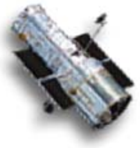
Goddard Space Flight Center



Science Benefits of SM4

Dr. Randy Kimble

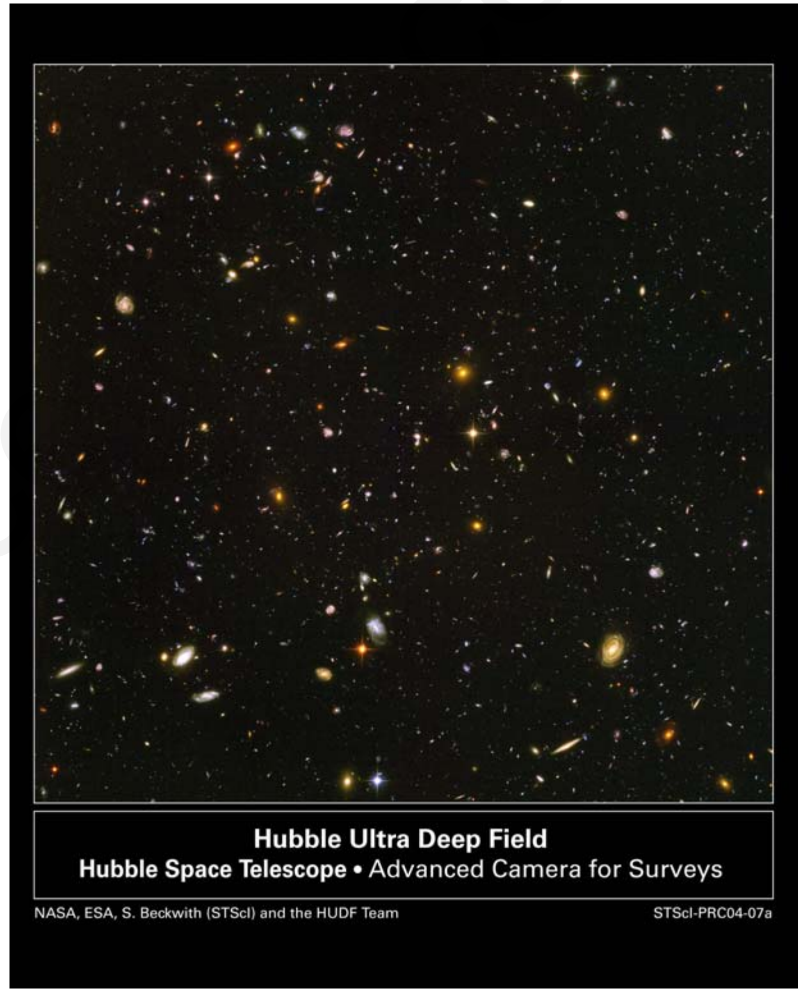
HST Development Project Scientist (Code 667/442)

Goddard Space Flight Center

The Glorious History of HST

- Over its lifetime, HST has carried out ground-breaking work over the full range of astronomical research

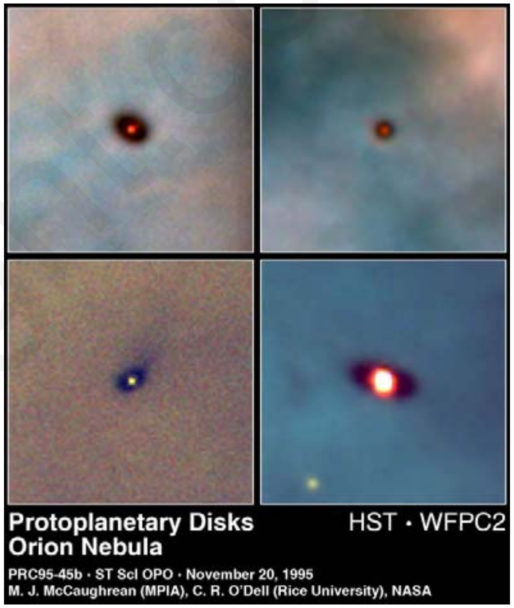
From dramatic solar system events

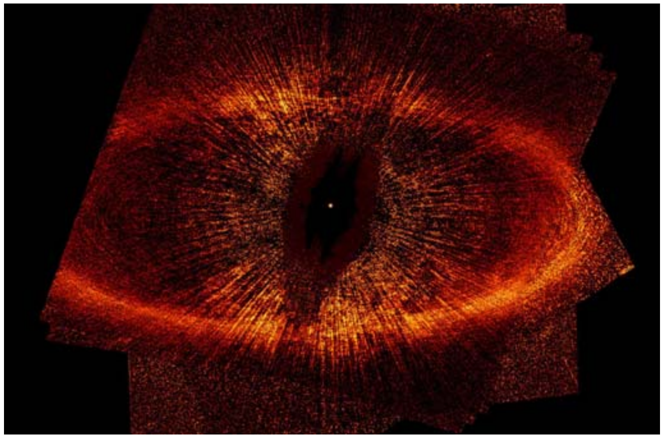


To the formation of galaxies in the early universe

Goddard Space Flight Center

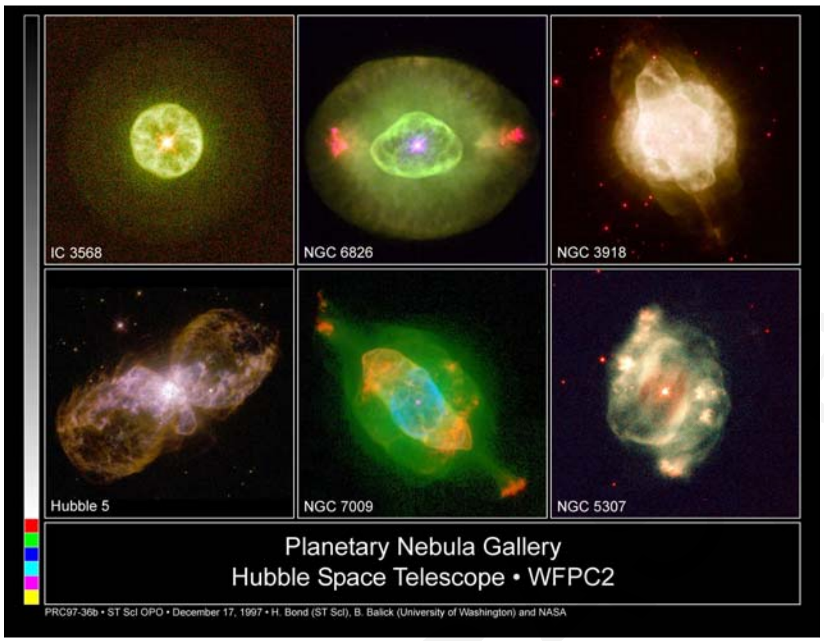
From the Birth of Stars and Planetary Systems



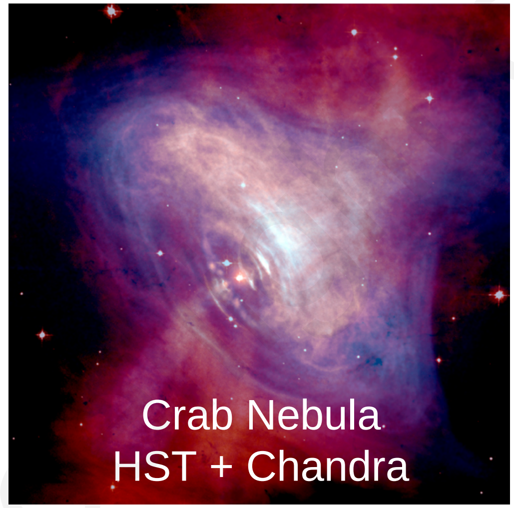


Protoplanetary disk with ACS coronagraph

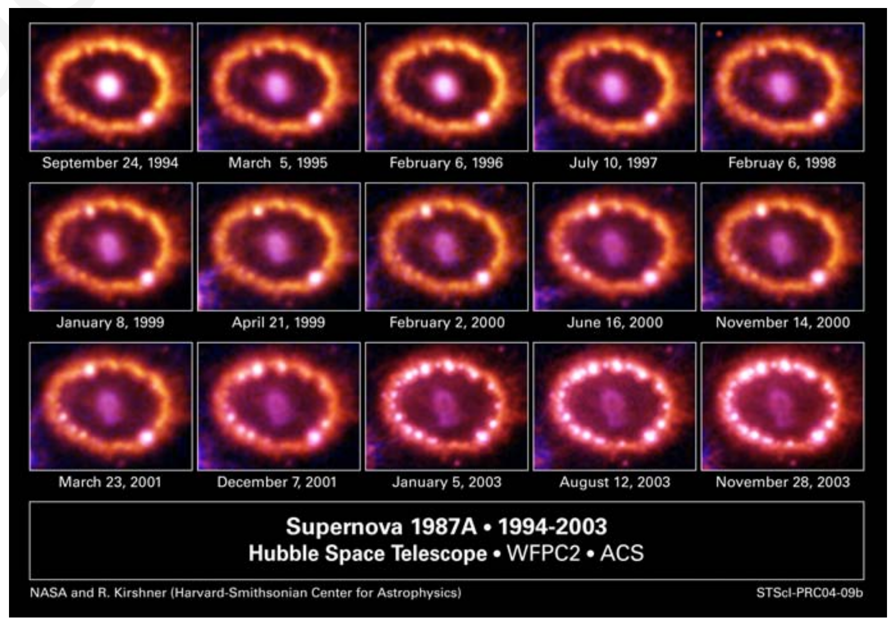
To the Old Age and Death of Stars



Late planetary nebula phase of low-mass stars

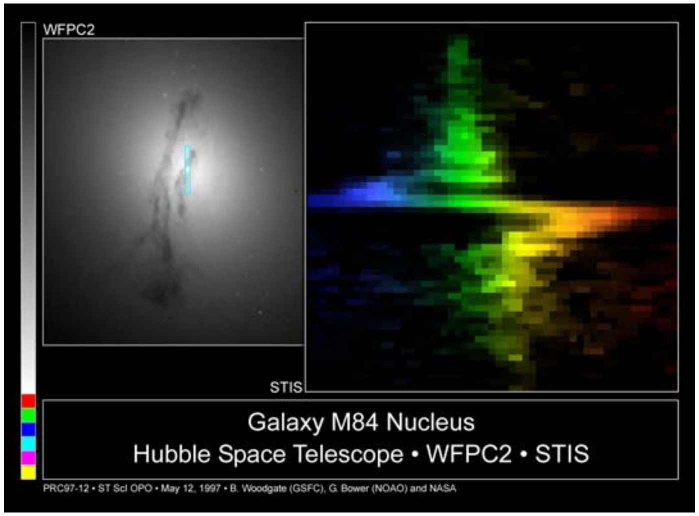


Supernova remnants of high-mass stars



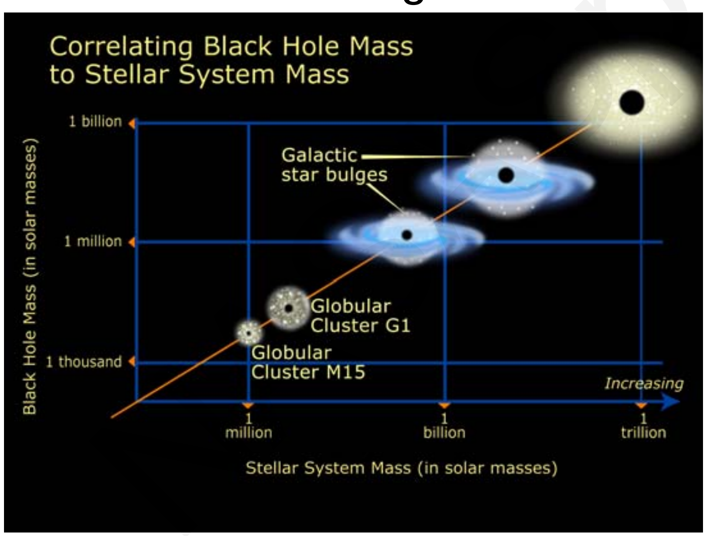
Goddard Space Flight Center

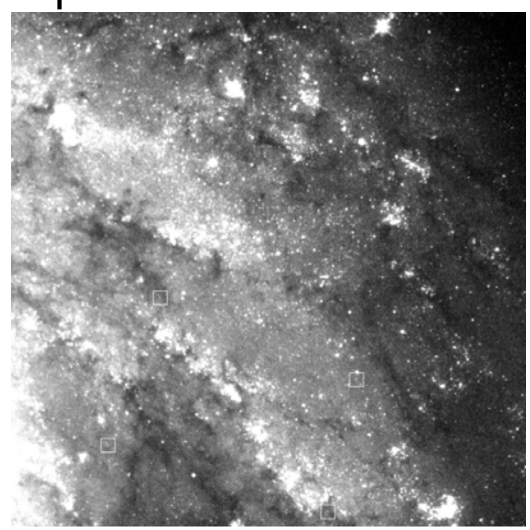
Accomplishing Critical Tasks That HST Was Specifically Designed to Perform



