Telescope Deploy with:

Wide-Field/Planetary Camera
Faint Object Camera
High Resolution Spectrograph
Faint Object Spectrograph
High Speed Photometer

SM1 (1993) [STS61]

Install COSTAR (fix for FOC, HRS, FOS)
Install Wide-Field/Planetary Camera-2
Replace Solar Arrays
Replace Solar Array Drive Electronics
Install Flight Computer Co-processors
Replace (2) Rate Sensor Units
Replace (2) Gyro Electronic Control Units
Install HRS "Redundancy" Kit

SM2 (1997) [STS-82]

Install Near-IR Camera/MultiObject Spectrom.
Install ST Imaging Spectrograph (STIS)
Replace 1st Fine Guidance Sensor (FGS)
Replace Optical Control Electronics Kit
Install Solid State Recorder (replace ESTR)
Replace (1) Reaction Wheel
Replace (1) set of Solar Array Drive Elect.
Replace (1) Data Interface Unit with upgrade
Install Sci/Eng Tape Recorder
Install New Magnetic Sensing System Covers
Repair tears in HST insulation

SM3A (1999) [STS-103]

Changeout Failed Gyros
Replace 2nd FGS
Upgrade (Replace) Flight Computer
Install Solid State Recorder (replace ESTR)
Replace S-Band Antenna
Replace Voltage (charging) Improvement Kit
Replace Outer Thermal Blanketing

SM3B (2002) [STS-109]

Install Advanced Camera for Surveys
Install NICMOS Cooling System
Replace Power Control Unit
Replace Solar Arrays with new solid panels
Replace (1) Reaction Wheel
Install New Outer Blanket Layers

SM4 (2009) [STS-125]

Install Wide Field Camera 3
Install Cosmic Origins Spectrograph
Repair STIS
Repair ACS Wide Field Channel
Replace all 6 Gyroscopes
Replace 3rd FGS
Replace all 6 HST Batteries
Install New Outer Blanket Layers
Install "Soft Capture" Mechanism

HOST (1998) [STS-95 {not to HST}]

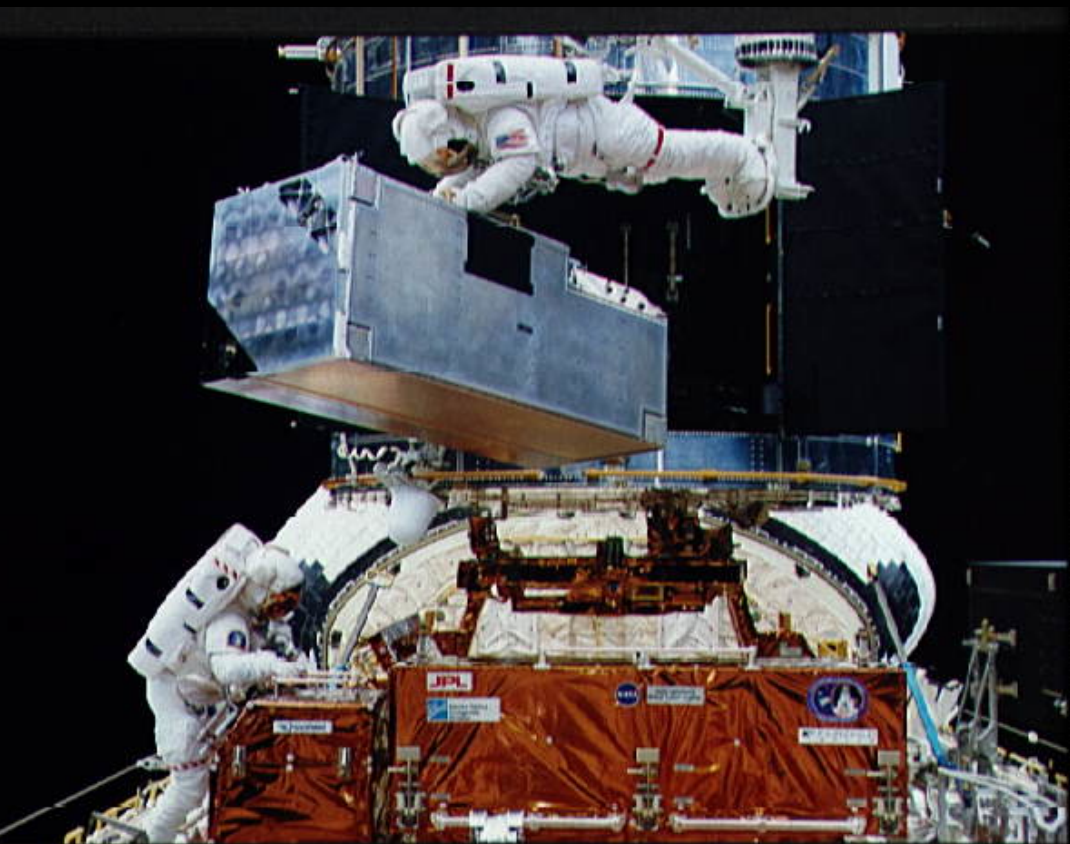
Shuttle-bay on-orbit test of SM3B hardware



Hubble Space Telescope (HST)

First Servicing Mission, December 1993

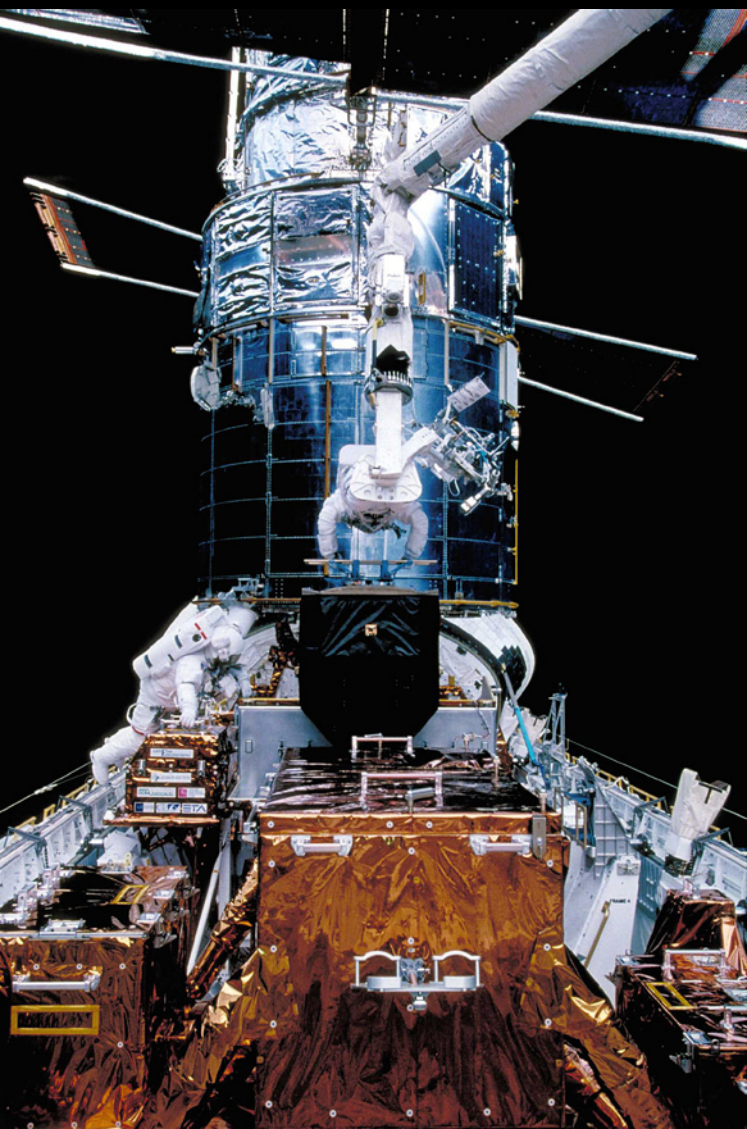
COSTAR INSTALLATION



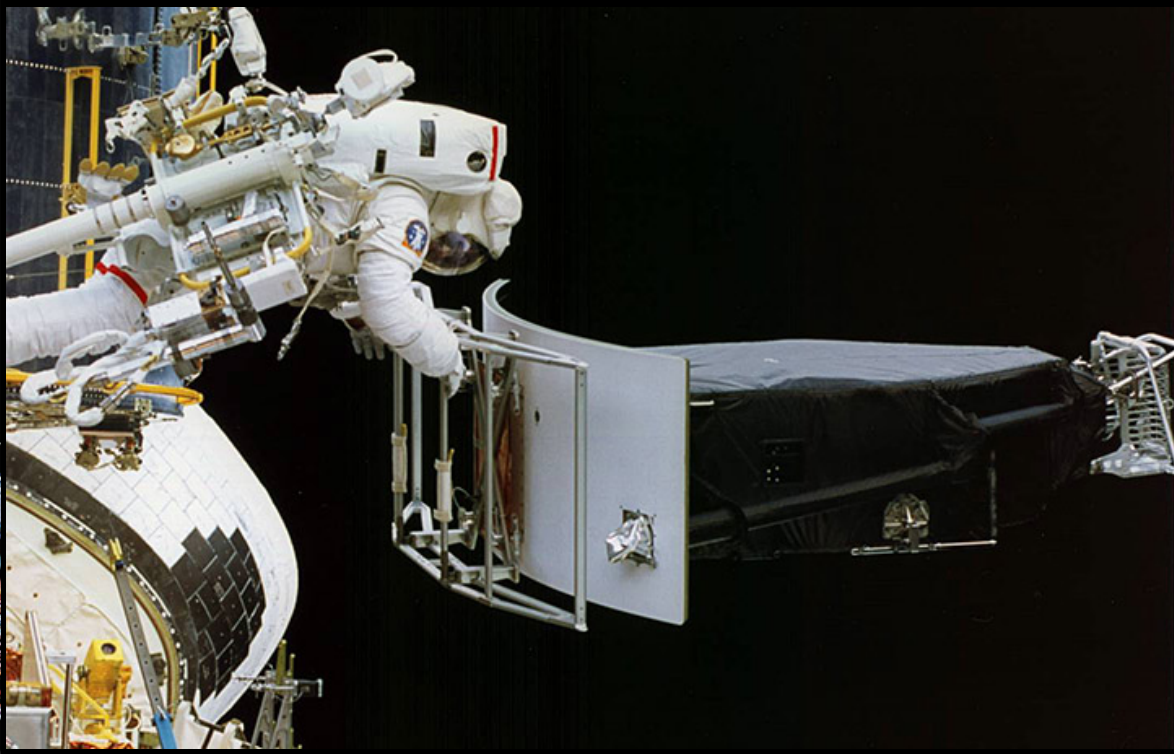


Hubble Space Telescope (HST)

First Servicing Mission, December 1993



WFPC-2 INSTALLATION



Hubble Space Telescope (HST)

First Servicing Mission, December 1993

AWAITING THE FIRST POST-SERVICING HST STAR IMAGE



Hubble Space Telescope (HST)

First Servicing Mission, December 1993

AWAITING THE FIRST POST-SERVICING HST STAR IMAGE



Hubble Space Telescope (HST)

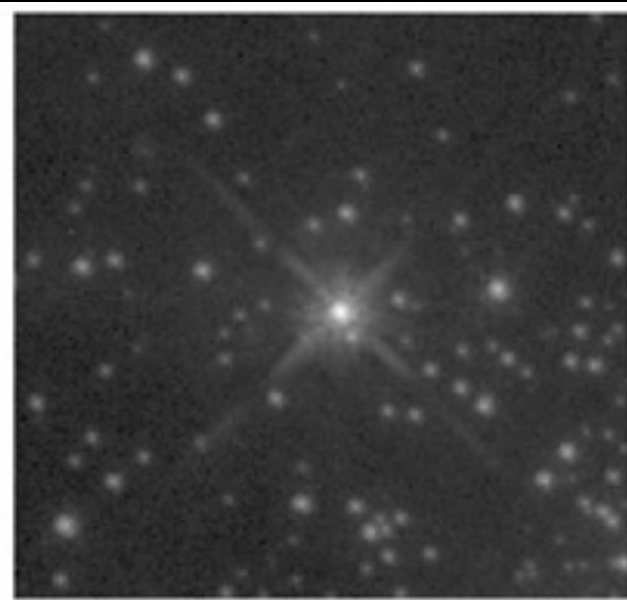
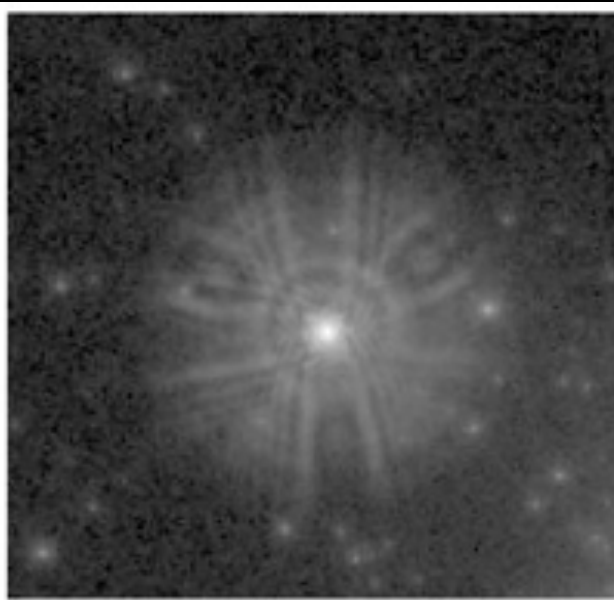
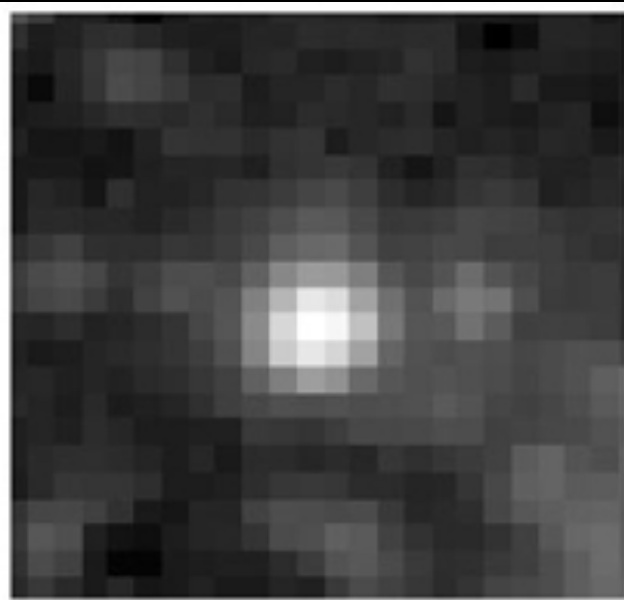
First Servicing Mission, December 1993

CROSS-CHECK WITH THE FAINT OBJECT CAMERA (FOC)

GROUND

FOC PRE-COSTAR

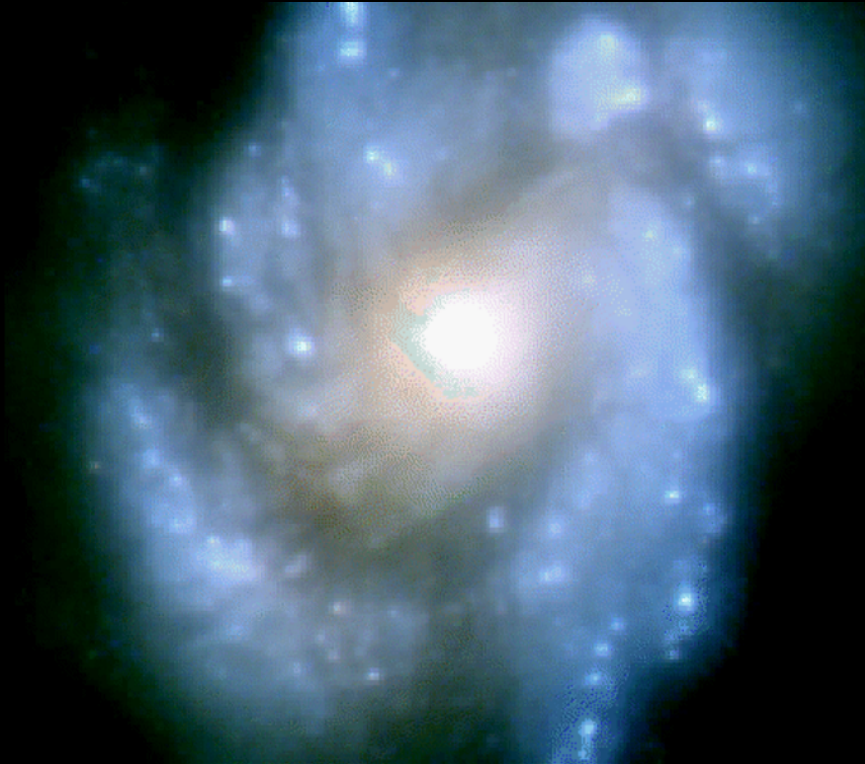
FOC POST-COSTAR



Hubble Space Telescope (HST)

First Servicing Mission, December 1993

*HST's Vision and the Promise of the Observatory
Were Fully Restored*



November 27, 1993

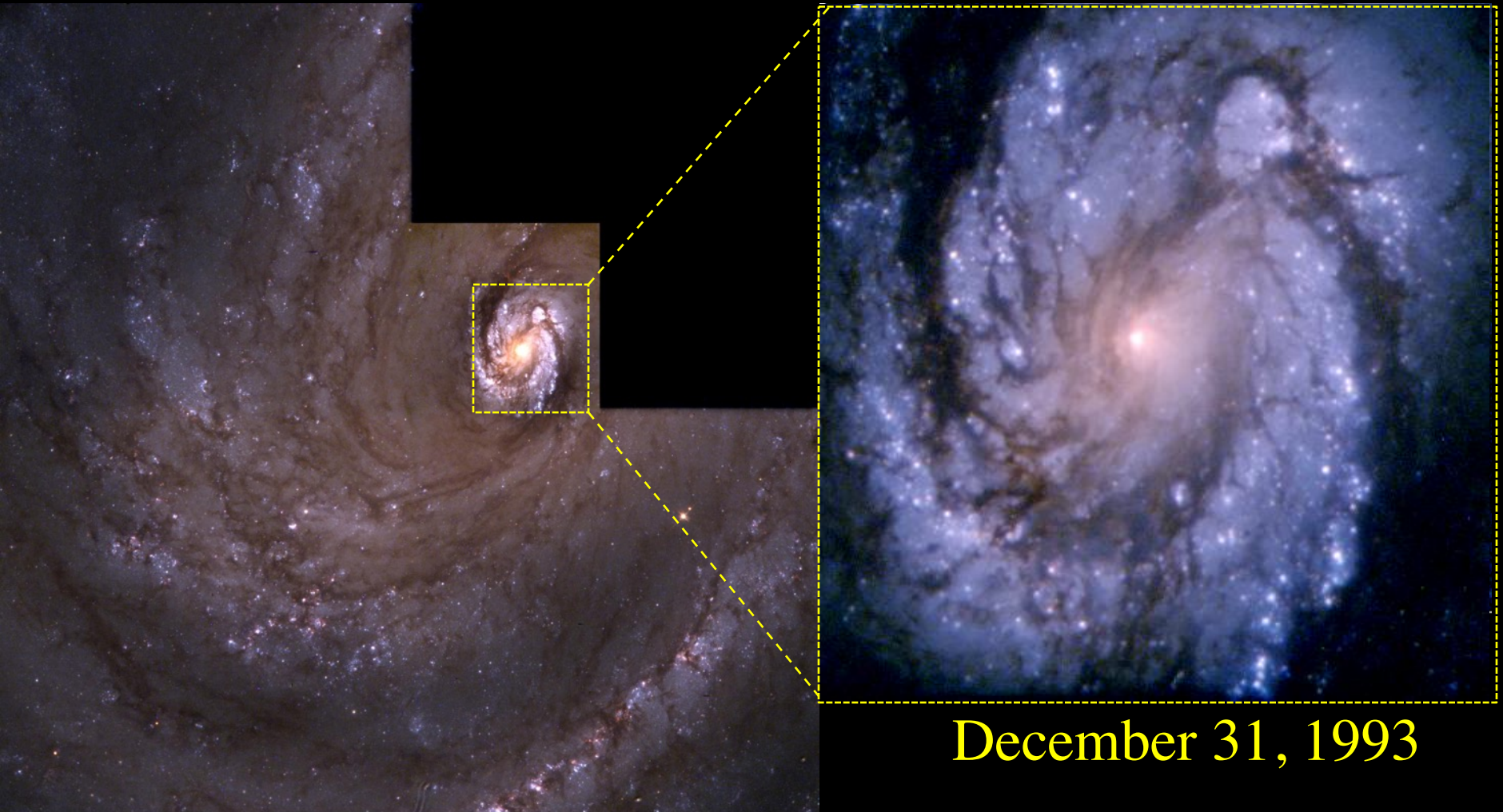


December 31, 1993

Hubble Space Telescope (HST)

First Servicing Mission, December 1993

*HST's Vision and the Promise of the Observatory
Were Fully Restored*



December 31, 1993

Hubble Space Telescope (HST: WF/PC-2)

COMET SHOEMAKER-LEVY 9 (SL-9)

17 May 1994

ON COLLISION COURSE WITH JUPITER



- Discovered (> 20 pieces) in 1993 orbiting Jupiter ($P \sim 2\text{yr}$)
- Post-discovery analysis: Single-body captured into Jupiter orbit 1982.
Torn apart in 1992 in close-approach to Jupiter

SL-9 IMPACTS WITH JUPITER (WF/PC-2 images not to scale)

16 – 22 July 1993

Impact Velocity: 60 km/second (134,000 mph)



Fragment G impact plume 5 minutes after impact

- Impact just over visible edge of planet
- Impact plume rising ~2000 miles vertically
- Central plume ~18,000°F 10s after impact

Fragment G impact site 1.5 hours after impact

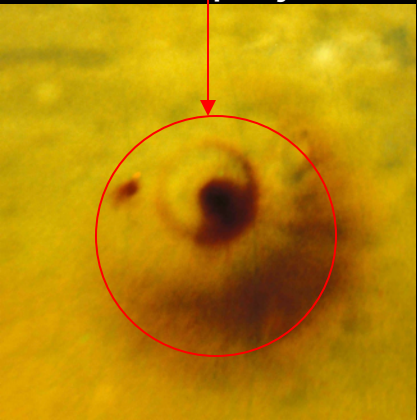
size of
Earth



Fragment G site + 3 days

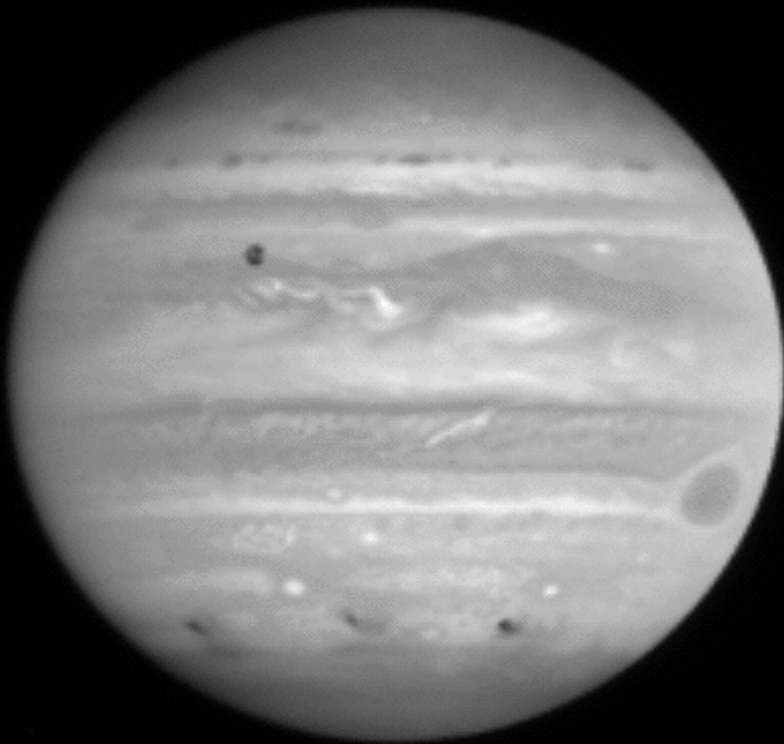
G site + 5 days

overhead projection

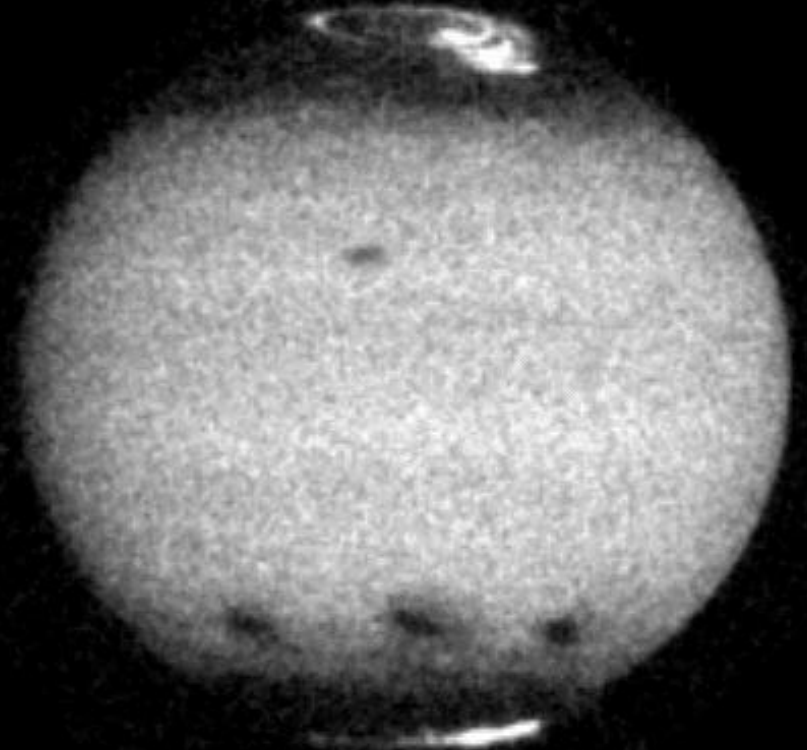


PROBING DIFFERENT DEPTHS IN JUPITER'S ATMOSPHERE

VISIBLE LIGHT



ULTRAVIOLET LIGHT



solar system
size EGGs

Hubble Space Telescope (HST)

M16 (Eagle Nebula) “Pillars of Creation”

