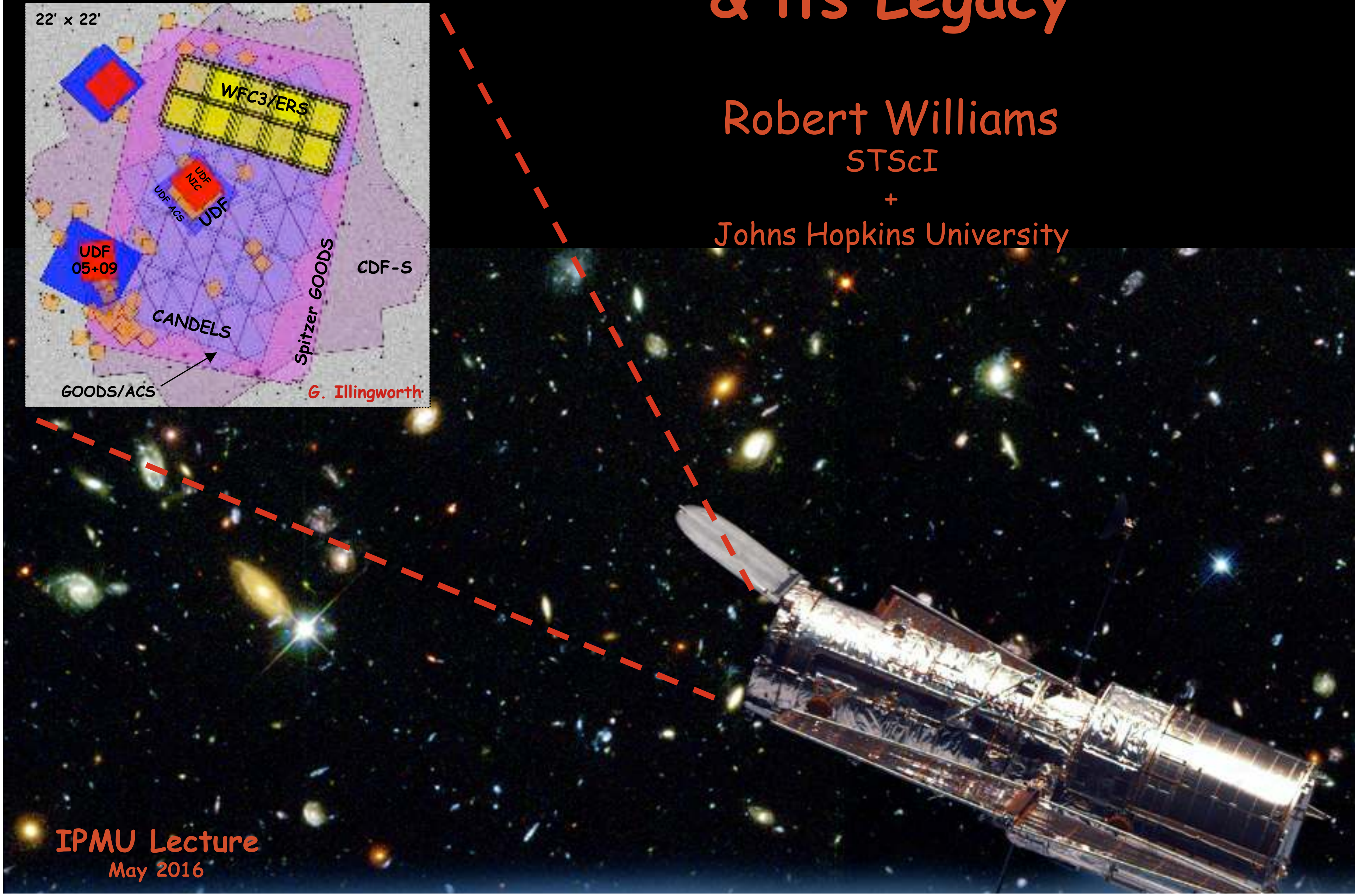
The Hubble Deep Field & its Legacy

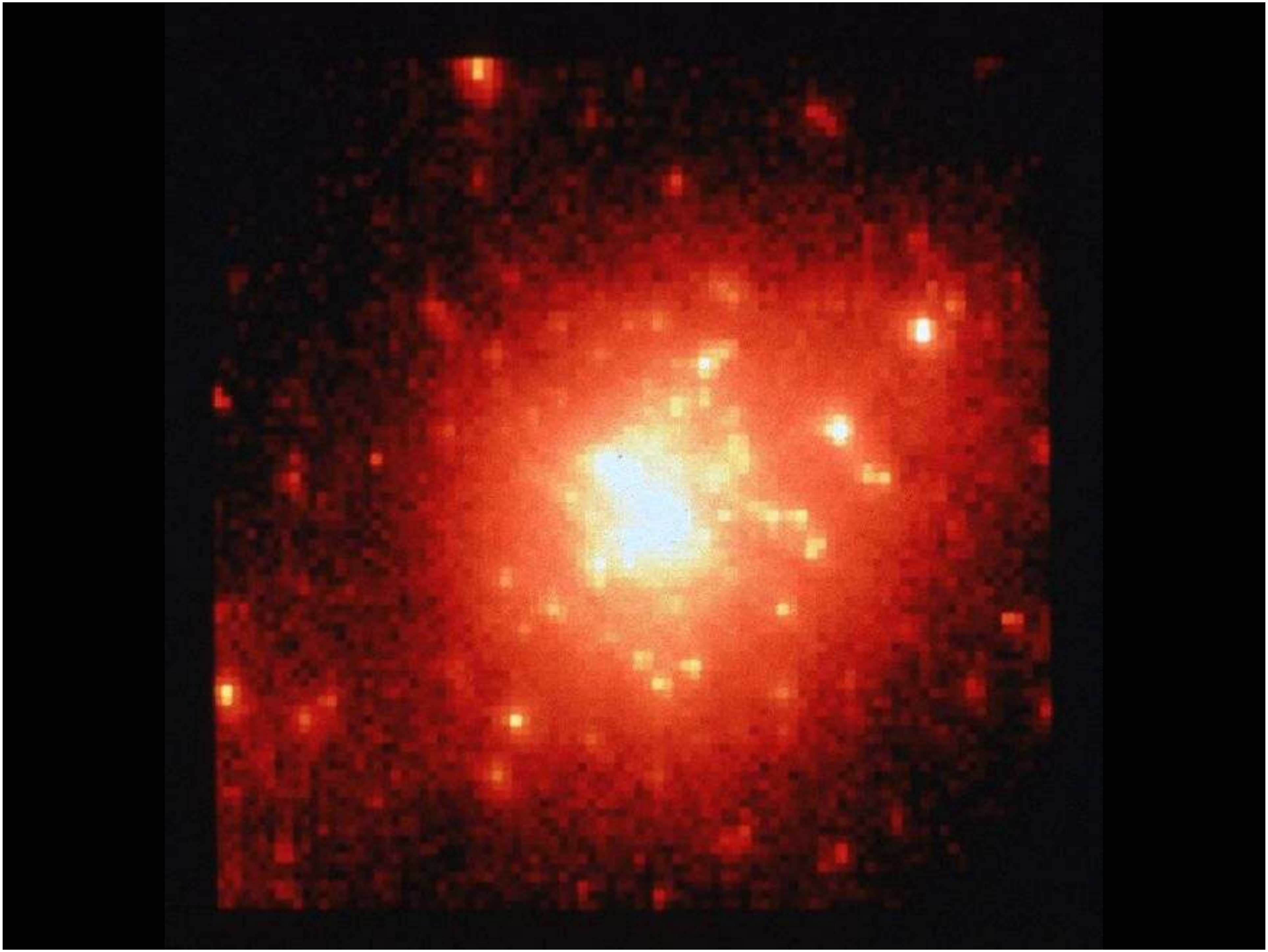
Robert Williams

STScI
+
Johns Hopkins University



G. Illingworth

IPMU Lecture
May 2016



New York Times
28 June 1990

HUBBLE TELESCOPE LOSES LARGE PART OF OPTICAL ABILITY

Most Complex Instrument in Space Is Crippled by Flaw in a Mirror

JUN 28 1990

Times, Page A1

By WARREN E. LEARY

Special to The New York Times

WASHINGTON, June 27 — Engineers have found a major flaw in the main light-gathering mirrors of the $1.5 billion Hubble Space Telescope that is likely to cripple its ability to view the depths of the universe for several years, the space agency said today.

The engineers for the National Aeronautics and Space Administration said at a news conference that there was distortion in one of the two mirrors used to focus light aboard the orbiting observatory, but they were not sure which one.

Although there may be ways for ground controllers to compensate for some of the problems caused by the distortion, a permanent correction in the largest and most complex scientific instrument ever put in space will probably have to wait two or three years for astronauts to visit the craft and replace some parts, they said.

'Incredibly Disappointing'

Some of the instruments on the spacecraft, which was proposed 45 years ago and has been in the active

rector of the National Optical Astronomy Observatories in Tucson, Ariz., the nation's largest array of ground-based telescopes.

