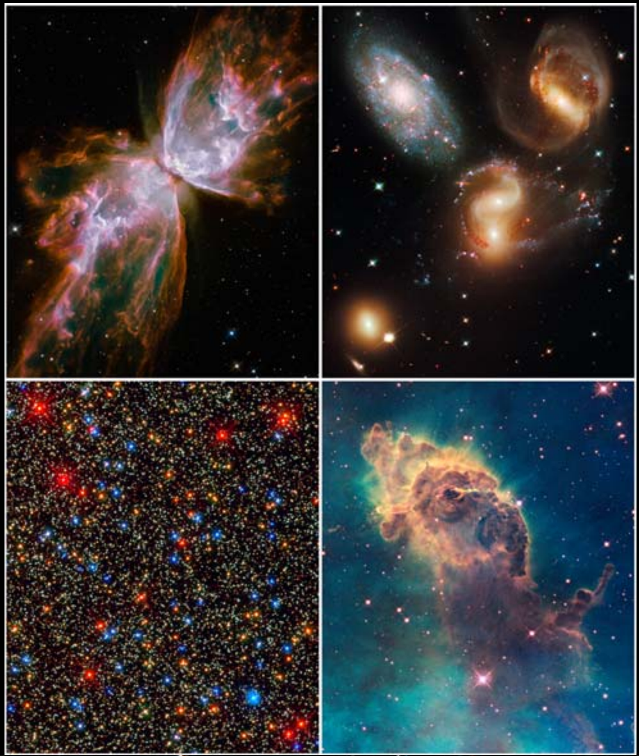
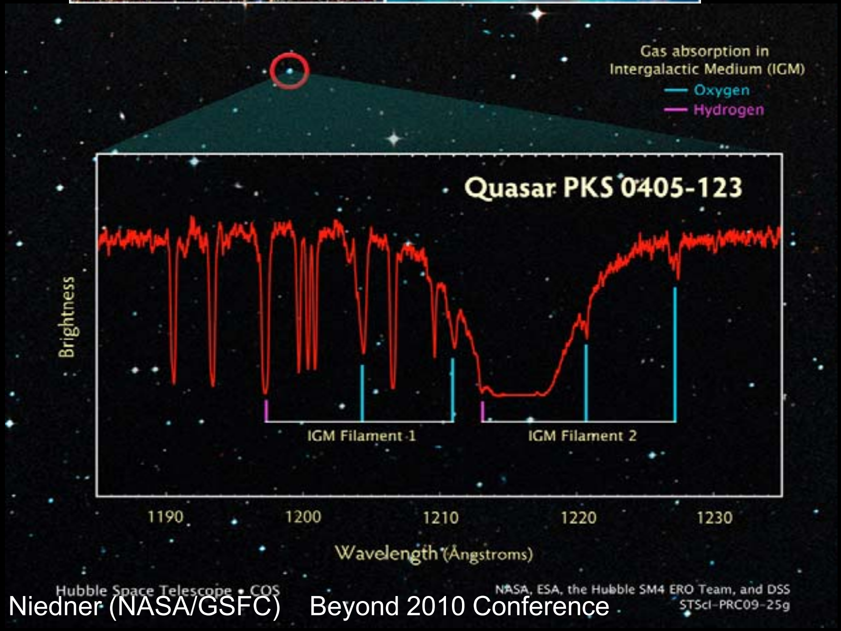


Early scientific results from the rejuventated Hubble Space Telescope



Malcolm B. Niedner

HST Observatory Project Scientist

NASA/Goddard Space Flight Center

Presentation to Beyond 2010 Conference

February 4, 2010

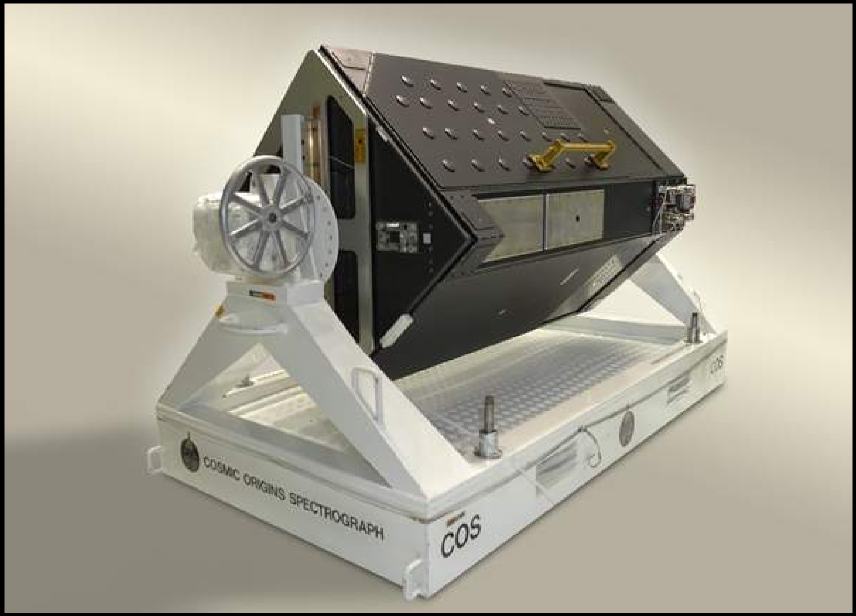
Hubble is an *Observatory* whose universe spans the solar system to the highest-redshift galaxies

- Servicing Mission 4 (SM4) *rejuvenated* Hubble with the installation of two new science instruments, the repair of two others, and the refurbishment of key engineering subsystems. *Unprecedented.*
- The post-SM4 scientific "toolkit":

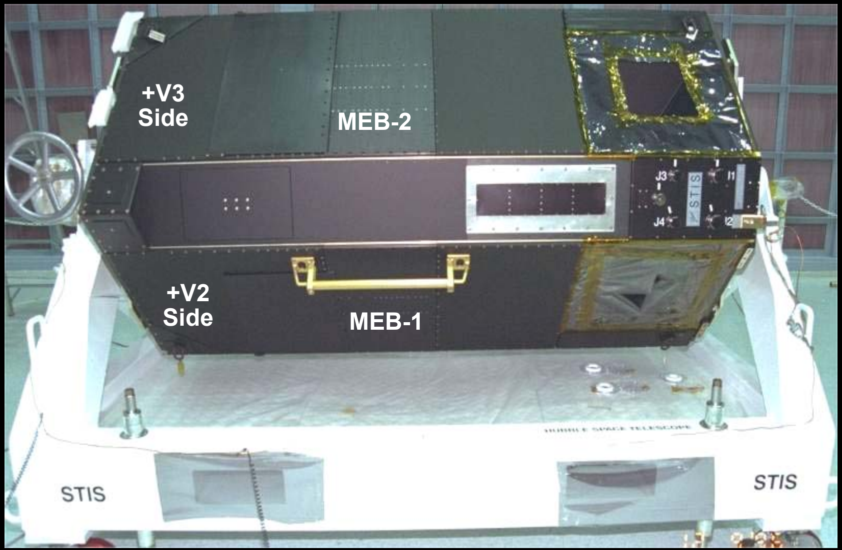
SM4

  - ***Wide Field Camera 3 (WFC3)***, new 2-channel panchromatic imager covering 200-1700 nm. *The scientific backbone of HST.*
  - ***Cosmic Origins Spectrograph (COS)***, new UV point-source spectrograph spanning 115-320 nm. *HST's fastest spectrograph ever.*
  - ***Advanced Camera for Surveys (ACS)***, flown 2002, repaired. *Widest HST field w/ red-optimized visible* light *CCD, complements WFC3.*
  - ***Space Telescope Imaging Spectrograph (STIS)***, flown 1997, repaired. *Spatially resolved slit spectra over 120-1100nm, not as fast as COS but hugely versatile and complementary to it.*
  - **Near-Infrared Camera and Multi-object Spectrometer (NICMOS)**, *Narrow-medium field imaging from 800 to 2500 nm (cryocooler issues).*

WFC3 (new)

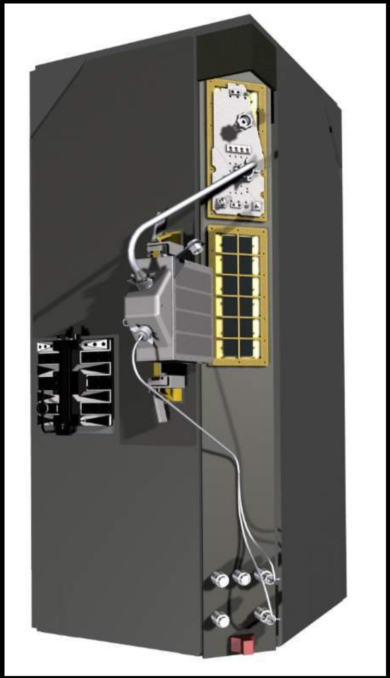


COS (new)