Star-Forming Region, $d = 6500$ ly
Dense clouds of dust & H_2

Erosion by “Photoionization
from nearby UV-bright stars

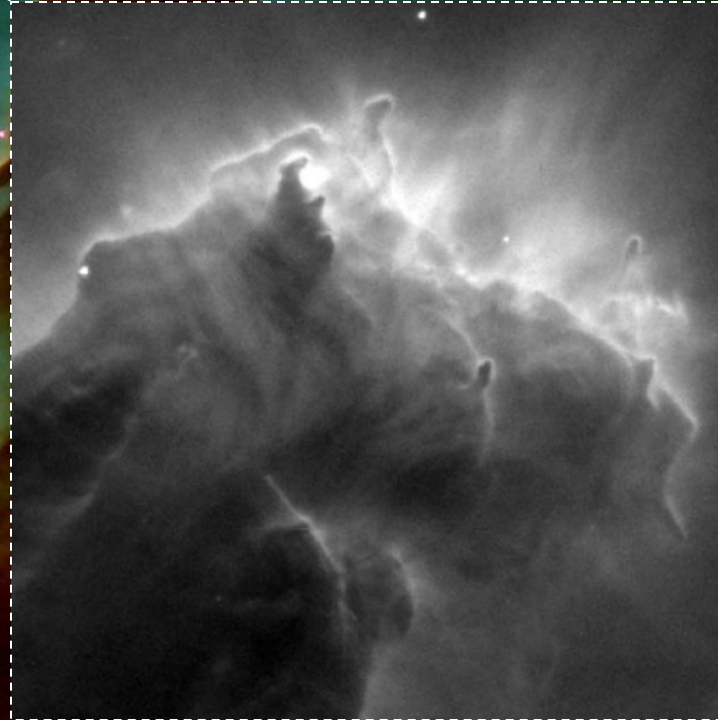
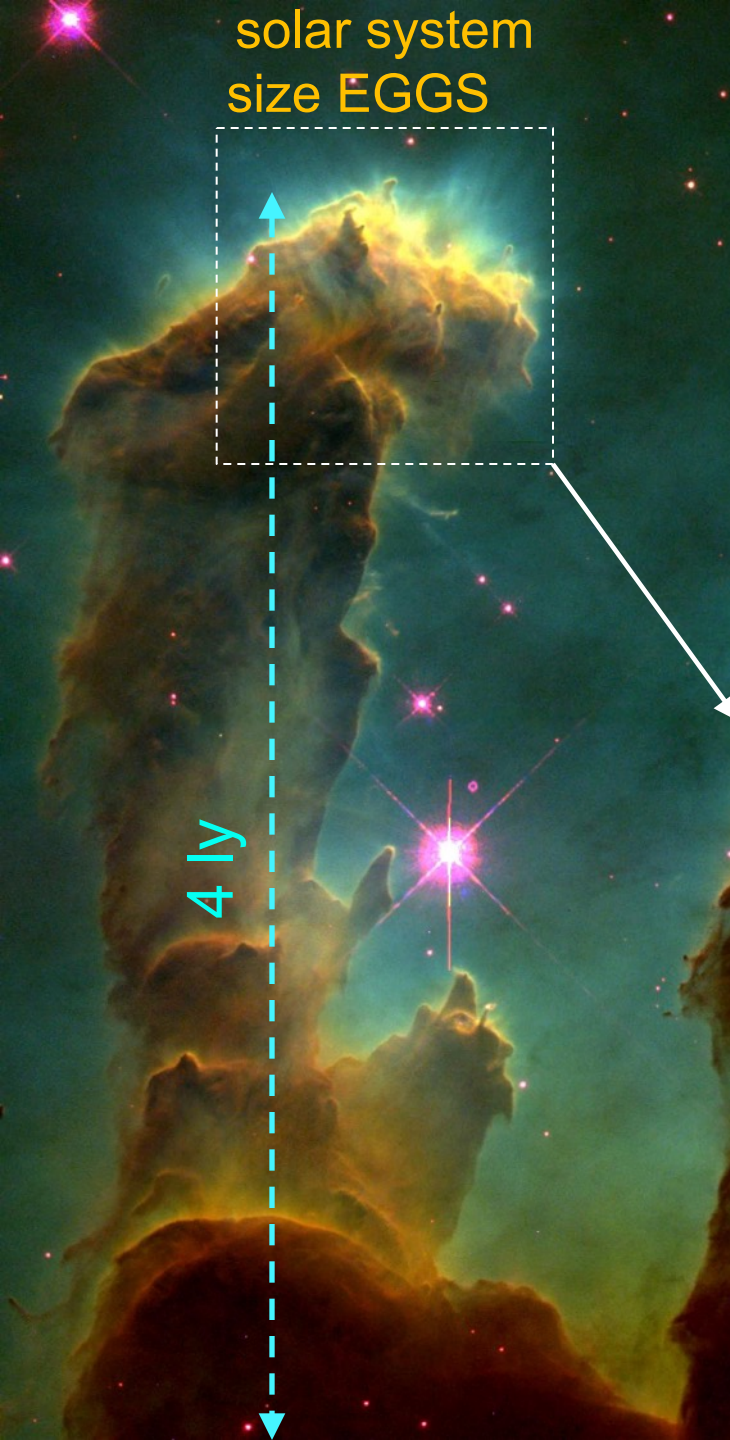
Exposes denser globules:

“EGGs”:
Evaporating
Gas
Globules

→ embryonic
stars

in a harsh
environment

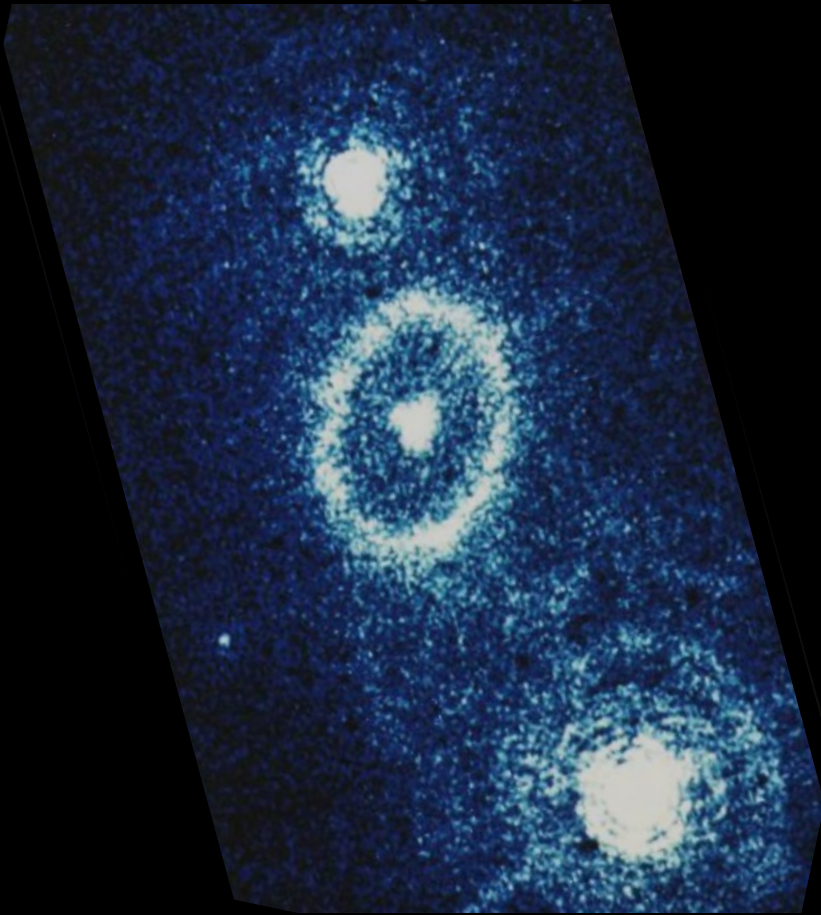
4 ly



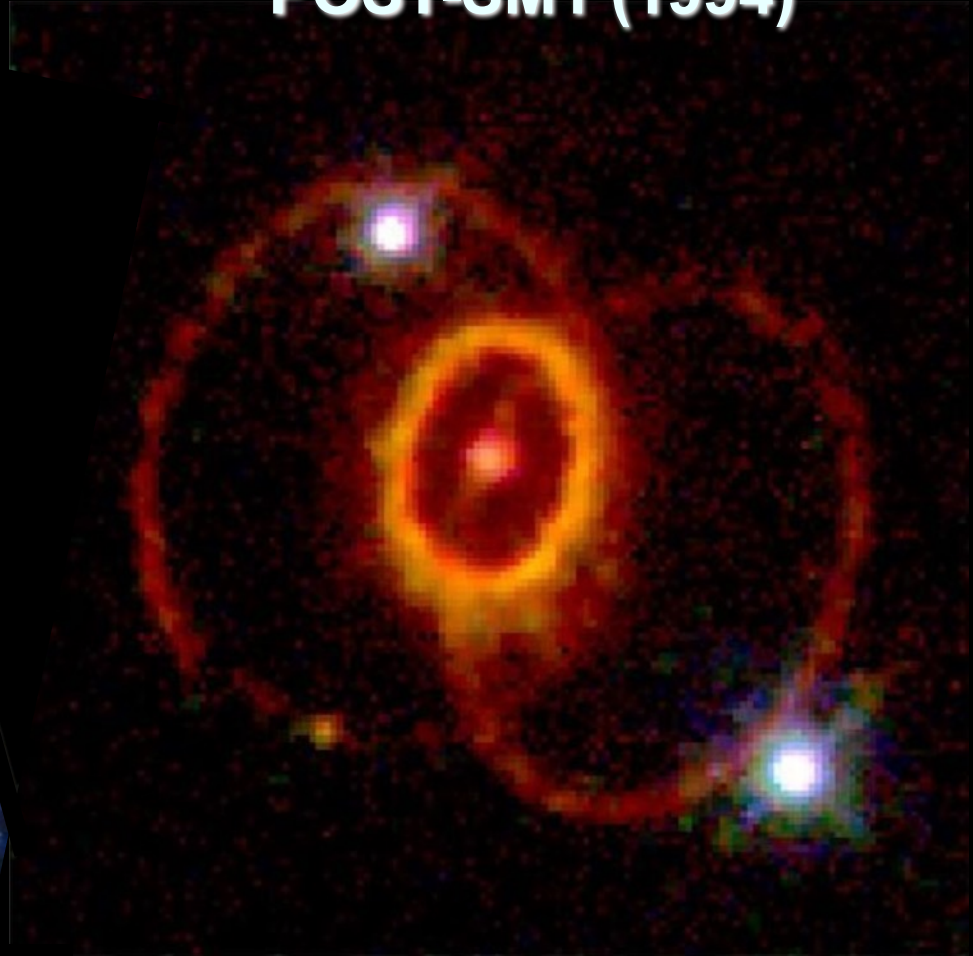
Hubble Space Telescope (HST)

Super-Nova 1987a in the LMC – Revisited

PRE-SM1 (1990)



POST-SM1 (1994)

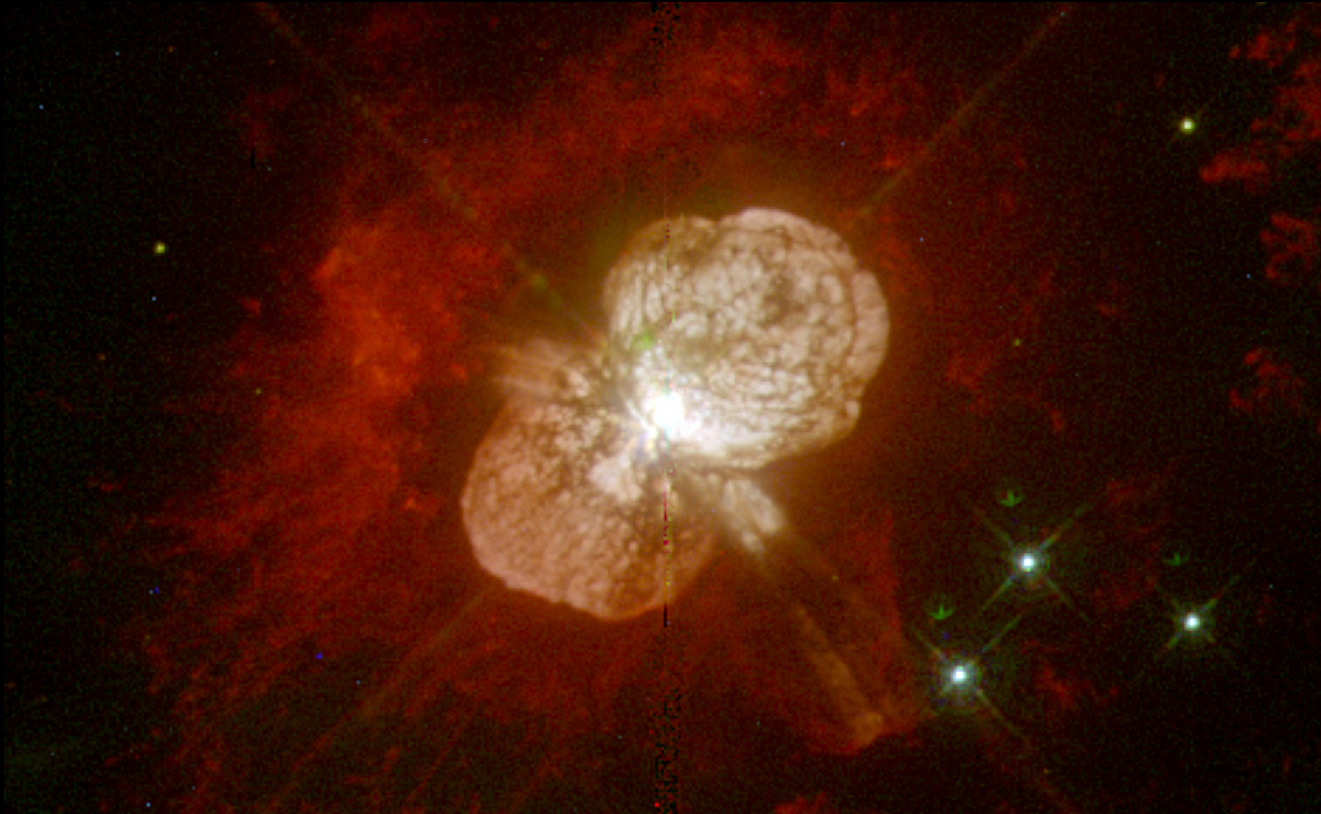


Prior unseen secondary rings likely from gas expelled by the progenitor star $\sim 20,000$ years before the SN explosion.

Hubble Space Telescope (HST)

Eta Carina – Massive Star on the Edge of Destruction

4,000,000x brighter, and 150x more massive than the Sun, $d = 7,500$ ly



Unstable: Major outburst in 1841, briefly became 2nd brightest star in sky

Ejecting material into space at up to 2 million mph

Dusty, bi-polar ejecta close to star with solar system size “knots”

High velocity material spraying out in the plane between the two lobes.

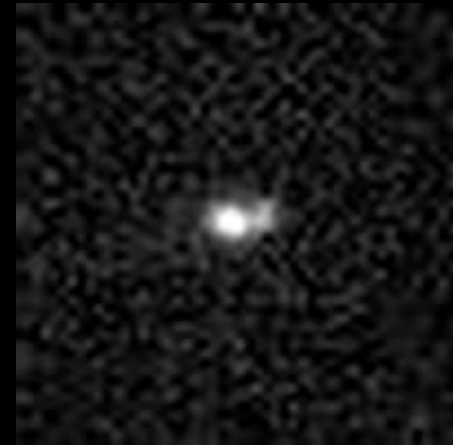
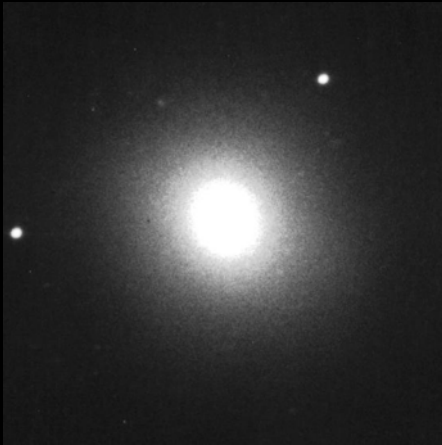
Hubble Space Telescope (HST)

COSMIC LOOKBACK: Galaxy Morphology

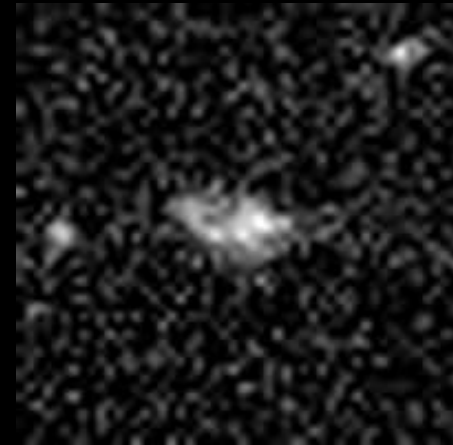
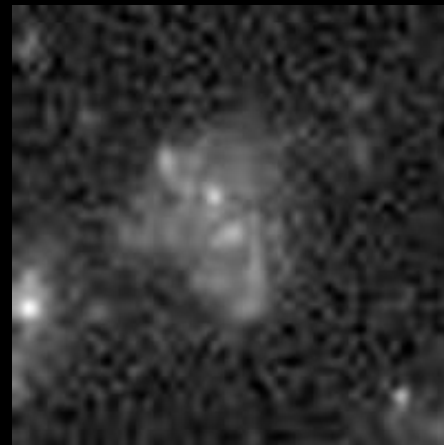
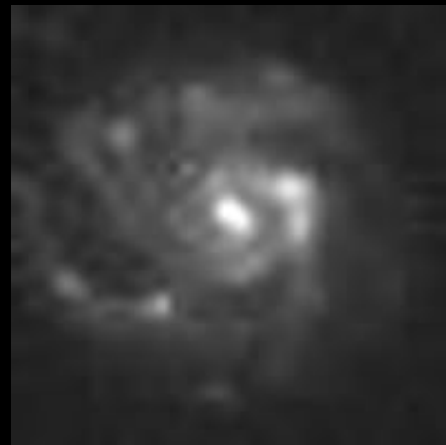
Older galaxies look more “lumpy” & fragmented (more later!...)

Today (~ 13.7 G yr) 5 billion years ago 9 billion years ago 12 billion years ago

Elliptical Galaxies



Spiral Galaxies



Hubble Space Telescope (HST)

COSMIC LOOKBACK: Galaxy Morphology



**GALAXY CLUSTER
CL 0939+4713**

**Age: 9 Gyr
(2/3 age of universe)**

**Both Spirals and
Ellipticals, but ratio
several times > than
today.**

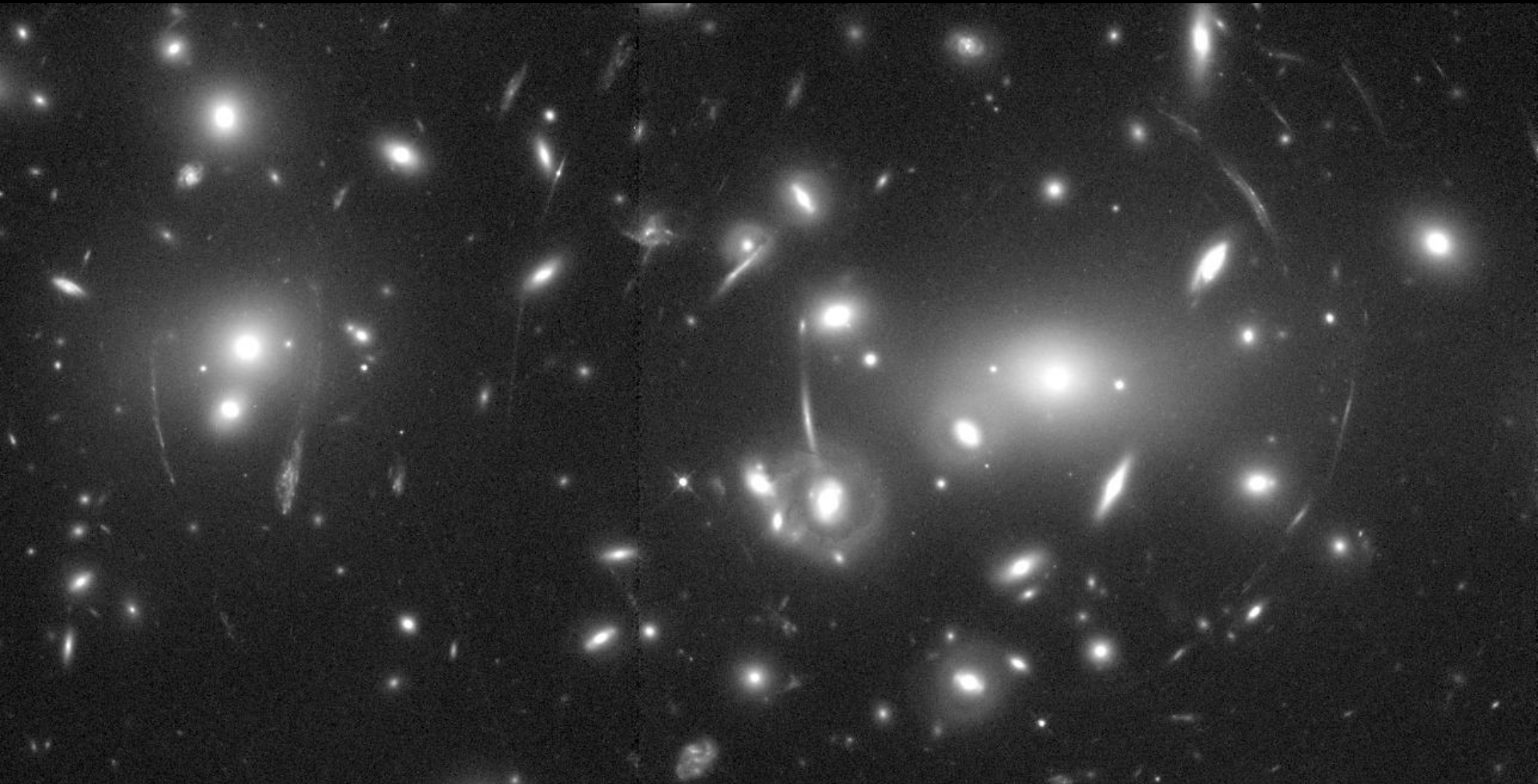
+ “fragments”

**∴ Fraction of Spirals
decline with age.**

→ Galaxy Mergers

Hubble Space Telescope (HST)

Gravitational Lensing: Distant Galaxy “Arcs” (Abell 2218)

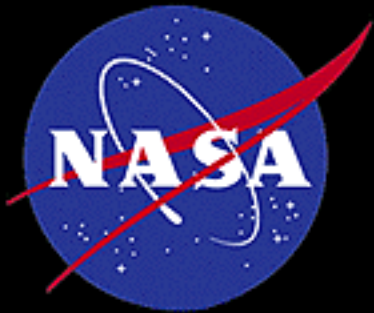


Gravitational field of the massive foreground cluster deflects, distorts, and amplifies the light from 5-10x more distant galaxies beyond that are $\sim \frac{1}{4}$ the age of the current universe

Hubble Space Telescope (HST)

SM1 – SUCCESS!

And so, unabated...



LEVEL 1 HST MISSION REQUIREMENT:

“The Hubble Space Telescope Shall Provide a Near-Infrared Observing Capability (in the Spectral Region 0.8 to 2.4 microns) with an On-Orbit Life-Time of Five Years.”

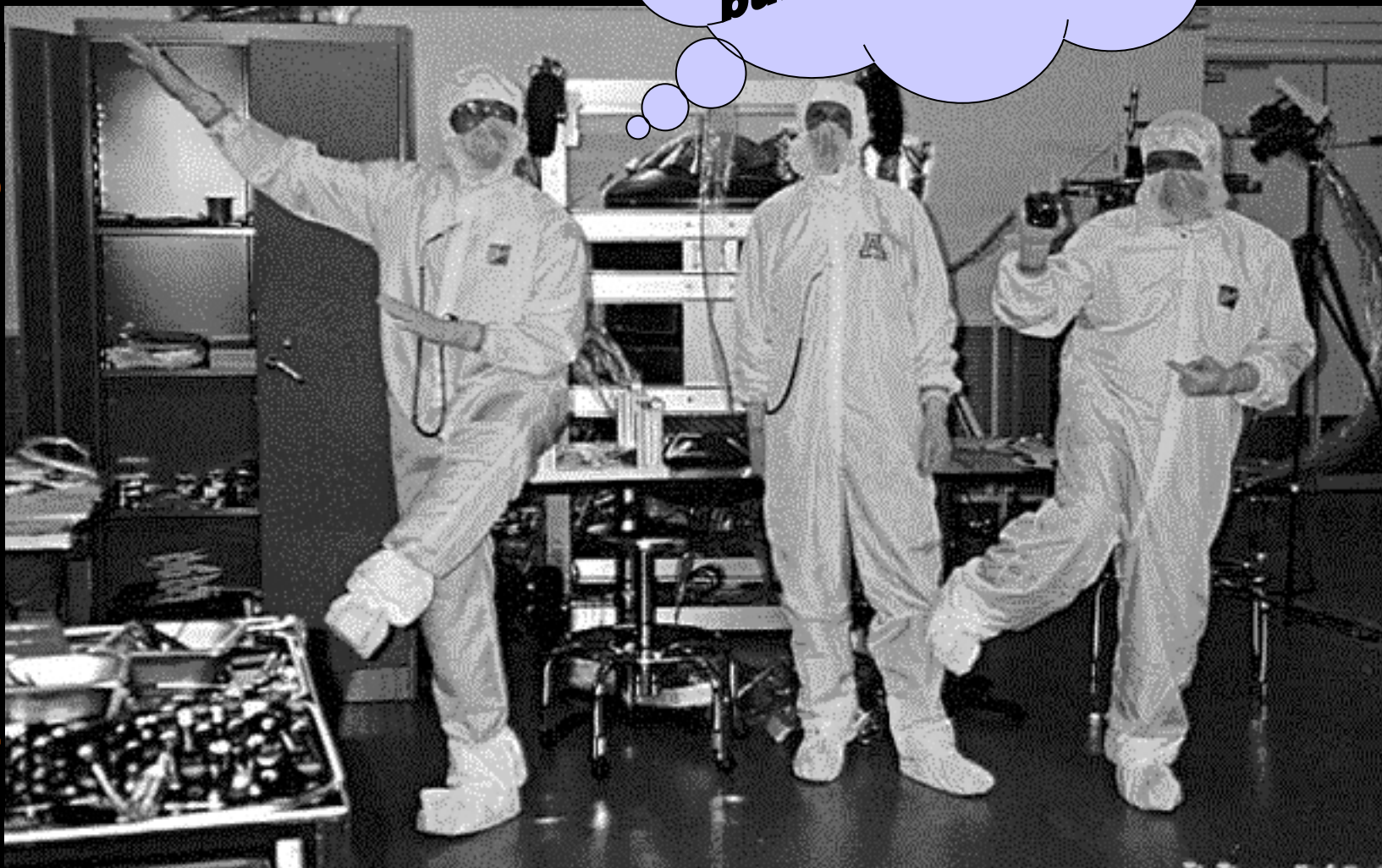


1994 — NASA C... Mission 2
A Green Light

Yee-HA! We are
actually going to
build and fly NICMOS

Near Infrared Camera & Multi-Element Integral Spectrometer

Rejoice, Fabrication Begins...



NICMOS Extends HST UV/Optical Panchromatic Vision into the Near IR ($0.8\mu\text{m}$ — $2.4\mu\text{m}$)

WHY NEAR INFRARED?

We can see in places with NearIR light that we can not with visible or ultraviolet light.

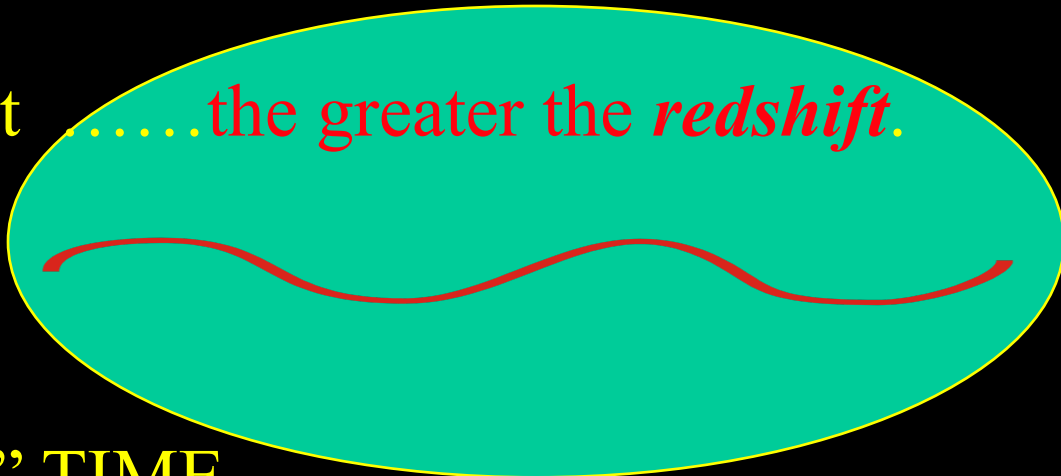
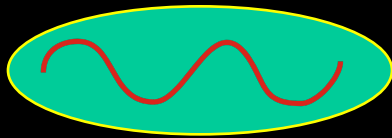
- Dust clouds in the universe hide many of the most interesting objects from view with optical light.
 - Birthplaces of planets, stars and galaxies
 - The centers of the most powerful galaxies in the universe
- NearIR light can penetrate the dust to reveal these objects.

NICMOS Extends HST UV/Optical Panchromatic Vision into the Near IR ($0.8\mu\text{m} - 2.4\mu\text{m}$)

WHY NEAR INFRARED?

We can see further in NearIR light than in with visible or ultraviolet light.