But Ray Villard, a spokesman for the Space Telescope Institute in Baltimore, Md., the center for analysis of Hubble data, said all was not lost. "Obviously we're not pleased," he said, "but we don't see this as diminishing the science mission of the telescope. It will call for a shift of the kinds of observations and when you do them. We're thinking about ways to optimize the science from the mission. At worst, it may mean deferring some of the science that was planned to be done early on."

Manufacturing Flaw Feared

Jean Olivier, deputy project manager, said the cause of the latest problem aboard the troubled spacecraft was unknown. But he said engineers suspect that one of the two precisely ground mirrors was made with slightly wrong specifications.

"We don't know if it's on the primary or secondary mirror yet," he said, "but it looks like a textbook-perfect aberra-

DEFECT CRIPPLES SPACE TELESCOPE

Continued From Page A1

of the images for astronomers to examining, will not be useable, he said.

Operated in its wide-field mode, the camera is intended to survey vast areas of deep space. In its narrow-angle mode, it would make detailed pictures of nearby planets and other featuraes in the solar system.

Dr. Weiler said the problem would also affect the faint-object camera, an instrument built by the European Space Agency that is intended to focus on very dim objects, like extremely distant stars never before observed, and clumps of interstellar dust.

Nature of the Problem

"We're all frustrated, very obviously," Dr. Weiler said. But he added, "We can still do important and unique science" until the problems are solved.

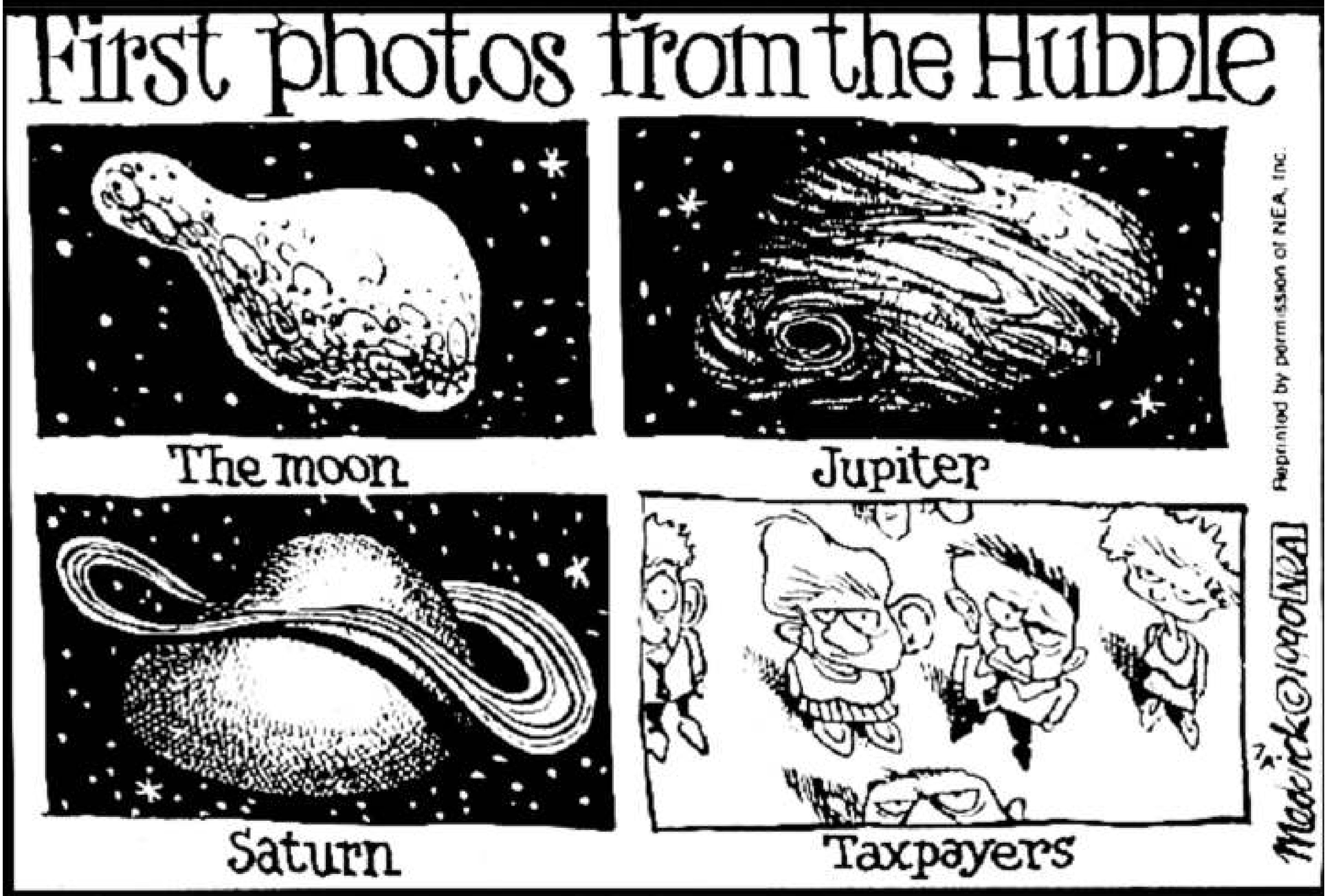
The distortion, called a spherical aberration, prevents the telescope from finely focusing the light it gathers. Because of this, engineers said, the instrument loses the ability to separate very close objects or to see very faint ones.