STIS-R (repaired)

The Scientific Instruments of SM4



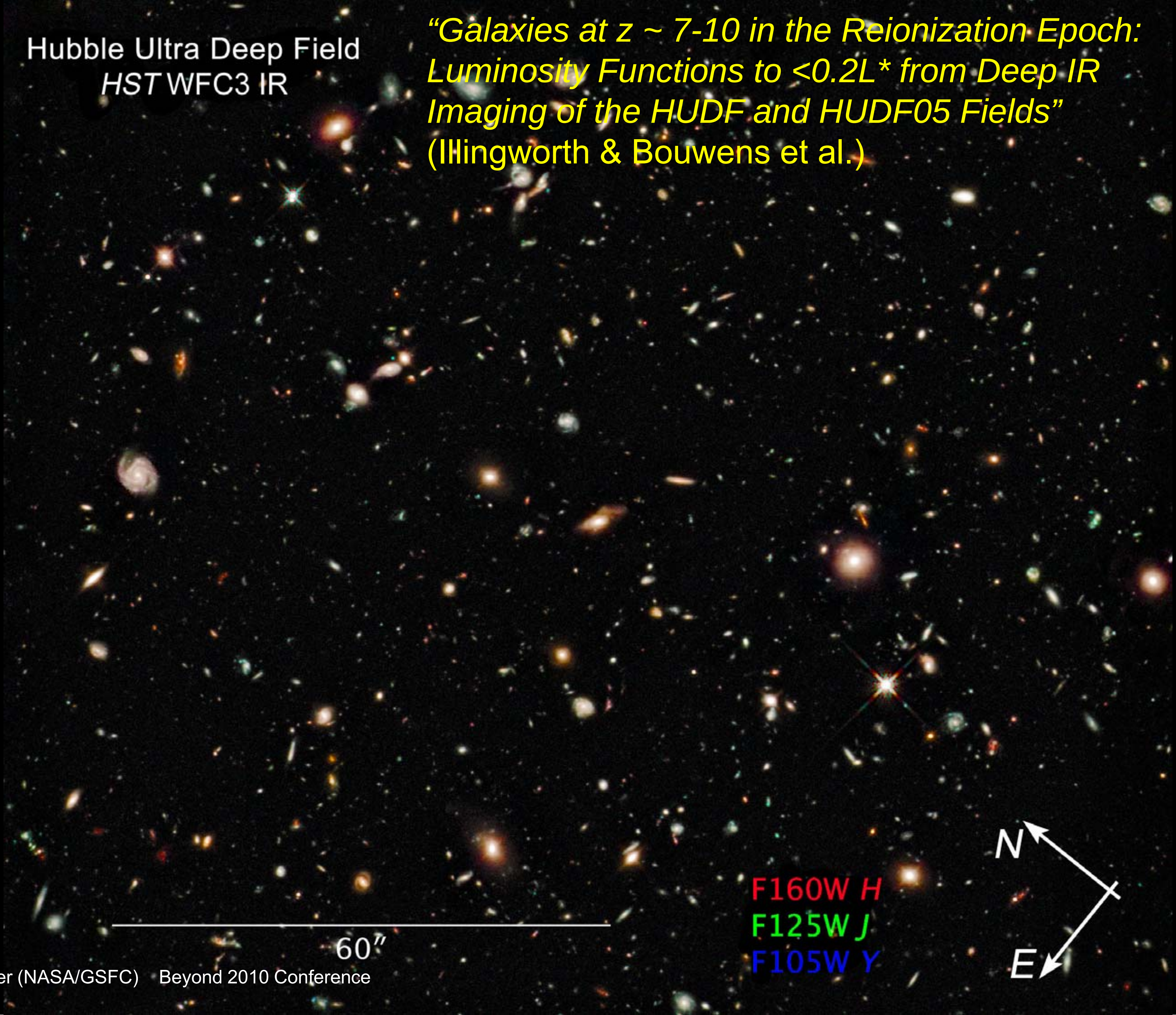
ACS-R (repaired)

Topics

- Most distant galaxies
- Large-scale structure & IGM ("cosmic web")
- Dark Matter via lensing
- Accurate H_o & Dark Energy

- **Most Distant Galaxies with WFC3/IR**

"Galaxies at z ~ 7-10 in the Reionization Epoch: Luminosity Functions to <0.2L from Deep IR Imaging of the HUDF and HUDF05 Fields"*
(Illingworth & Bouwens et al.)

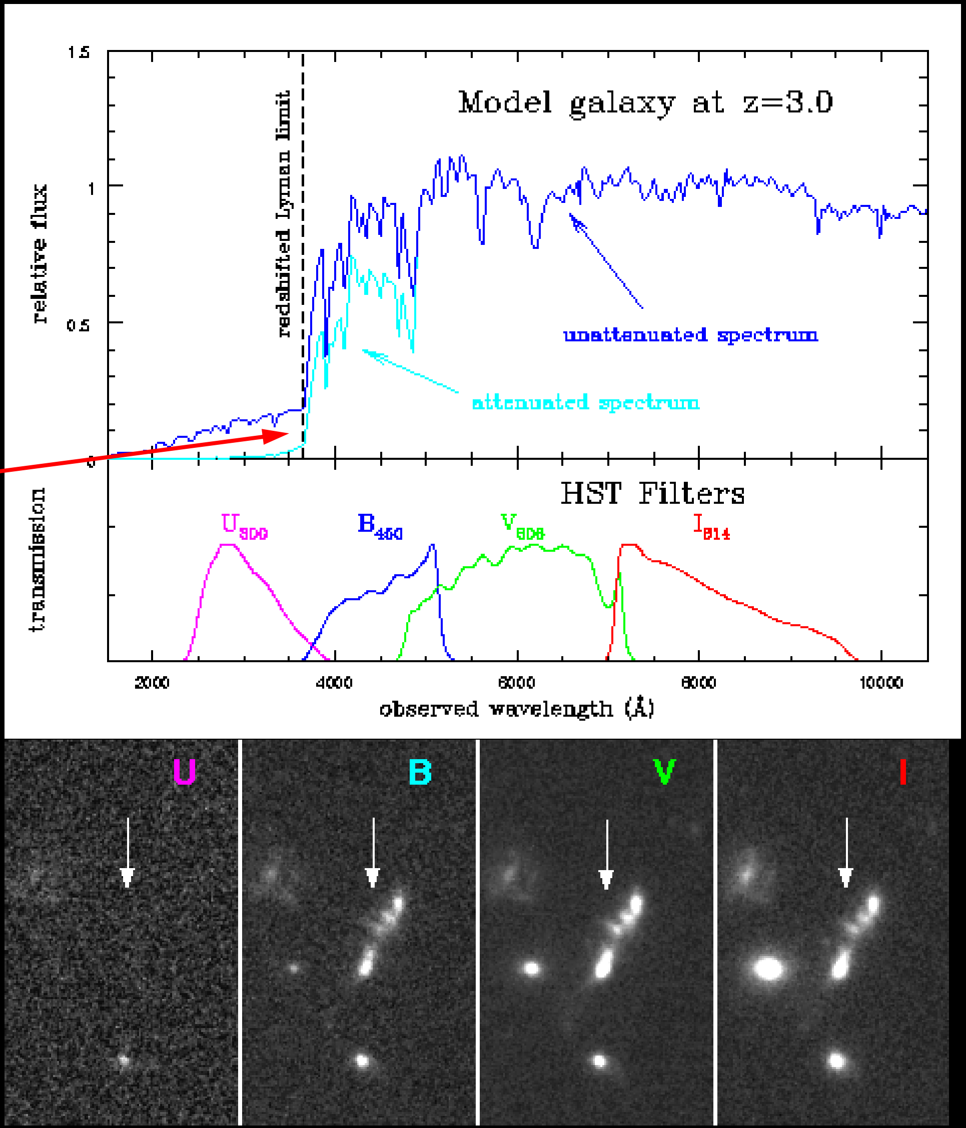


Photometric Redshifts, Lyman Break Galaxies, Ly-α Dropouts

"Photometric redshifts" are derived from intensity ratios (colors) in broad filters

Hydrogen completely absorbs light shortward of 0.0912 μm in the rest frame

As you move to higher redshift (era before re-ionization), you hit a wall for everything shortward of Ly-α



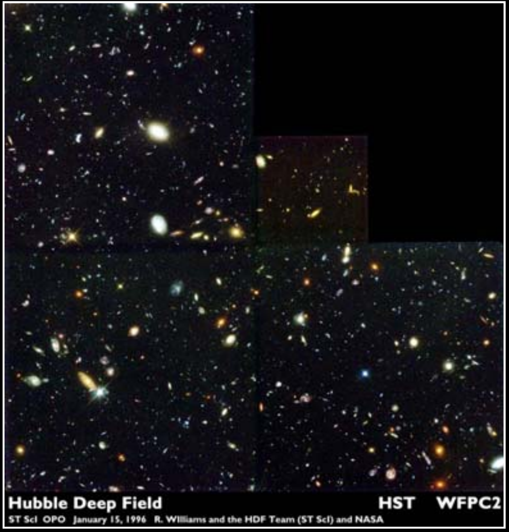
Redshift & lookback time: where we were *before* WFC3/IR