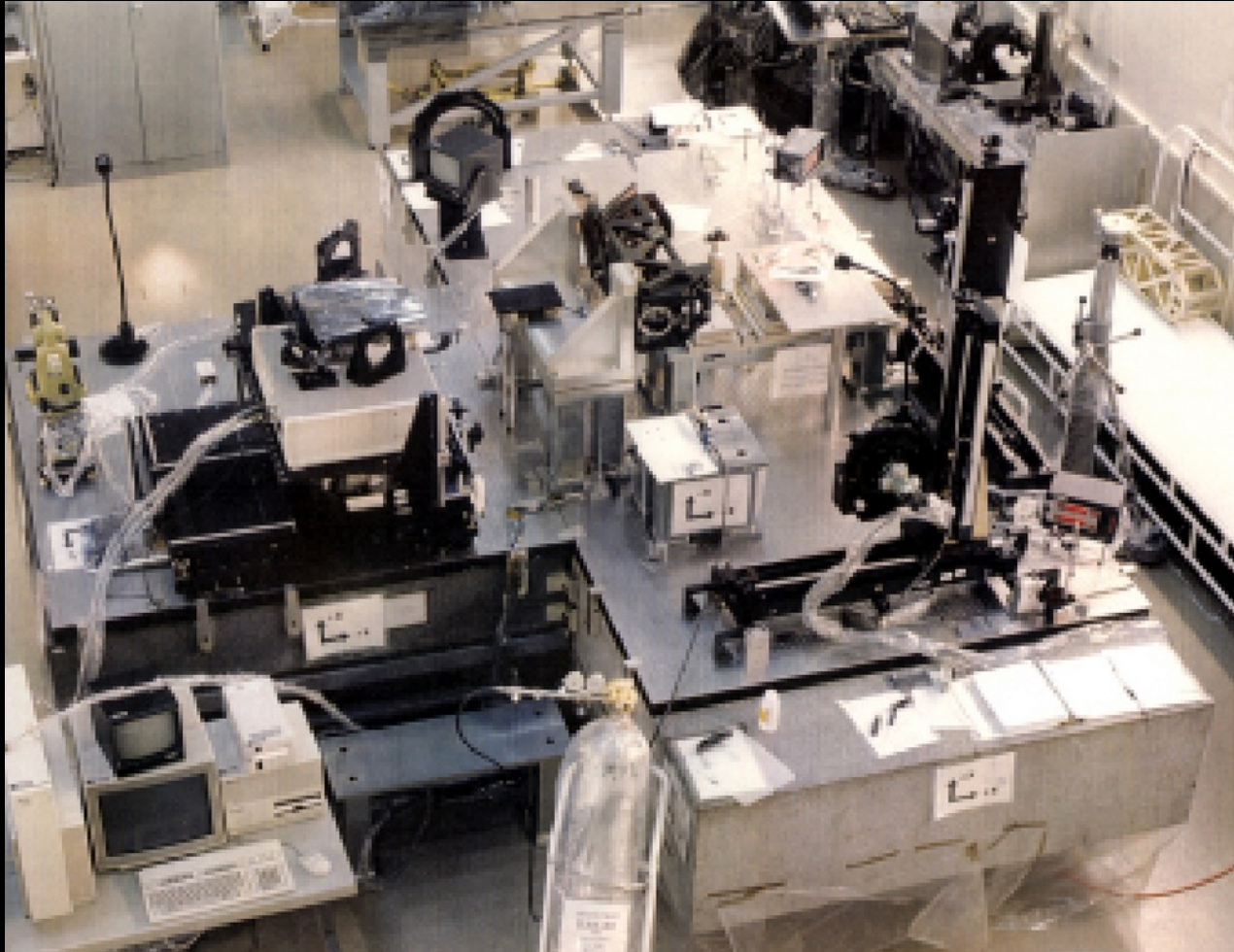
- As the universe expands it stretches light to longer wavelengths (I.e., the light is *redshifted*).
- The more distant an objectthe greater the *redshift*.



- More distant = *Older*:
COSMIC “LOOKBACK” TIME

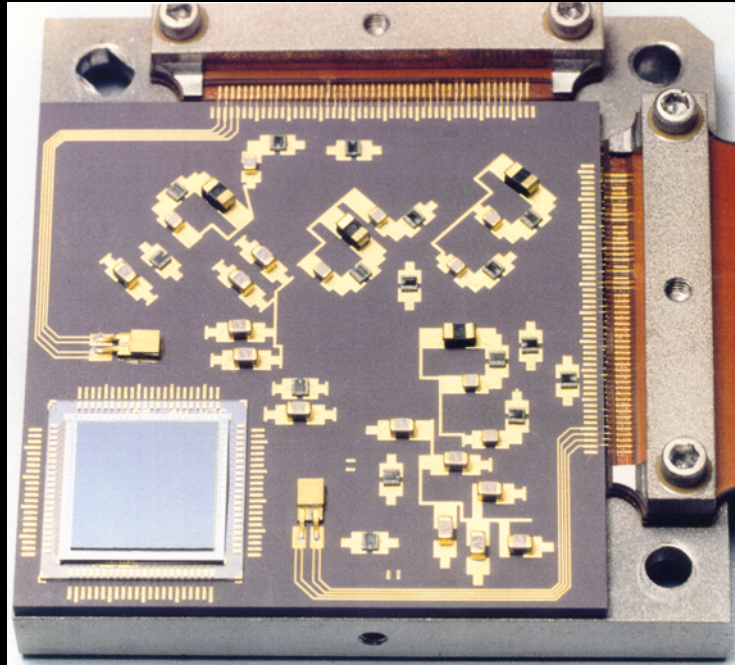
NICMOS 3 Cameras ($0.8\mu\text{m}$ — $2.4\mu\text{m}$) in one box

Three near-IR channels with: Wide Field & High Resolution Imaging and Slitless Spectrophotometry, Coronagraphy, and Polarimetry



Aligning and Testing the NICMOS Optics at Ball Aerospace

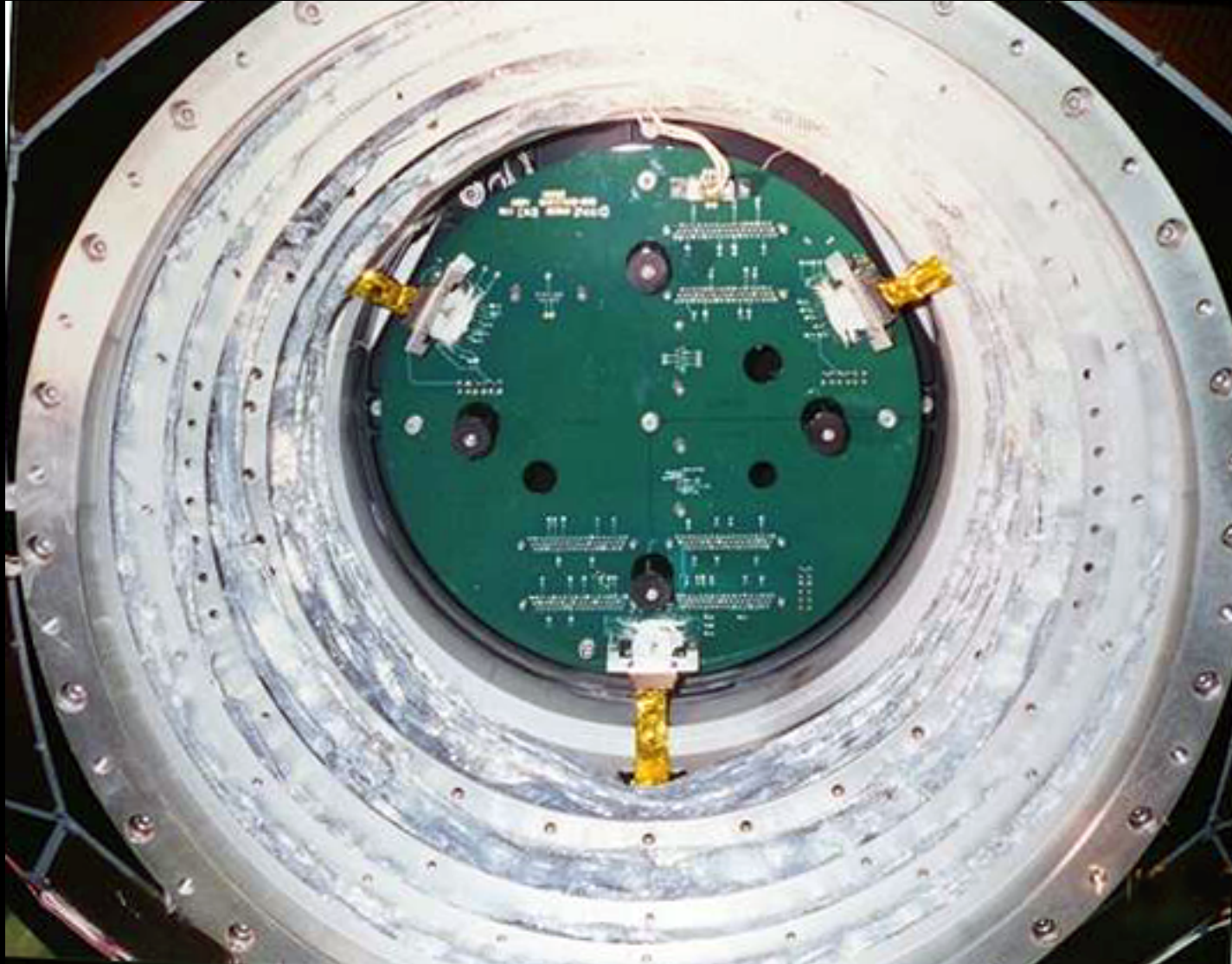
NICMOS IR Detectors MUST Be Run *COLD*



INITIAL Operating Temperature: -350° F

FINAL Operating Temperature: -321° F

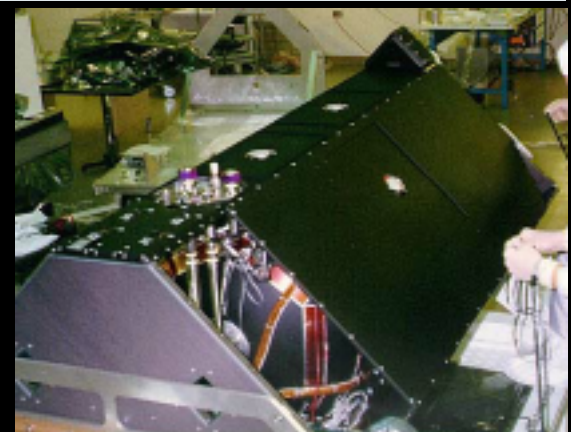
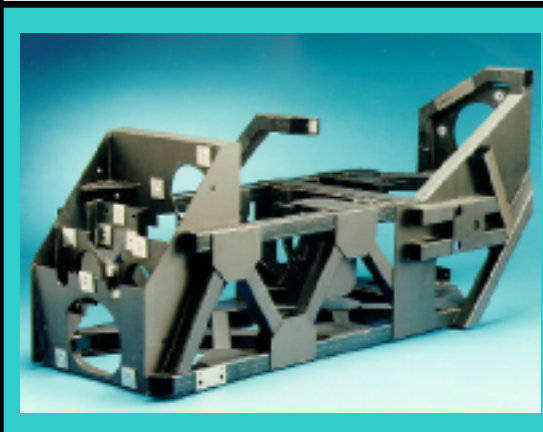
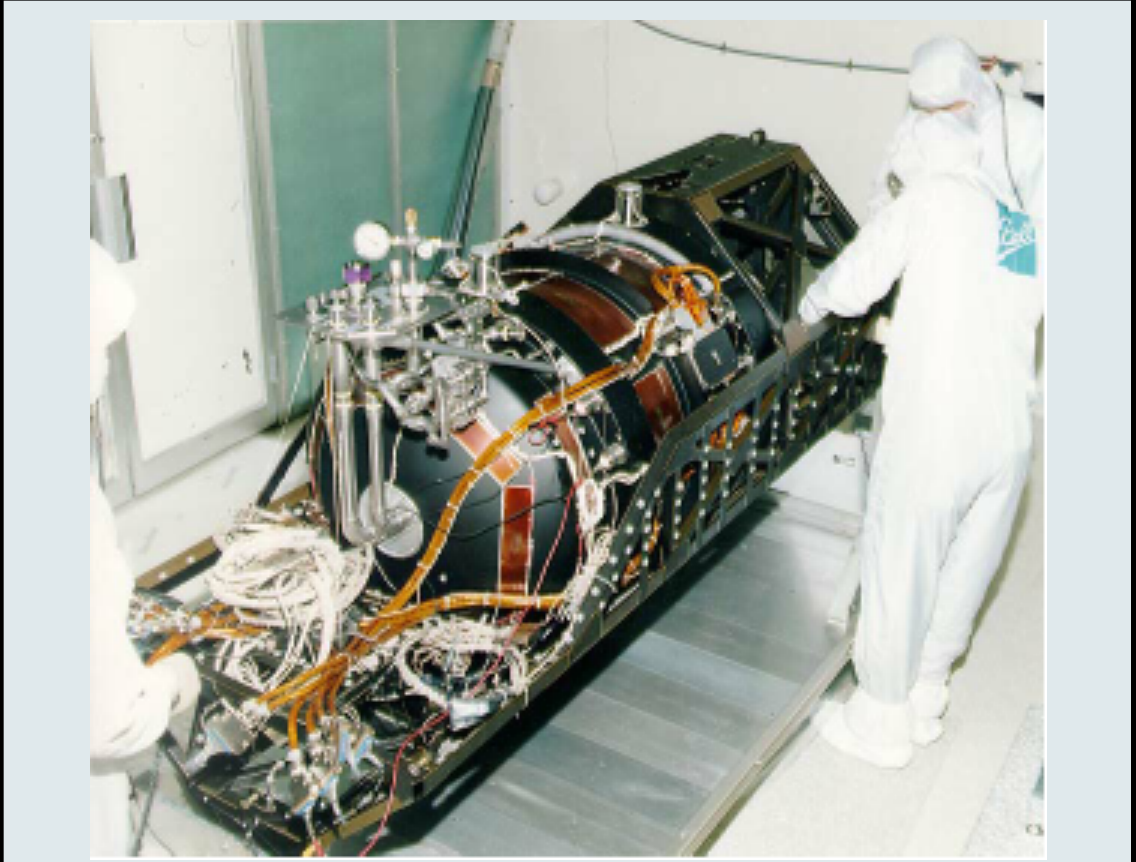
CRYOSTAT (a.k.a. Dewar) with 127 layers of Thermal Insulation



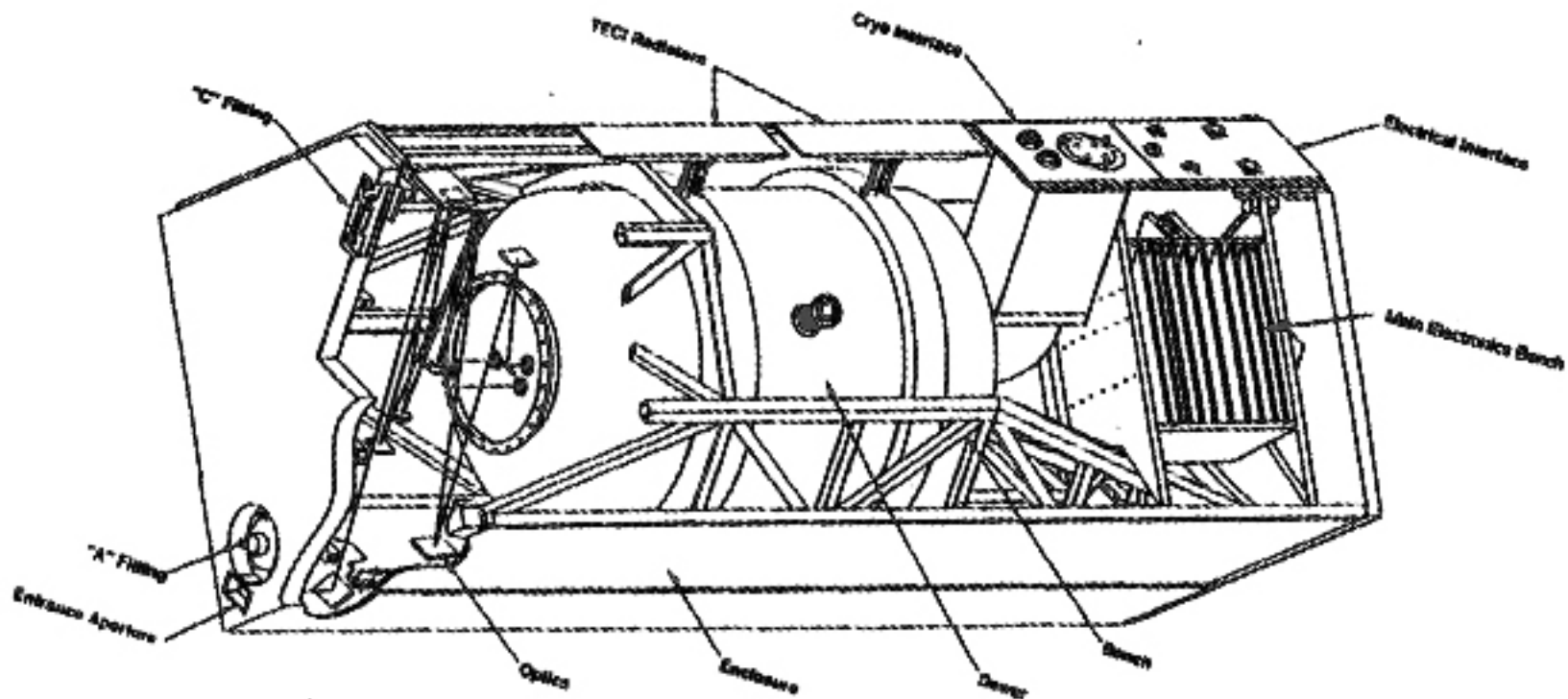
Assembled NICMOS CRYOSTAT



Putting it Together - NICMOS Dewar Integration



NICMOS is Born in Boulder, Colorado



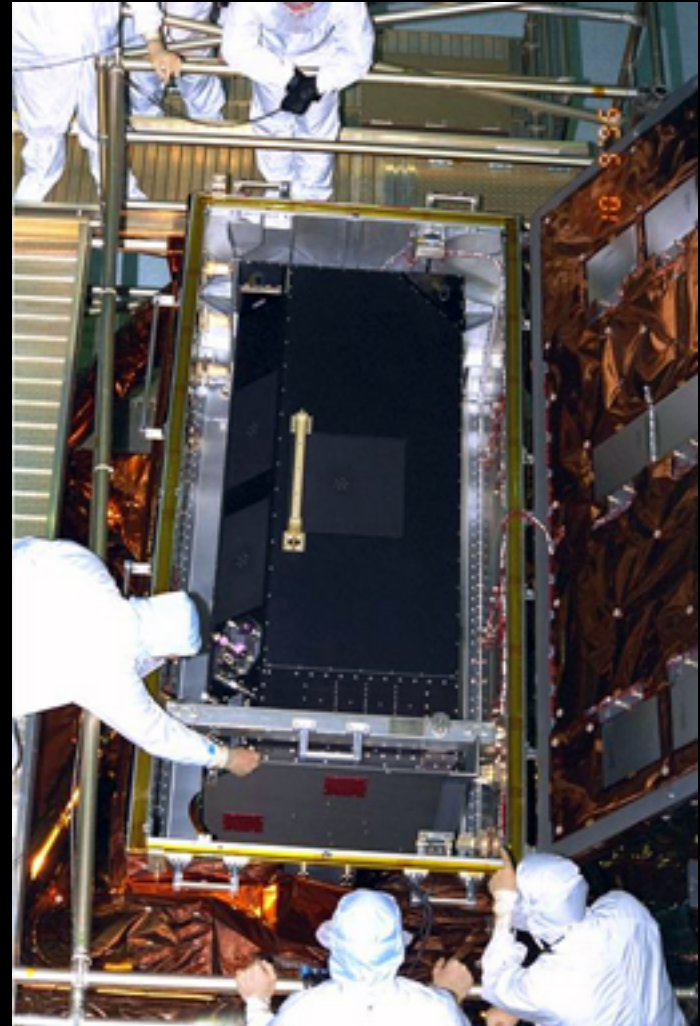
NICMOS

... a 852 lb. baby, with a belly filled with SN_2

And, is prepared for its first trip (to GSFC, MD)...



...and later, to Kennedy Space Center,



*NICMOS is buttoned up in its Protective Enclosure,
in Preparation for its Final Ride*



Putting it To Work
**NICMOS Was Installed
into the Hubble Space
Telescope During
Servicing Mission #2 in
13-14 February 1997**



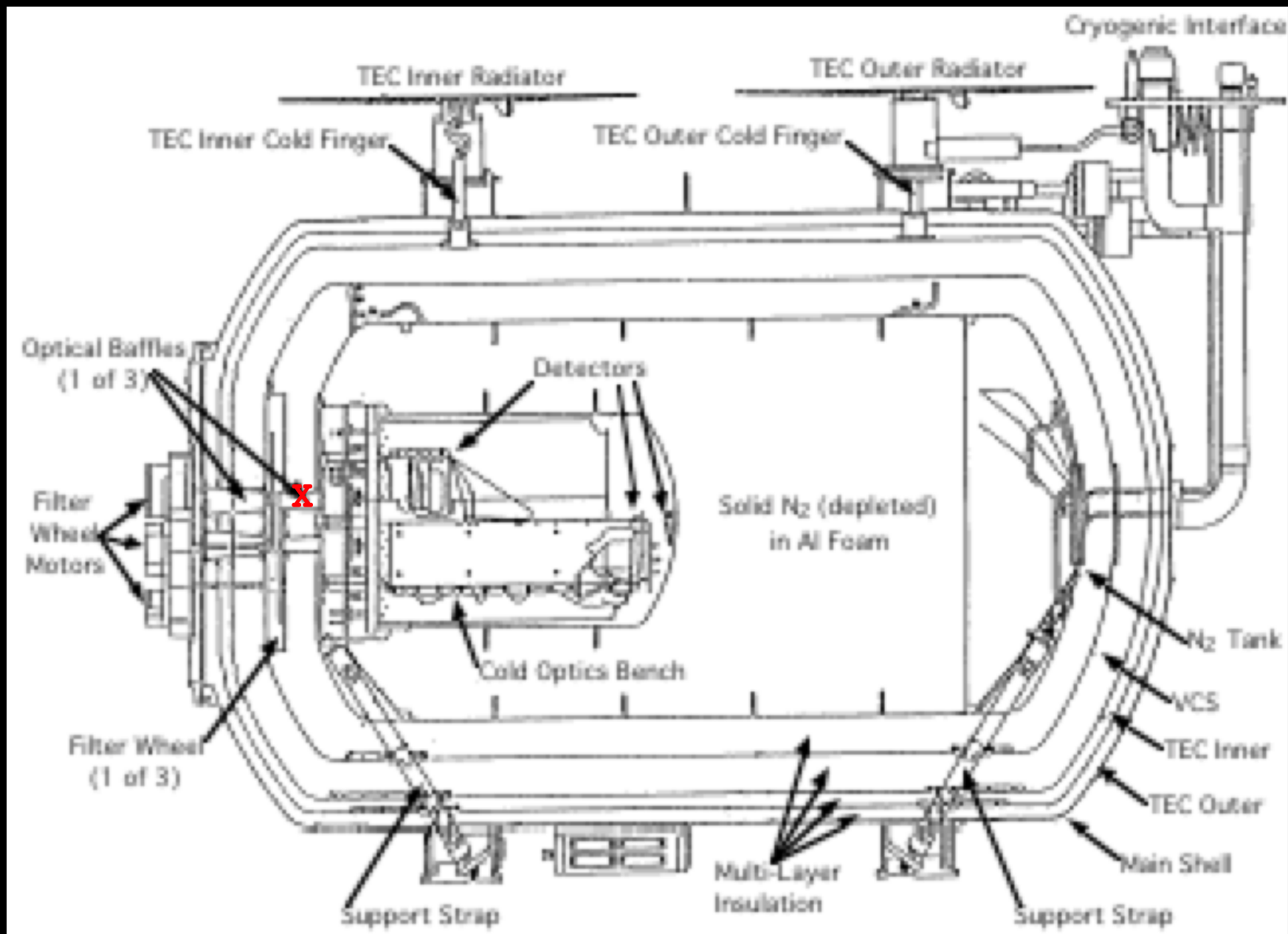
(No One Every Said It Was Easy...)
The Ecstasy & The Agony

First Light: 04 March 1997



Thermal Short: 04 March 1997

Thermal Short: 04 March 1997



Thermal Short: 04 March 1997

MAJOR IMPACTS

1. NICMOS LIFETIME REDUCED FROM 4.5 to ~ 2 Years
2. CAMERA #3 NOT CONFOCAL WITH CAMERAS #1 & #2

NASA PROGRAMMATIC RESPONSE

1. FRONT-LOAD & ACCELERATE NICMOS SCIENCE (do first)
2. ADOPT CAMERA #3 “Focus Campaigns”
(refocus by moving HST’s secondary mirror by 60 microns [1/400 inch])
3. *INVESTIGATE/DEVELOP/INSTALL an On-Orbit Cryo-Cooler*
(prior unconceived HST hardware)

HUBBLE GETS NEAR-INFRARED VISION

Probing Planetary Surfaces and Atmospheres

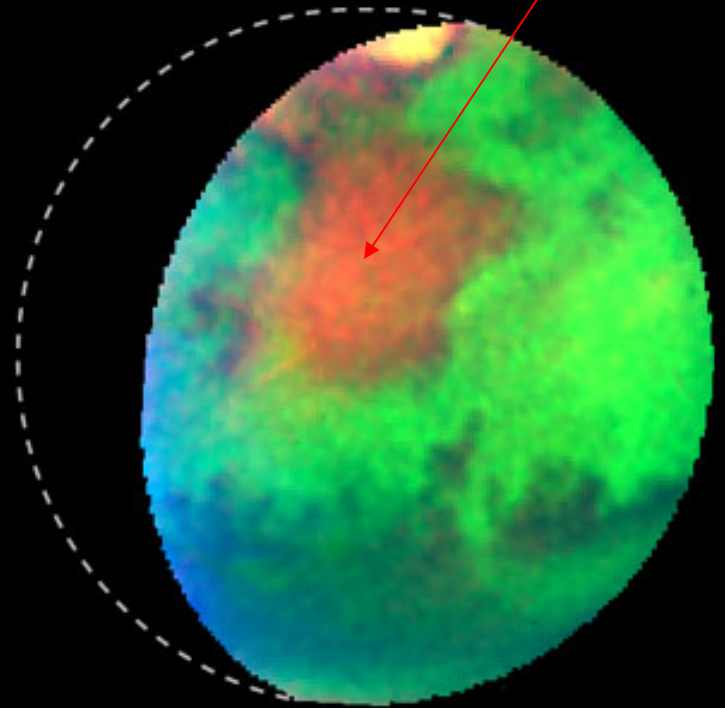
Near AND Far...