But Dr. Weiler said the problems do not affect experiments in the ultraviolet and infrared bands of the light spectrum. So even without much of its visible-light work, the telescope can be kept busy full time until problems are corrected, he said.

The Mirrors' History

"We are deferring some of the science," Dr. Weiler said. "We are not losing science."

Dr. Lennard Fisk, NASA associate director for space science, said the agency was forming a review board to investigate the matter.He said the



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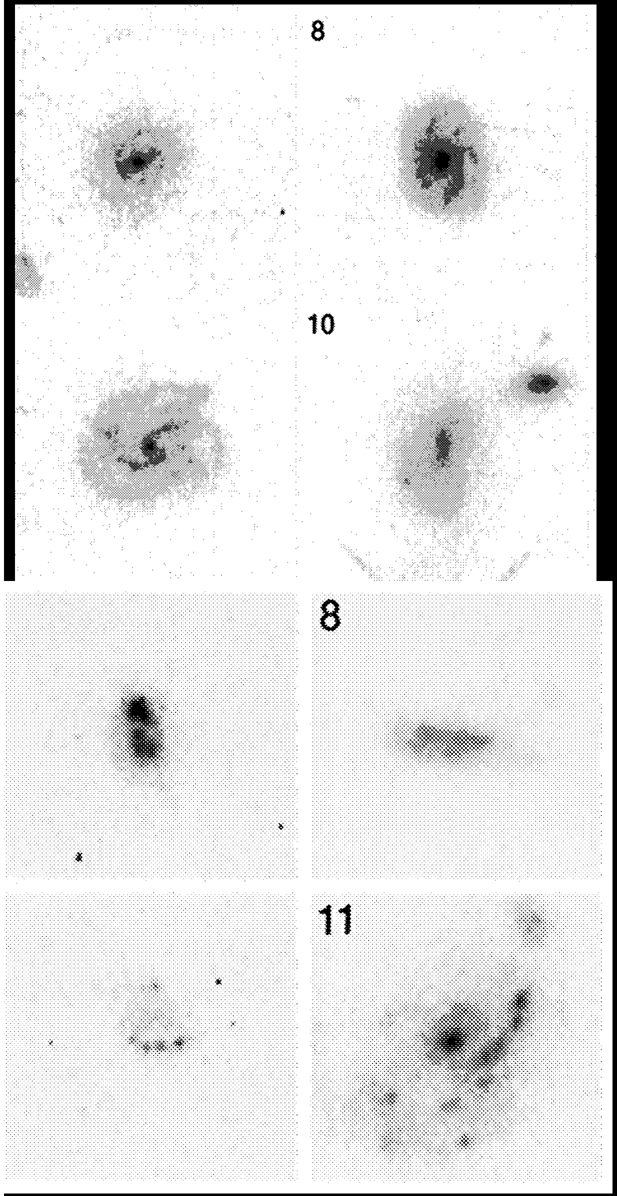
Medium Deep Survey