Measuring black hole masses in the nuclei of galaxies

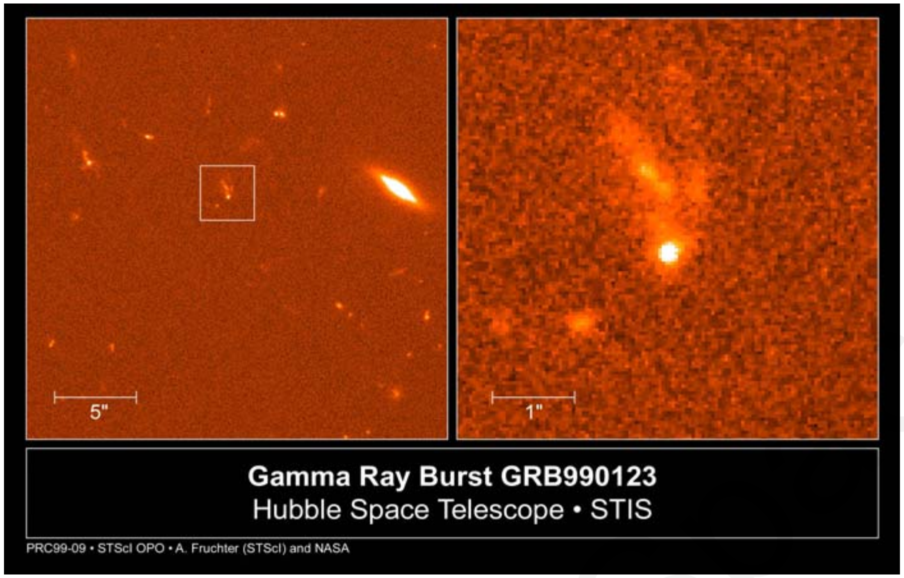
Using Cepheid variables to measure the expansion rate of the universe

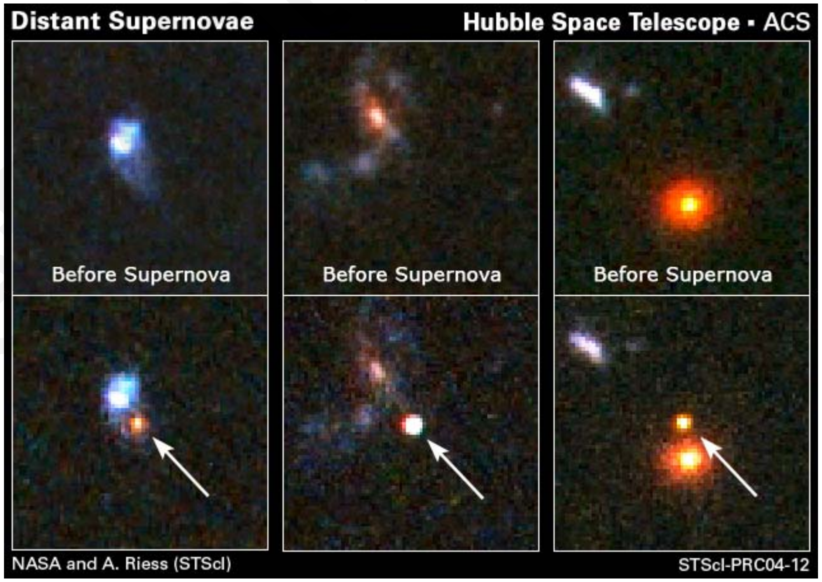




Goddard Space Flight Center

While Discovering the Completely Unexpected





Helping to prove that Gamma Ray Bursts are at cosmological distances, and thus are cataclysmic explosions visible across the universe

And using distant supernovae to prove that a mysterious "dark energy" is accelerating the expansion of the universe

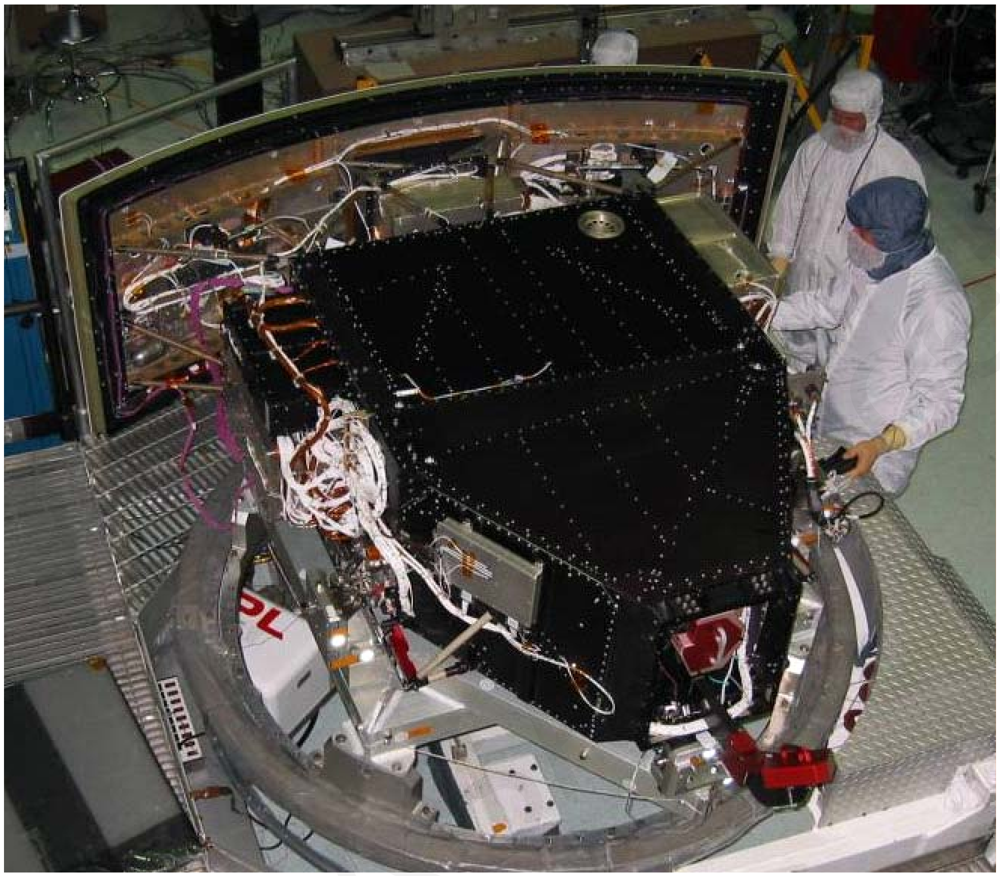
After SM4, HST's Tremendous Scientific Record Will Continue To Grow

>5 more years of science enabled by infrastructure improvements

- Batteries, gyros, FGS, NOBLs, OVP

With a spectacularly enhanced instrument complement:

- **Wide Field Camera 3 (WFC3)**
  - HST's first panchromatic UV-IR, wide-field imager
- **Cosmic Origins Spectrograph (COS)**
  - The most sensitive UV spectrograph ever flown
- **A restored Space Telescope Imaging Spectrograph (STIS)**
  - Highly productive, versatile spectroscopic complement to COS
- **A restored Advanced Camera for Surveys (ACS)?**
  - If possible; previous workhorse, beautifully complementary to WFC3
- ***After SM4, Hubble will be at the absolute peak of its scientific capabilities***



Wide Field Camera 3

Purpose of WFC3

WFC3 is a facility instrument, developed by the HST Project on behalf of the astronomical community

- Ball Aerospace is principal outside partner; much of the work done in-house at Goddard Space Flight Center

The purpose of WFC3 is to:

- **Ensure an imaging capability through end of HST mission**
  - Replaces WFPC2, provides complementary capabilities to ACS
- **Provide panchromatic coverage over a wide field**
  - Widest spectral coverage of any HST instrument
  - 200-1000 nm in UVIS channel; 800-1700 nm in IR channel
- **Thereby enabling a broad program of forefront astronomical observations**

Key Aspects of WFC3

WFC3 provides far more than imaging "insurance" for HST

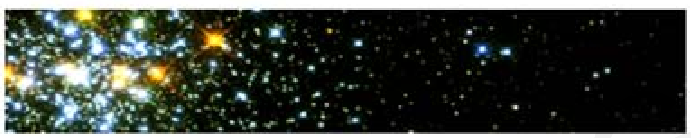
- **Unique capabilities in the near-UV**
  - 200 to 400 nm wavelength range
- **Unique capabilities in the near-IR – without expendable cryogen or mechanical cryocooler**
  - 800 to 1700 nm (though warm, HST is very powerful in this range)
- **Large and diverse set of filters and grisms: 63 UVIS, 16 IR**
- **Complementary to I-band-optimized ACS**
  - And a very capable accompaniment to ACS in the region of overlap, with more filters, fresh start with respect to radiation damage, and greater tolerance of CTE degradation

WFC3 Supports Wide-Ranging Science Program

WFC3's combination of *sensitivity, field of view, angular resolution* and *panchromatic capabilities* will enable forefront research across the full range of astrophysical investigation:

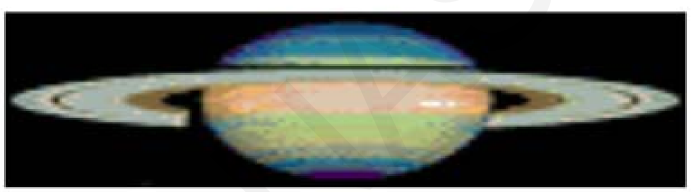
High-z Universe : What were the first luminous objects? How did galaxies assemble? What do distant supernovae tell us about dark energy?

Nearby Galaxies : How universal are the processes of star formation in galaxies?



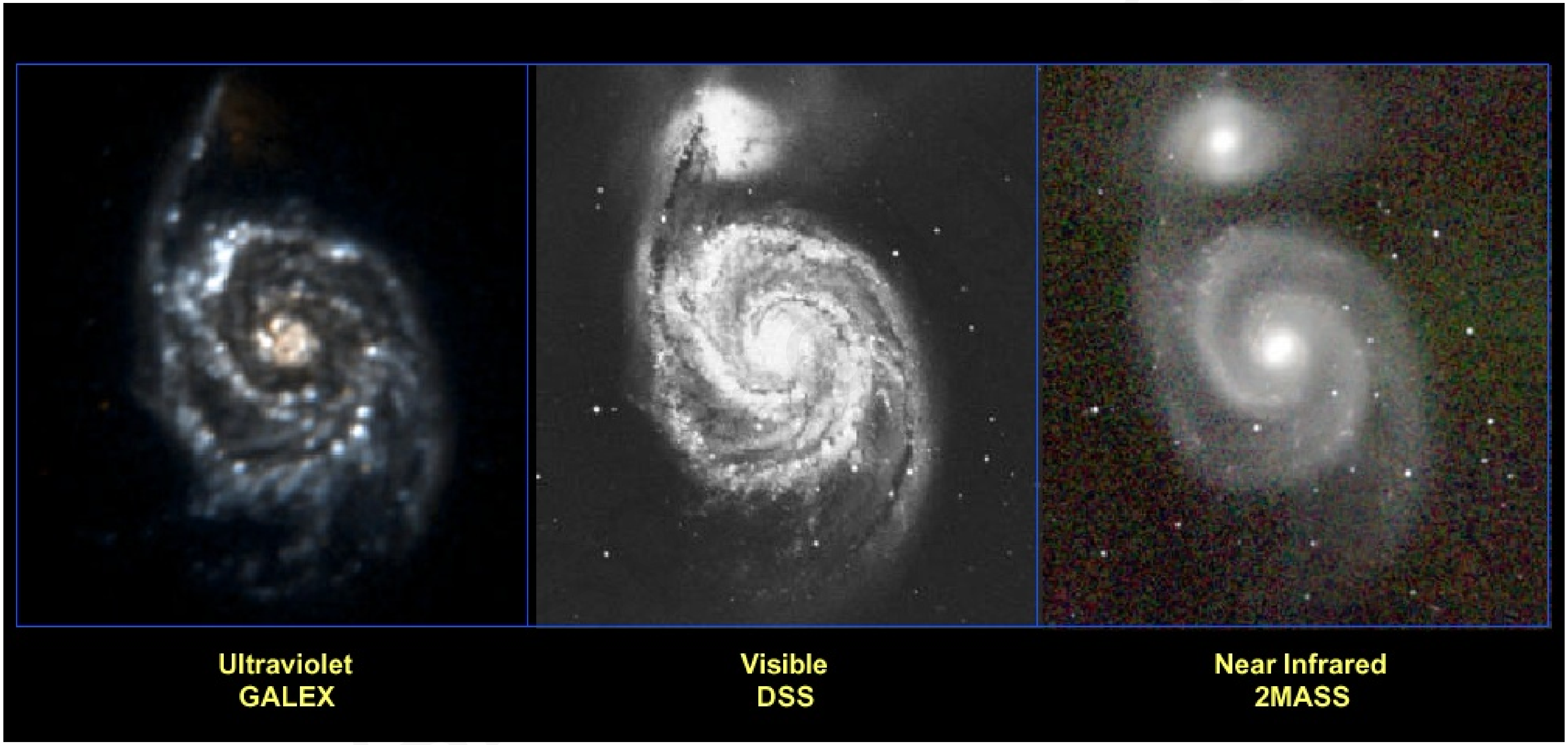
Resolved Stellar Populations : How old are globular clusters? How much mass is locked into low mass stars?