MARS: Near-IR imagery reveals enhanced concentrations of water-bearing minerals (coded red) in Mare Acidalium

Visible Light

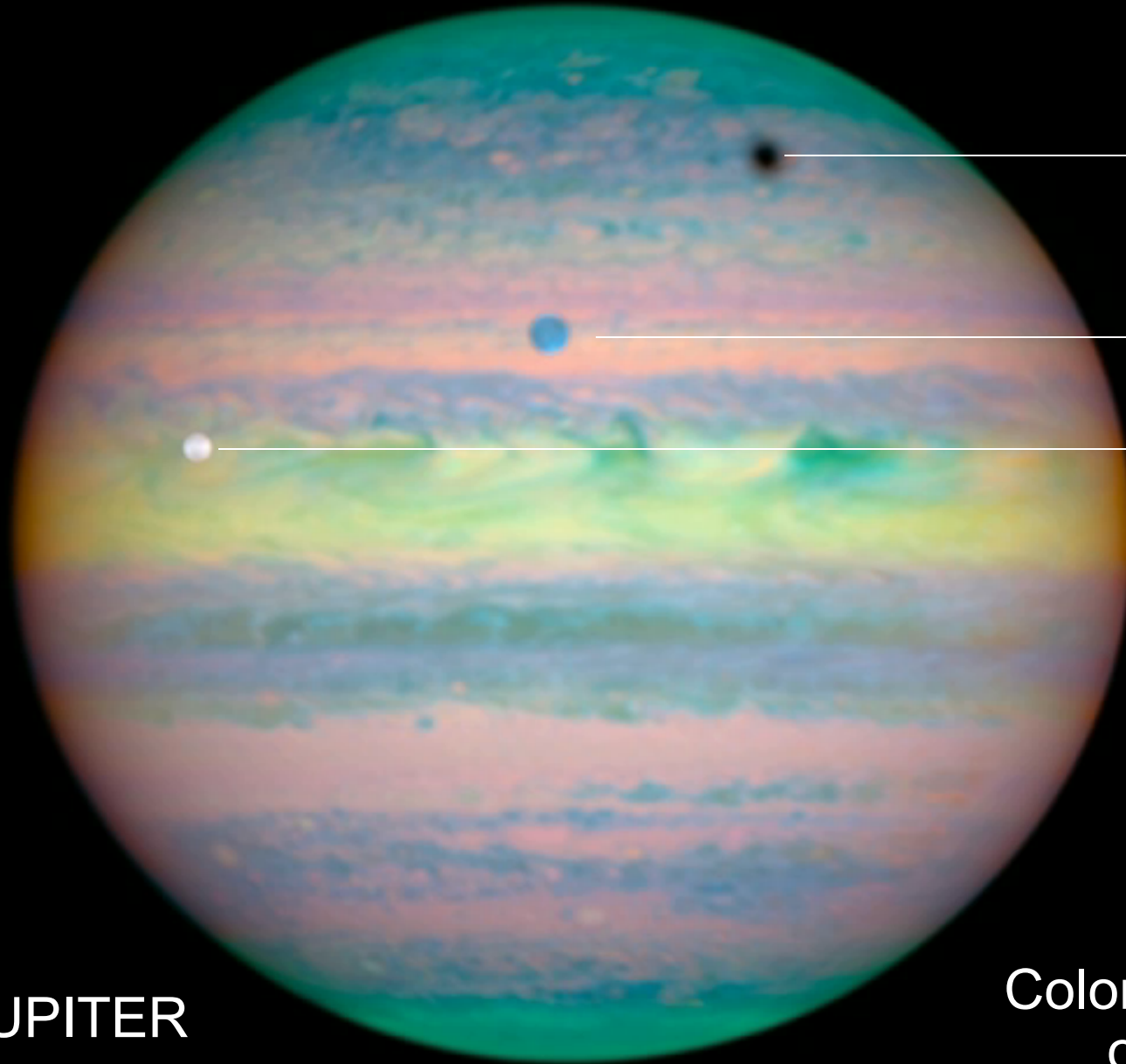


Near-Infrared



HST • WFPC2 • NICMOS

Probing the Atmospheres of the Gas Giant Worlds in our Outer Solar System



Callisto's
Shadow

Ganymede
& shadow

Io &
shadow

Colors indicate depths
of cloud layers...

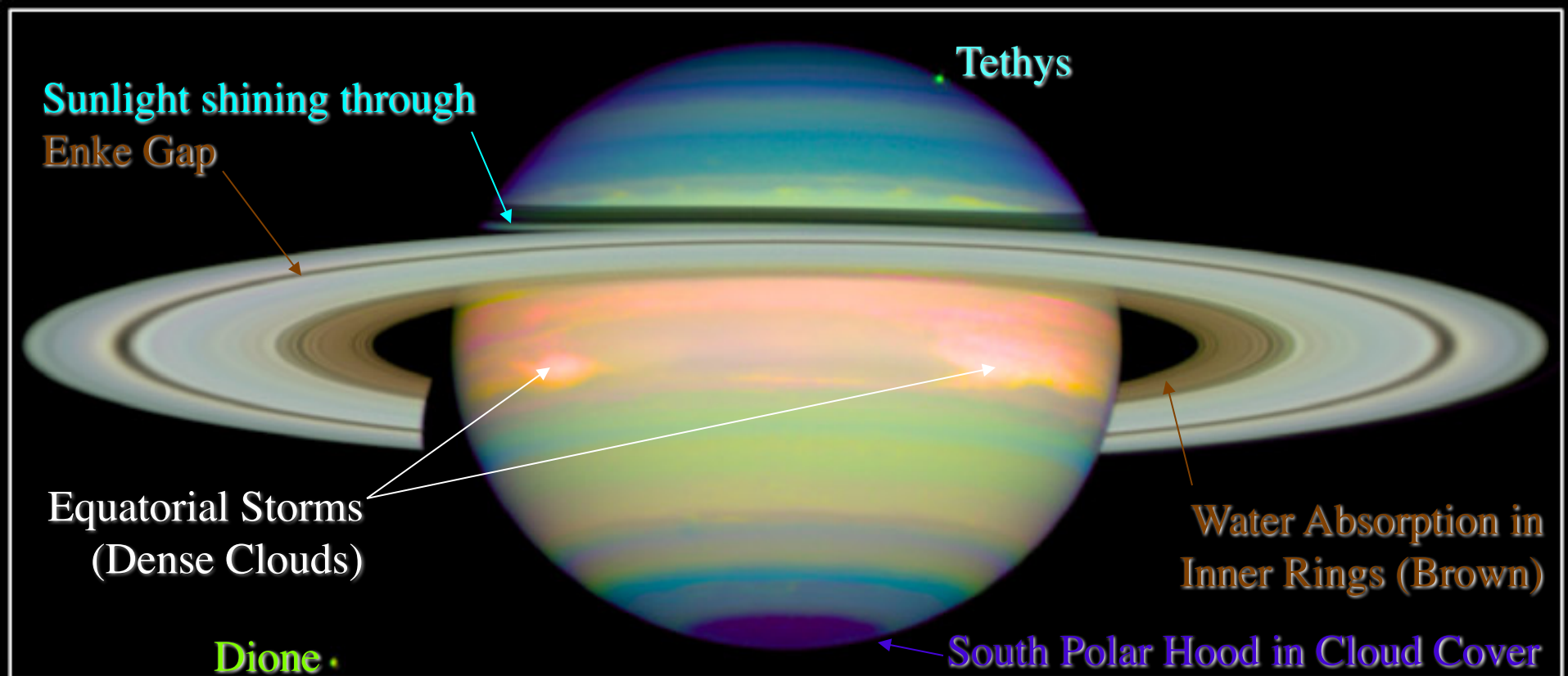
JUPITER

Saturn: Probing the Atmospheric Depths in the Near-IR

Blue: Clear Down to the Main Cloud Layer ($1\mu\text{m}$)

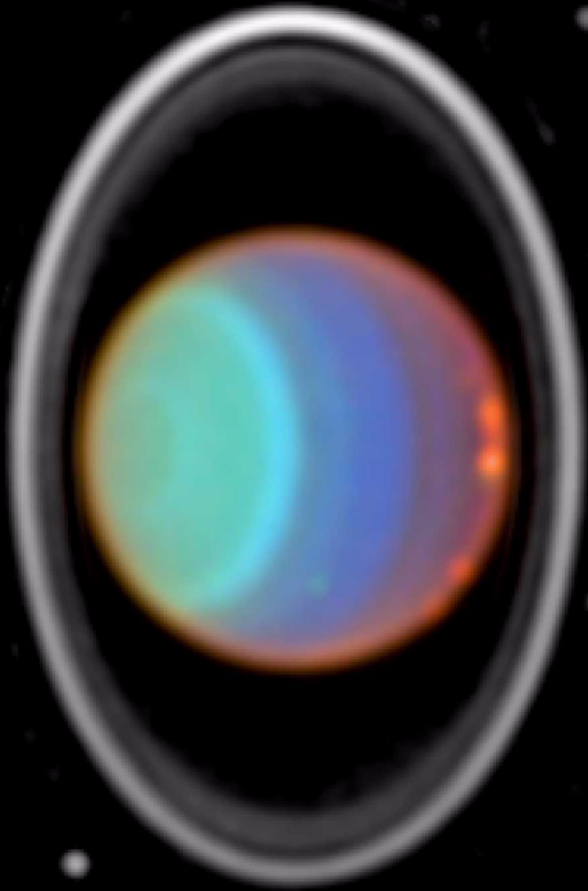
Green/Yellow: Haze Above Main Cloud Layer ($1.8\mu\text{m}$)

Orange/Red: High-Altitude Clouds ($2.1\mu\text{m}$)

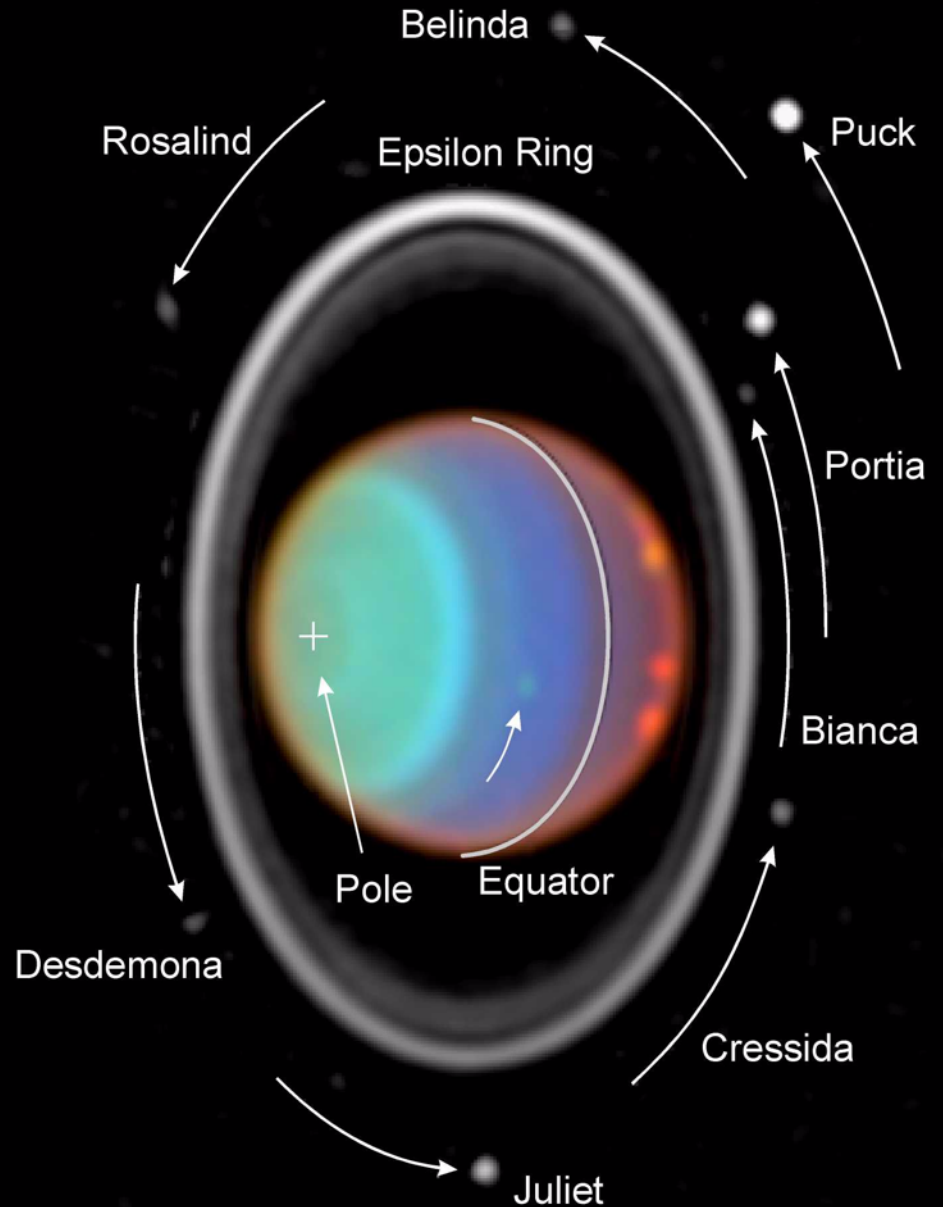


HST • NICMOS

Uranus, Rings & Satellites

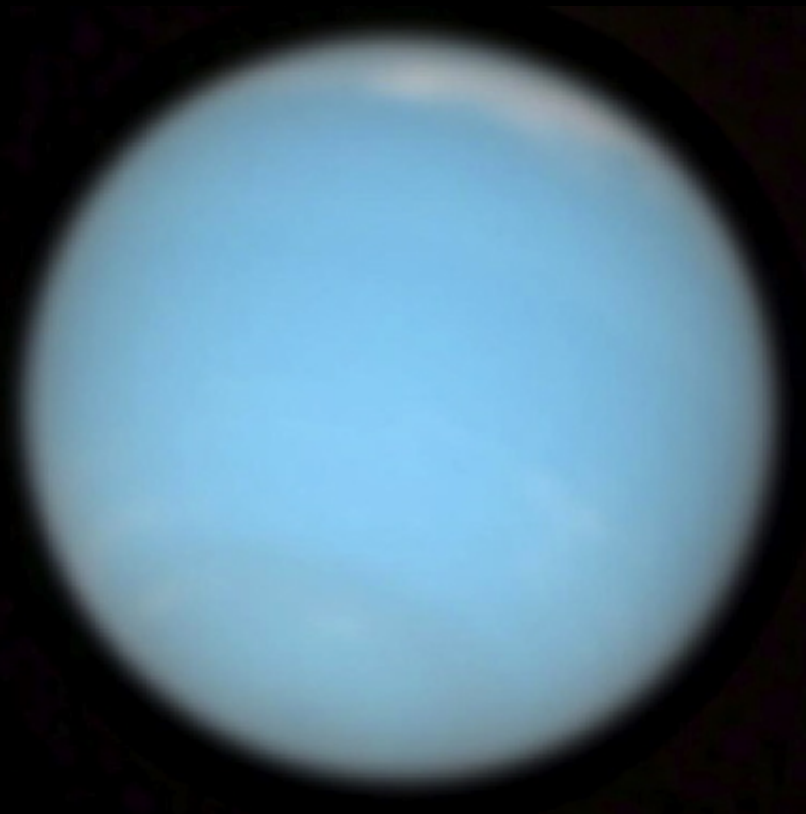


Bright high-altitude (orange) clouds
circle the planet @ > 300 mph



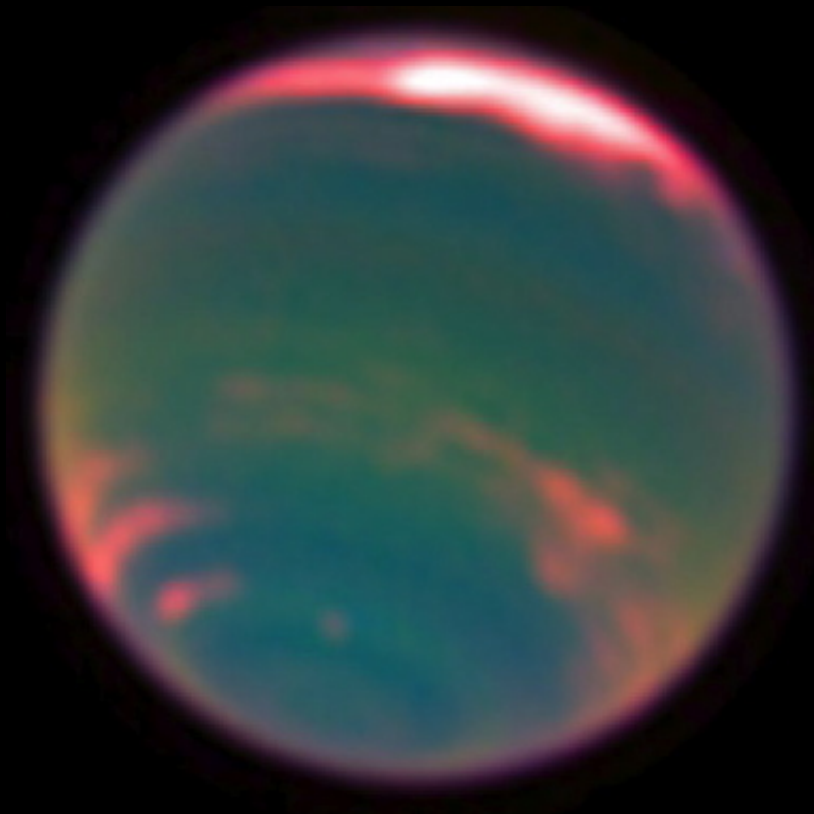
NICMOS: Imaging Methane (CH₄) Clouds on Neptune

VISIBLE LIGHT



HST/ACS

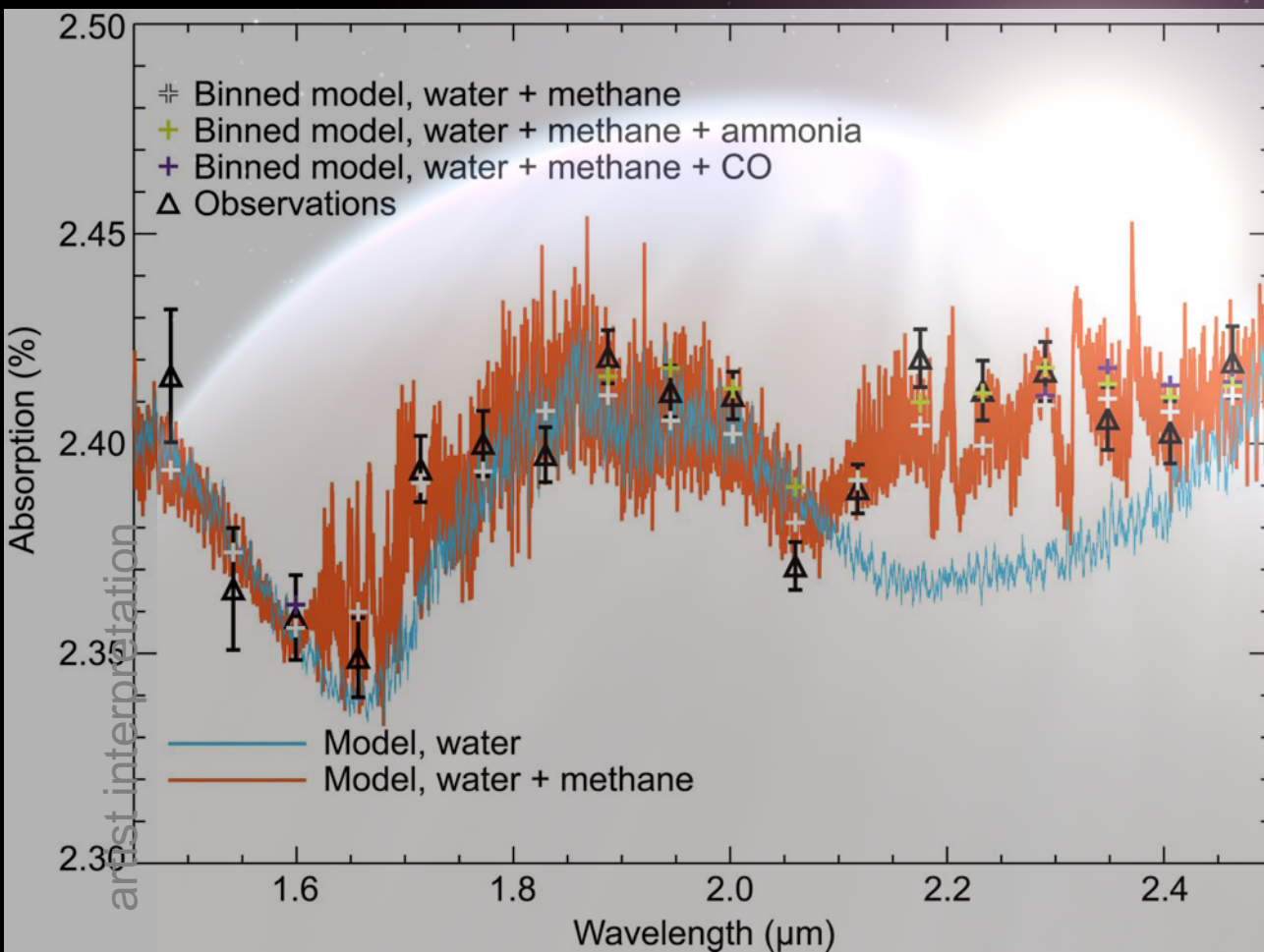
NEAR INFRA-RED



HST/NICMOS

*NICMOS: Detection Methane (CH₄) on HD 189733b**

**A Primitive ORGANIC MOLECULE in the Atmosphere of a
*Jupiter-Sized Transiting Planet Orbiting a K0V Star
65 Light-Years from Earth**



TRANSIT discovery

RV detected

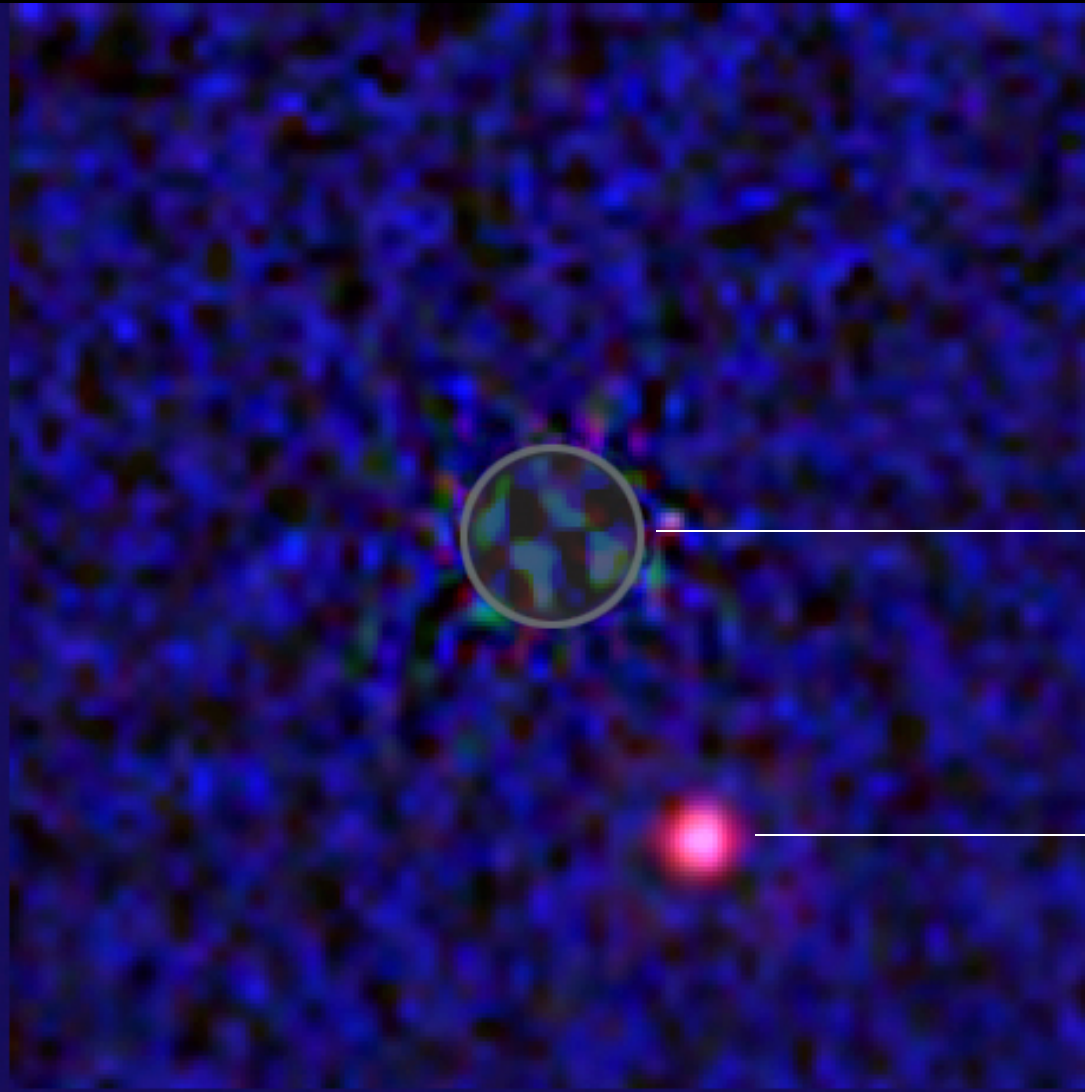
Orbit period: 2.2 days

Orbit distance: 0.03 au

Radius: 1.16 Jup

Mass: 1.12 Jup

Coronagraphy & High-Contrast Imaging of a Young Extrasolar Planet around a Brown Dwarf Host: 2MASS WJ 1207334-393254b



2M1207 is a young (10 My) brown dwarf in a star-forming association 170 light-years from the Earth.

Bright near-IR light from the 25 Jupiter-mass BD primary is suppressed revealing...

A 2–5 Jupiter-mass, 2400° F, planetary companion orbiting at ~ 41 au, still hot from formation due to its youth.

CUTTING THROUGH THE DUST:

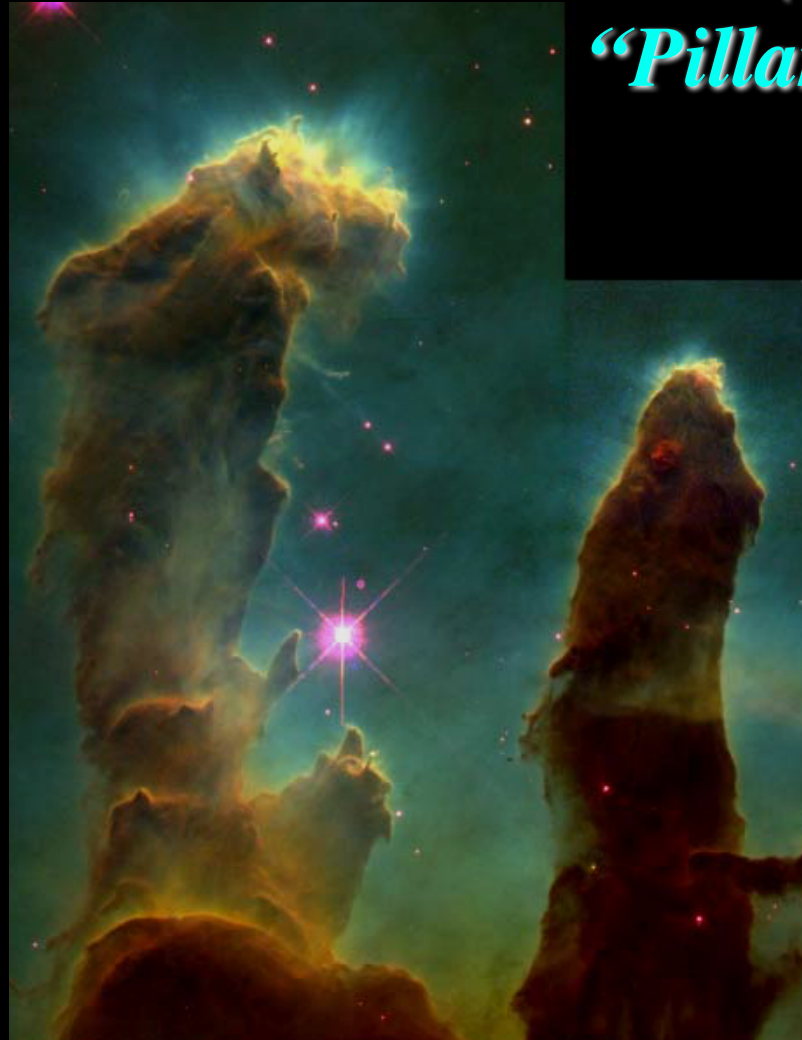
Stellar Birth and Death

The Eagle Nebula

HST/WFPC-2 VISIBLE-LIGHT IMAGE

M16 (Eagle Nebula)
“Pillars of Creation”
-revisited

Vast Columns
of Gas & Dust
Thought to Be
Regions of
Intensive Star
Formation



J. Hester & the
WFPC-2 Science Team

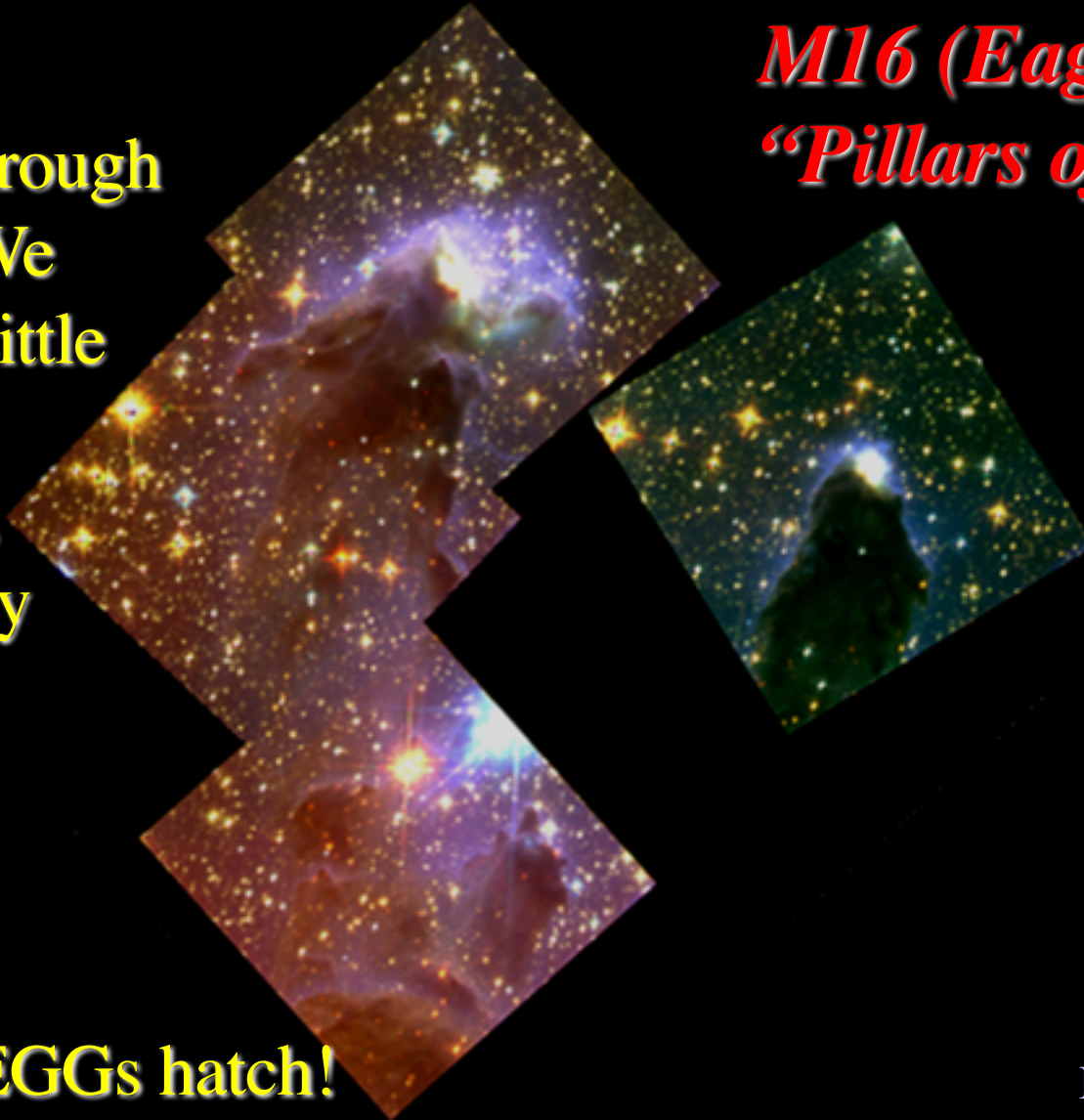
The Eagle Nebula

HST/NICMOS NEAR-IR IMAGE

M16 (Eagle Nebula)
“Pillars of Creation”