<z> ~ 0.5

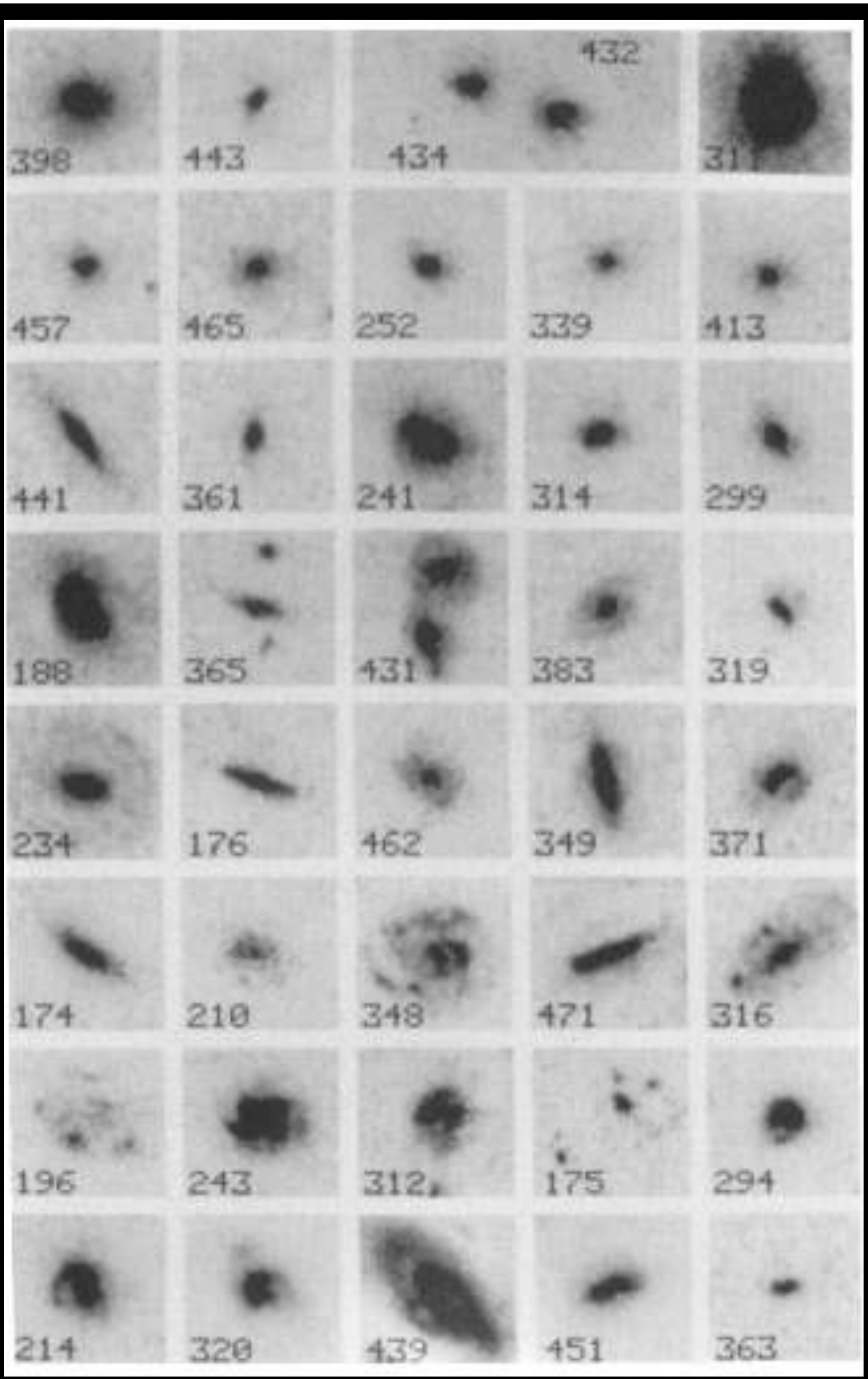


Griffiths, R. et al. 1994, ApJL, 435, L19

CL0939+4713

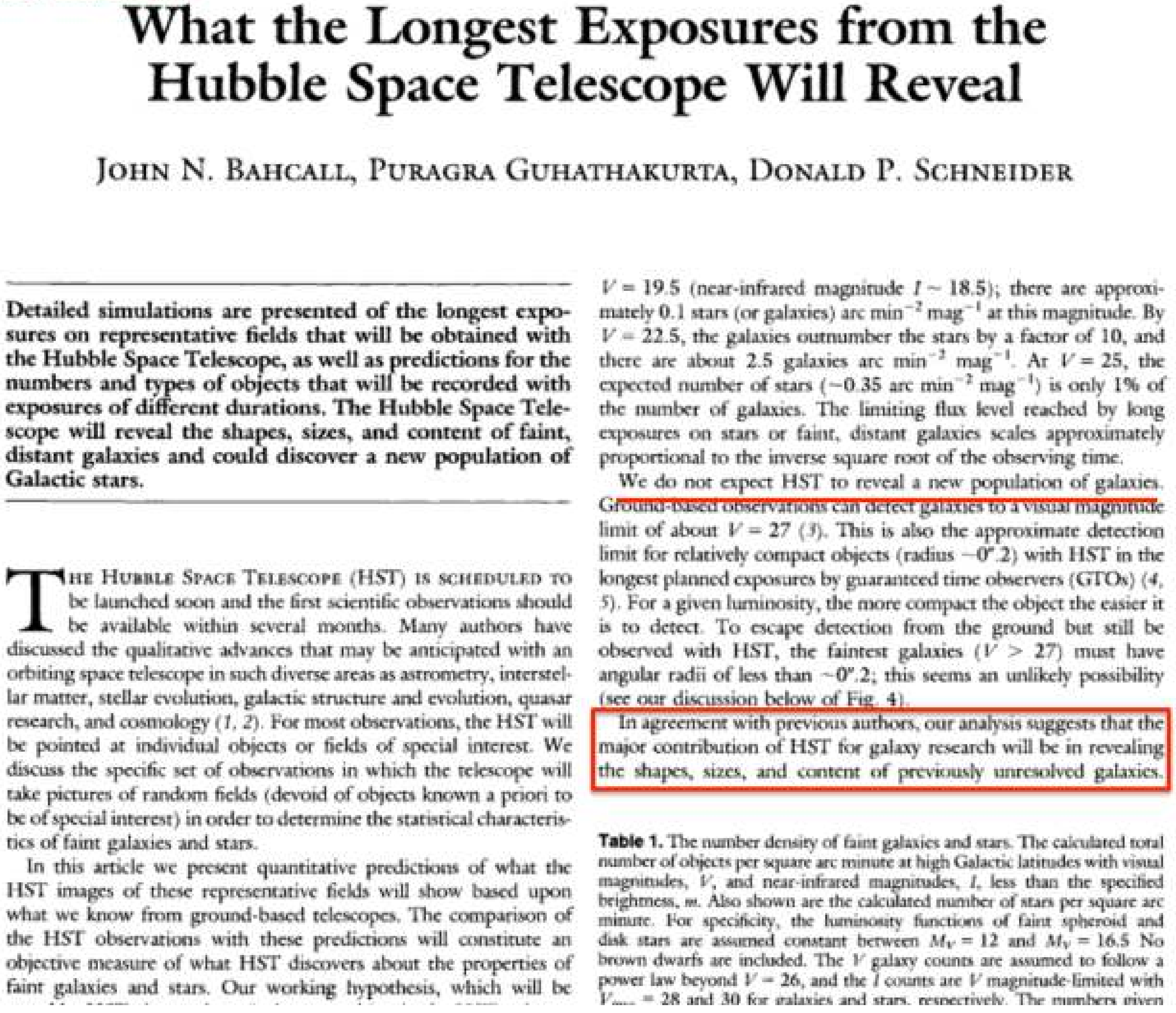
(z=0.41)

WFPC
+ Lucy-Richardson



Dressler, A. et al. 1994, ApJ, 430, 107

Science 1990, **248**, 178



What the Longest Exposures from the Hubble Space Telescope Will Reveal

John N. Bahcall, Puragra Guhathakurta, Donald P. Schneider

Detailed simulations are presented of the longest exposures on representative fields that will be obtained with the Hubble Space Telescope, as well as predictions for the numbers and types of objects that will be recorded with exposures of different durations. The Hubble Space Telescope will reveal the shapes, sizes, and content of faint, distant galaxies and could discover a new population of Galactic stars.

The Hubble Space Telescope (HST) is scheduled to be launched soon and the first scientific observations should be available within several months. Many authors have discussed the qualitative advances that may be anticipated with an orbiting space telescope in such diverse areas as astrometry, interstellar matter, stellar evolution, galactic structure and evolution, quasar research, and cosmology (*1, 2*). For most observations, the HST will be pointed at individual objects or fields of special interest. We discuss the specific set of observations in which the telescope will take pictures of random fields (devoid of objects known a priori to be of special interest) in order to determine the statistical characteristics of faint galaxies and stars.