Stars and Interstellar Medium : How does the star formation rate depend on the environmental conditions?



Solar System : What are the properties of the relic remnants of the early solar system?

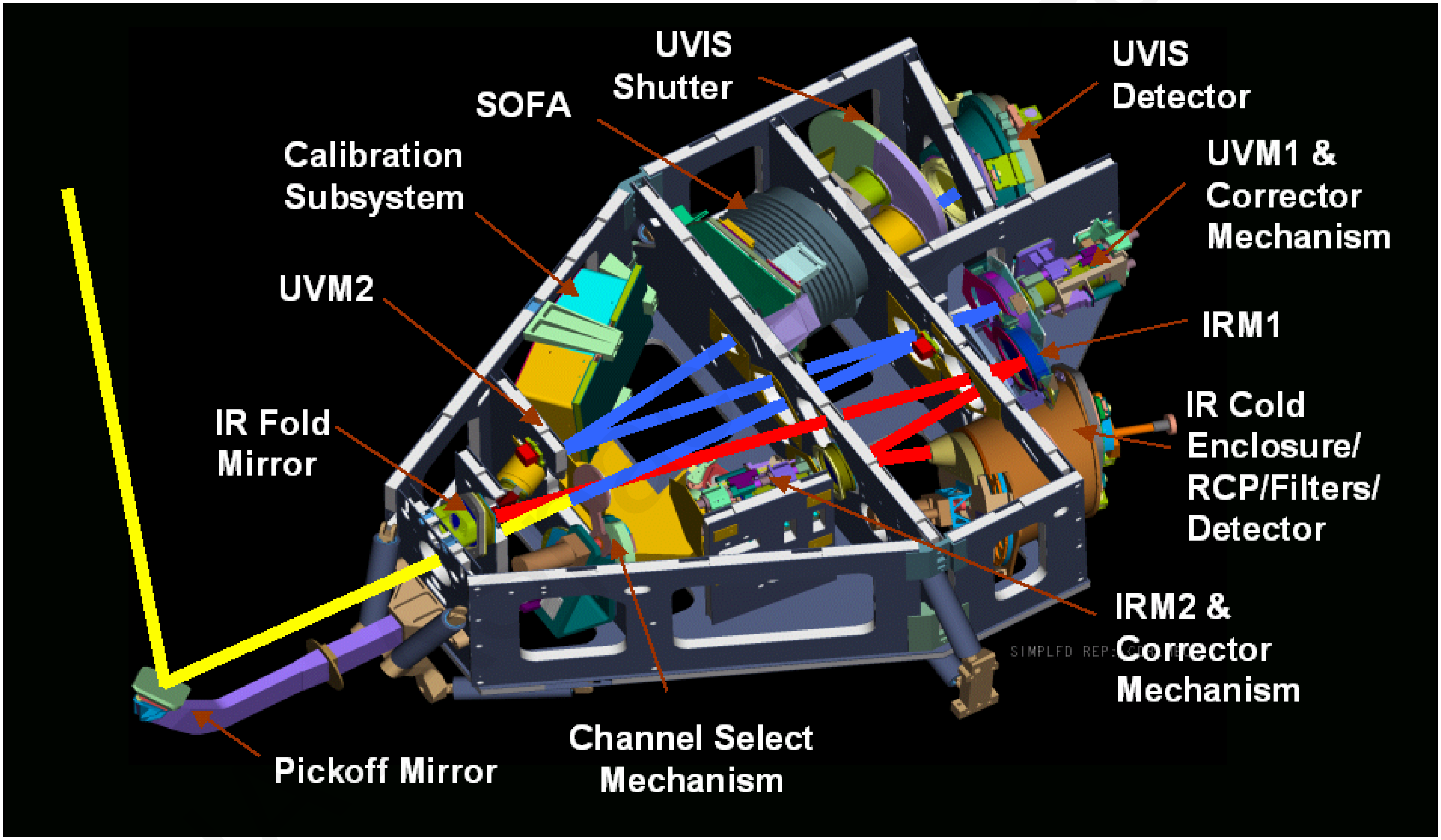
The Panchromatic Galaxy



Multi-wavelength observations are crucial to astrophysical interpretation.

Goddard Space Flight Center

WFC3 Interior Configuration

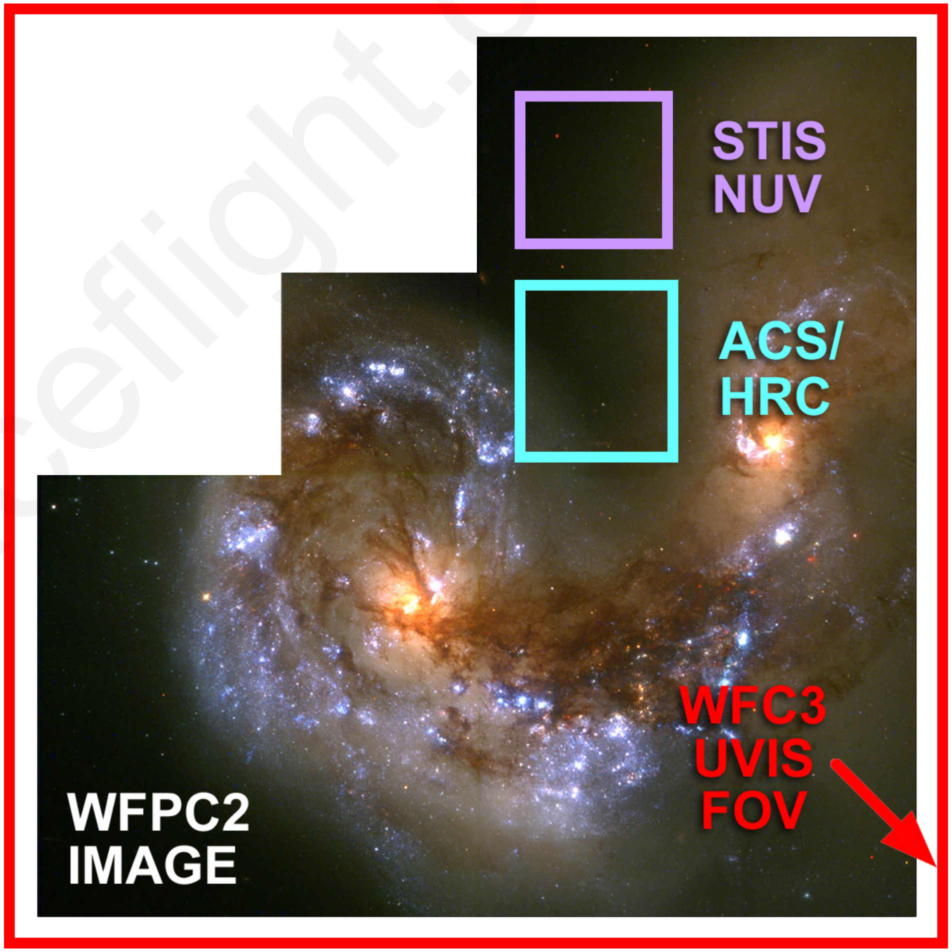


UVIS Channel Summary

Key Properties

- 200 – 1000 nm
- 4K x 4K CCD mosaic (two 2K x 4K UV-optimized CCDs)
- 0.04” x 0.04” pixels, 160” x 160” field of view

The WFC3 UVIS channel will extend high-sensitivity, large-format imaging at HST’s sharp angular resolution to the near UV.



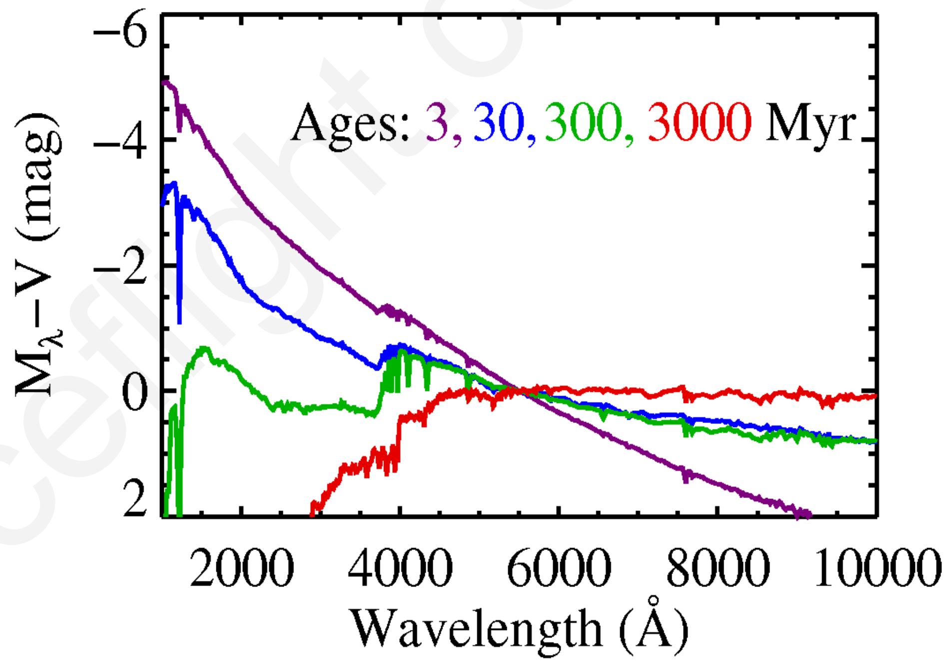
Relative fields of view of HST’s NUV imagers

Goddard Space Flight Center

UV Observations Yield Unique Information on Hot, Young Objects

UV observations:

- **Can not be made from the ground**
- **Are particularly sensitive to hotter astronomical objects**
- **Are strongly sensitive to the age of stellar populations (because the massive, hottest stars are short-lived – see figure at right)**
- **Of nearby galaxies reveal the kind of structures/processes that are seen at longer wavelengths when observing highly-redshifted galaxies in the early universe**
- **Probe one of the darkest regions of the natural sky background.**



WFC3 UVIS channel observations will be particularly well suited to the study of:

- Star formation history of galaxies
- Chemical enrichment history of galaxies
- Ly α dropouts at z = 1 – 2.