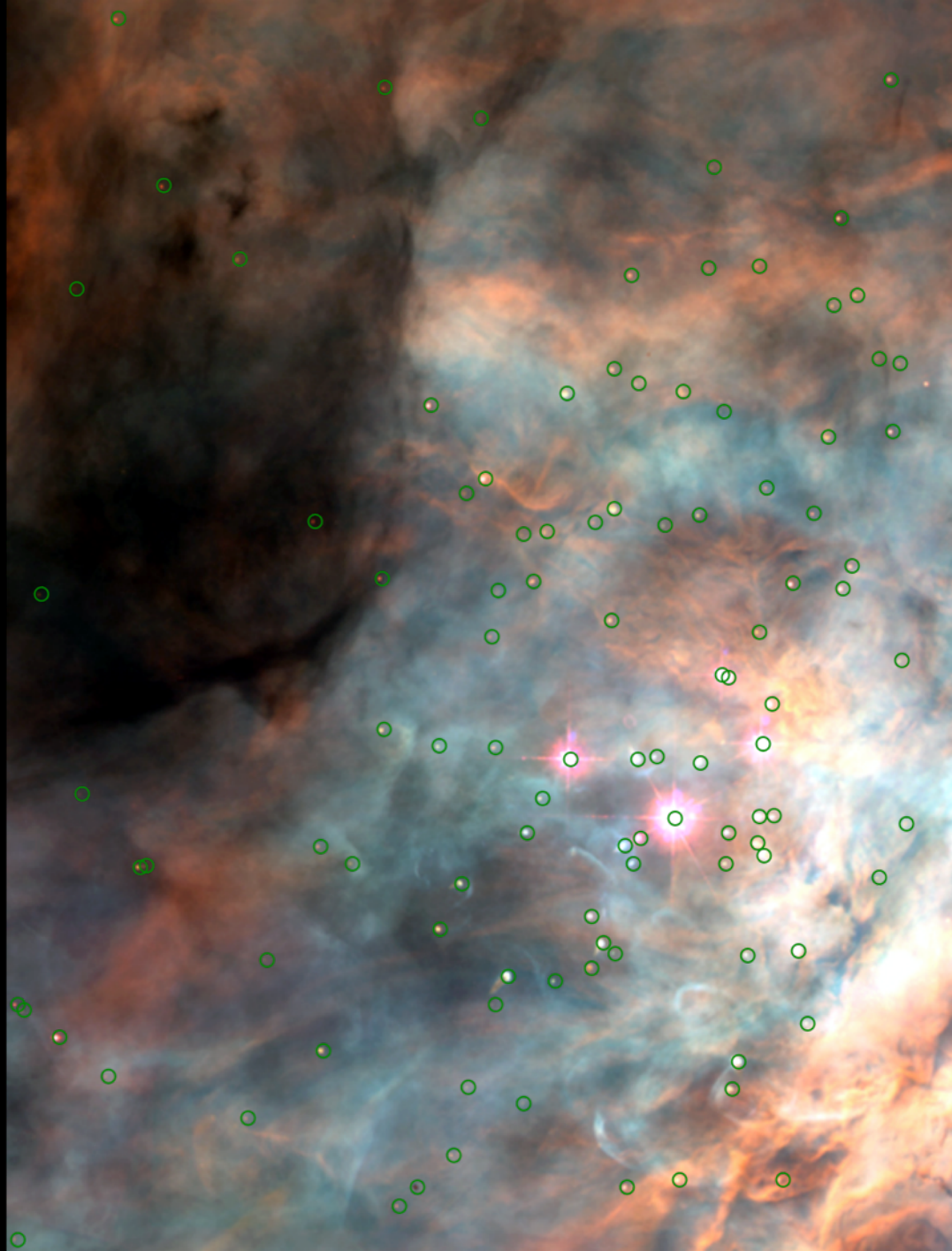
Peering Through
The Dust We
See Very Little
Star
Formation,
Active Only
at the Very
Tips of the
Pillars.

Only few EGGs hatch!



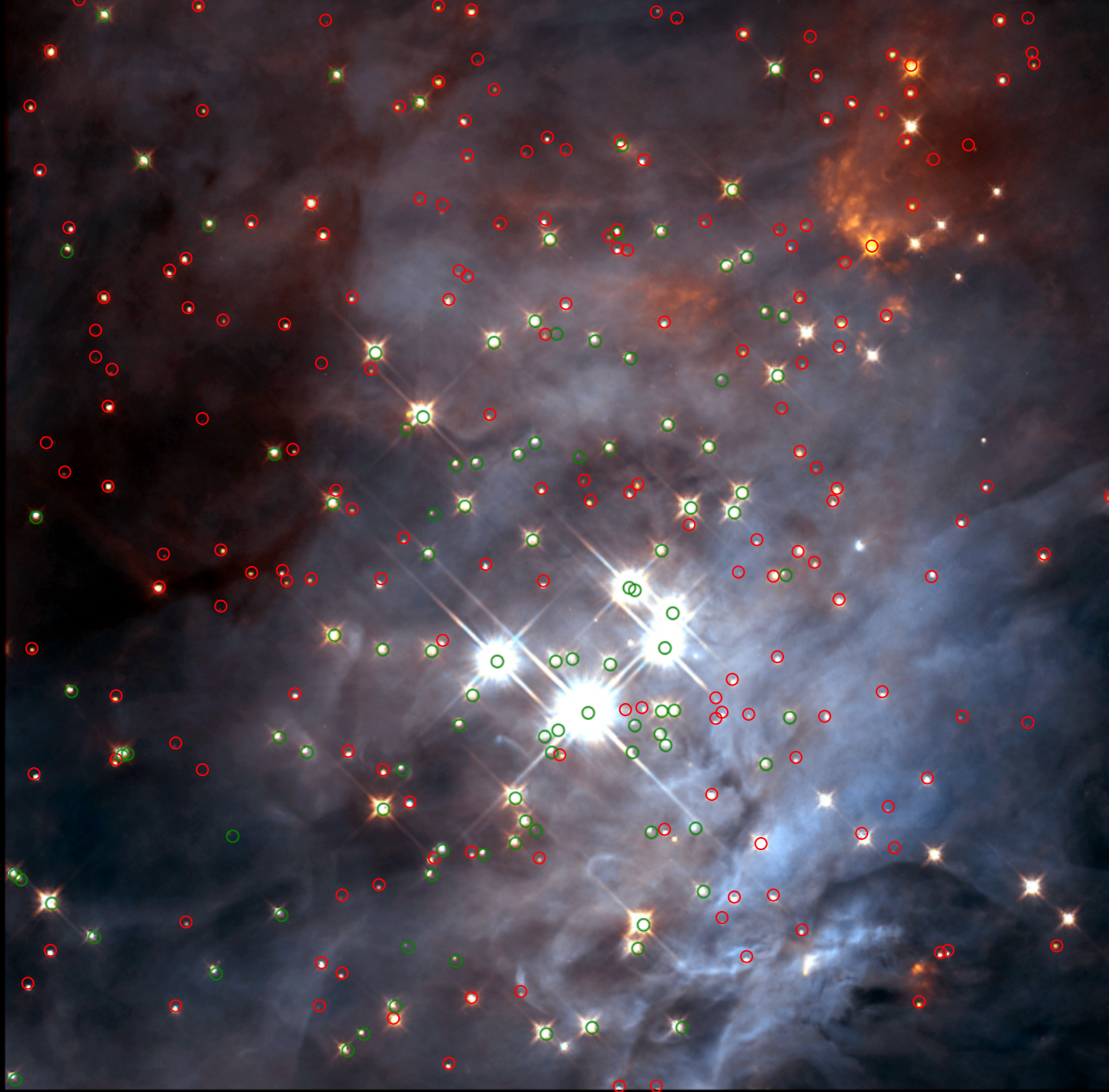
R. Thompson & the
NICMOS Science Team

***Trapezium
Cluster
In Orion
HST/WFPC-2***

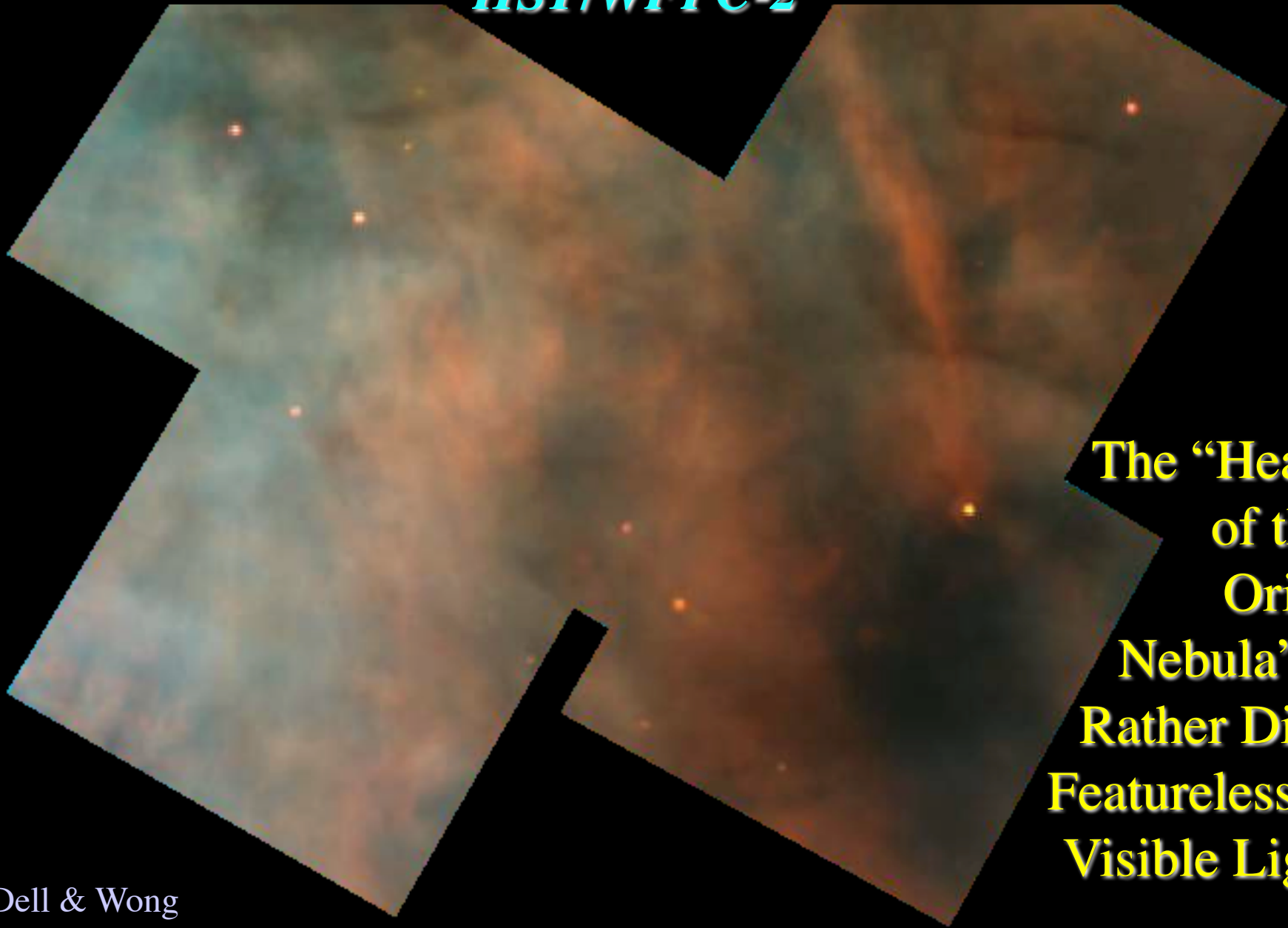


***Trapezium
Cluster
In Orion
HST/NICMOS***

***With 50
sub-stellar
10-75 M_{jupiter}
objects in the
field***



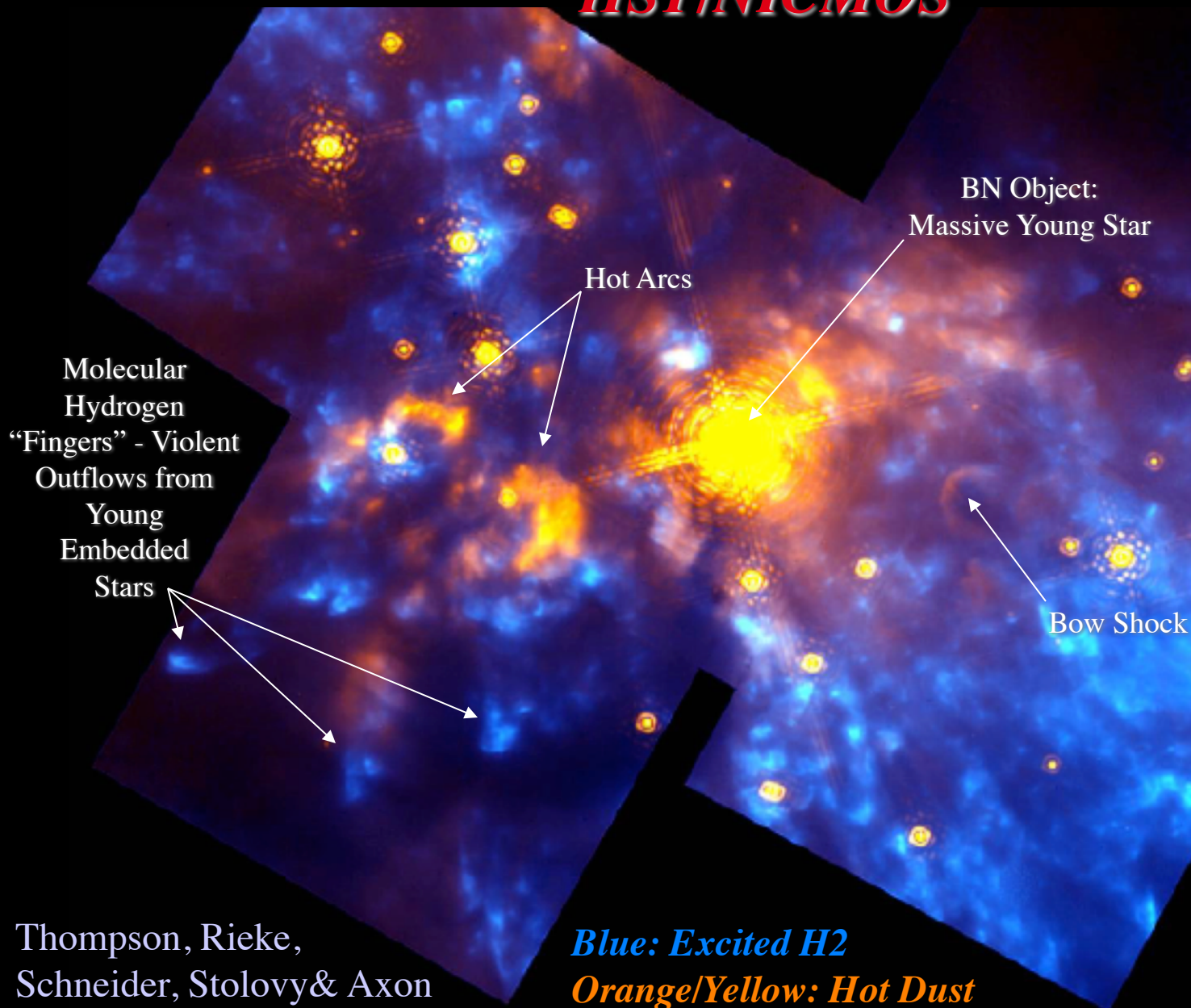
Orion OMC-1
HST/WFPC-2



The “Heart
of the
Orion
Nebula” is
Rather Dim
Featureless in
Visible Light

Orion OMC-1

HST/NICMOS



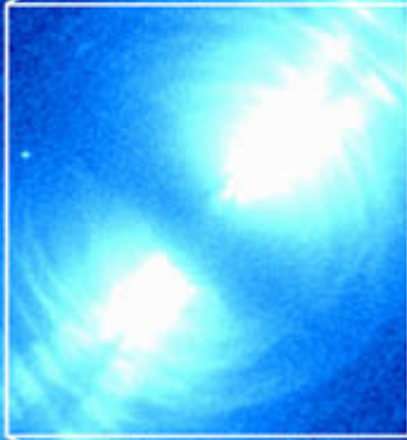
**But With
Active &
Chaotic
Star Birth
Seen in the
Near-IR**

Thompson, Rieke,
Schneider, Stolovy & Axon

The DEATH of A Star

CRL 2668 - The Egg Nebula

WFPC-2



0.6 μ m (V-band)

Typical dying Sun-like stars, having burned most of their nuclear fuel, were thought to eject matter in slowly-expanding spherical winds.

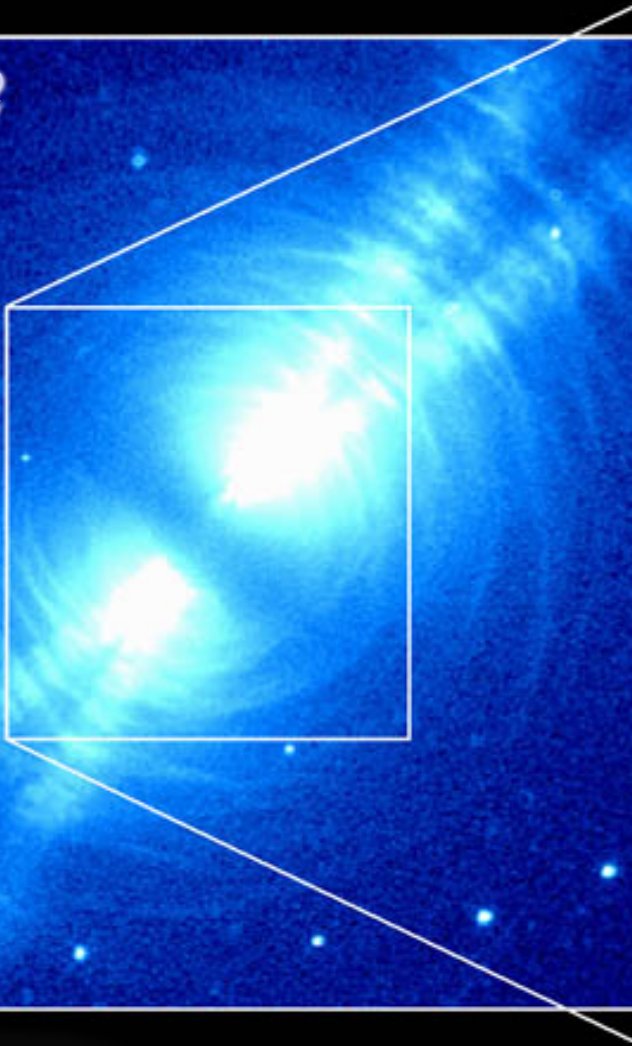
Such material returned to the interstellar medium is re-processed to form new stars, planets (and life?)

“ Planetary Nebulae ” , were pictured as gently expanding clouds of gas and dust.

The DEATH of A Star
CRL 2668 - The Egg Nebula

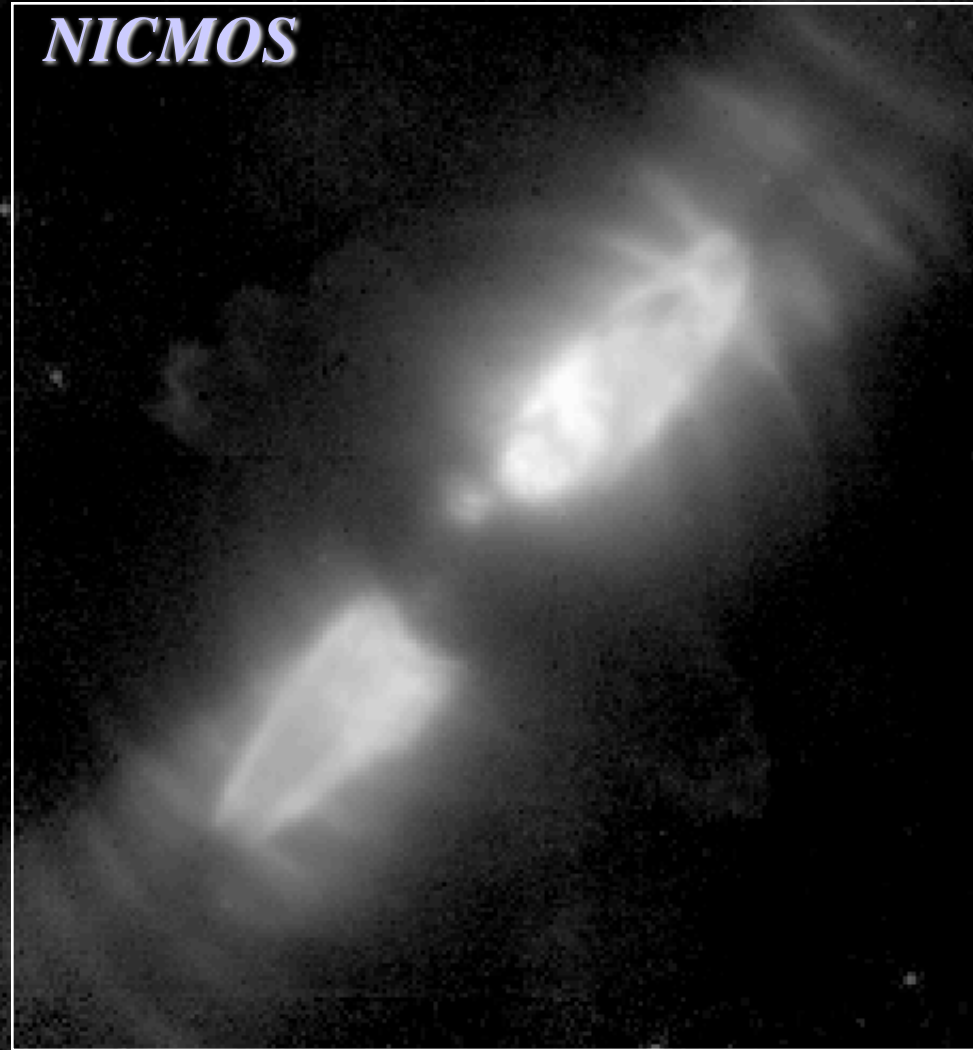
NICMOS Observing Modes
Medium Bandwidth Imaging
NICMOS reveals high-speed
(100 km/sec) ejection along the poles

WFPC-2



0.6 μ m (V-band)

NICMOS

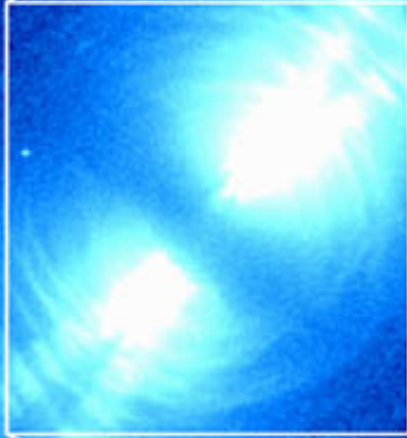


1.65 μ m (10%)

The DEATH of A Star
CRL 2668 - The Egg Nebula

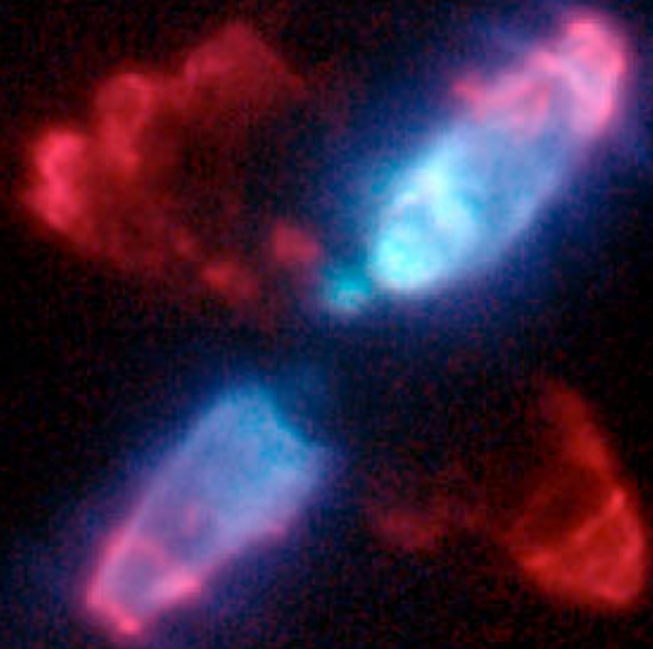
NICMOS Observing Modes
Atomic/Molecular Line Imaging
...and, hot H₂ emission in the
plane of the star's equator.

WFPC-2



0.6 μ m (V-band)

NICMOS

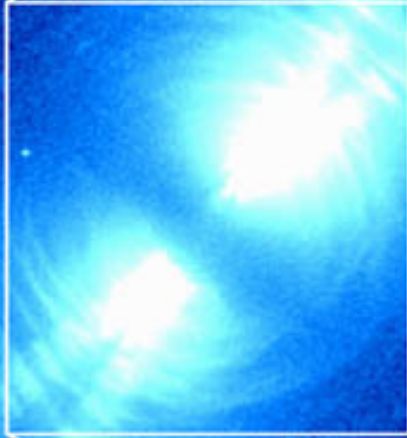


H2: 2.12 μ m (1%)

The DEATH of A Star
CRL 2668 - The Egg Nebula

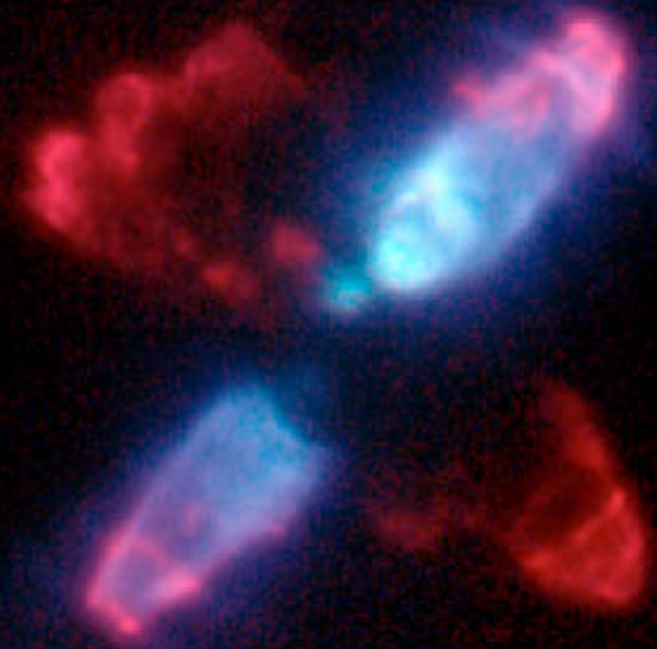
NICMOS Observing Modes
Atomic/Molecular Line Imaging
...and, hot H₂ emission in the
plane of the star's equator.