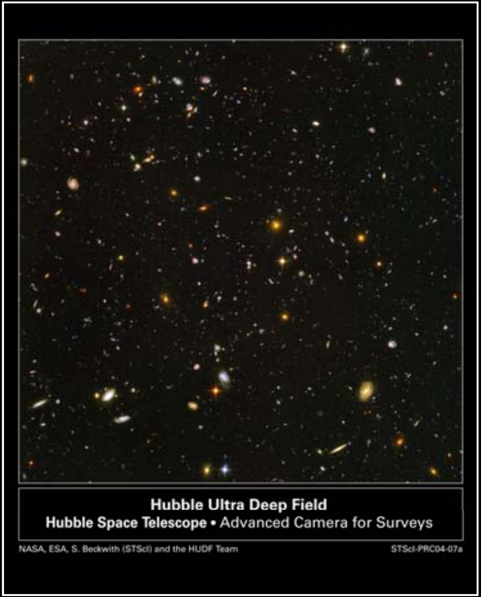
z redshift	millions of years since the Big Bang
2	3300
3	2200
4	1600
5	1200
6	950
7	750
8	650
9	550
10	500
11	400

UDF (WFPC2)

HUDF (ACS & NICMOS)

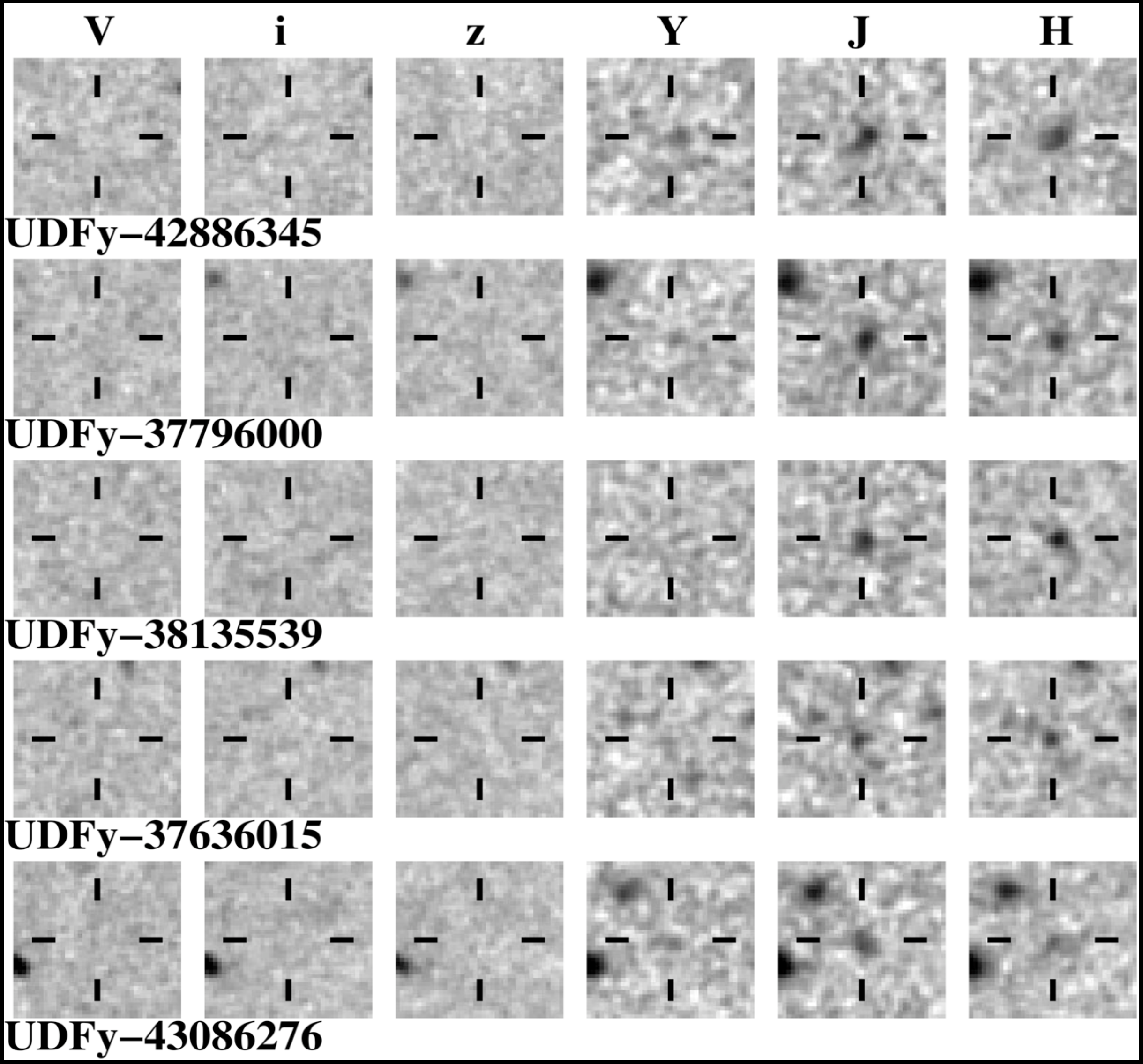
Reionization





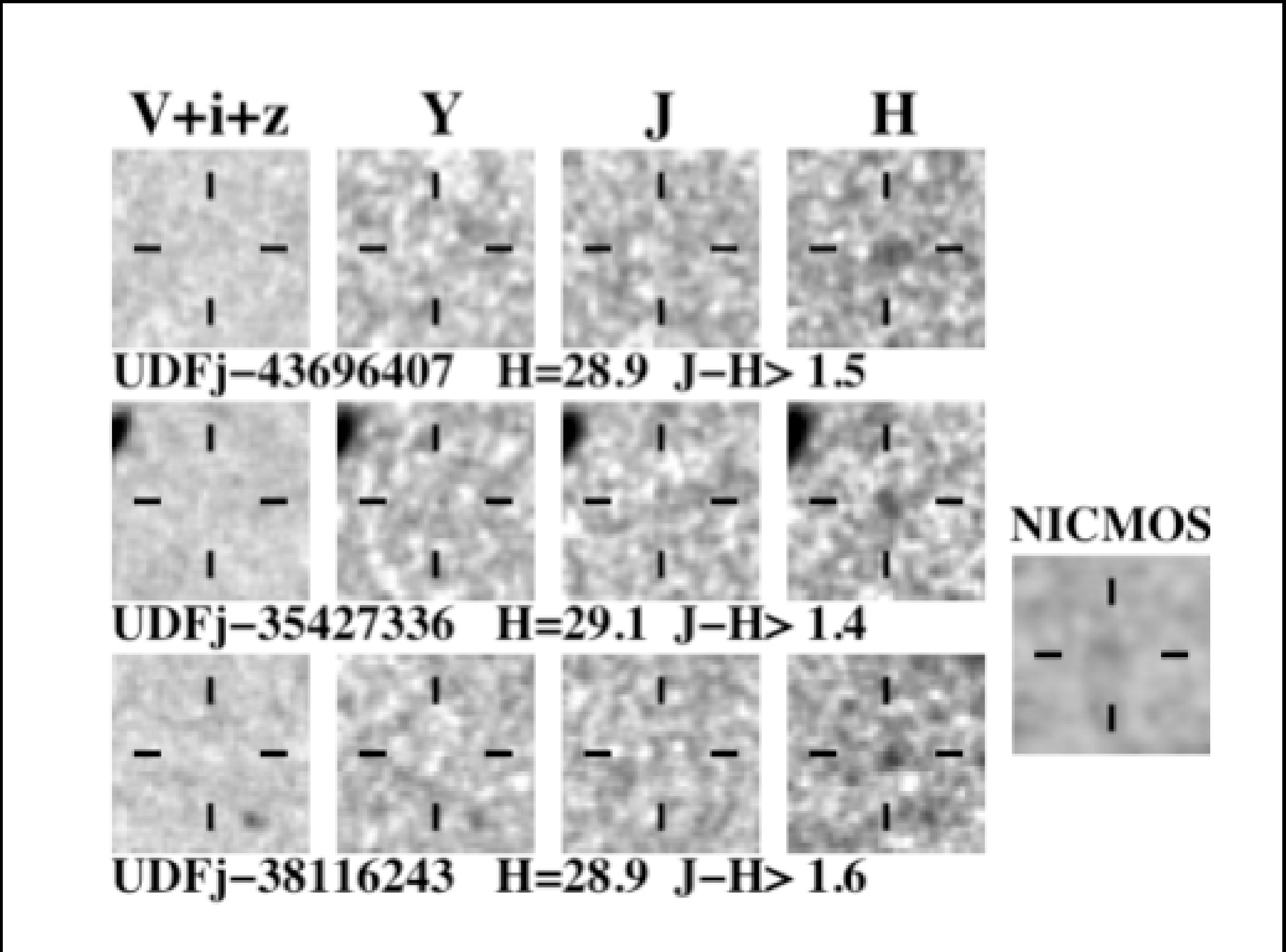
With WFC3/IR

Y(1050 nm) dropouts
Redshift ~ 8 - 8.5
Age ~ 600 Myr



Bouwens et al. 2009, ApJL, in press

Evidence for z ~ 10 galaxies in HUDF/IR!