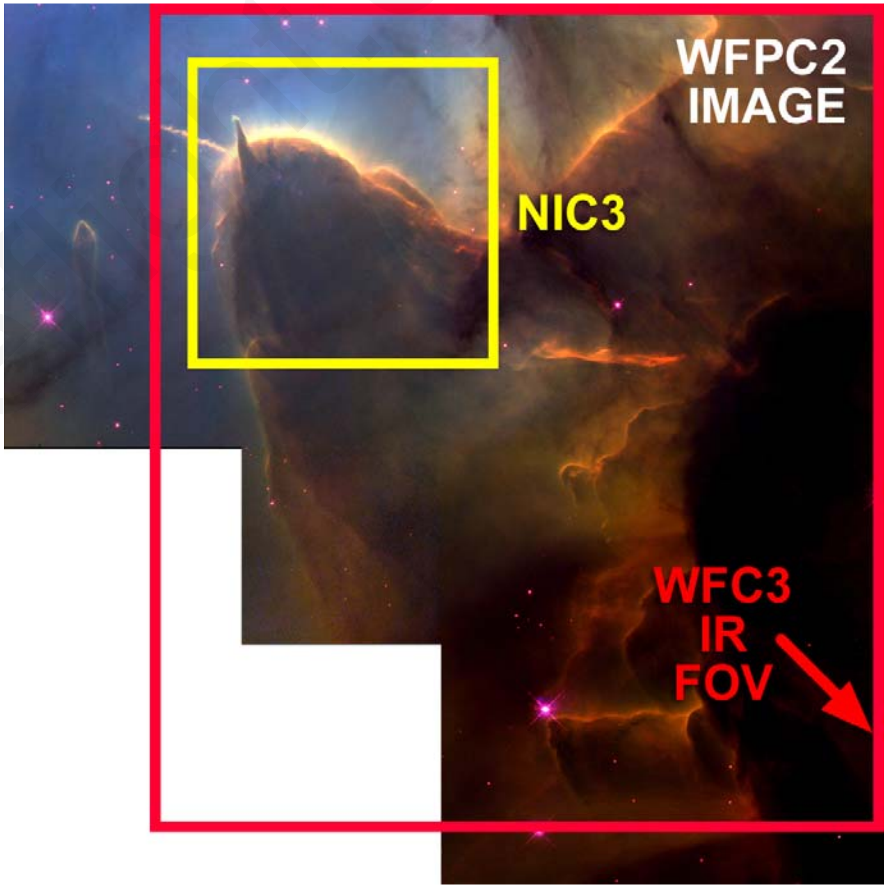
Goddard Space Flight Center

IR Channel Summary

<u>Key Properties</u>

- 800 – 1700 nm
- 1K x 1K HgCdTe array with 1.7 micron cutoff
- 0.13” x 0.13” pixels, 136” x 123” field of view
- zodiacal-background-limited sensitivity in broadband filters

The WFC3 IR channel will provide a 10-20+ x increase in survey speed vs. NICMOS + cryocooler, with finer angular resolution and improved stability, photometric accuracy, and cosmetics.

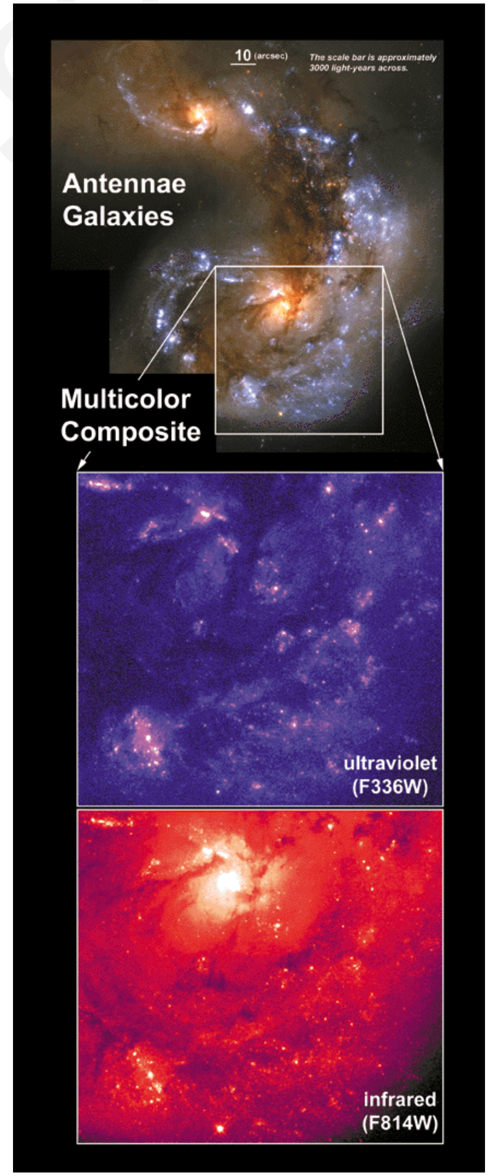


Relative fields of view of HST’s IR imagers

IR Observations Yield Unique Information on Cool, Dust-Embedded, or High-Redshift Objects

IR observations:

- Are very competitive with HST vs. larger ground-based telescopes, due to the high brightness of the Earth's atmosphere at IR wavelengths
- Are able to penetrate interstellar dust to probe regions that can be too absorbed in the UV/visible (star-forming regions, nuclei of galaxies)
- Probe the distant, early universe, due to the red-shifting of the emitted light by cosmic expansion.



WFC3 IR Channel observations will thus advance the study of:

- Type Ia supernovae and the accelerating universe
- High-redshift galaxy formation
- Sources of cosmic re-ionization
- Dust-enshrouded star formation
- Water and ices in the solar system.

Galaxies at z~10

WFC3's near-IR capability can reveal early galaxies out to z ~10, blazing the trail for JWST.

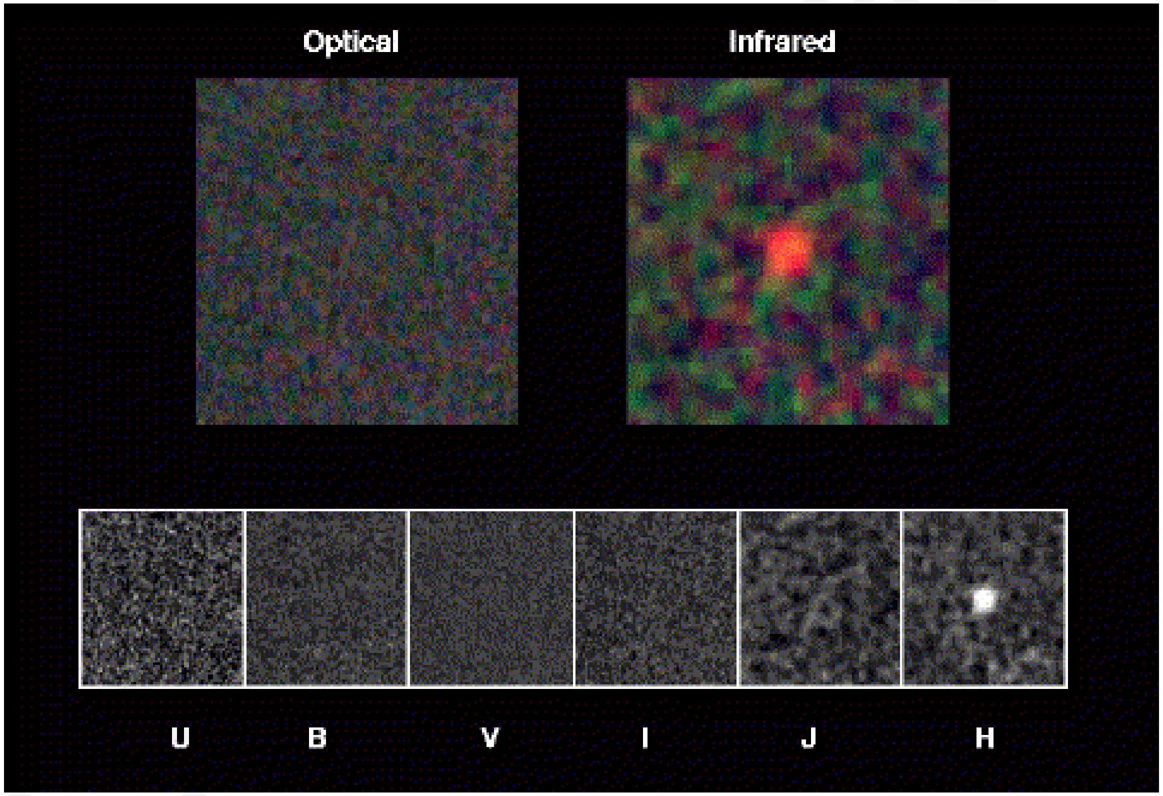
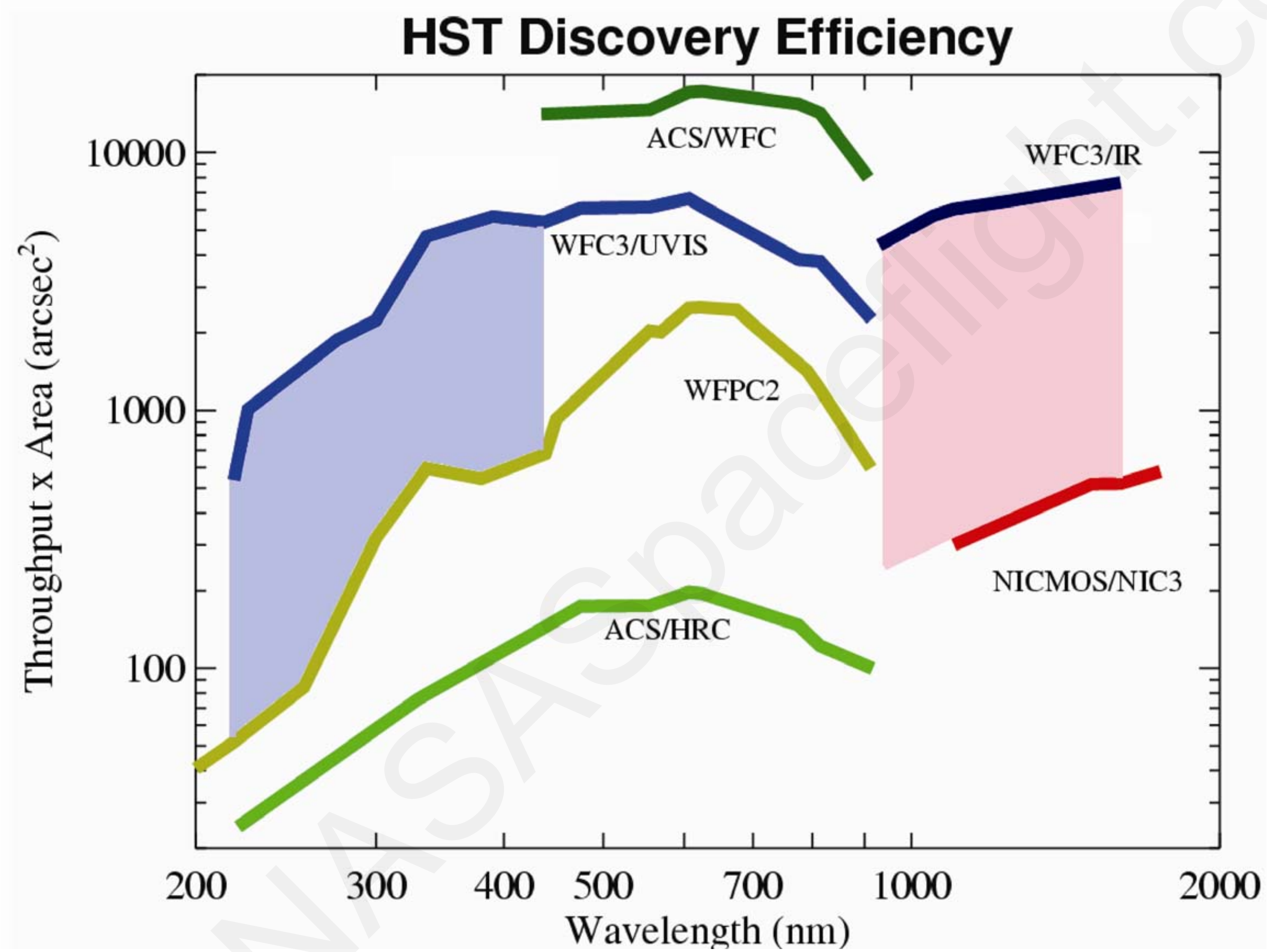


Figure 8. J-dropout object identified in the Hubble Deep Field North. This object is visible only in the NICMOS F160W (H) image. The U, B, V, and I images were obtained with WFPC2, the J and H images with NICMOS. Similar objects could be found in large numbers by WFC3 by searching a large area for sources bright in the H band and faint in the J band (M. Dickinson).