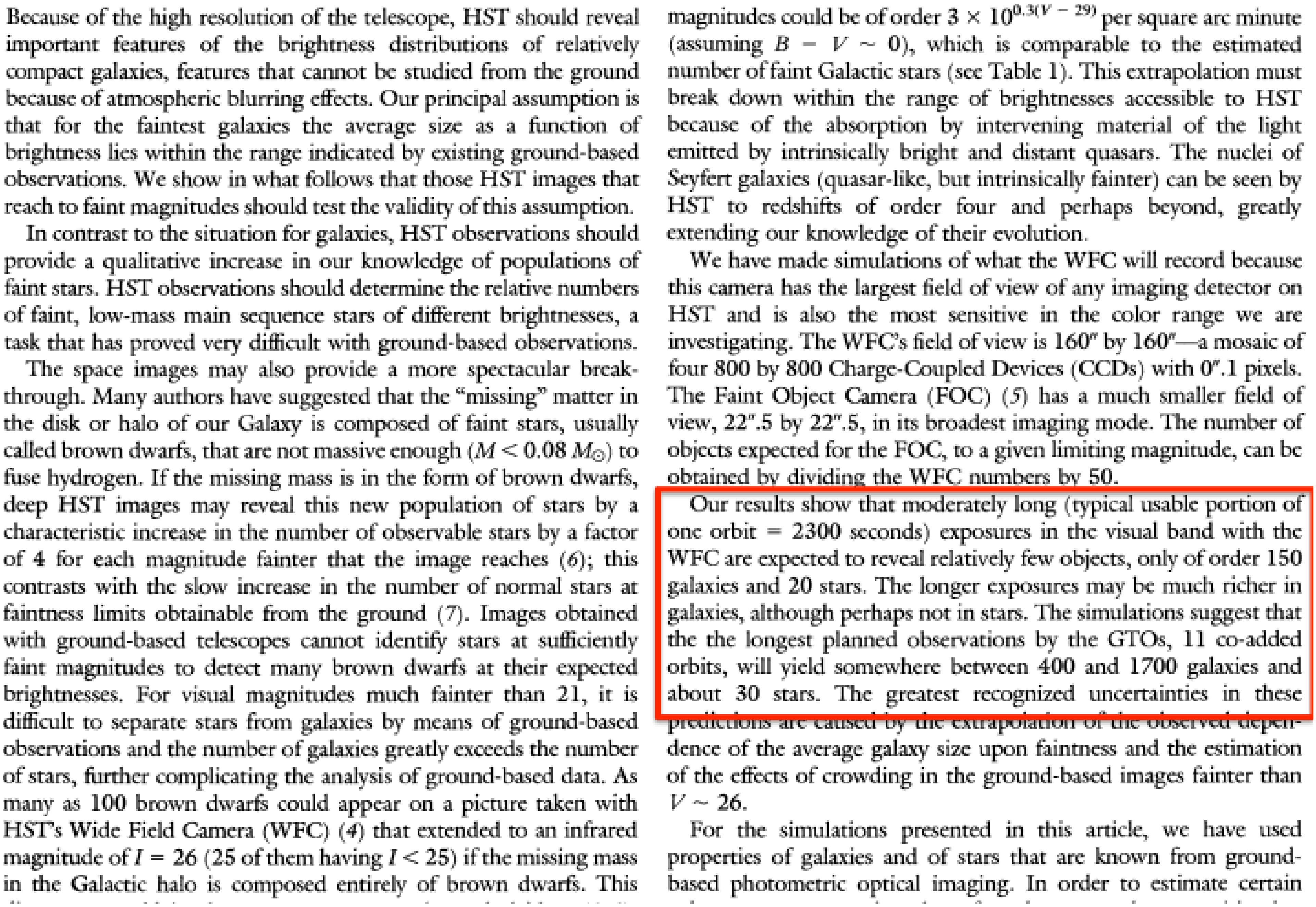
In this article we present quantitative predictions of what the HST images of these representative fields will show based upon what we know from ground-based telescopes. The comparison of the HST observations with these predictions will constitute an objective measure of what HST discovers about the properties of faint galaxies and stars. Our working hypothesis, which will be

V = 19.5 (near-infrared magnitude $I \sim 18.5$); there are approximately 0.1 stars (or galaxies) arc min^{-2} mag^{-1} at this magnitude. By V = 22.5, the galaxies outnumber the stars by a factor of 10, and there are about 2.5 galaxies arc min^{-2} mag^{-1}. At V = 25, the expected number of stars (~0.35 arc min^{-2} mag^{-1}) is only 1% of the number of galaxies. The limiting flux level reached by long exposures on stars or faint, distant galaxies scales approximately proportional to the inverse square root of the observing time.

We do not expect HST to reveal a new population of galaxies. Ground-based observations can detect galaxies to a visual magnitude limit of about V = 27 (*3*). This is also the approximate detection limit for relatively compact objects (radius ~0″.2) with HST in the longest planned exposures by guaranteed time observers (GTOs) (*4, 5*). For a given luminosity, the more compact the object the easier it is to detect. To escape detection from the ground but still be observed with HST, the faintest galaxies ($V > 27$) must have angular radii of less than ~0″.2; this seems an unlikely possibility (see our discussion below of Fig. 4).

In agreement with previous authors, our analysis suggests that the major contribution of HST for galaxy research will be in revealing the shapes, sizes, and content of previously unresolved galaxies.

Table 1. The number density of faint galaxies and stars. The calculated total number of objects per square arc minute at high Galactic latitudes with visual magnitudes, V, and near-infrared magnitudes, I, less than the specified brightness, m. Also shown are the calculated number of stars per square arc minute. For specificity, the luminosity functions of faint spheroid and disk stars are assumed constant between $M_V = 12$ and $M_V = 16.5$ No brown dwarfs are included. The V galaxy counts are assumed to follow a power law beyond V = 26, and the I counts are V magnitude-limited with V_{max} = 28 and 30 for galaxies and stars, respectively. The numbers given



Because of the high resolution of the telescope, HST should reveal important features of the brightness distributions of relatively compact galaxies, features that cannot be studied from the ground because of atmospheric blurring effects. Our principal assumption is that for the faintest galaxies the average size as a function of brightness lies within the range indicated by existing ground-based observations. We show in what follows that those HST images that reach to faint magnitudes should test the validity of this assumption.

In contrast to the situation for galaxies, HST observations should provide a qualitative increase in our knowledge of populations of faint stars. HST observations should determine the relative numbers of faint, low-mass main sequence stars of different brightnesses, a task that has proved very difficult with ground-based observations.

The space images may also provide a more spectacular breakthrough. Many authors have suggested that the "missing" matter in the disk or halo of our Galaxy is composed of faint stars, usually called brown dwarfs, that are not massive enough ($M < 0.08\ M_\odot$) to fuse hydrogen. If the missing mass is in the form of brown dwarfs, deep HST images may reveal this new population of stars by a characteristic increase in the number of observable stars by a factor of 4 for each magnitude fainter that the image reaches (*6*); this contrasts with the slow increase in the number of normal stars at faintness limits obtainable from the ground (*7*). Images obtained with ground-based telescopes cannot identify stars at sufficiently faint magnitudes to detect many brown dwarfs at their expected brightnesses. For visual magnitudes much fainter than 21, it is difficult to separate stars from galaxies by means of ground-based observations and the number of galaxies greatly exceeds the number of stars, further complicating the analysis of ground-based data. As many as 100 brown dwarfs could appear on a picture taken with HST's Wide Field Camera (WFC) (*4*) that extended to an infrared magnitude of $I = 26$ (25 of them having $I < 25$) if the missing mass in the Galactic halo is composed entirely of brown dwarfs. This