WFPC-2



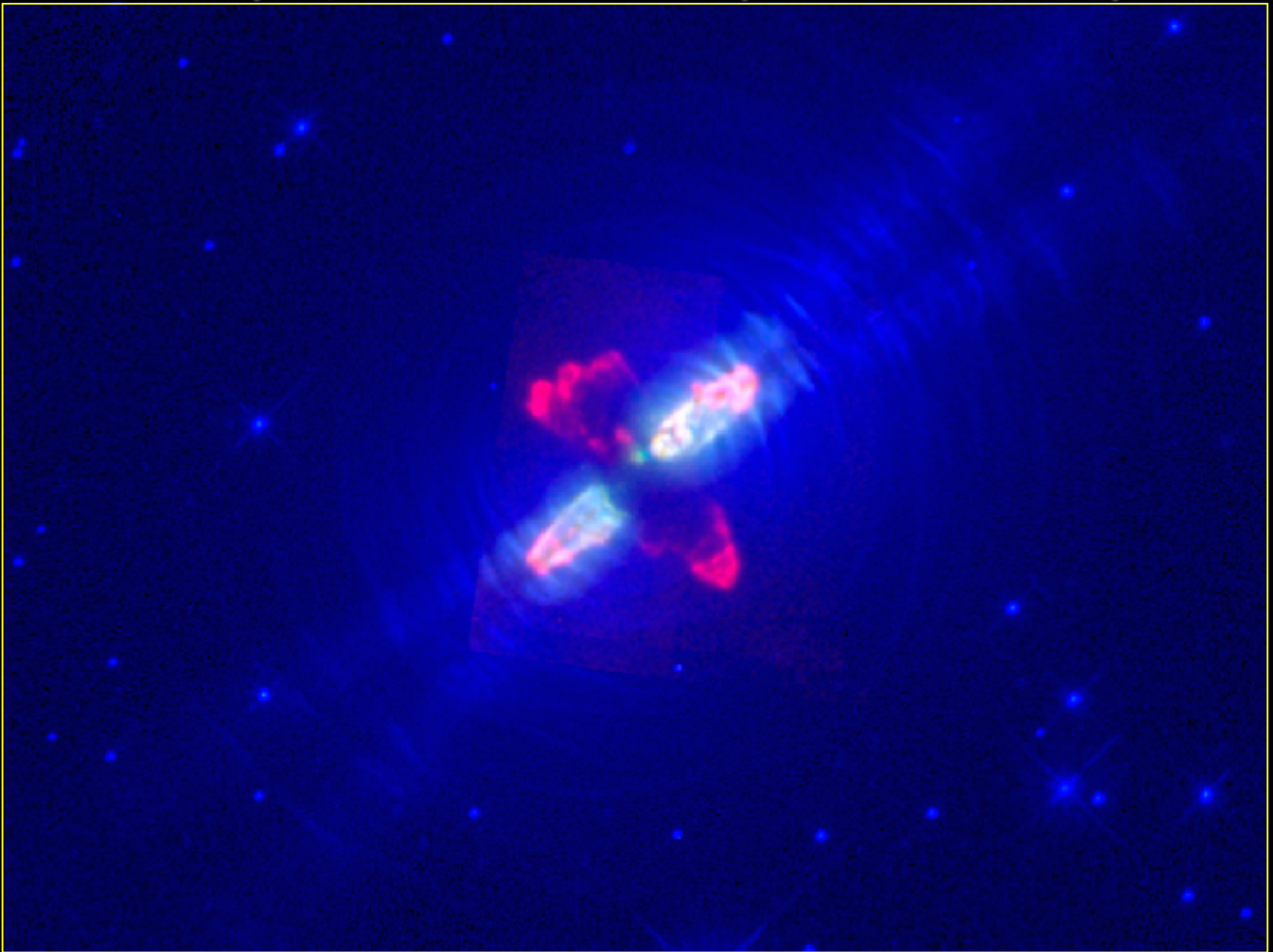
0.6 μ m (V-band)

NICMOS



H2: 2.12 μ m (1%)

WFPC-2: $0.6\mu\text{m}$; NICMOS: $2.122\mu\text{m}$ H2(S1), $1.65\mu\text{m}$ (10%)



Combining the Optical and Near-IR we now have a very different picture.

RED-SHIFT:

Going Deep, Faint, Far, and Old

Redshifted Galaxies and Quasars

- The most distant objects in the universe have redshifts that are so high that they move all of the light out of the visible region and into the **infrared**.
- Observations of the very distant universe require **infrared** observations.
- As we look back in distance we also *look back in time*.



*1996 - The Deepest
Exposure Ever Taken*

Until...

*The Hubble
“Deep Field”
WFPC-2*

Exp. Times

- F300W: 49h
- F450W: 37h
- F606W: 35h
- F814W: 35h

Mag. Limits

- F300W: 27.5
- F450W: 28.1
- F606W: 28.7
- F814W: 28.0



The Hubble *“Deep Field”* *NICMOS*

- 49.1”x48.4”
- 36.5h in each of two spectral bands (1.1 μ m & 1.6 μ m).
- 342 galaxies are seen in the NICMOS field.
- 105 more than in the same region imaged in the optical by WFPC-2

Thompson, Storrie-Lombardi,
Weymann, Schneider, Rieke,
Stobie & Lytle

The image is a deep-field astronomical photograph showing a vast number of galaxies. The galaxies are of various shapes and sizes, some appearing as bright, distinct objects while others are faint and diffuse. They are scattered across a dark background. A small red square in the lower-left quadrant is magnified into a larger red square on the right, showing a closer view of the galaxies in that region. The text on the right side of the image provides context about the image's origin and the faintness of the galaxies.

The Hubble
“Deep Field”
NICMOS

The faintest
galaxies in this
image are:

About 30th
magnitude.

About 13 billion
light-years
away.

The image is a deep-field astronomical photograph showing a vast number of galaxies. The galaxies vary in size, shape, and color, appearing as bright spots or fuzzy patches against a dark background. Some are yellowish-white, others reddish, and some bluish. Two red rectangular boxes are overlaid on the image. The first box is on the left side, and the second box is larger and positioned to the right of the first. Dashed red lines connect the top-right corner of the first box to the top-left corner of the second box, and the bottom-left corner of the first box to the bottom-left corner of the second box, indicating that the second box is a magnified view of the area in the first box.

The Hubble “Deep Field” NICMOS

The faintest
galaxies in this
image are:

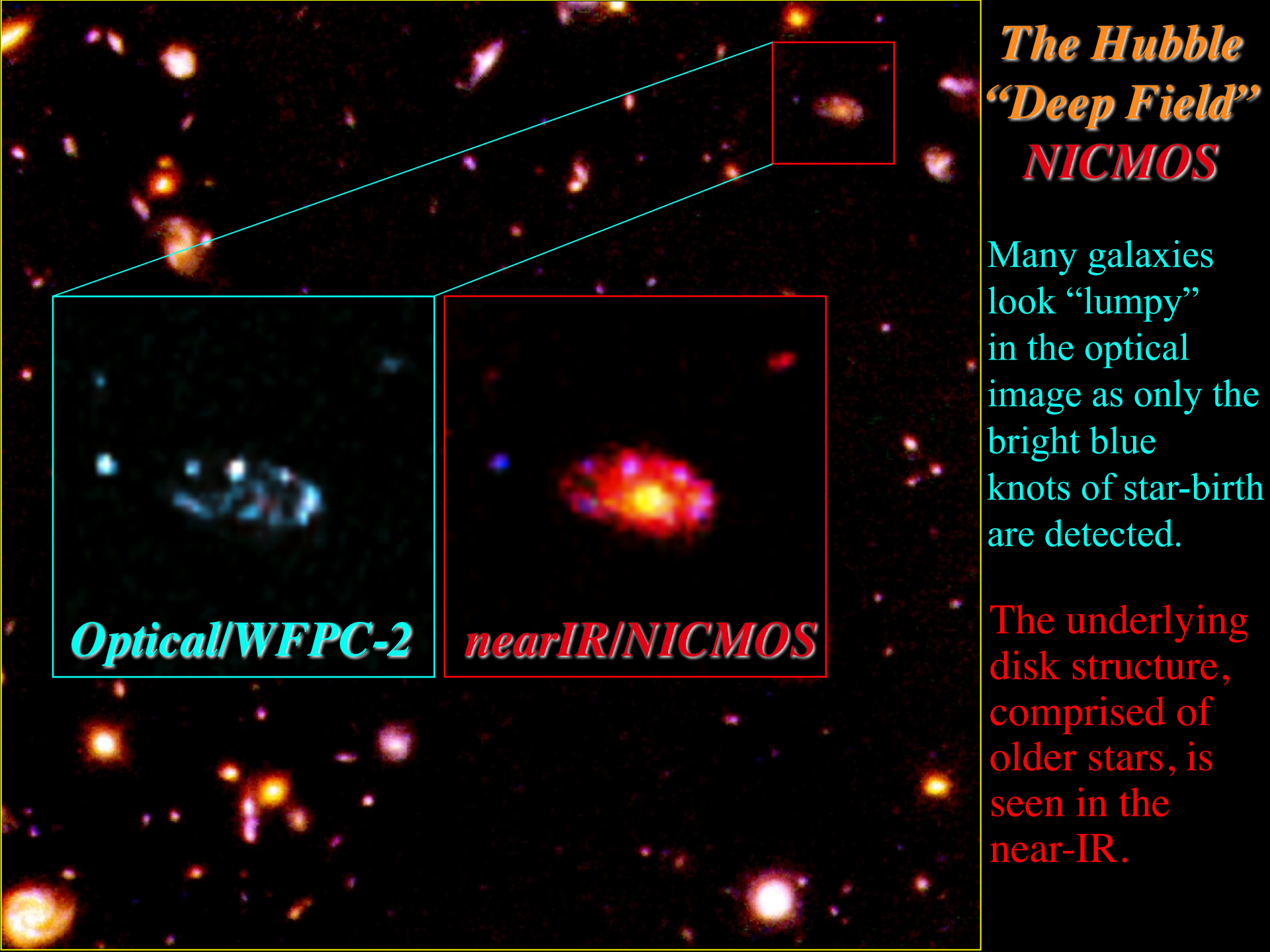
About 30th
magnitude.

About 13 billion
light-years
away.

The Hubble “Deep Field” NICMOS

Many galaxies look “lumpy” in the optical image as only the bright blue knots of star-birth are detected.

The underlying disk structure, comprised of older stars, is seen in the near-IR.



Optical/WFPC-2

nearIR/NICMOS

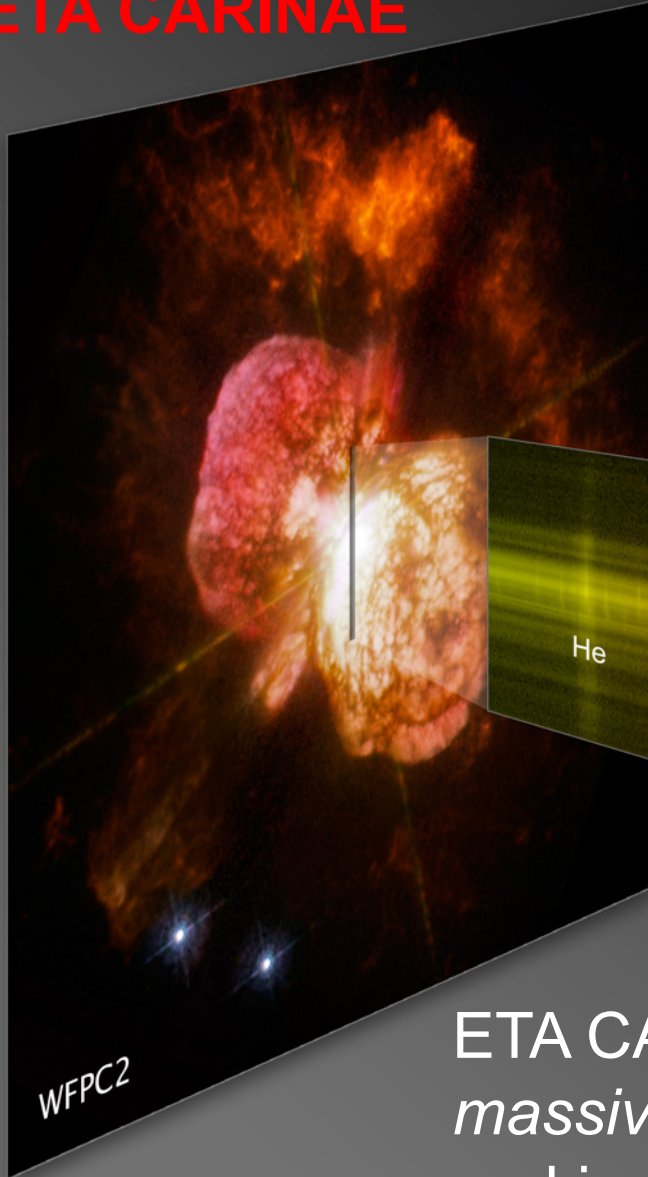
***Even Deeper:
The NICMOS
ULTRA-Deep
Field***

**Looking back
in time 95%
of the age of
the Universe*
to when the
first galaxies
just recently
formed.**

***13.7 billion yr**

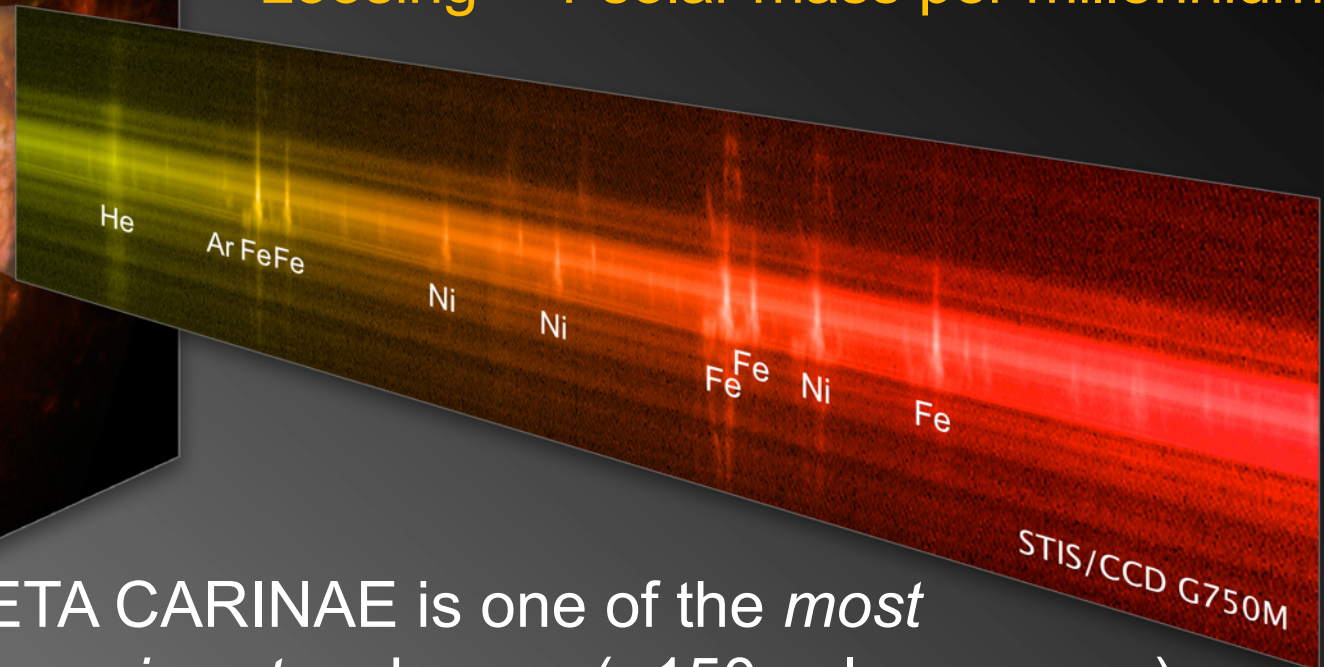
SPACE TELESCOPE IMAGING SPECTROGRAPH (STIS) (installed with NICMOS in SM-2)

ETA CARINAE



STIS *SPECTROSCOPY* reveals:

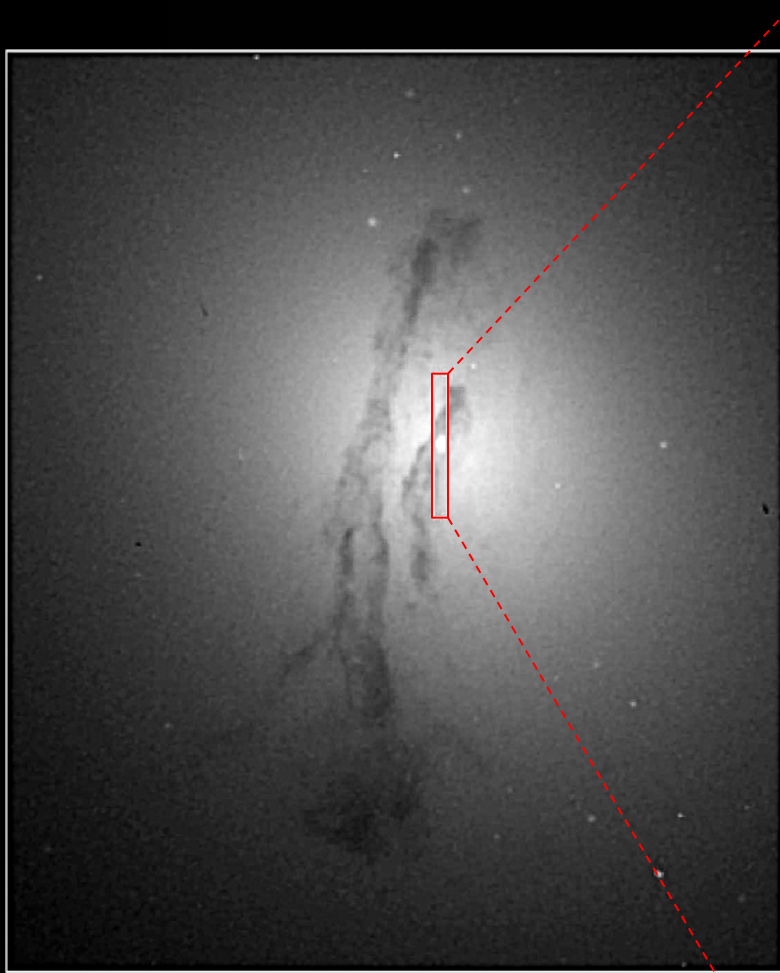
- Massive stellar wind from 1834 eruption
- Heavy elements Iron (Fe) and Nickel (Ni), created in the star ejected into space (replenishing the interstellar medium)
- Loosing ~ 1 solar mass per millennium



ETA CARINAE is one of the *most massive stars* known (~ 150 solar masses) and is on the verger of destruction.

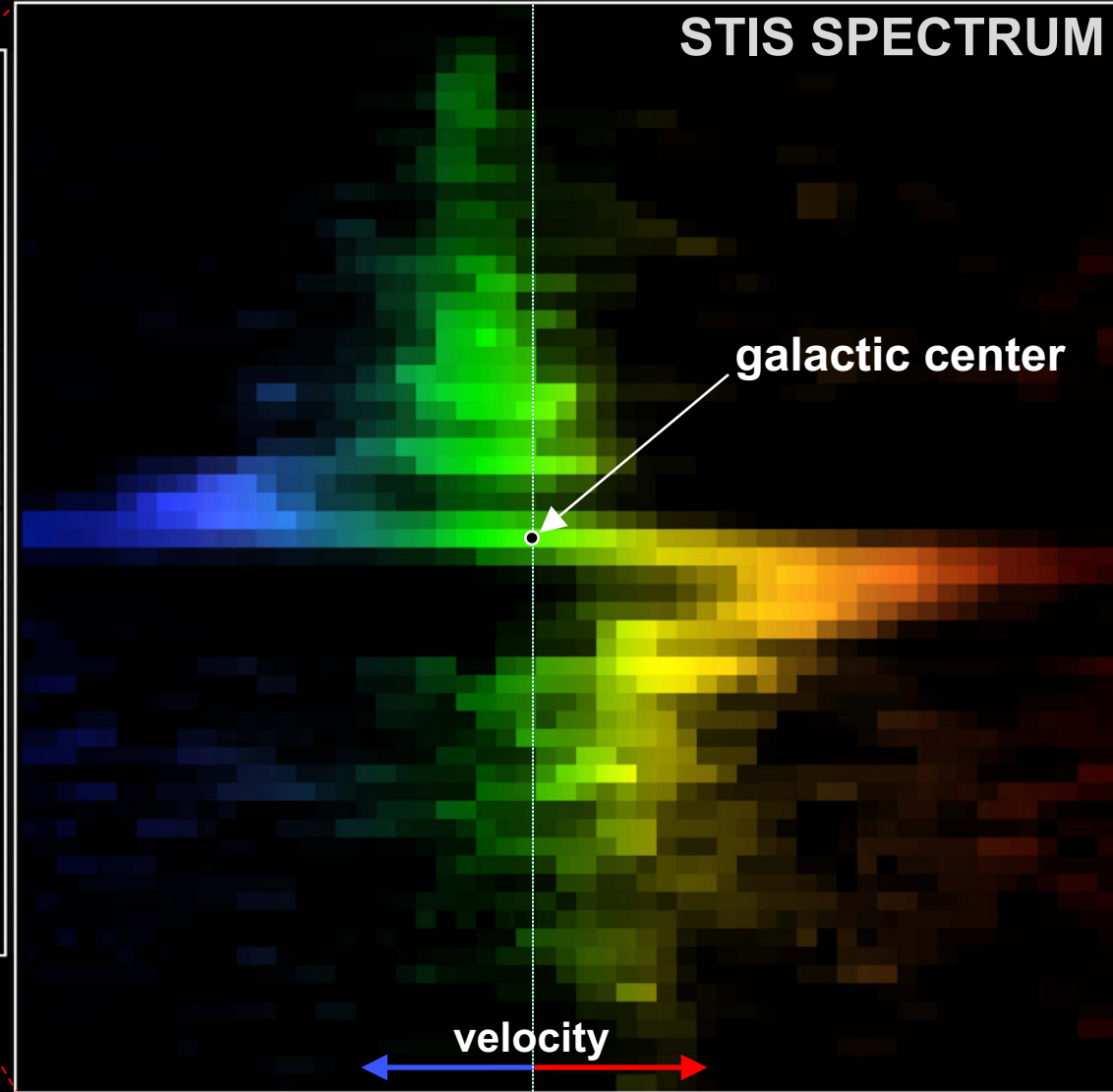
SPACE TELESCOPE IMAGING SPECTROGRAPH (STIS)

SPECTROSCOPY: Super-Massive Black Hole in the Core of Galaxy M84



WF/PC-2 IMAGE

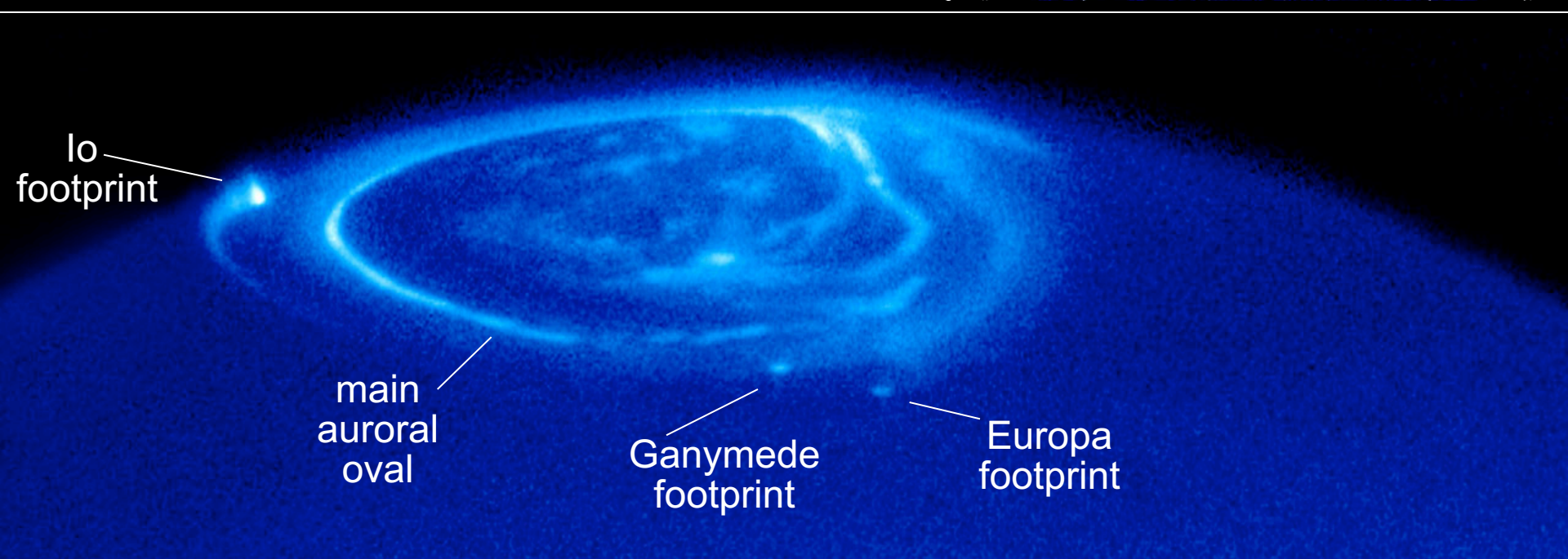
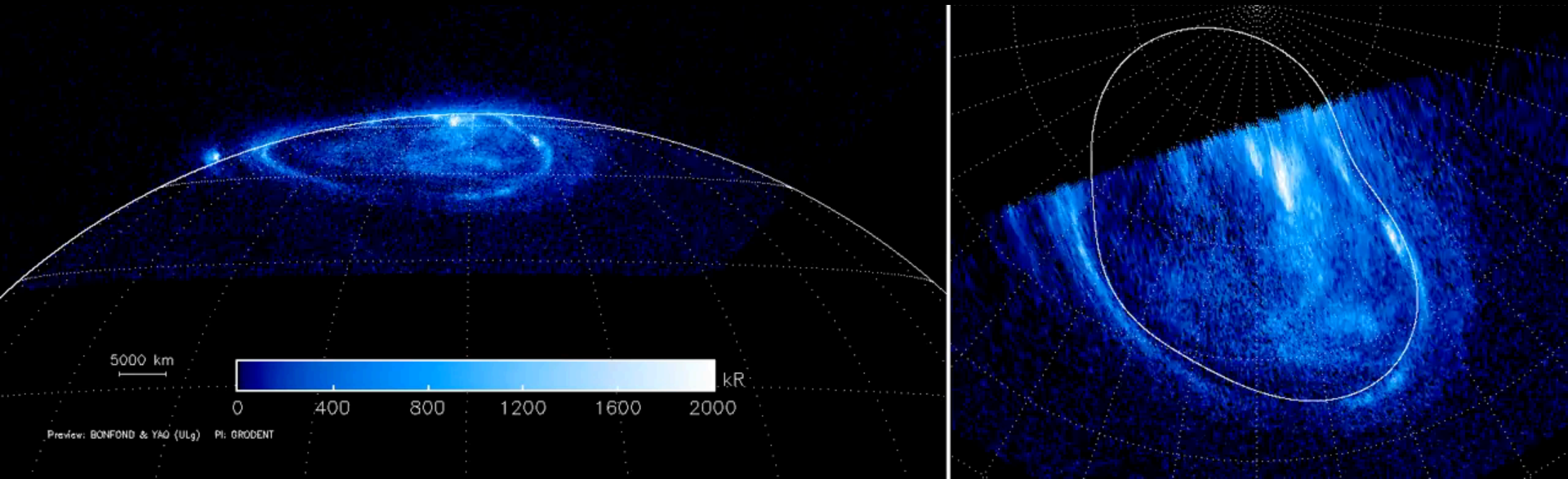
M84 is a member of the Virgo Cluster of galaxies 50 million Light years from Earth



Rotation Velocity: $\pm 880,000$ mph
→ Mass: 300,000,000 solar masses!