Goddard Space Flight Center

WFC3 Offers A Dramatic Increase in NUV/NIR Survey Capability

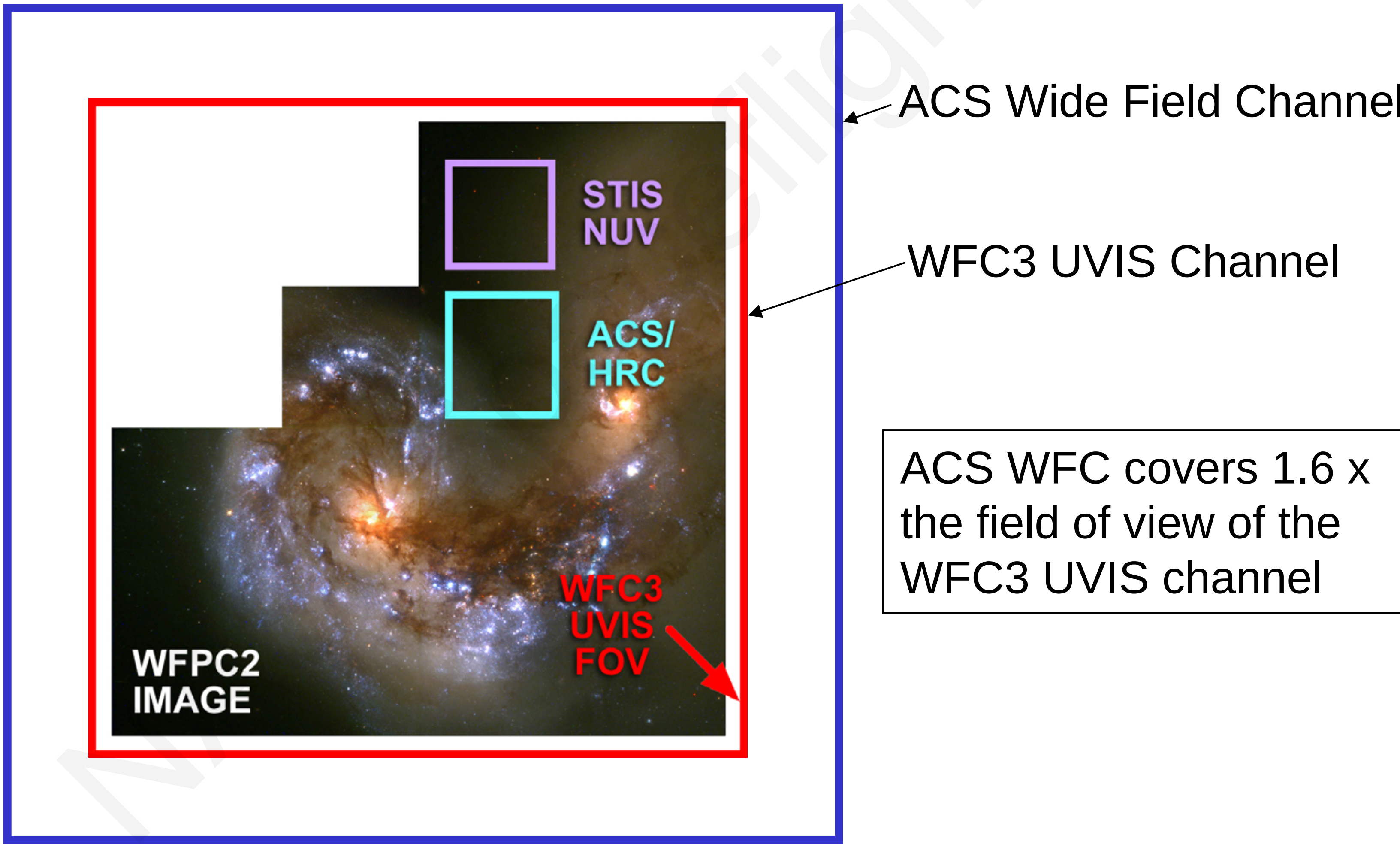


Curves connect values at central wavelengths of available broadband filters

Demonstrates dramatic survey advantage of WFC3 in NUV and NIR

What Have We Lost With ACS: Visible Field of View

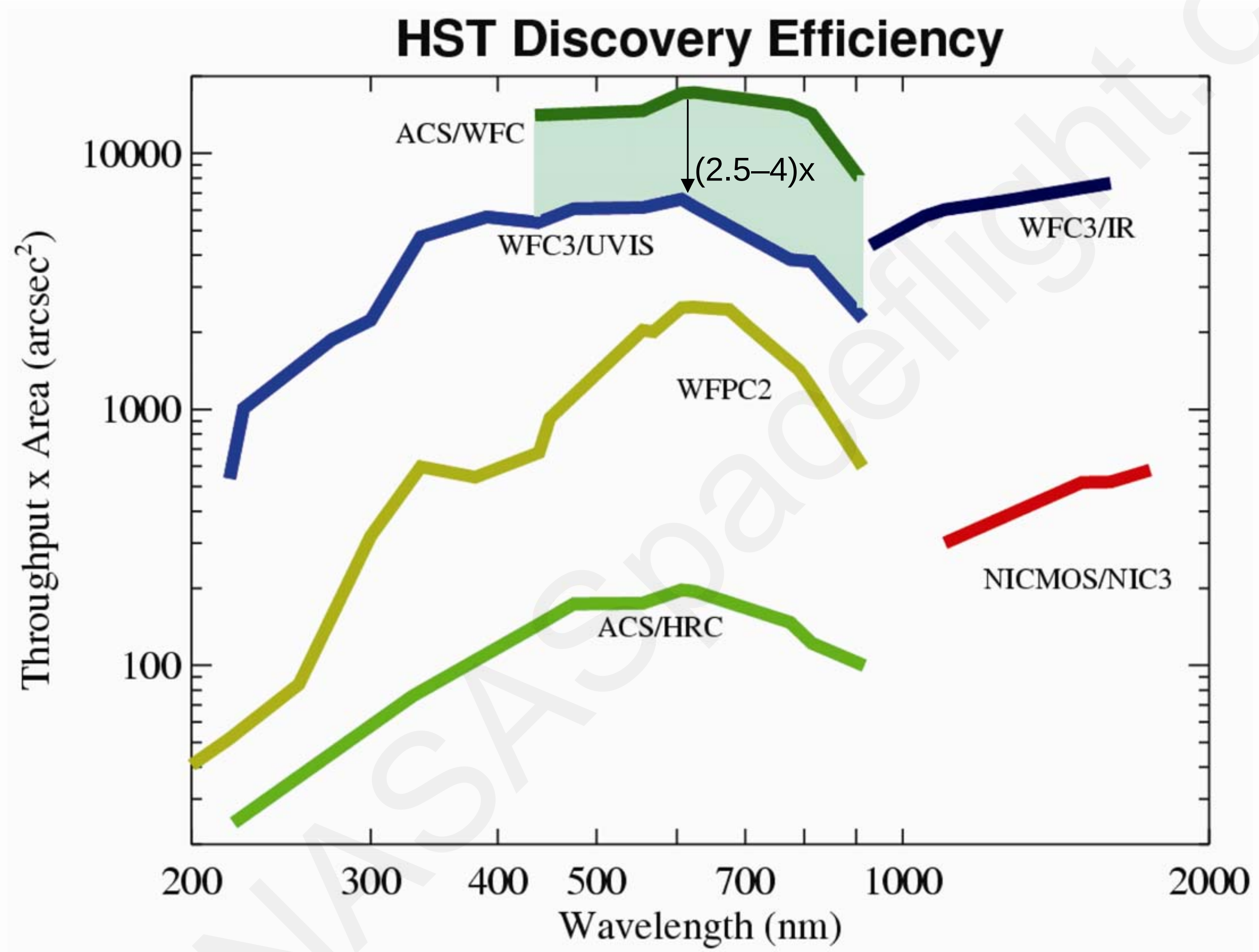
- **Until the recent failure, ACS was Hubble's workhorse instrument, for its powerful imaging capabilities, some of which are not replaced by WFC3**



ACS WFC covers 1.6 x the field of view of the WFC3 UVIS channel

Goddard Space Flight Center

What Have We Lost With ACS: Visible Discovery Efficiency

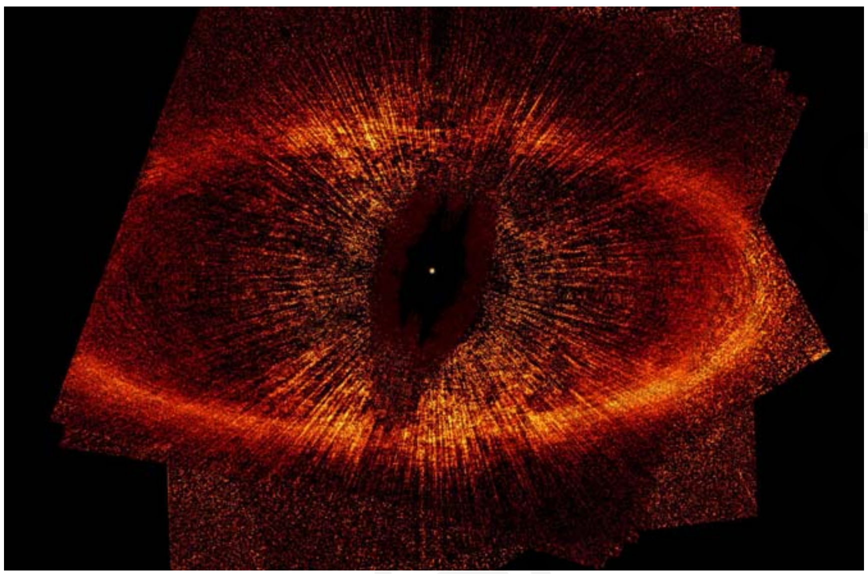


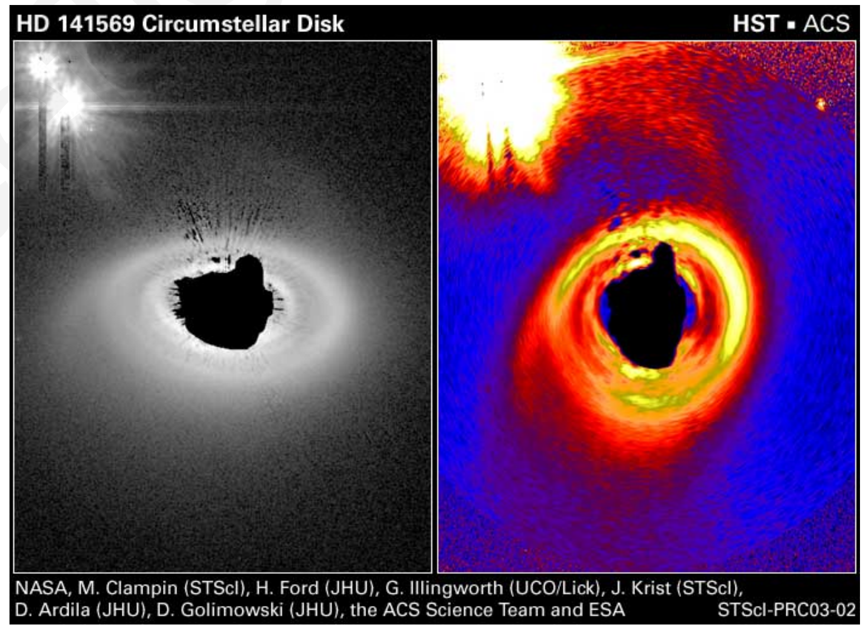
ACS WFC silver mirror coatings and red-optimized CCDs give higher throughput (1.5-2.5x) in the 400-900nm region

Yields, for example, a factor of ~2.5 ACS advantage in dark energy surveys for supernovae at z ~1.