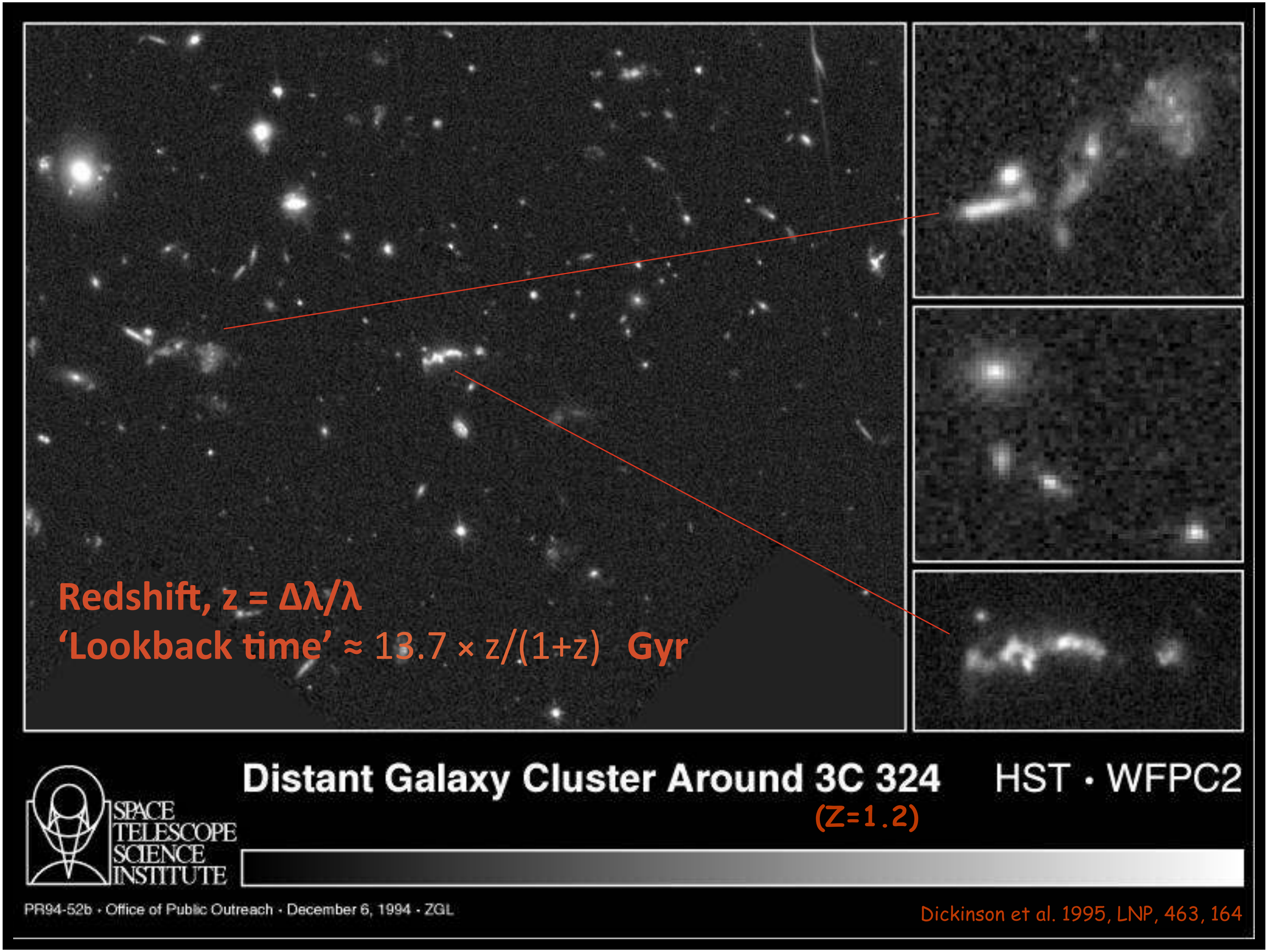
magnitudes could be of order $3 \times 10^{0.3(V - 29)}$ per square arc minute (assuming $B - V \sim 0$), which is comparable to the estimated number of faint Galactic stars (see Table 1). This extrapolation must break down within the range of brightnesses accessible to HST because of the absorption by intervening material of the light emitted by intrinsically bright and distant quasars. The nuclei of Seyfert galaxies (quasar-like, but intrinsically fainter) can be seen by HST to redshifts of order four and perhaps beyond, greatly extending our knowledge of their evolution.

We have made simulations of what the WFC will record because this camera has the largest field of view of any imaging detector on HST and is also the most sensitive in the color range we are investigating. The WFC's field of view is 160″ by 160″—a mosaic of four 800 by 800 Charge-Coupled Devices (CCDs) with 0″.1 pixels. The Faint Object Camera (FOC) (*5*) has a much smaller field of view, 22″.5 by 22″.5, in its broadest imaging mode. The number of objects expected for the FOC, to a given limiting magnitude, can be obtained by dividing the WFC numbers by 50.

Our results show that moderately long (typical usable portion of one orbit = 2300 seconds) exposures in the visual band with the WFC are expected to reveal relatively few objects, only of order 150 galaxies and 20 stars. The longer exposures may be much richer in galaxies, although perhaps not in stars. The simulations suggest that the the longest planned observations by the GTOs, 11 co-added orbits, will yield somewhere between 400 and 1700 galaxies and about 30 stars. The greatest recognized uncertainties in these predictions are caused by the extrapolation of the observed dependence of the average galaxy size upon faintness and the estimation of the effects of crowding in the ground-based images fainter than $V \sim 26$.

For the simulations presented in this article, we have used properties of galaxies and of stars that are known from ground-based photometric optical imaging. In order to estimate certain

Bahcall et al. 1990, *Science*, **248**, 178



Redshift, $z = \Delta\lambda/\lambda$

'Lookback time' $\approx 13.7 \times z/(1+z)$ **Gyr**

Distant Galaxy Cluster Around 3C 324 HST • WFPC2

(Z=1.2)