Bouwens et al. 2010, submitted to Nature

Now, after the HUDF/IR

z redshift	millions of years since the big bang
2	3300
3	2200
4	1600
5	1200
6	950
7	750
8	650
9	550
10	500
11	400

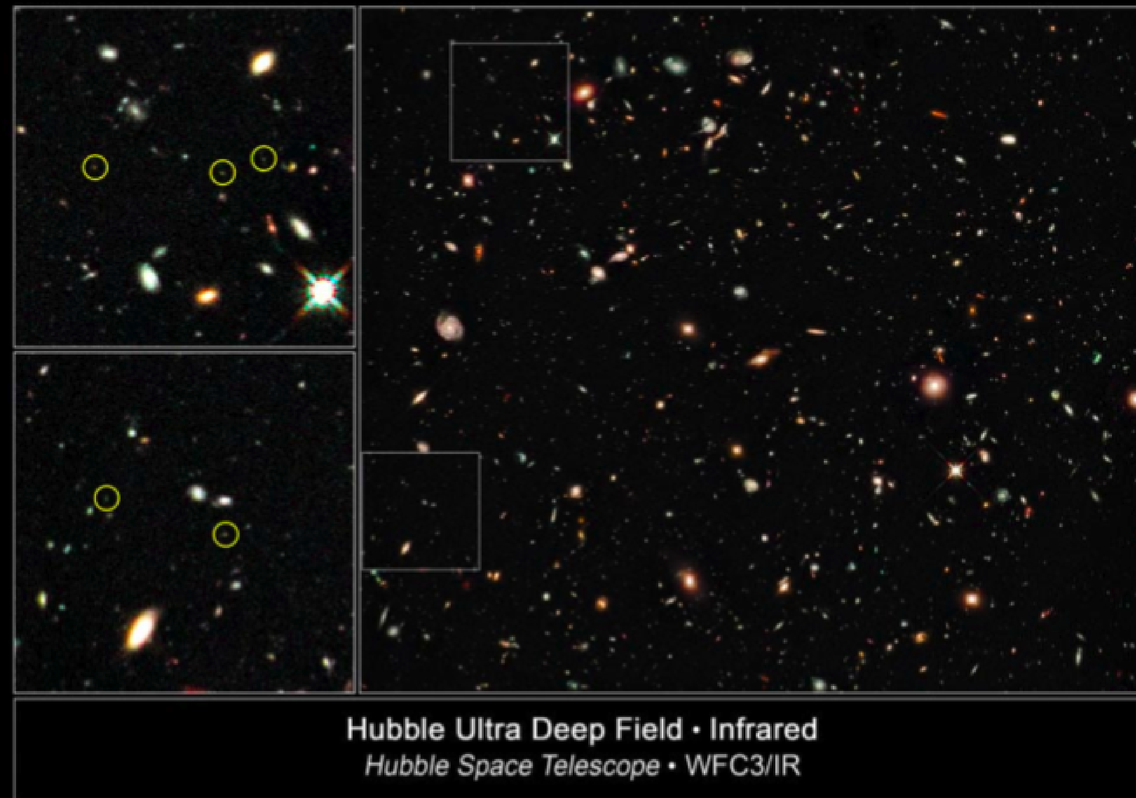
UDF (WFPC2)

HUDF (ACS & NICMOS)

HUDF/IR (WFC3/IR)

Reionization

galaxies at z~8



NASA, ESA, G. Illingworth (UCO/Lick Observatory and University of California, Santa Cruz), and the HUDF09 Team STScI-PRC10-02

WFC3/IR is 40-50x faster than NICMOS picking up z ~ 7 galaxies, and by probing the z = 8-10 regime has gone into new territory. JWST awaits!

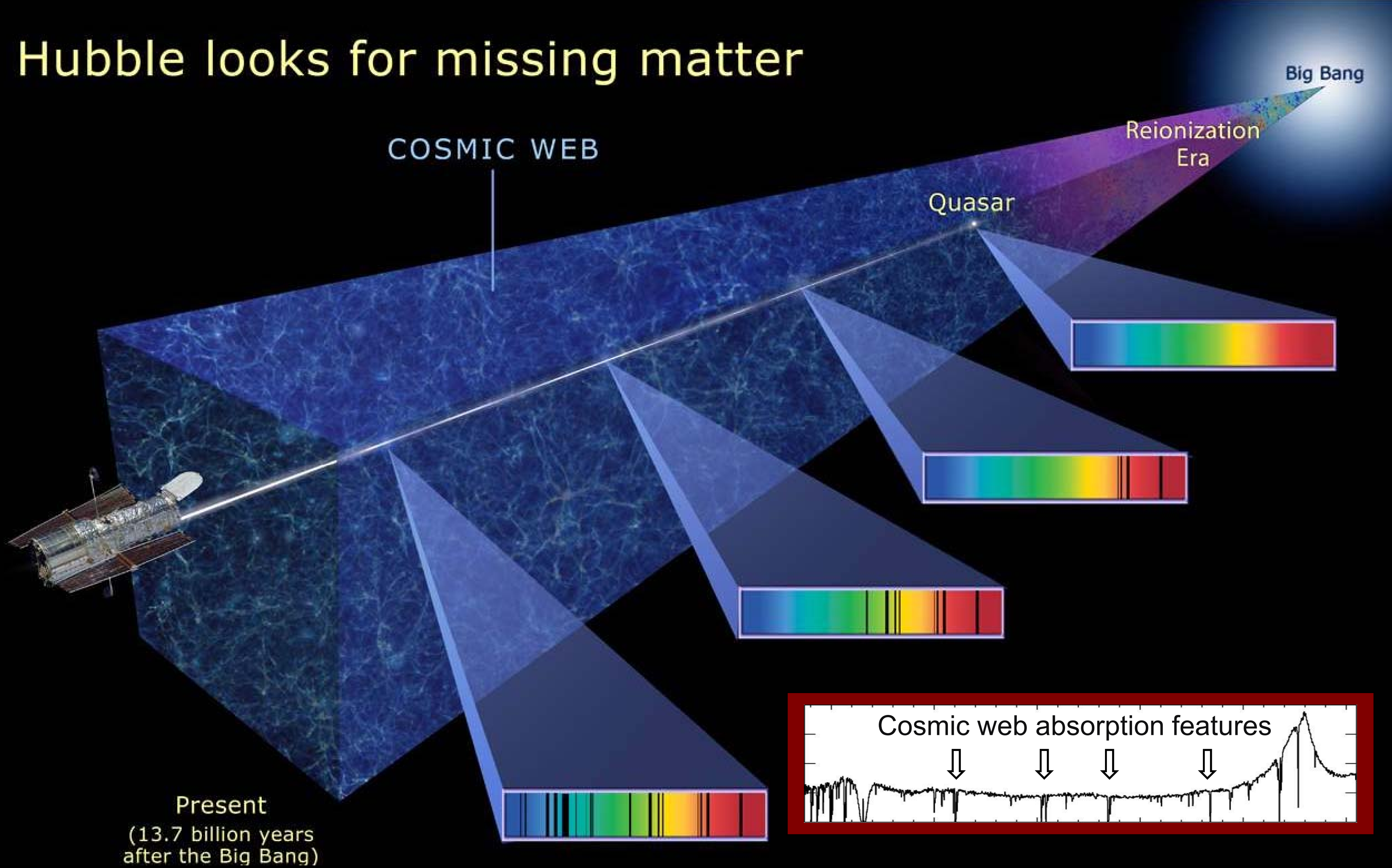
What have we learned so far from HUDF/IR?

- WFC3 = fabulous camera (so say teams analyzing data)
- From Bouwens, Illingworth and colleagues:
  - galaxies smaller the higher the redshift: consistent with hierarchical merging producing today's great galaxies
  - z ~ 7 galaxies very blue (in the rest frame): consistent with extremely low metallicity stellar populations soon after BB
  - Characteristic luminosity (L^*) decreases with increasing z: fewer "bright" galaxies at high z, *i.e., luminosity function (LF) evolution*.
  - LF has steep slope over z = 7-8: faint galaxies far outnumber bright ones
  - Extrapolation of LF to faint (sub-detection) limits at z ~ 10 results in UV luminosity density ~ 13% of that needed for reionization
  - WFC3/IR's z ~ 8 galaxies seen by Spitzer Observatory: *some stars at 650 Myr post-Big Bang were already 300 Myr old!* JWST will have much to look for at z = 10-15.