What Have We Lost With ACS: Multiband UV/Visible Coronagraphic Imaging

- **ACS High Resolution Channel has a powerful coronagraphic capability that has been applied to the study of protoplanetary systems around other stars**





- **STIS offers some coronagraphic capability, but it is purely broadband (no filters); NICMOS offers lower resolution at longer wavelengths**

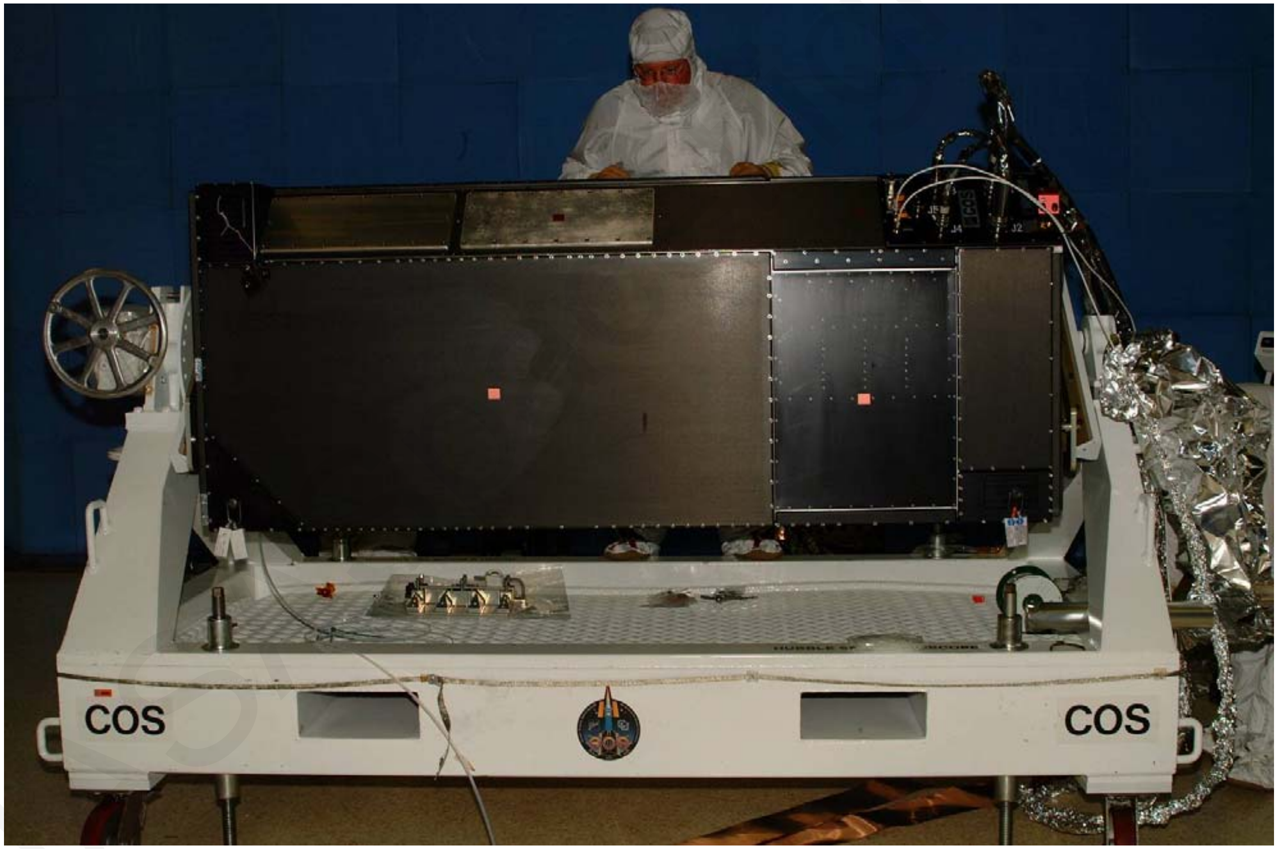
What Have We Lost With ACS: Valuable Parallel Observing

- WFC3 and ACS can bring their powerful imaging capabilities to bear simultaneously, in parallel observing programs
- Mosaic observations of large astronomical objects, with the telescope pointing stepped around the sky to "tile" the object: e.g. with ACS covering the visible, and WFC3 the IR or NUV
- Deep field observations in parallel with each other or COS/STIS (statistical surveys of high-redshift objects can be carried out in any pointing direction away from the galactic plane or bright objects).

Cosmic Origins Spectrograph

PI: Dr. James Green

University of Colorado



The Importance of Spectroscopy

- Spectroscopy puts the “physics” into “astrophysics”, **providing the determinations of temperatures, composition, dynamical motions, densities, ionization states, etc. that permit the development of quantitative physical models of the constituents of the universe**

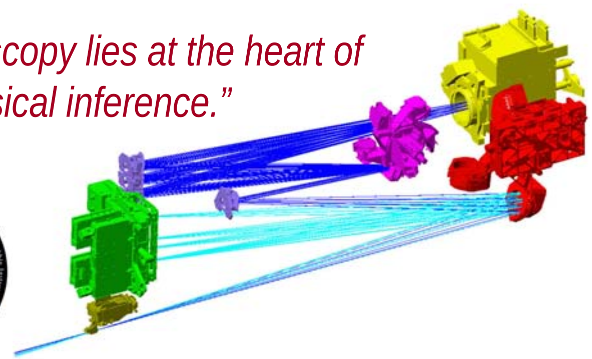
- **Accordingly, broad spectroscopic capability has always been a core requirement for the Hubble observatory**

- **SM4 will install a uniquely powerful new spectrograph and restore a highly productive old one**

COS Science Themes

- What is the large-scale structure of matter in the Universe?
- How did galaxies form out of the intergalactic medium?
- How were the chemical elements for life created in massive stars and supernovae?
- How do stars and planetary systems form from dust grains in molecular clouds in the Milky Way?
- What are planetary atmospheres and comets in our Solar System made of?

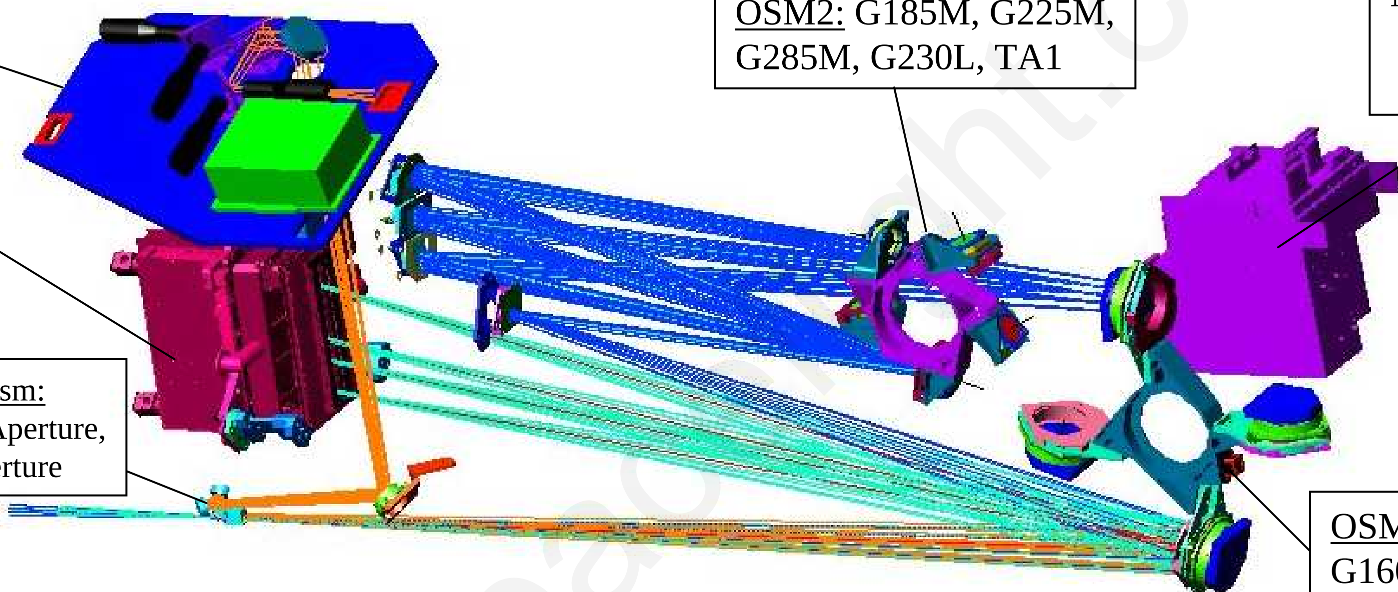
"Spectroscopy lies at the heart of astrophysical inference."



COS Spectroscopy

- **The tool COS brings to bear on these problems is spectroscopy in the ultraviolet wavelength range**
  - The UV range contains the principal spectral features of the most abundant atomic and ionic constituents of the universe
  - Absorption line spectroscopy is highly sensitive and can detect small amounts of material whose emission is too faint to be detected – e.g. in the interstellar and intergalactic medium
- **COS provides observing modes with resolving power, R , of ~20,000 (15 km/sec) to resolve D I on wings of H I features, measure Doppler widths of Lya clouds, and detect weak absorption features from continuum**
- **"Survey modes" with R = ~1500-3500 are also available for characterization of spectral energy distributions, UV extinction curves, and detection of the very faintest UV sources**

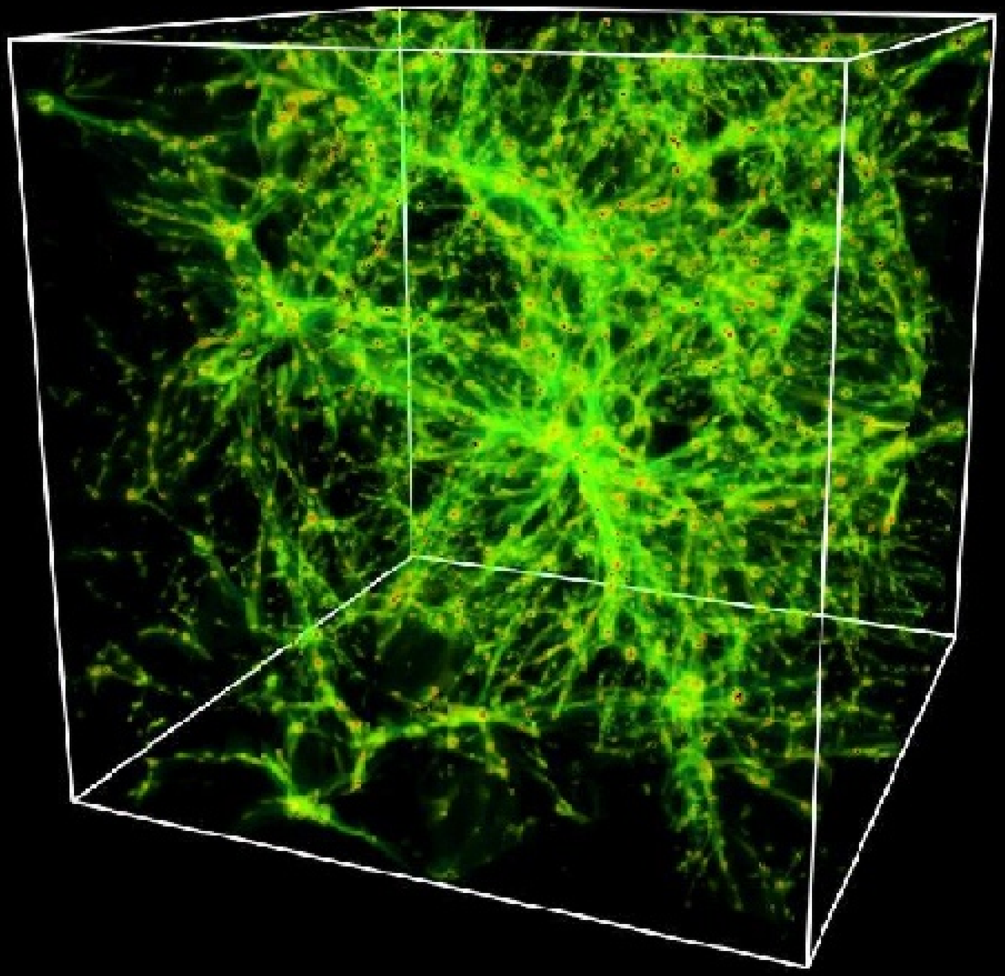
The Optical Layout of COS



COS has two channels to provide low- and medium-resolution spectroscopy from 115-320nm