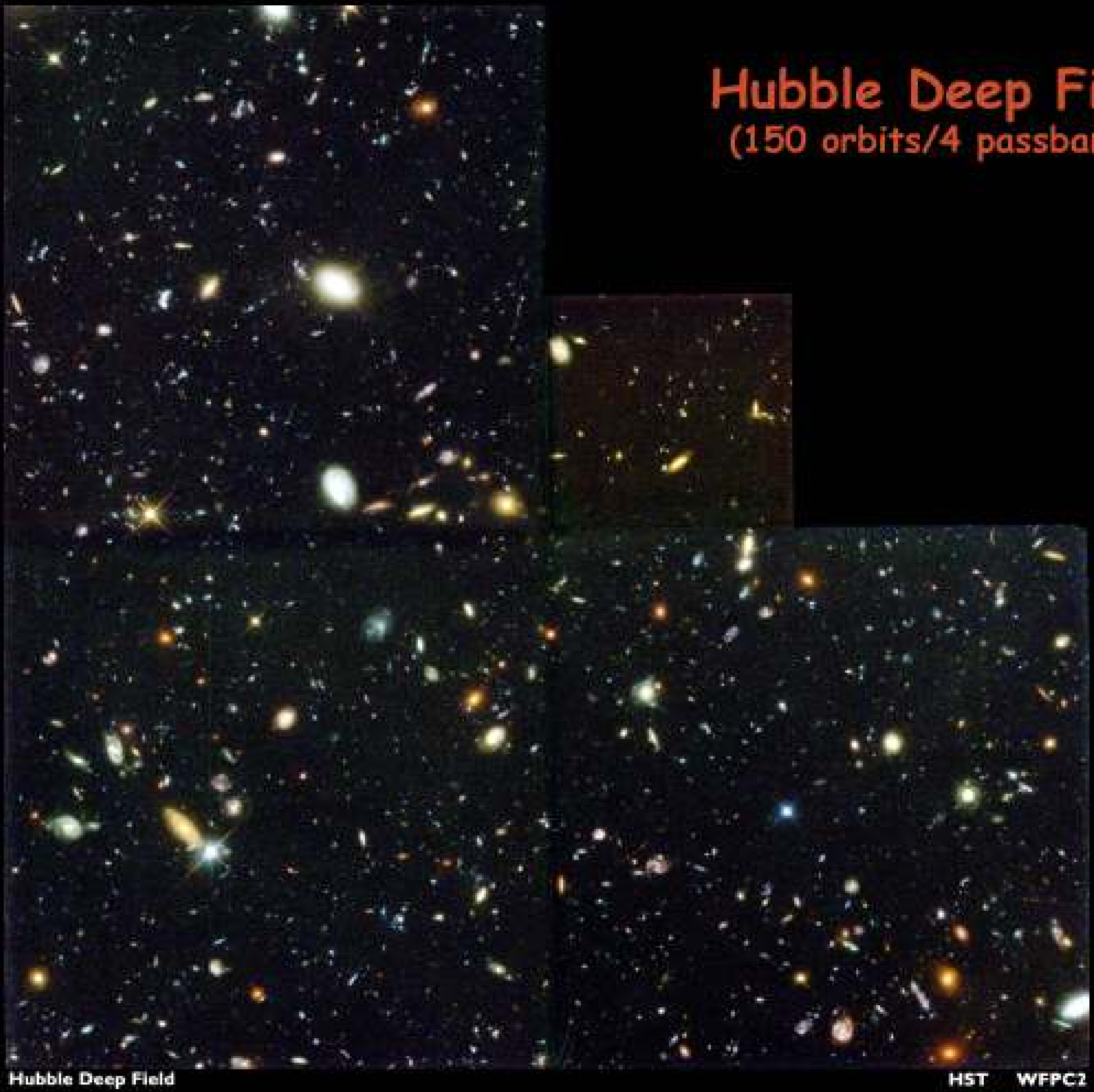
PR94-52b • Office of Public Outreach • December 6, 1994 • ZGL

Dickinson et al. 1995, LNP, 463, 164

Nov 1995

Hubble Deep Field

(150 orbits/4 passbands)