• Large-scale structure & IGM with COS

(Contributions from Cynthia Froning and the COS Team gratefully acknowledged)

Hubble looks for missing matter

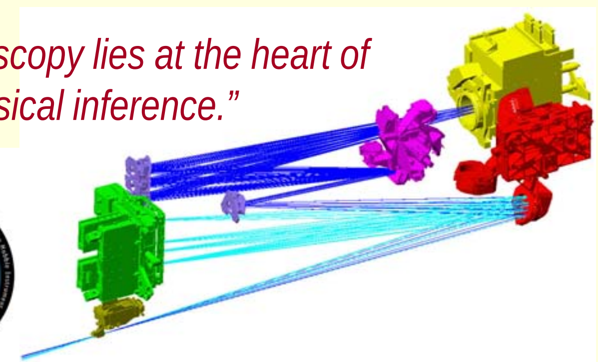


With just a few weeks of observing time, Hubble's new Cosmic Origins Spectrograph will probe more of the cosmic web than all previous Hubble spectrographs combined.

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 (and beyond) made of?

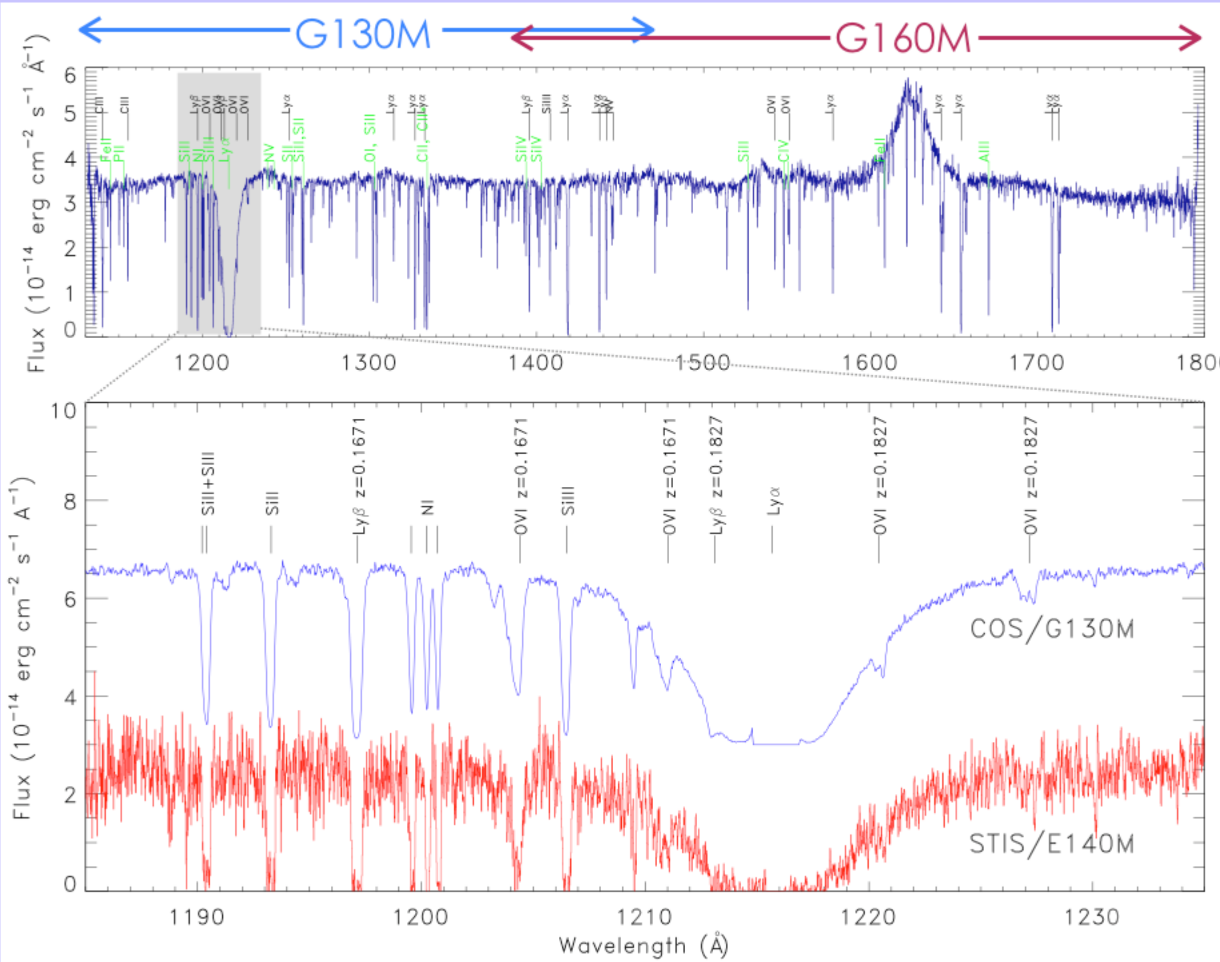
“Spectroscopy lies at the heart of astrophysical inference.”



PKS 0405-12 Overview

- Well-studied, bright QSO, z=0.573 (lookback time=5.5 Gyr)
- Rich in IGM Lyα/metal ion lines
- Observed by every generation of HST far-UV spectrograph: FOS, GHRS, STIS, and now COS, as well as HUT, FUSE
  - FUSE: 150 ksec → **S/N=5-10** per 20 km s^{-1} resel
  - STIS/E140M: 27 ksec → **S/N≈12** per 7 km s^{-1} resel
  - COS: 17 ksec (7 orbits) → **S/N≈50** per 15 km s^{-1} resel

Cosmic Origins Spectrograph
Hubble Space Telescope



The Intergalactic Medium

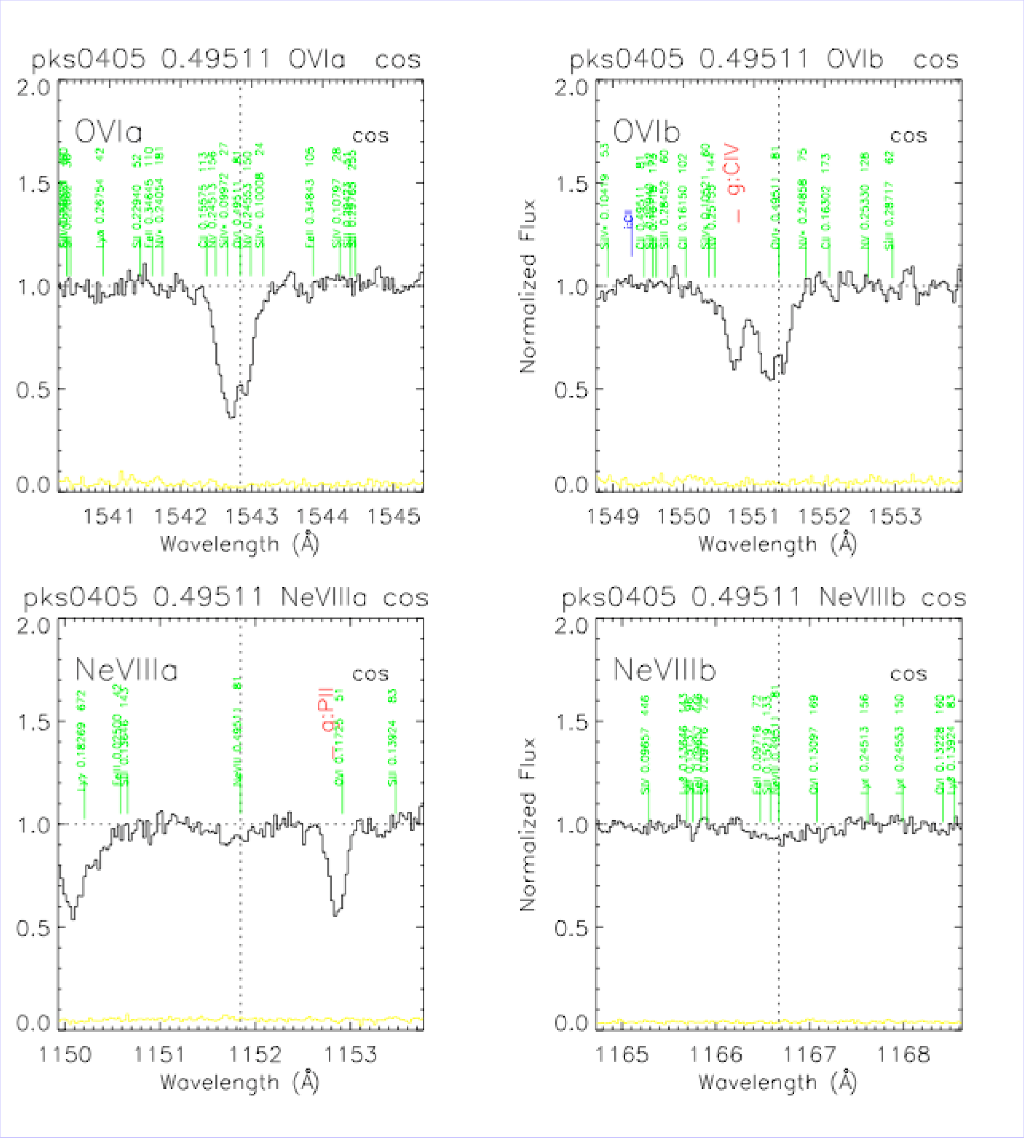
PKS0405

- z=0.573, F□□□ 2e-14 ergs/cm2/s/Å
- 9.7 ksec (G130M) vs. 27 ksec (STIS) gives substantial S/N improvement
  - ⇒Survey capabilities
  - ⇒Spatial mapping
  - ⇒Metals, diffuse IGM