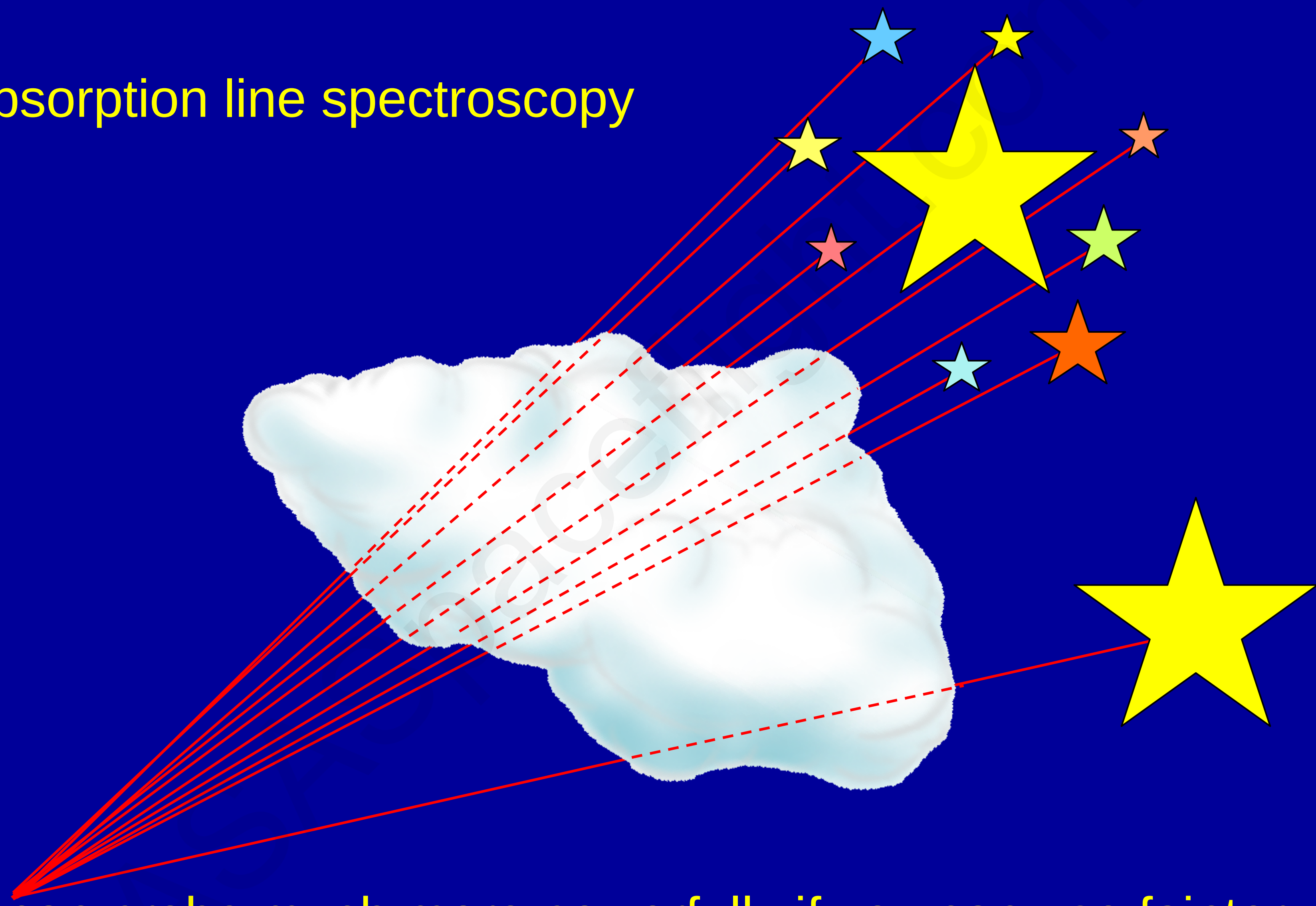
- **Elegant one-reflection FUV design provides ~15x the throughput of the corresponding STIS echelle mode!**
- **NUV layout using first order gratings provides higher throughput (though less simultaneous wavelength coverage than the corresponding STIS echelle mode)**

Dynamical simulation of the formation of cosmic structure: the "cosmic web"

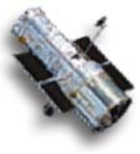


Galaxies and clusters form at the cusps of this structure – but much of the matter in the universe remains in a tenuous Intergalactic Medium whose properties tell a great deal about the history of the cosmos. *This will be the focus of COS.*

Absorption line spectroscopy

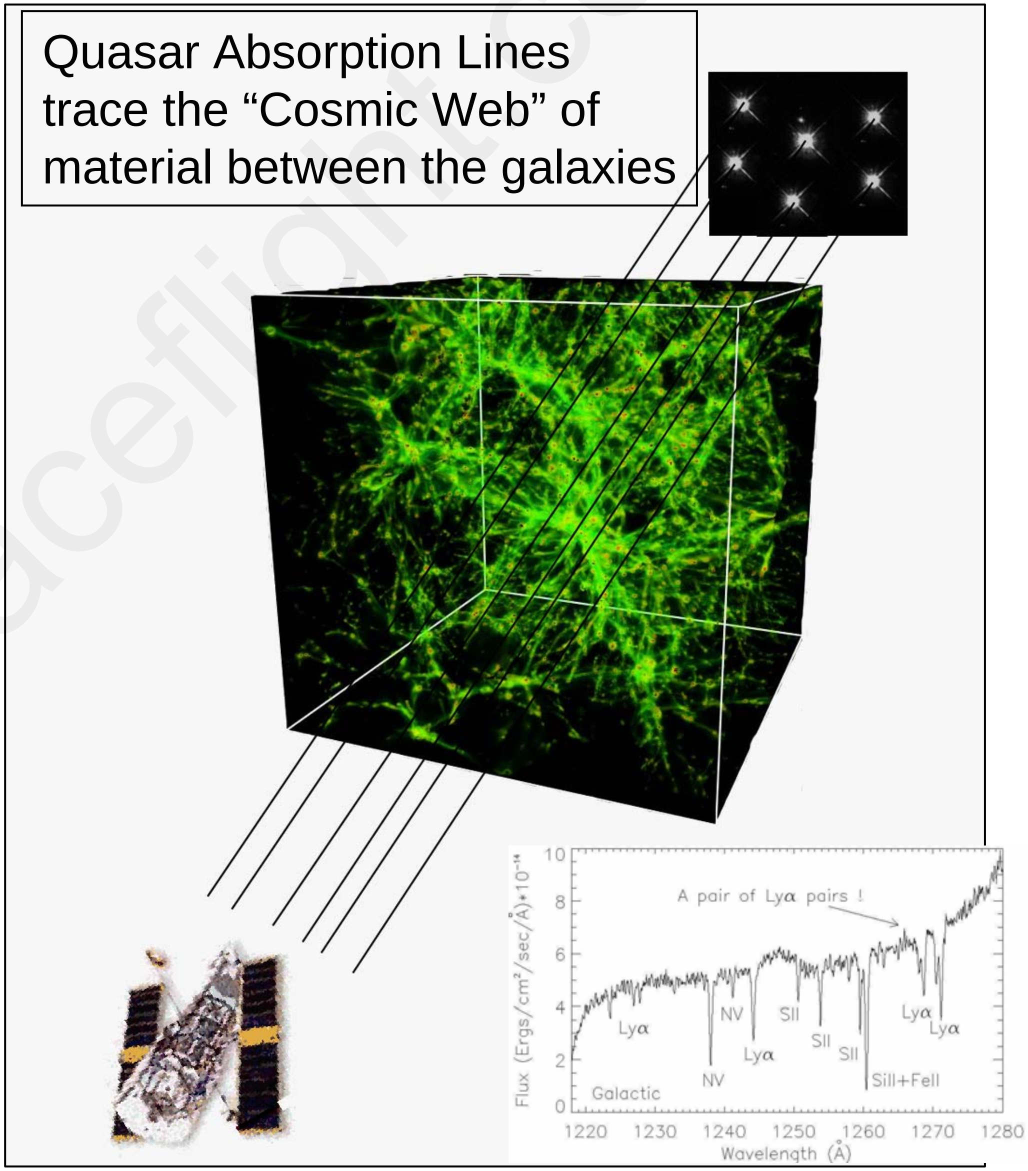


can probe much more powerfully if you can use fainter background targets. *COS will make this possible*



COS will study:

- Large-scale structure by tracing Hydrogen Lyman a absorptions
- Formation of galaxies
- Chemical evolution of galaxies and the intergalactic medium
- Hot stars and the interstellar medium of the Milky Way
- Supernovae, supernova remnants and the origin of the elements
- Young Stellar Objects and the formation of stars and planets
- Planetary atmospheres in the Solar System



- **Visualization concept from Schiminovich & Martin**
- **Numerical simulation from Cen & Ostriker (1998)**
- **Songaila et al. (1995) Keck spectrum adapted by Lindler & Heap**

The Complementary Nature of COS and STIS

COS is a superb, point-source, low- and medium-resolution, UV-only spectrograph, with the high priority science goals outlined above

STIS is a powerful general-purpose spectrograph with its own unique capabilities that are *not* superseded by COS, including:

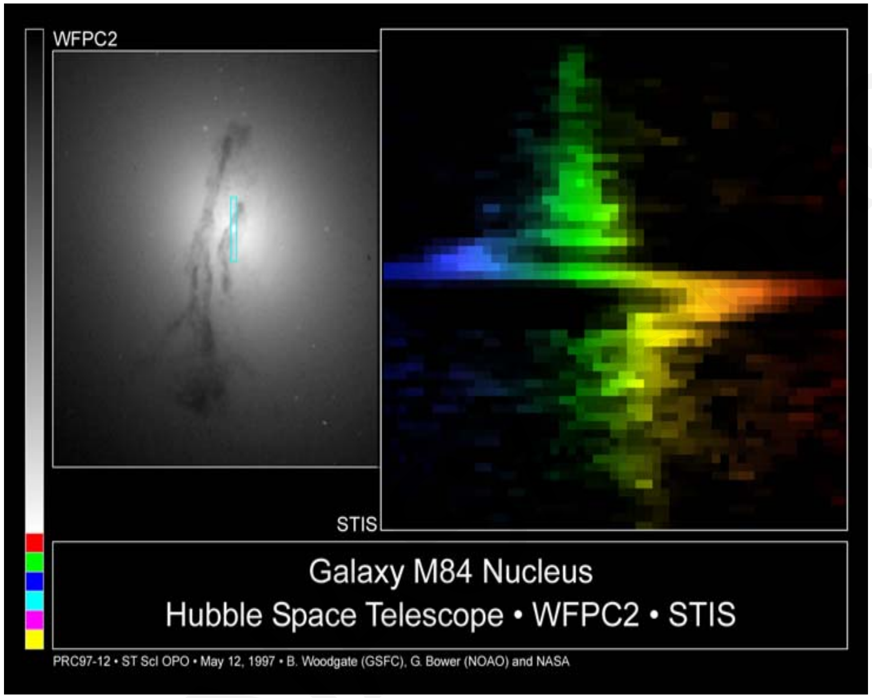
- Imaging spectroscopy **at the superb angular resolution of HST**
  - Both low- and medium-resolution modes in four bands spanning the far UV *through the visible* (115-1000nm)
- High-resolution UV spectroscopy **from 115 to 320nm**
  - Nominal resolving power of 110,000 (3 km/s resolution), pushed as high as 200,000!
- High-time-resolution **(128 μs) UV spectroscopy and imaging**
- Very high S/N visible spectrophotometry

Together, COS and STIS provide a full set of spectroscopic tools for astrophysics

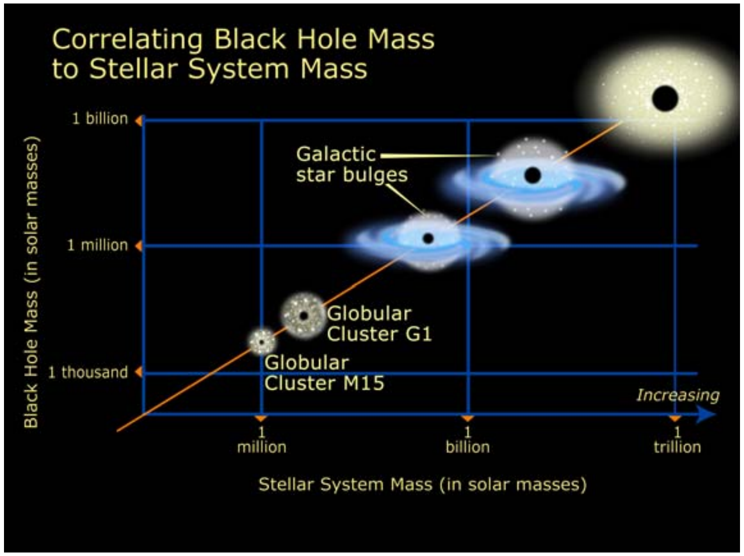
Goddard Space Flight Center

Imaging Spectroscopy: Black Holes

- **STIS high-spatial-resolution spectroscopy in the visible has shown that nearly all galaxy nuclei harbor a massive black hole**



- **STIS observations now permit demographic study of the population of black holes and reveal a tight correlation between the black hole mass and the properties of the stellar bulge – a fundamental clue to galaxy formation**