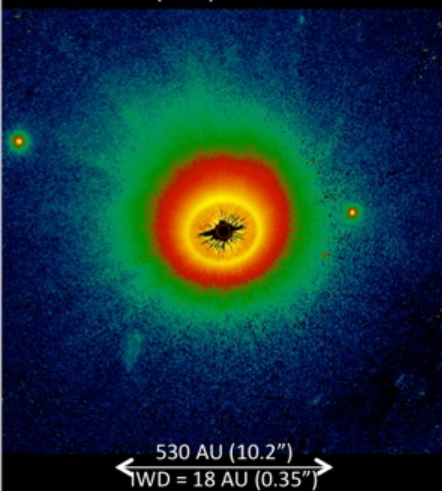
SPACE TELESCOPE IMAGING SPECTROGRAPH (STIS)

ULTRA-VIOLET IMAGING JUPITER's NORTH POLAR AURORA

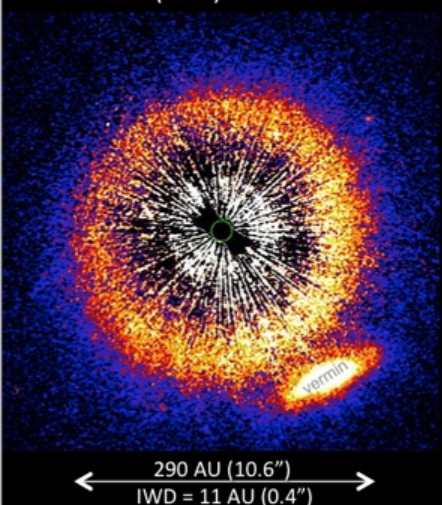


STIS CORONAGRAPHY of Exoplanetary Debris Systems

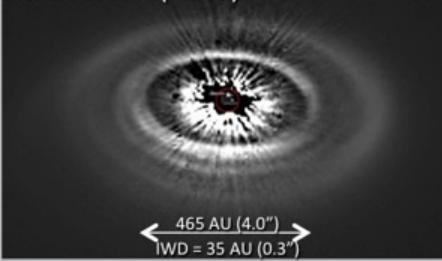
HD 181327 (F6V)



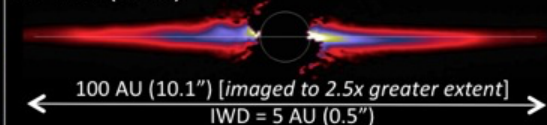
HD 107146 (G2V)



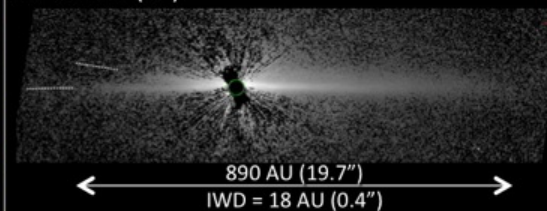
HD 141569A (A2Ve)



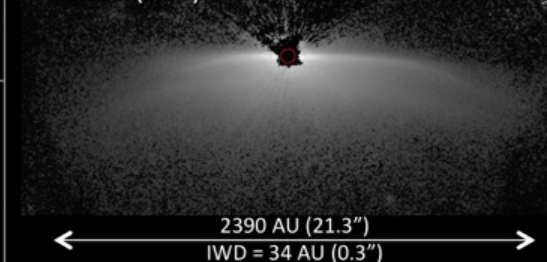
AU MIC (M1V)



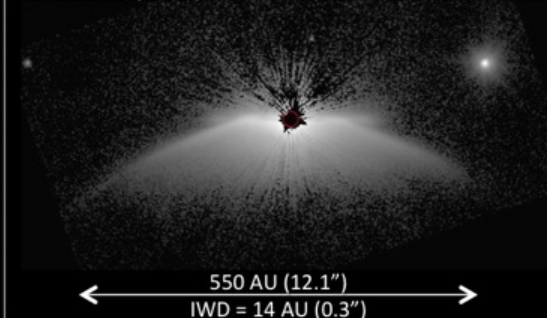
HD 15115 (F2)



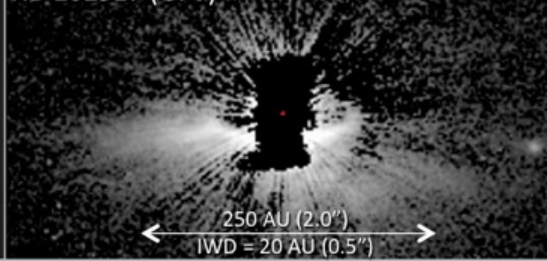
HD 32297 (A0V)



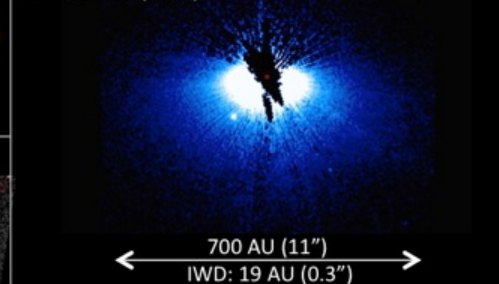
HD 61005 (G8V)



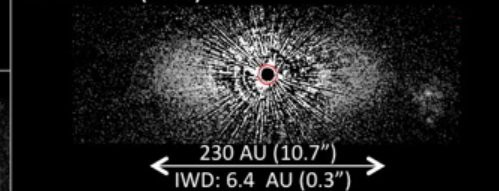
HD 202917 (G7V)



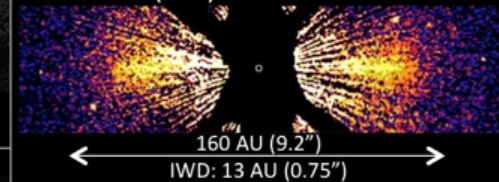
HD 15745 (F2V)



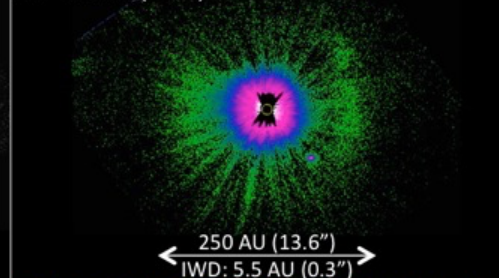
HD 92945 (K1V)



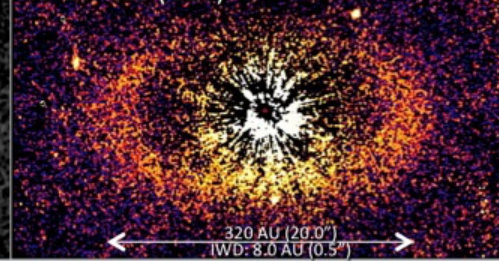
HD 139664 (F5V)



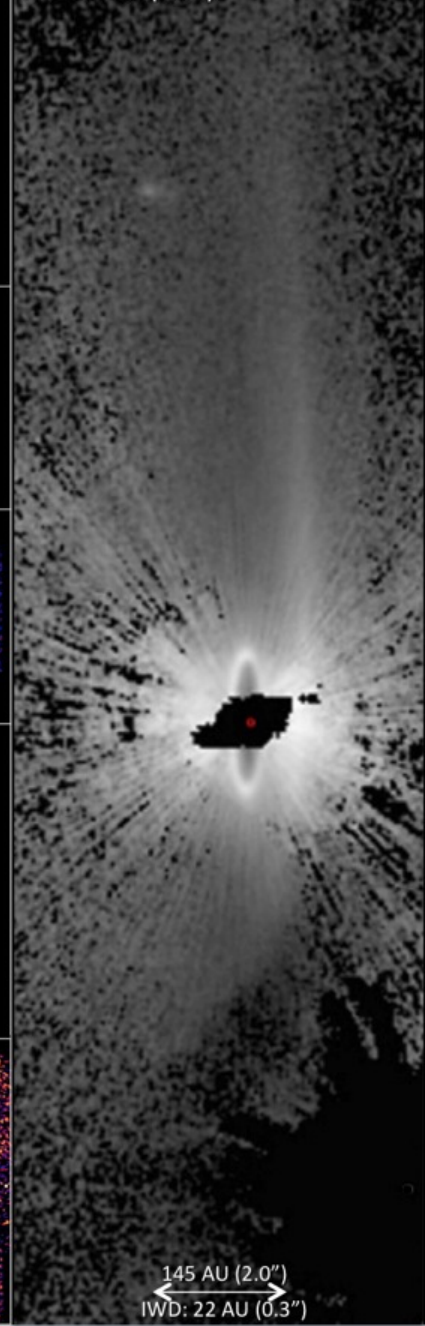
HD 53143 (G9V)



HD 207129 (G2V)



HR 4796 A (A0V)



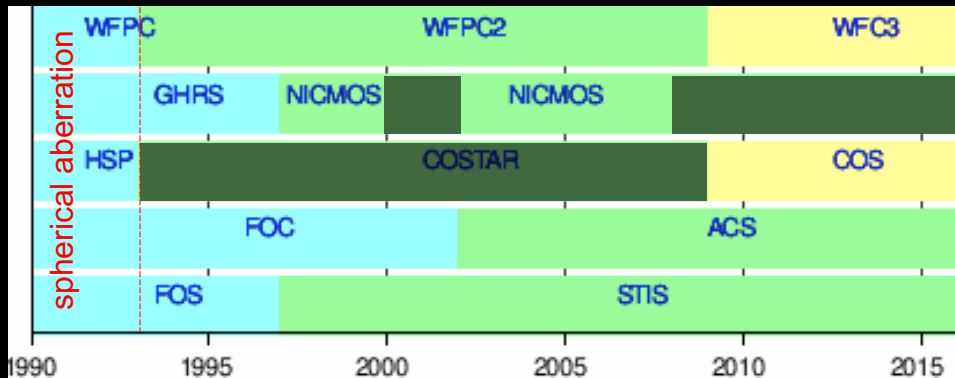
“Upgrades”: Following NICMOS & STIS, over time, NASA installed 3 additional state-of-the-art replacement instruments to expand Hubble’s vision.

SM3B (2002) [STS-109]

- **Advanced Camera for Surveys**

SM4 (2009) [STS-125]

- **Wide Field Camera 3**
- **Cosmic Origins Spectrograph**



HST is now in mission year 28 (!), with today the combined instrument suite: of **STIS, ACS, COS, WFC-3 (and FGSs)**.

Throughout the mission, has HST has continued to produce breakthrough science and exquisitely detailed and sensitive *views of our glorious universe...*

V838 Monocerotis Stellar Explosion – “Light Echoes”



Stellar explosion in 2002, months later was a million time brighter than the Sun
Embedded in prior dark dust cloud trillions of miles across
Illuminated now by “echoed” explosive light

Planetary Nebula NGC 3132



250x fainter of two central stars is a 180,000° F WHITE DWARF
Causes resulting nebulosity from blown-off stellar layers
to fluoresce in optical & UV emission lines.

Planetary Nebula

NGC 7635
(“Cat’s Eye”)



PN can be highly complex: knots, jets, concentric rings, bubbles.

Emitting energy at all wavelengths from radio to X-ray.

“BUBBLE” Nebula

NGC 7635

Ionized H bubble
created by stellar
wind from hot
central star and
ionized from its
UV radiation.

The bubble is
near a giant
molecular cloud
that restricts its
expansion.





Star-Forming Region

R 136

**in the Large
Magellanic
Cloud (LMC)**

Massive, young,
100 ly wide region
of star birth in the
LMC.

No comparable
regions to R 136
in our Milky Way.

Deep cavities in
the ISM carved by
UV radiation from
the hot stars.

**Star-
Forming
Region**

LH 95

**in the
LMC**

Co-mingled, Hubble-accessible low (red), and high (blue) mass young stars in SF region. The latter give rise to both stellar winds and UV radiation causing the glowing cloud of ionized hydrogen.



Globular Cluster

NGC 6397

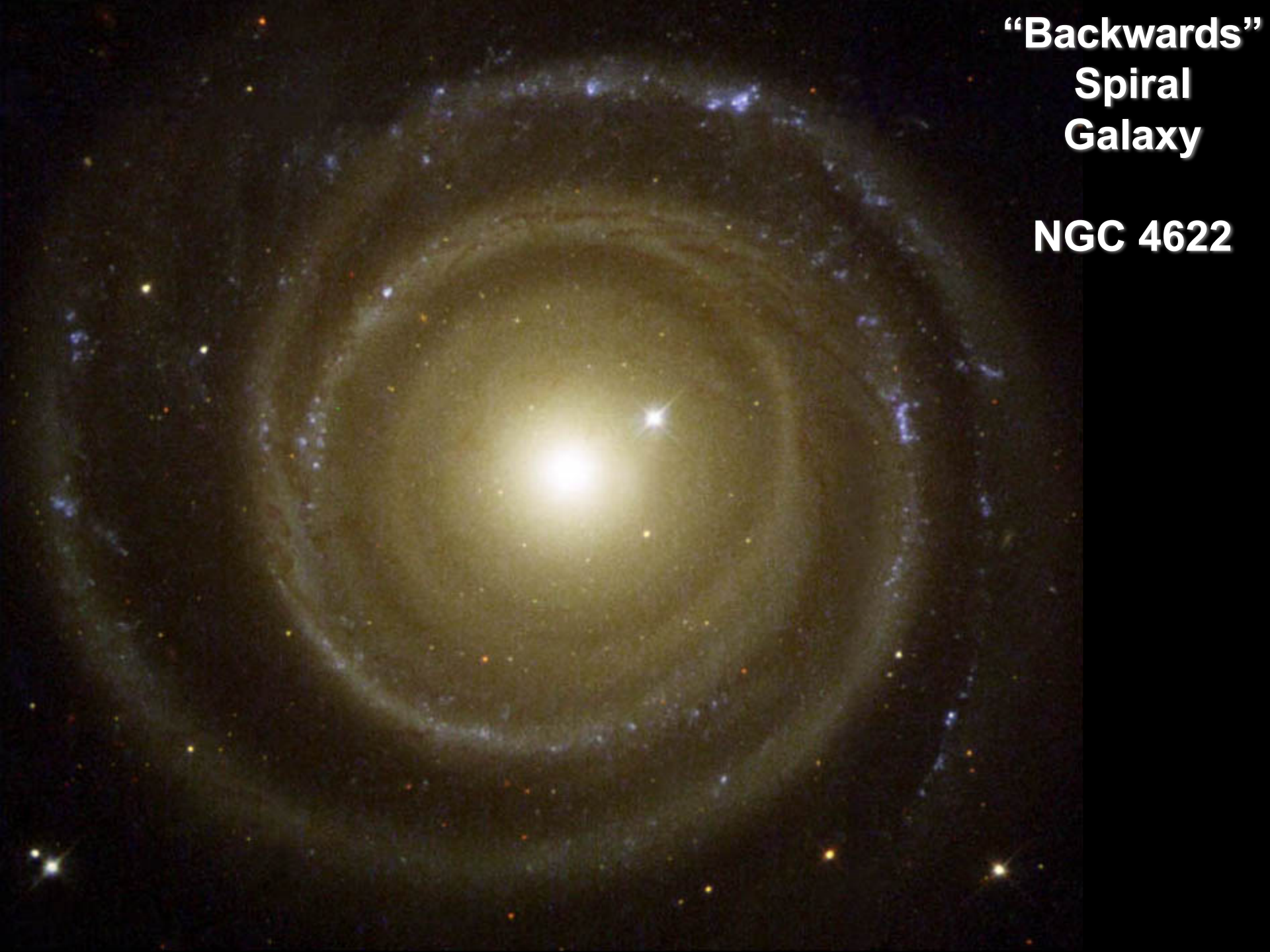
Old Stellar Populations

Globular clusters of stars surround our MW galaxy. At 7800 ly this is the 2nd closest to Earth. ~ 150 orbit the MW.

This GC contains ~ 400,000 stars with a very dense collapsed core, most at least 10 billion years old.

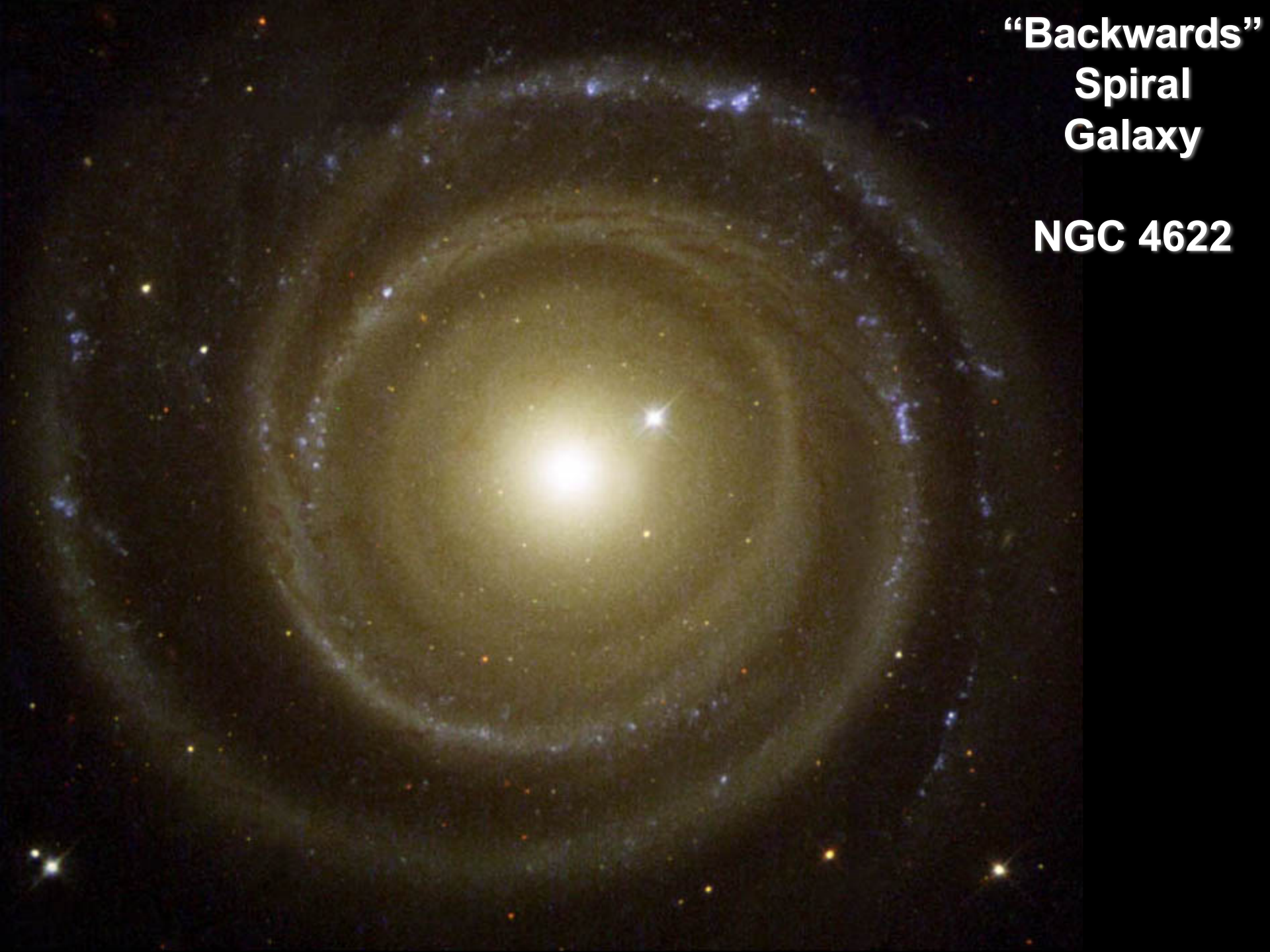
**“Backwards”
Spiral
Galaxy**

NGC 4622



**“Backwards”
Spiral
Galaxy**

NGC 4622





Dwarf Irregular Galaxy

**NGC 4622
(SagDIG)**

Not all galaxies
are grand spirals
or ellipticals.

HST can resolve
individual stars in
dwarf irregular
galaxies to large
distances.

This one,
relatively close at
3.5 million ly is a
laboratory for
studying star
formation history.

Ring Galaxy (RG) AM 0644-741

RG's exemplify how galactic collisions alter structure and trigger star formation.



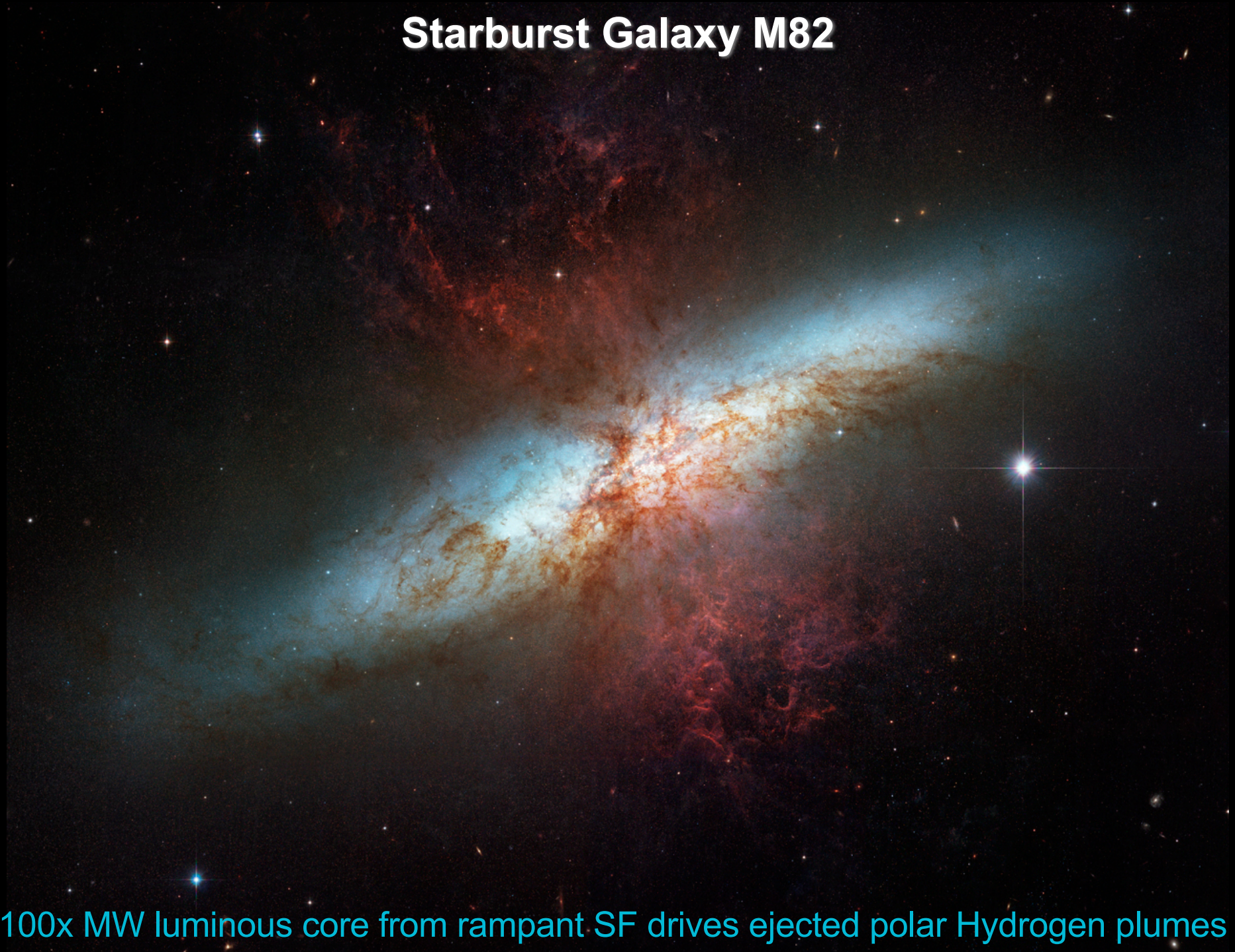
Hoag's Object



Here the blue ring of hot massive young stars is sharply separated from the older yellow stars around the nucleus.

The ring is likely the shredded remains of a galaxy passing “too near” about 3 billion years ago.

Starburst Galaxy M82



100x MW luminous core from rampant SF drives ejected polar Hydrogen plumes

Edge-On "Dusty" Galaxy NGC 5866



HST reveals a crisp dust lane bifurcating a blue halo and reddish nuclear bulge

“Sombrero” Galaxy AM 0644-741



The slightly inclined Sombrero ring galaxy has a rim of dust circumscribing its disk

“Black Eye” Spiral Galaxy M64

Unusually
dusty spiral
galaxy.

Gas beyond
the dusty disk
is rotating
opposite the
stars and gas
in the inner
regions.

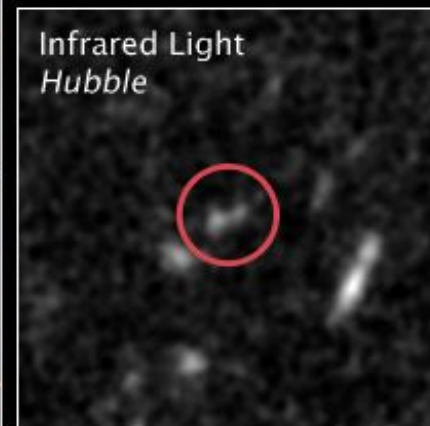
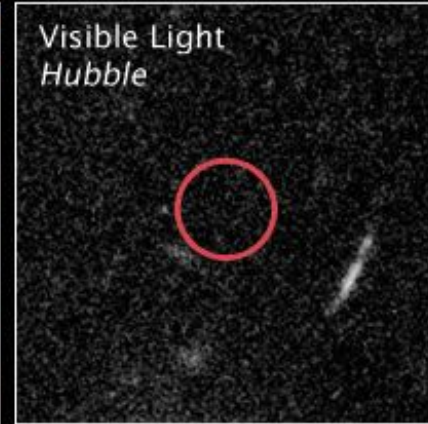
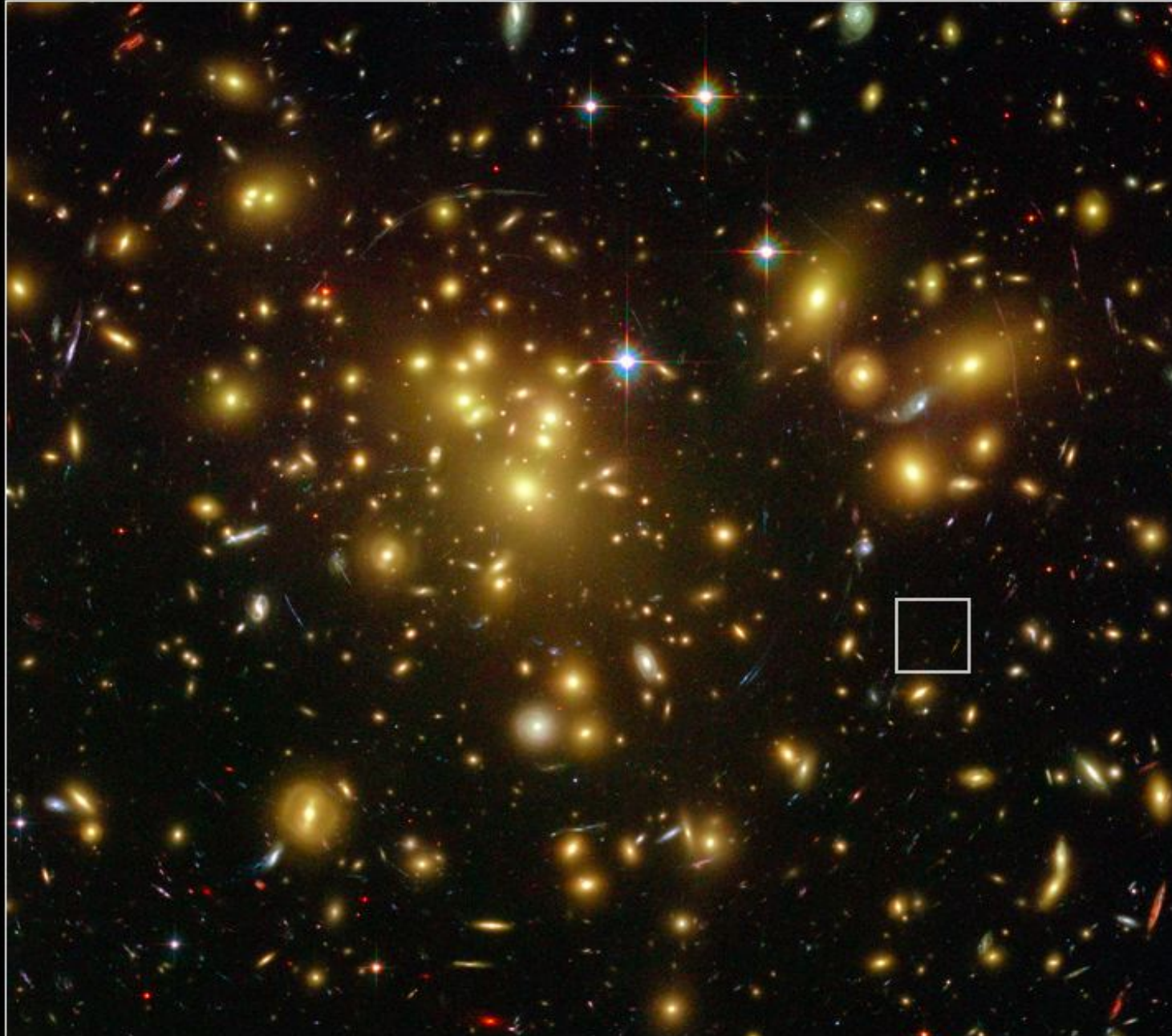
This suggests
a merger from
a collision of 2
galaxies ~ 1 B
years ago.