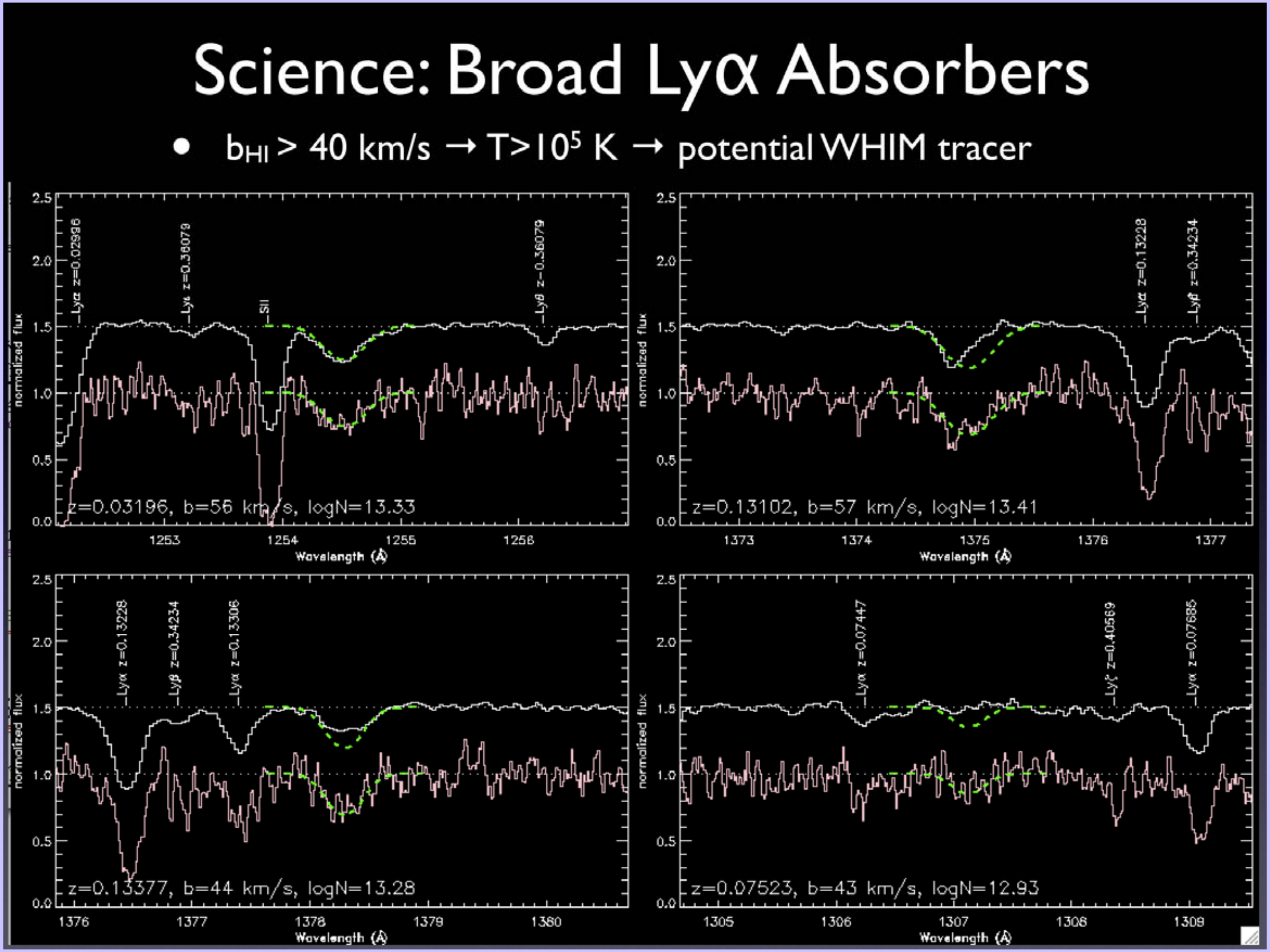
PKS0405, continued

Cosmic Origins Spectrograph
Hubble Space Telescope

- Ne VIII detection, z=0.495
- Tracer of WHIM (10^5 – 10^7 K), reservoir of 50% of baryons?
- Enters COS band z>0.47, sensitive to collisionally-ionized gas at ~10^6 K
- EW (770 Å) = 26.4±4 mÅ, log N_a = 13.71±0.07 dex
- Consistent Ne VIII/OVI ratio