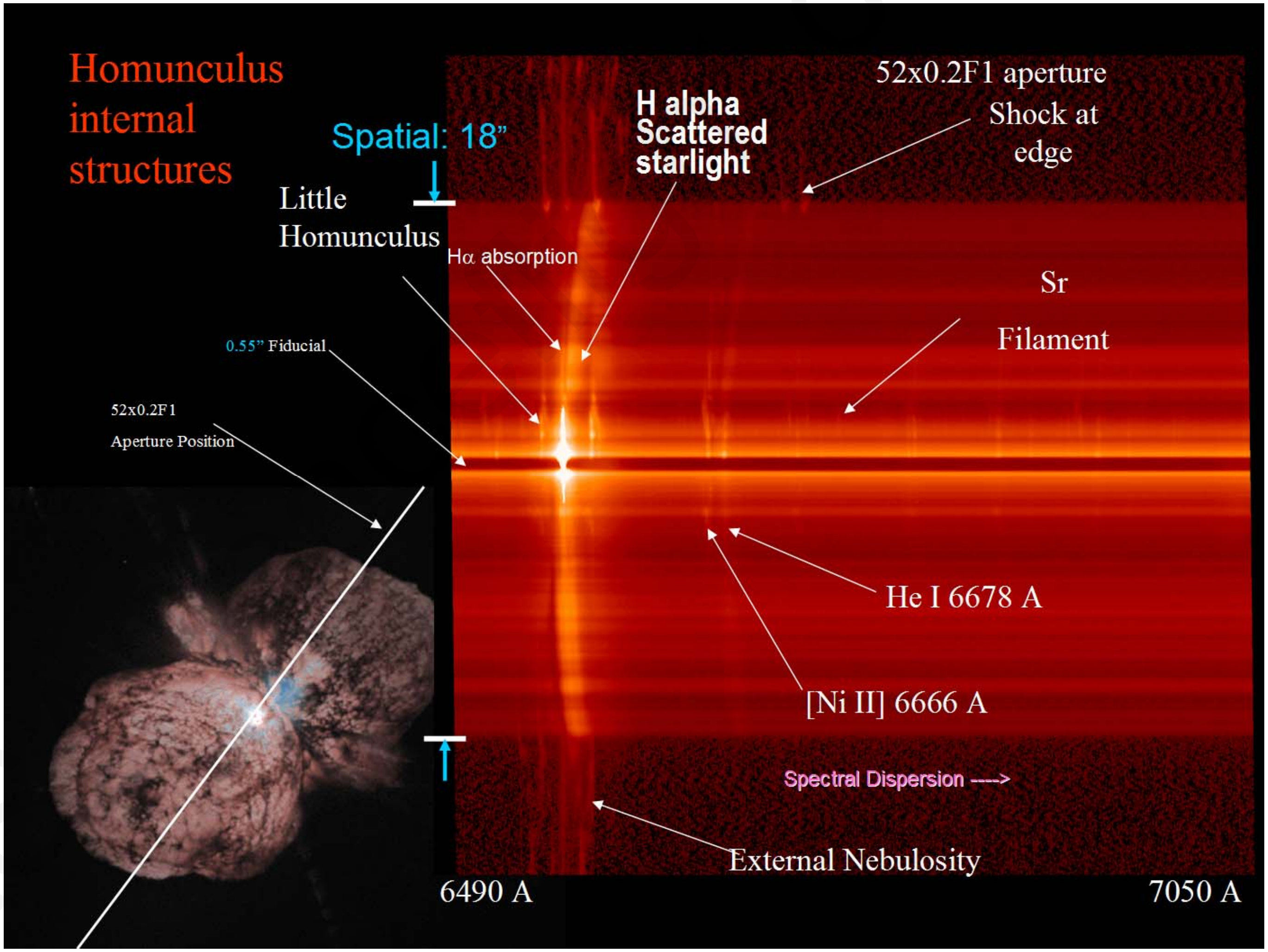


Goddard Space Flight Center

Imaging Spectroscopy: Eta Carinae

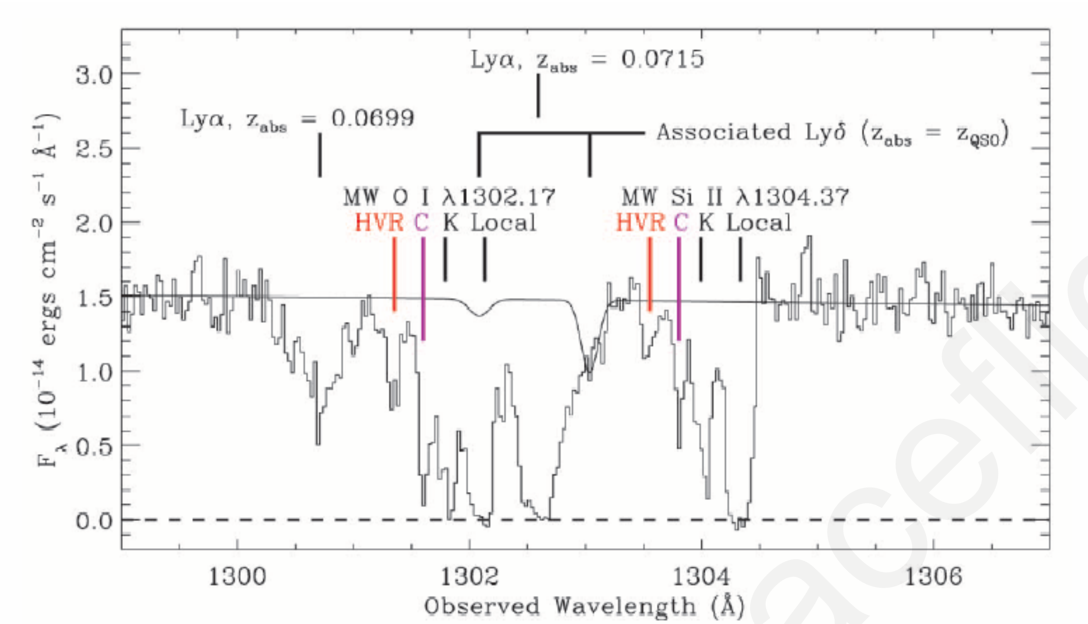
Eta Carinae: fascinating object whose study fully utilizes STIS's imaging spectroscopy capabilities: outflows, ejected shells, stellar winds...

Many think this nebula harbors the next Milky Way supernova!



T. Gull/GSFC, private communication

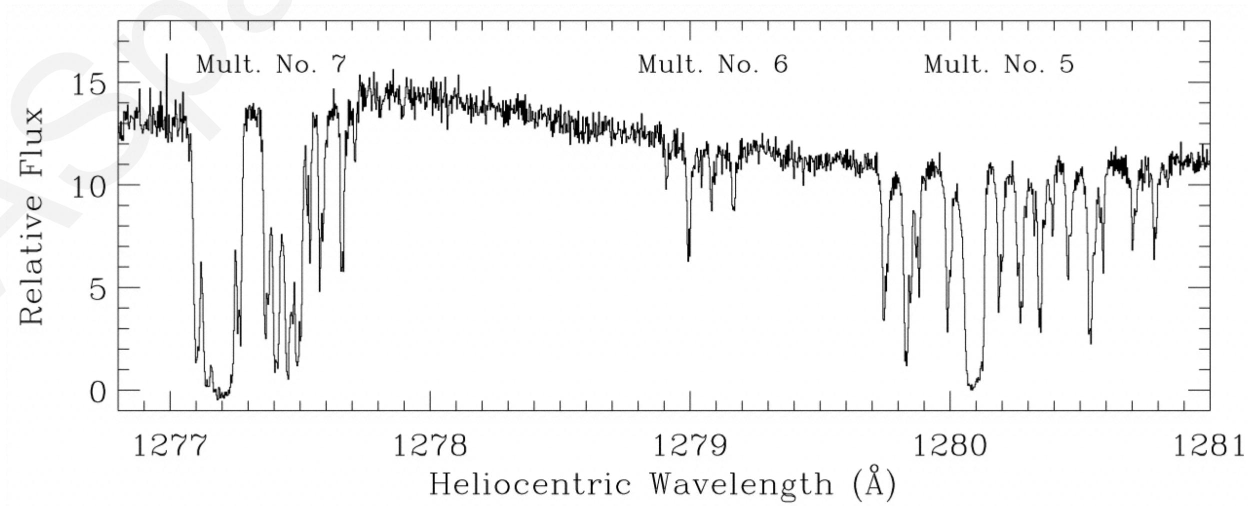
High Resolution UV Spectroscopy



- **R = 44,000 study of high-velocity gas clouds plunging into the Milky Way galaxy**

Tripp et. al. 2003, *AJ*, 125, **3122**

- **R = 200,000 (!) study of thermal pressures in the interstellar medium**

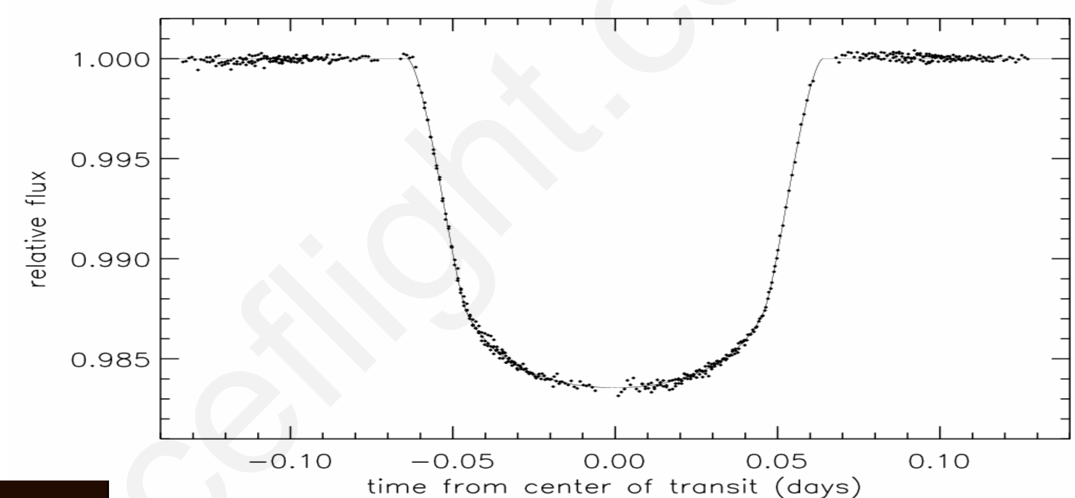


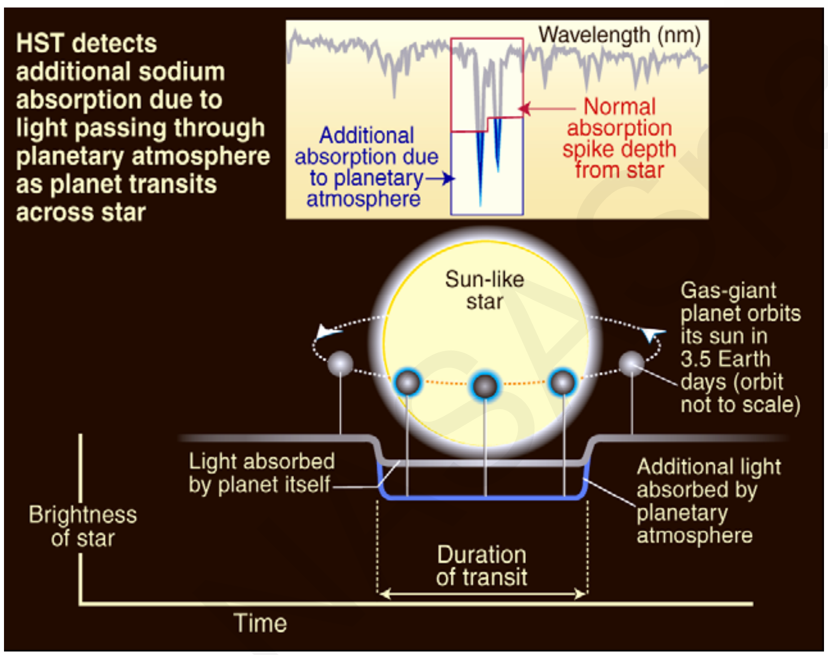
Jenkins & Tripp 2001, *ApJ Suppl*, 137, **297**

Goddard Space Flight Center

High S/N Spectrophotometry: Extrasolar Planetary Atmospheres

- First, STIS measured the light curve of the star HD209458 as its closely orbiting planetary companion transited across the face of the star





- Remarkably, STIS then detected constituents of the planetary atmosphere – sodium (seen in the visible) and an evaporating hydrogen envelope (seen in the UV)
- Ground-based visible observations have not approached the necessary precision
- More such transiting planets are now known

Conclusion

After SM4, HST will be at the apex of its scientific capabilities:

- **WFC3 + NICMOS + ACS? = most powerful imaging capability ever**
- **COS + STIS = full set of spectroscopic tools for astrophysics**
- ***The scientific promise is spectacular!***
- ***Thanks to all of you for your efforts in making that promise a reality!***