Counter-
rotating gas
sheer creates
active regions
of star birth.



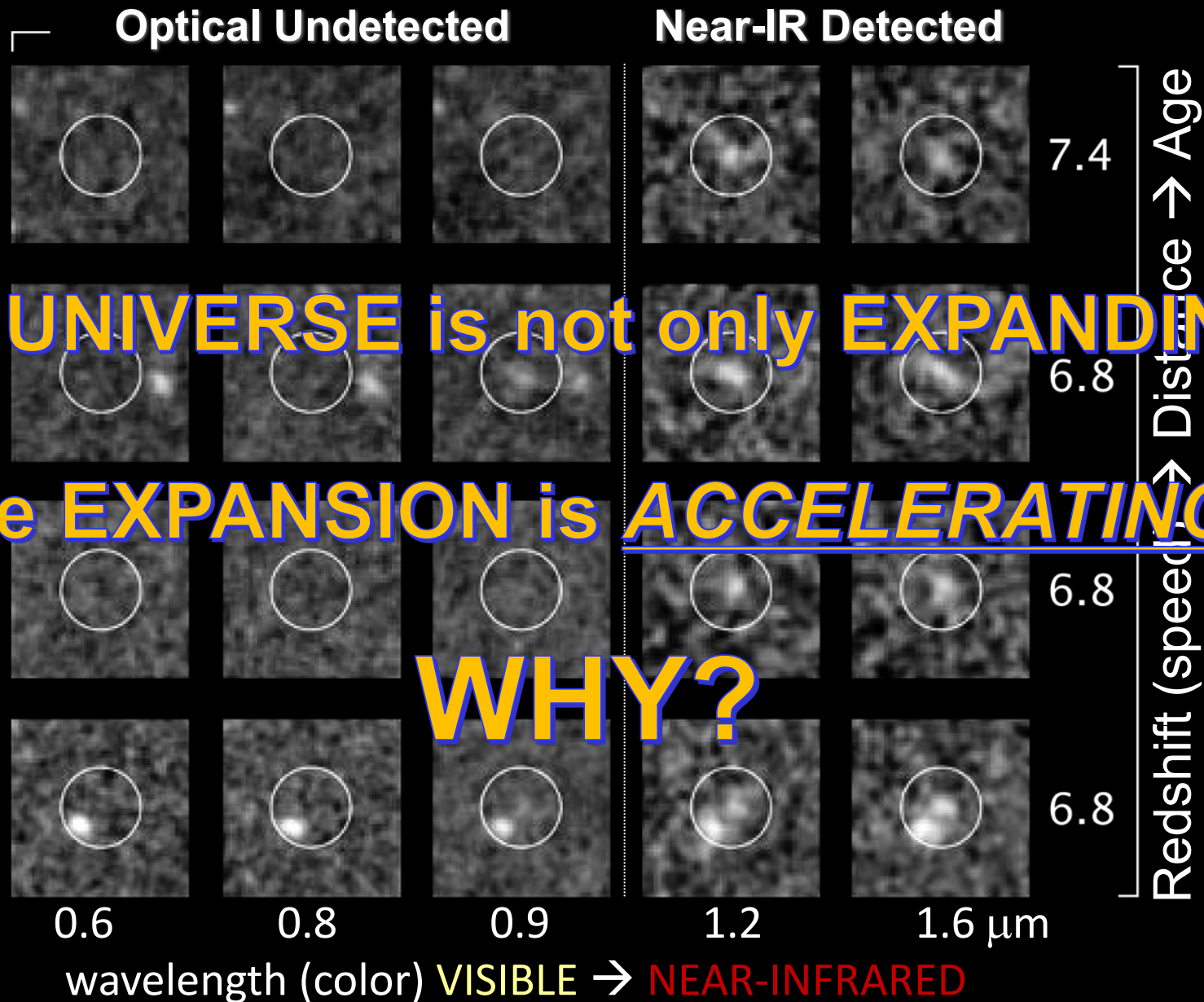
Gravitational Lensing from Galaxy Cluster Abell 1689

reaching 13 B ly @ 3% current age of universe



**One of the
Youngest &
Brightest
Galaxies in
The Early
Universe**

When the Universe Was Young — Ancient Galaxies

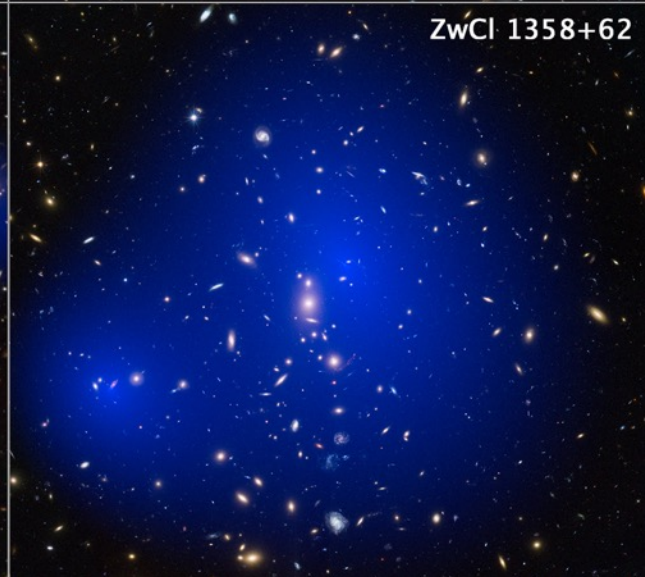


Postulated: **Only 5%** of the universe is ORDINARY Matter (/energy),
27% “dark matter” (and 63% “dark energy”)

HST is hunting for DARK MATTER (by its gravity signatures)



Stay Tuned!



John Grunsfeld (“Hubble Hugger”*) on SM-4 (2009) was the last human to touch (with gloved hand) the Hubble Space Telescope. Since then, it has been flying on its own to an eventual *end-of-mission*.

*** Hubble “Hugger”:**

- 5-time shuttle astronaut
- 3-time HST repairs SM3A, 3B, 4
- Deputy Director Space Telescope Science Institute
- Former NASA Science Mission Directorate Associate Administrator



How Long Can Hubble Continue To Operate?

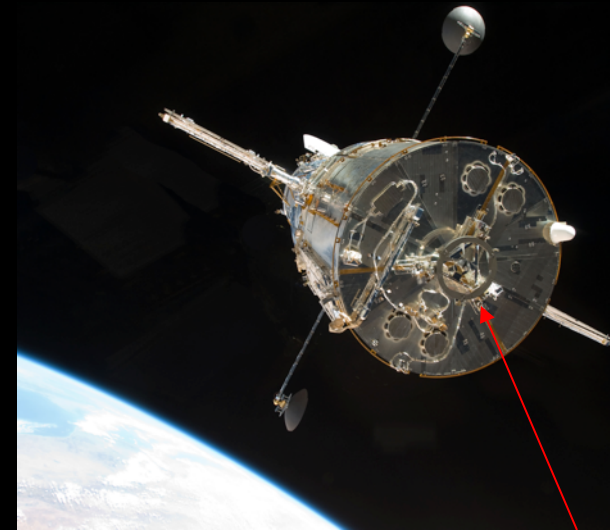
HST's eventual end

- HST launched in 1990
- HST design mission lifetime: 15 years
- HST now 28+ years in operation, thanks to Shuttle-enabled servicing
- Last servicing mission (SM4) 2009

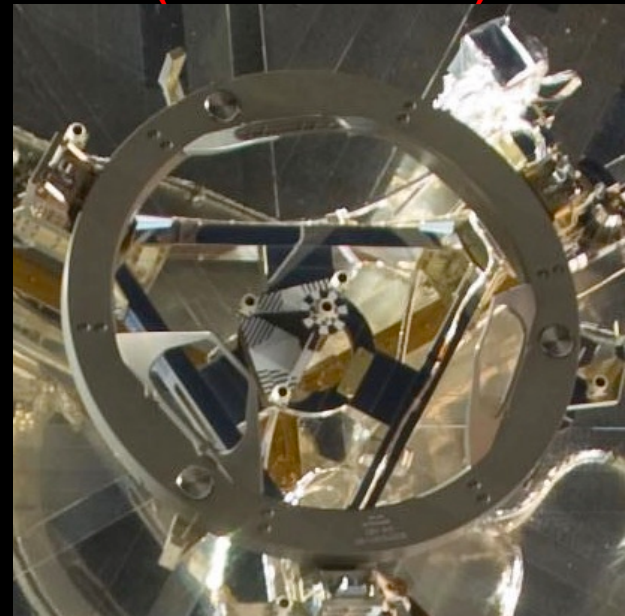
Major “Consumables” as of today:

- Gyros: 3 of (6 new installed SM4) [AOK]
- Electrical Power System [AOK]
 - Batteries: 6 (Ni-H 88 amp hour)
 - Solar Arrays: 2 (SM3B multi-cell GaAs)
- Orbit: [AOK] > next sunspot max 2024
- 1-Point Failures: still multiple redundancies
- \$\$\$ to continue operating: ???

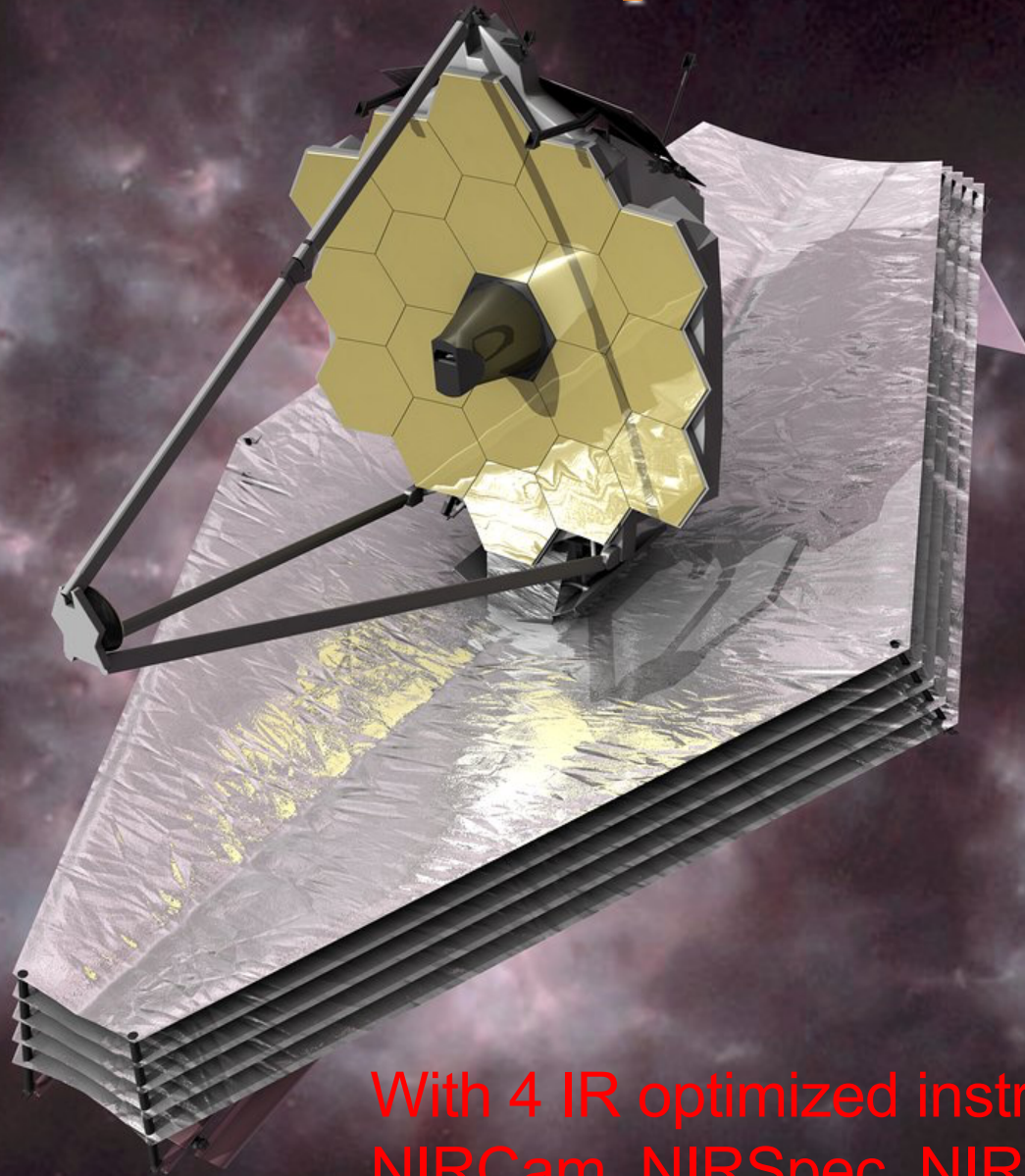
Combined Expectations:
Minimum of 5 to > 10 yrs



**Soft Capture Mechanism
(installed SM4)**



What's Next? The James Webb Space Telescope (JWST)

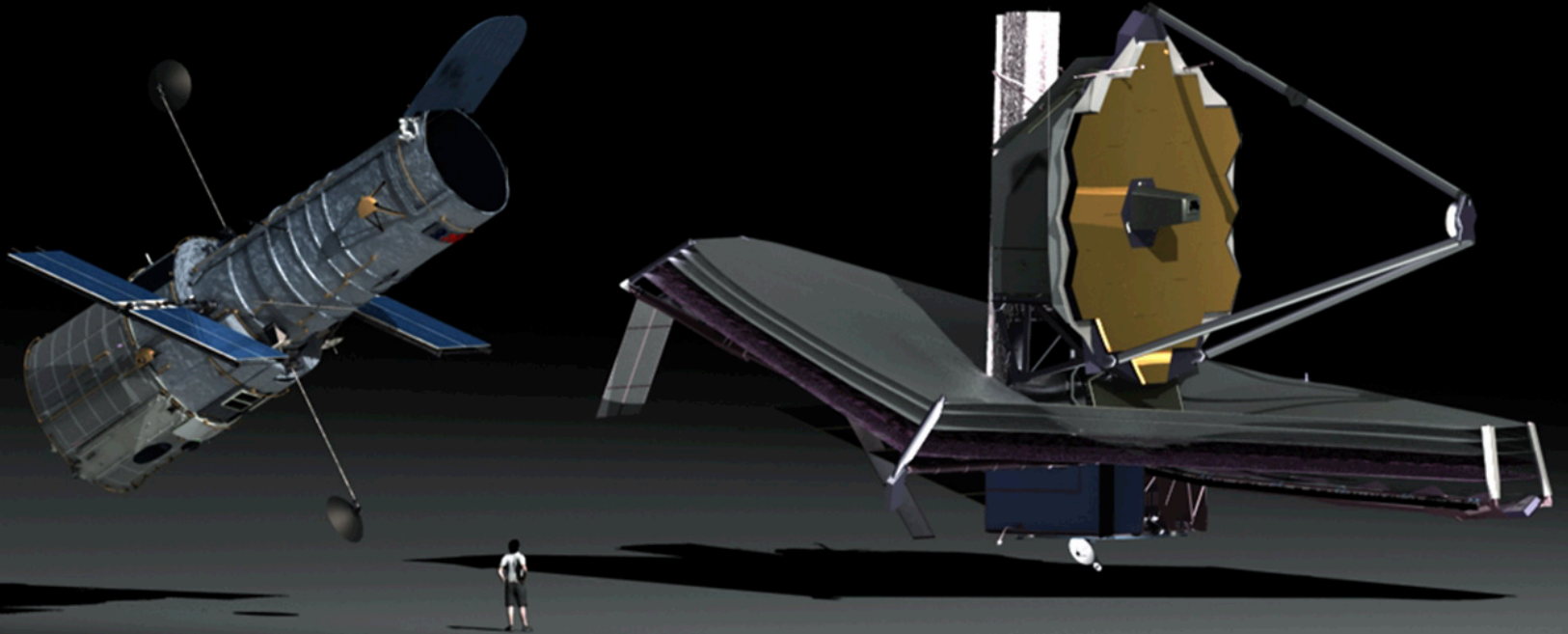


With 4 IR optimized instruments:
NIRCam, NIRSpec, NIRISS, MIRI

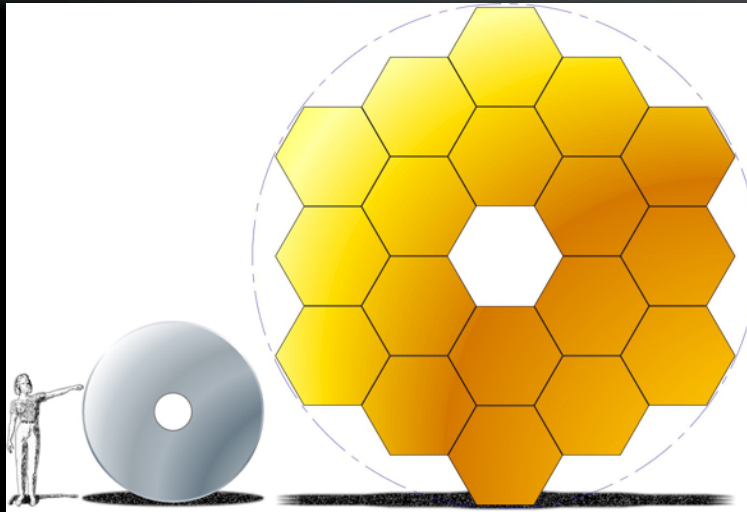
NASA's FLAGSHIP MISSION TO LAUNCH MARCH, 2021

What's Next? The James Webb Space Telescope (JWST)

A successor to Hubble, not a replacement!



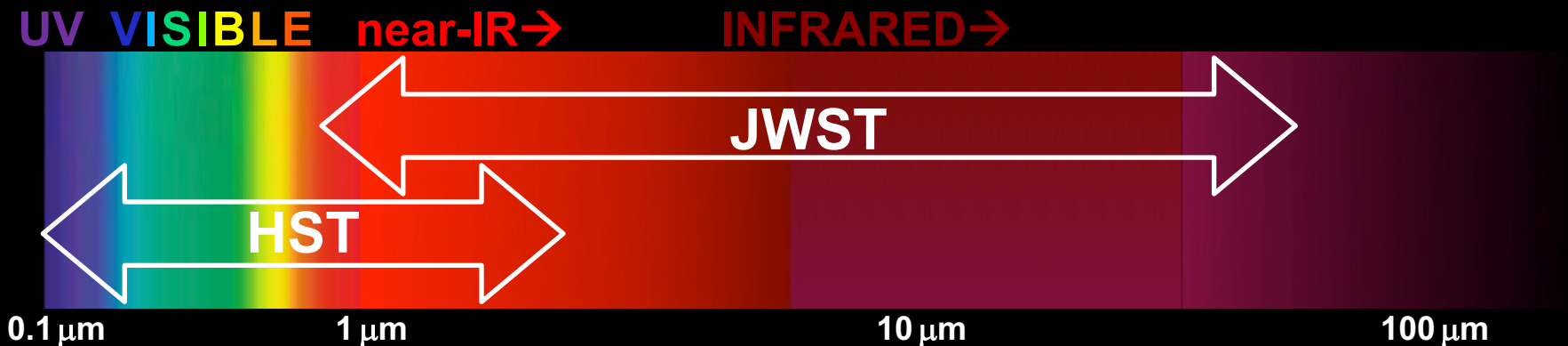
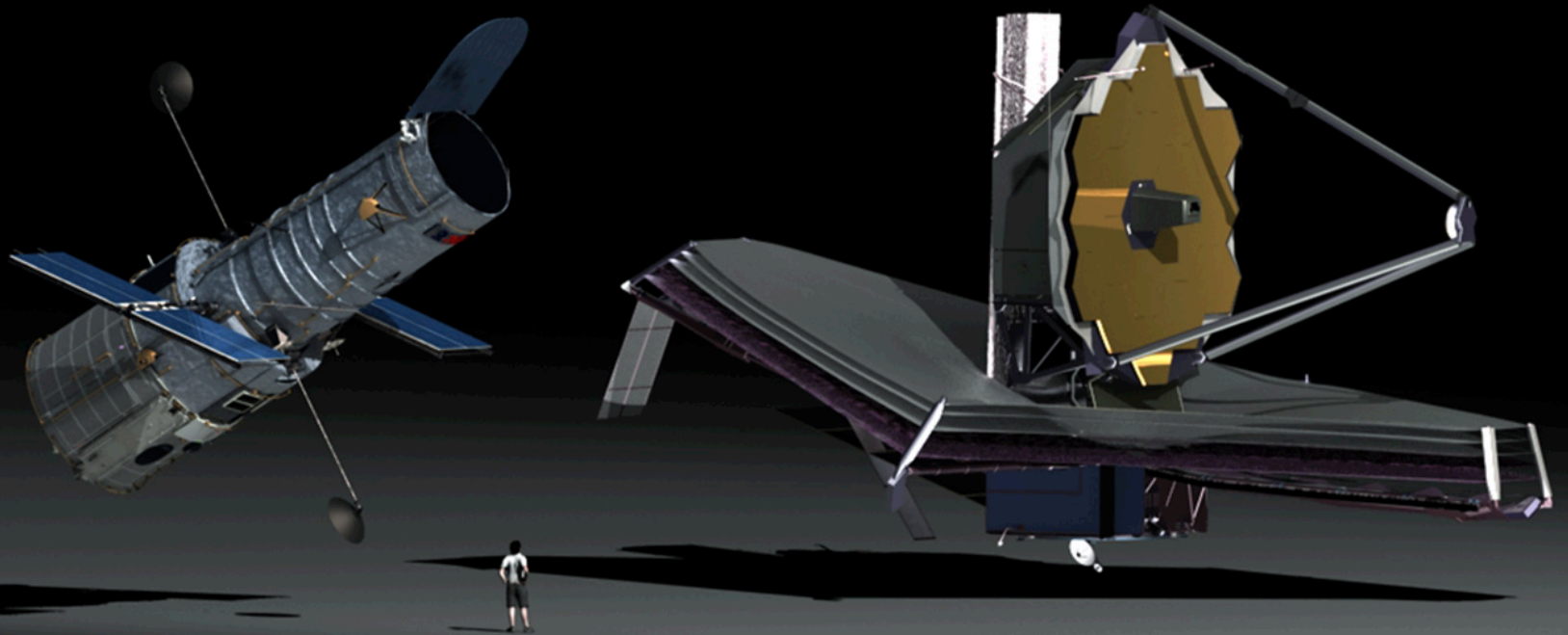
2.4 m
primary
mirror



6.5 m
primary
mirror

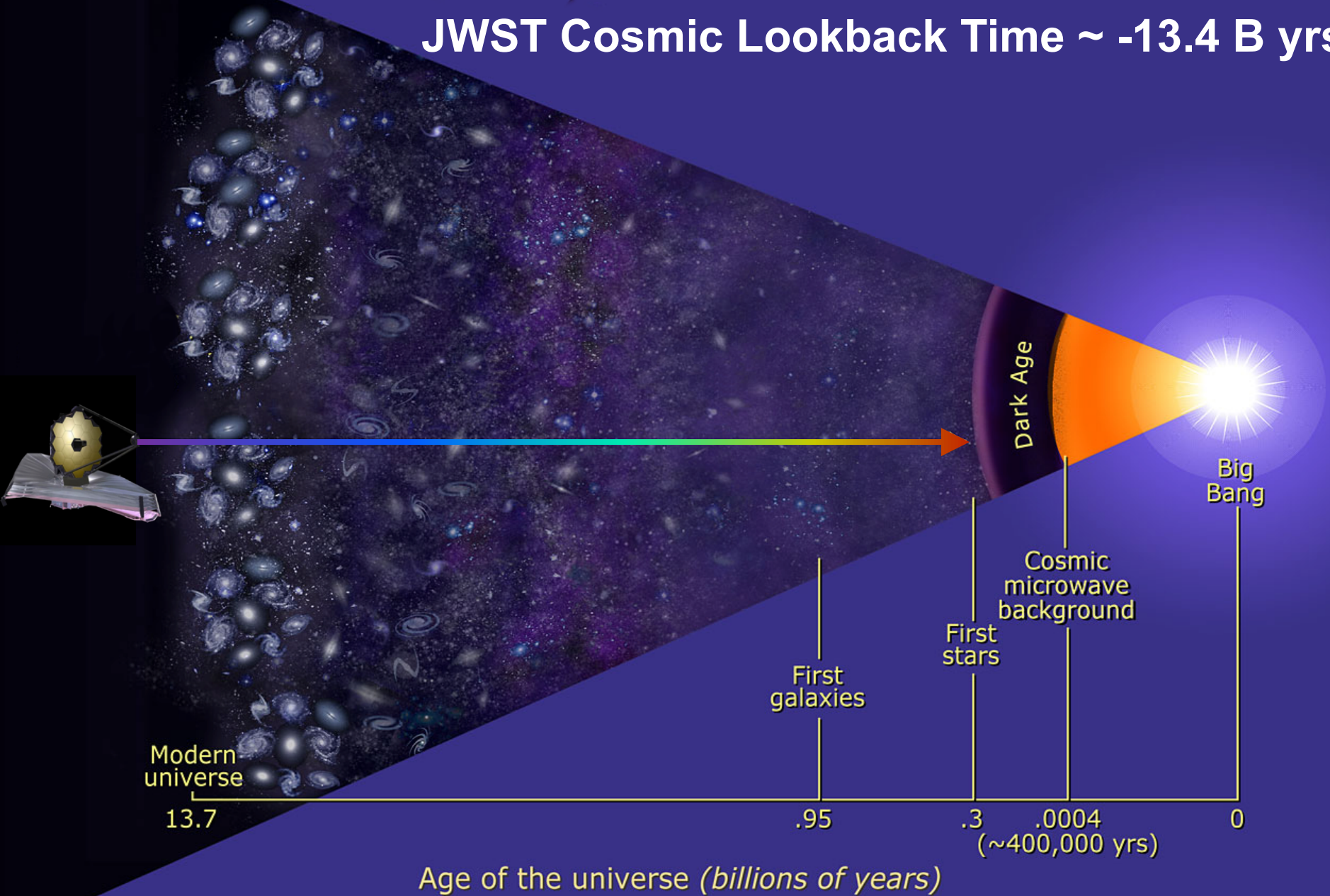
What's Next? The James Webb Space Telescope (JWST)

A successor to Hubble, not a replacement!



What's Next? The James Webb Space Telescope (JWST)

JWST Cosmic Lookback Time ~ -13.4 B yrs



THANK YOU!

And, Clear Skies!



**Dr. Glenn Schneider
Steward Observatory
Department of Astronomy
The University of Arizona
Tucson, Arizona 85721 USA**

**gschneider@as.arizona.edu
<http://nicmosis.as.arizona.edu:8000>
<http://tinyurl.com/EFLIGHT2019A>**