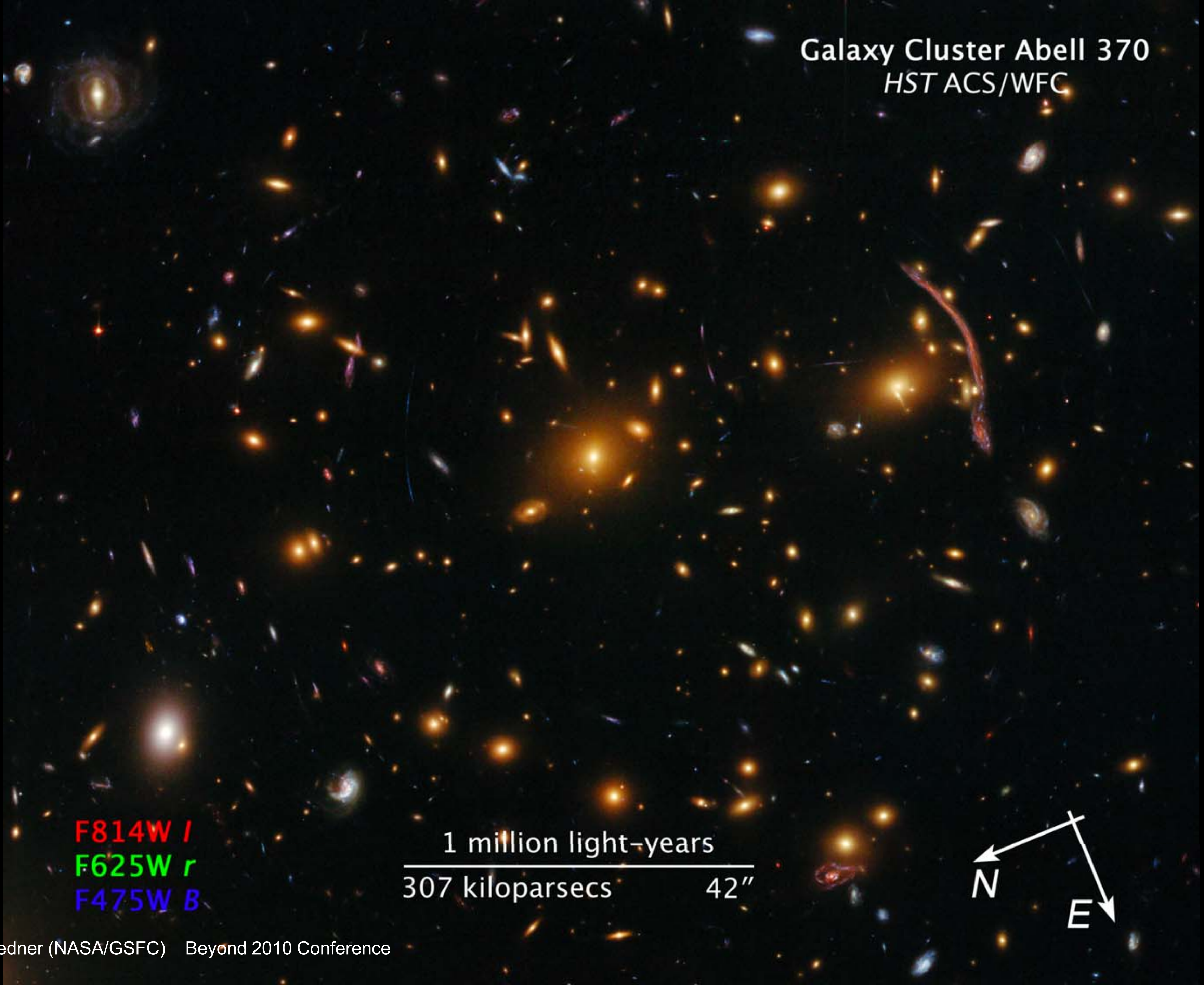


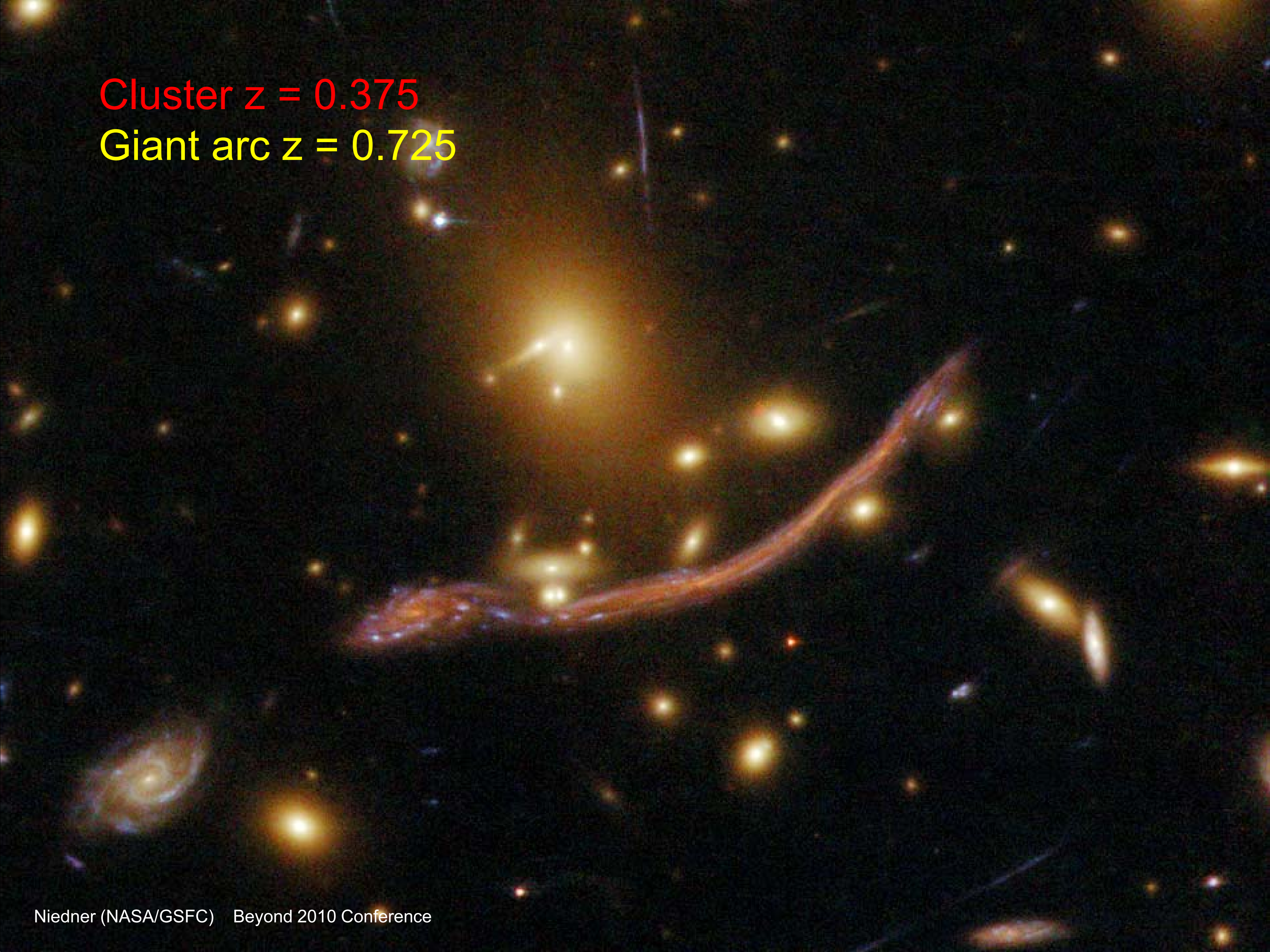
Cosmic Origins Spectrograph
Hubble Space Telescope



- **COS data are superb, and published IGM/cosmic web findings are "works in progress." Stay tuned.**

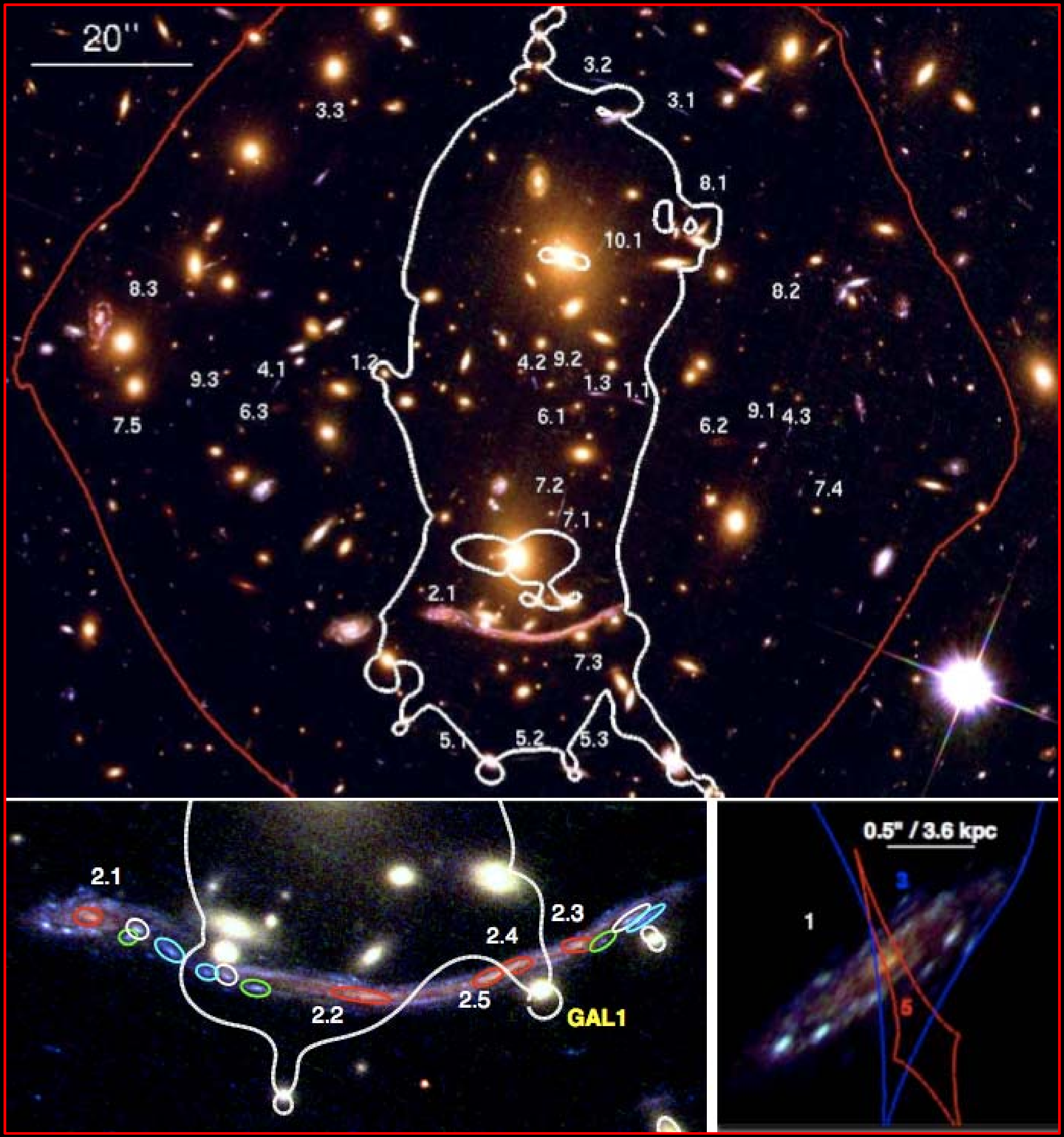
- **Dark Matter & Strong Lensing with ACS (the *repaired* ACS, that is!)**


Galaxy Cluster Abell 370
HST ACS/WFC
F814W I
F625W r
F475W B
1 million light-years
307 kiloparsecs
42″
N
E



Cluster z = 0.375
Giant arc z = 0.725
Niedner (NASA/GSFC) Beyond 2010 Conference

Abell 370 observed with ACS

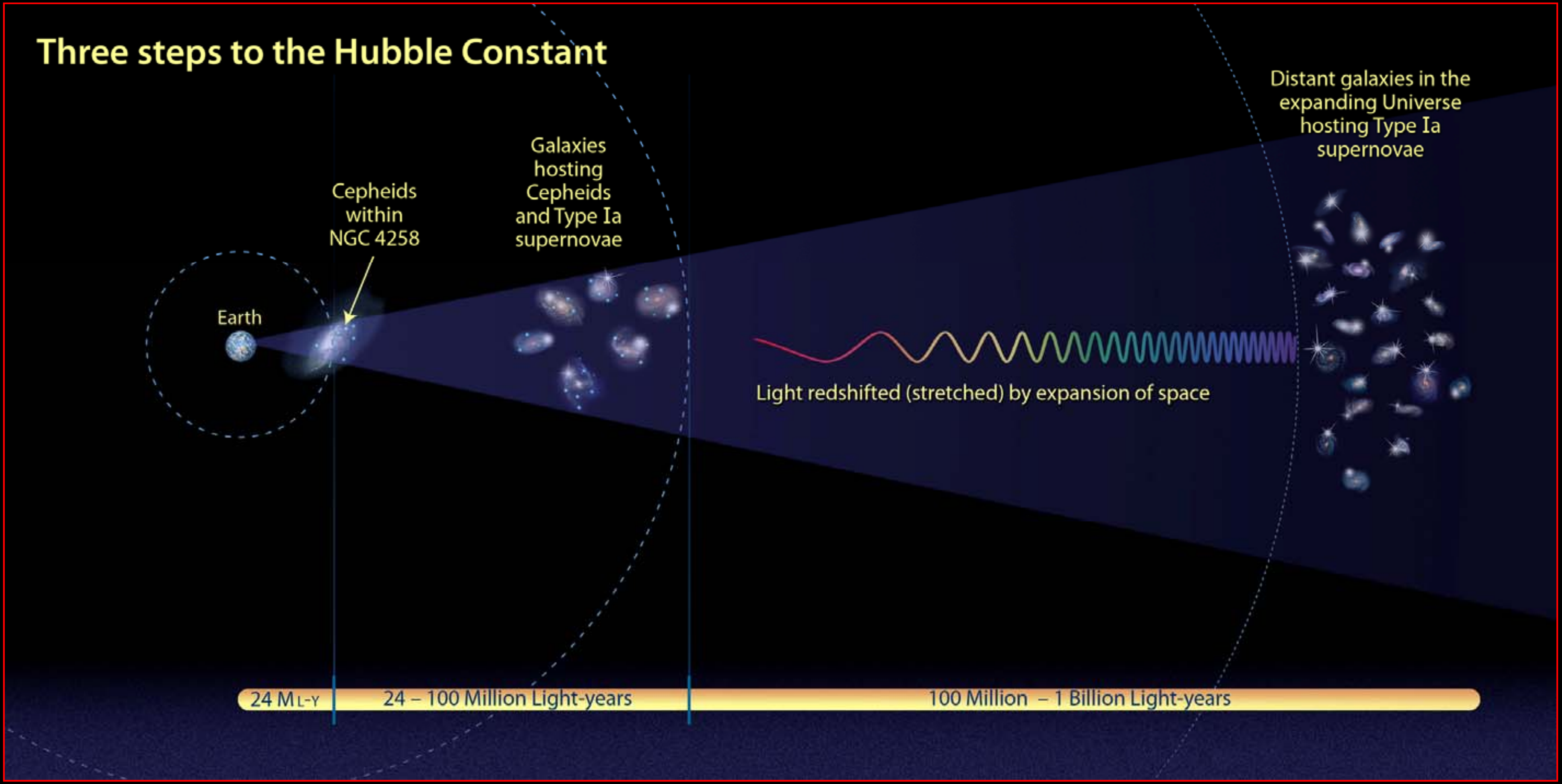


Richard *et al*., 2010, accepted *MNRAS Letters*

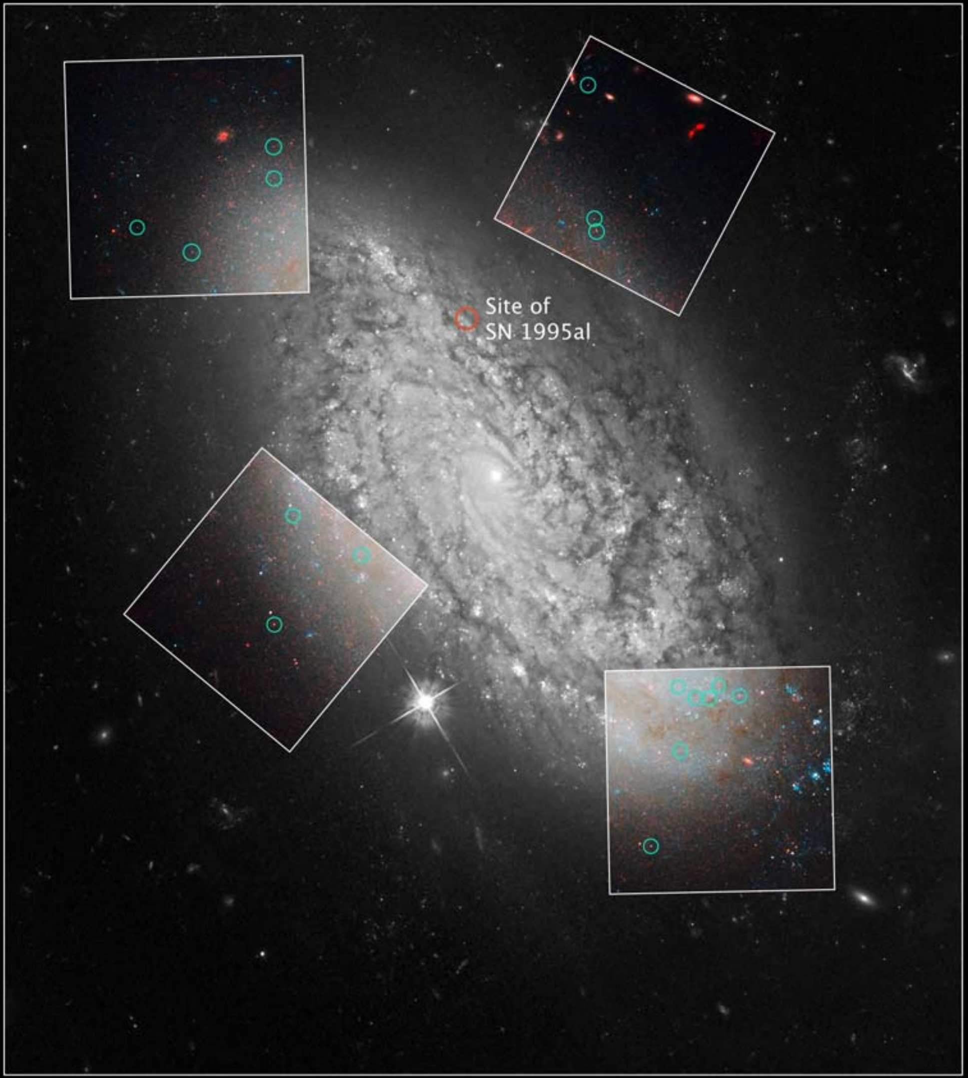
- Multi-color, hi-res imaging critical to finding multiply-imaged sources, constraining the DM distribution
- 10 multiply imaged sources in this system, 32 separate images
- "Giant arc" contains 5 images of spiral galaxy core, 3 and 1 images of other portions
- Cluster- and galaxy-scale DM components used in SL model, and accurate fit to observed arcs requires *bi-modal* cluster-scale DM
- Flux magnification factor of 32x for entire giant arc
- Chandra X-ray, visible light galaxy distribution, and radial velocities also show double peak
- Two colliding clusters along LOS

- **Accurate H_o & Dark Energy**

Riess et al. approach to a more accurate H_o (~ 5% error)



Riess et al., continued



Cepheid Variable Stars in Spiral Galaxy NGC 3021
Hubble Space Telescope • ACS/WFC • NICMOS

NASA, ESA, and A. Riess (STScI/JHU) STScI-PRC09-08a

Riess et al. 2009, *ApJ*, **699**, 539.

- NICMOS observations of 240 Cepheids in "maser galaxy" NGC 4258 (distance known to 3%) and 6 Type Ia host galaxies reduced H_o uncertainty by > 2x, to 4.8%

- Tighter error bars on H_o, in combination with WMAP 5-year data, halved uncertainty in the Dark Energy pressure term, w = -1.12 +/- 0.12, and gave added statistical weight to the possibility of a constant w(z) (i.e., Λ)

- Needed: even tighter error bars on H_o. Riess et al. are using WFC3/IR to efficiently go after Cepheids in more distant SNe hosts, with the goal of achieving ~ 3% accuracy. Again, stay tuned!

End