RW+. 1996, AJ, 112, 1335

Hubble Deep Field

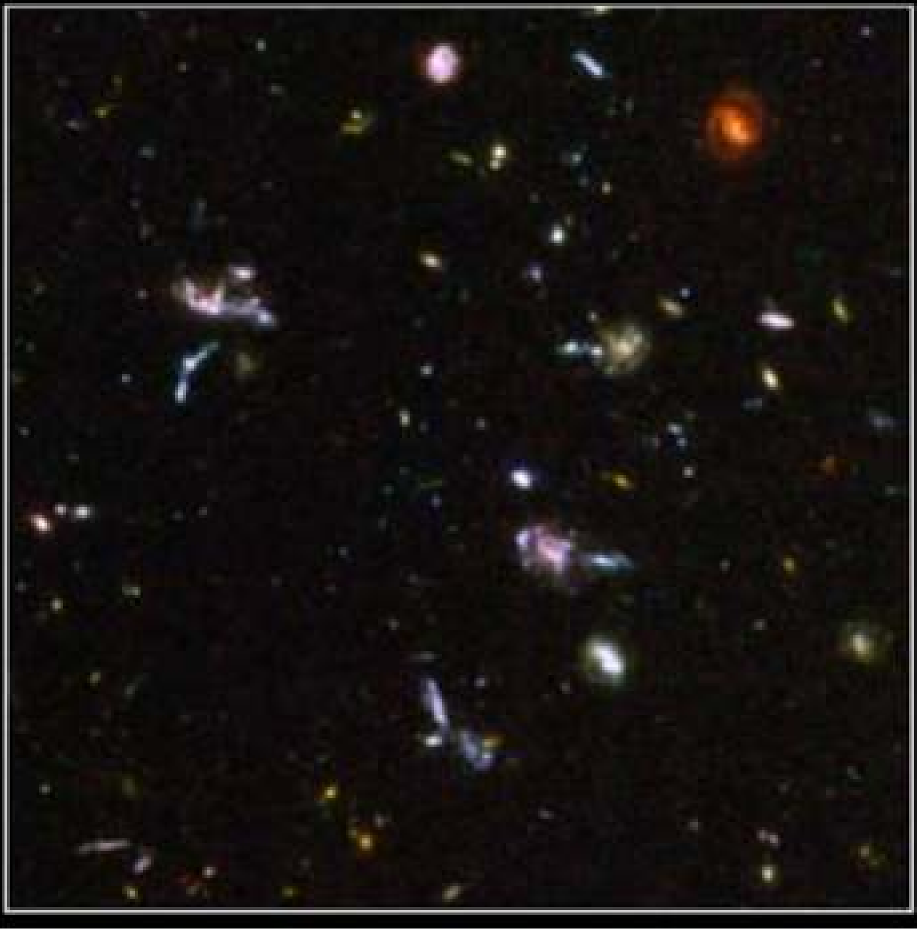
Image: HST WFPC2

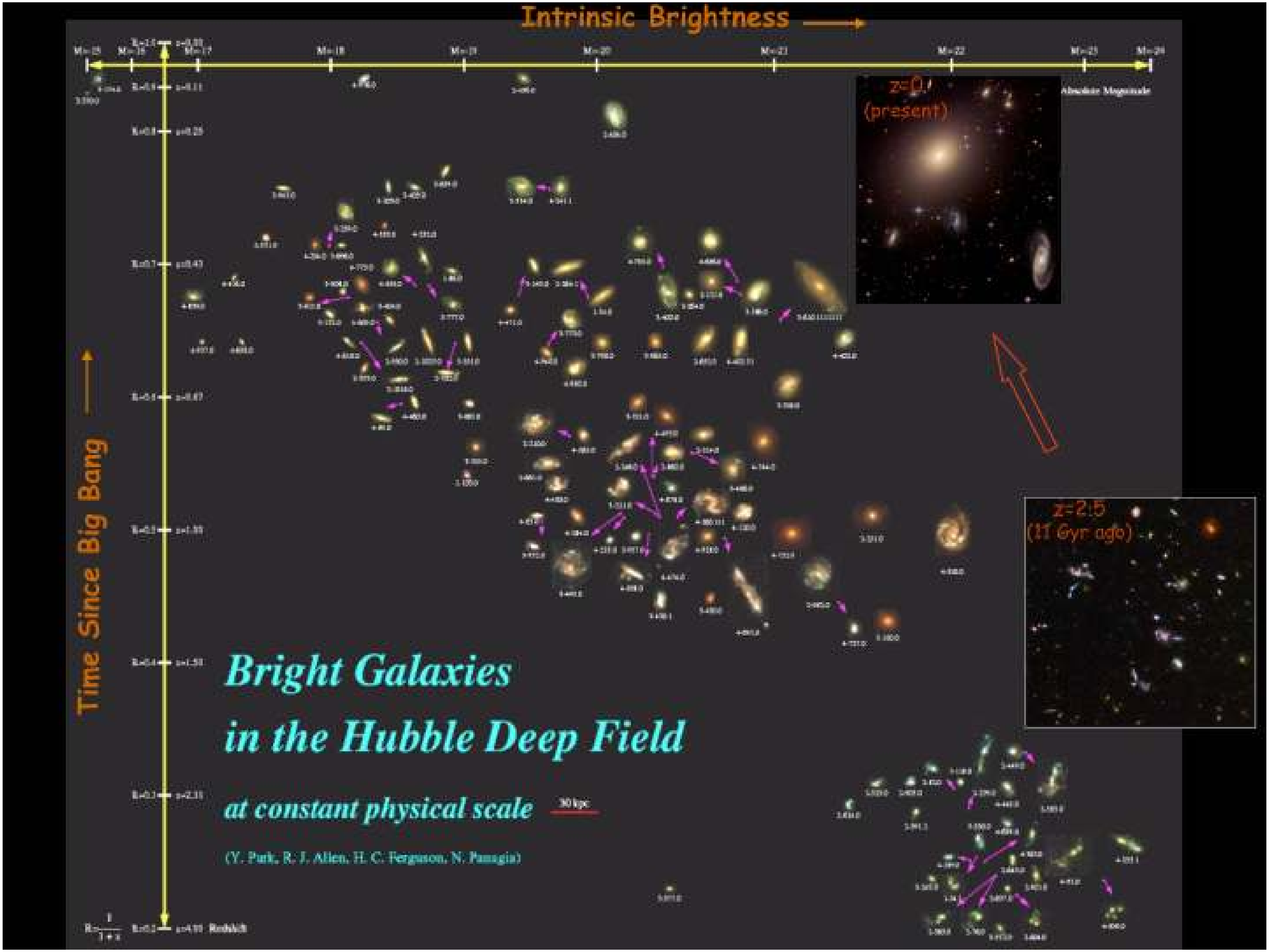
Redshifts: Keck 10m LRIS

Redshifts compiled by M. Dickinson and Z. Levay (ST ScI)

Nearby Galaxies
(Present epoch)

Distant Galaxies
(11 Gyr ago)



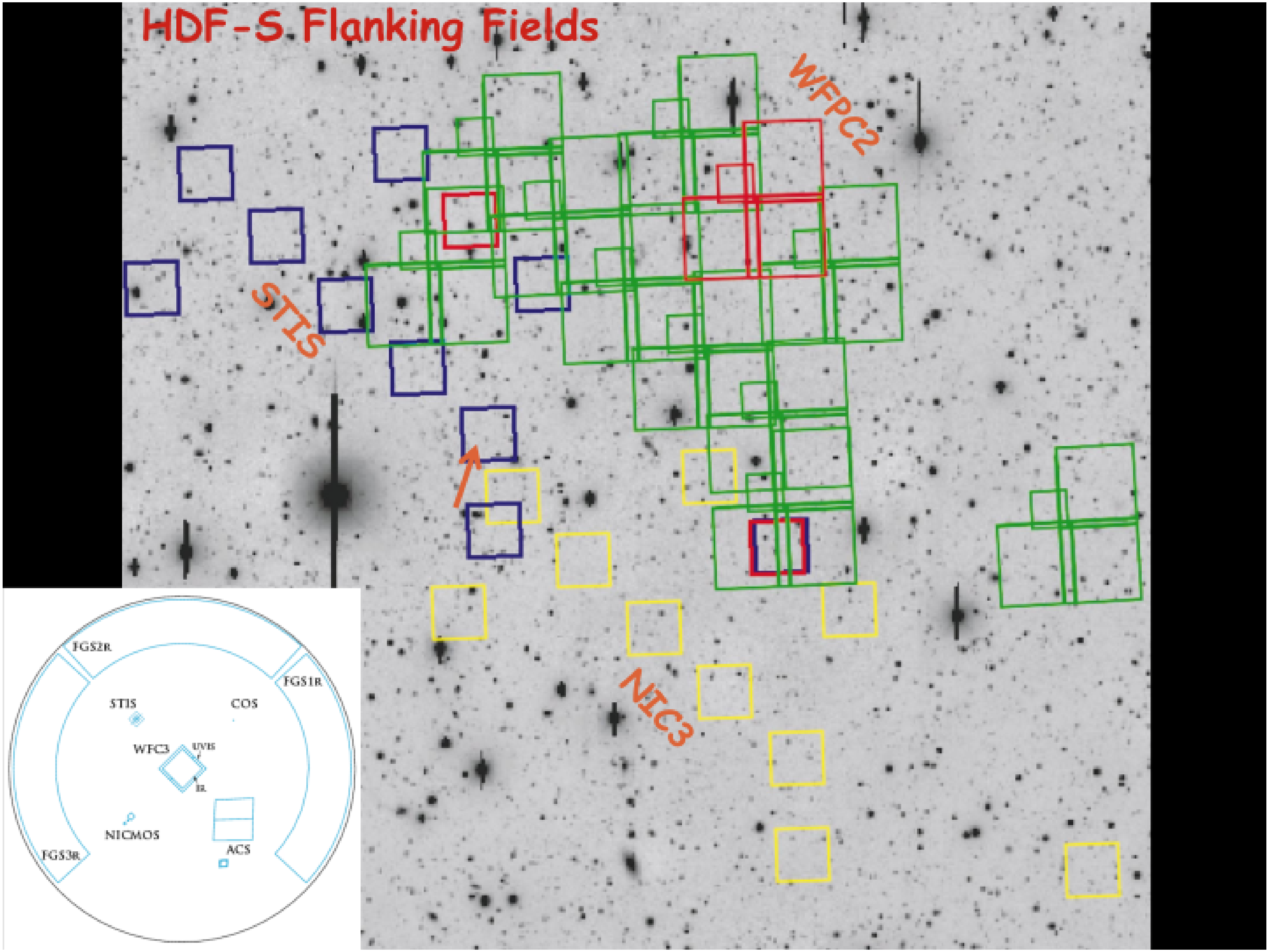


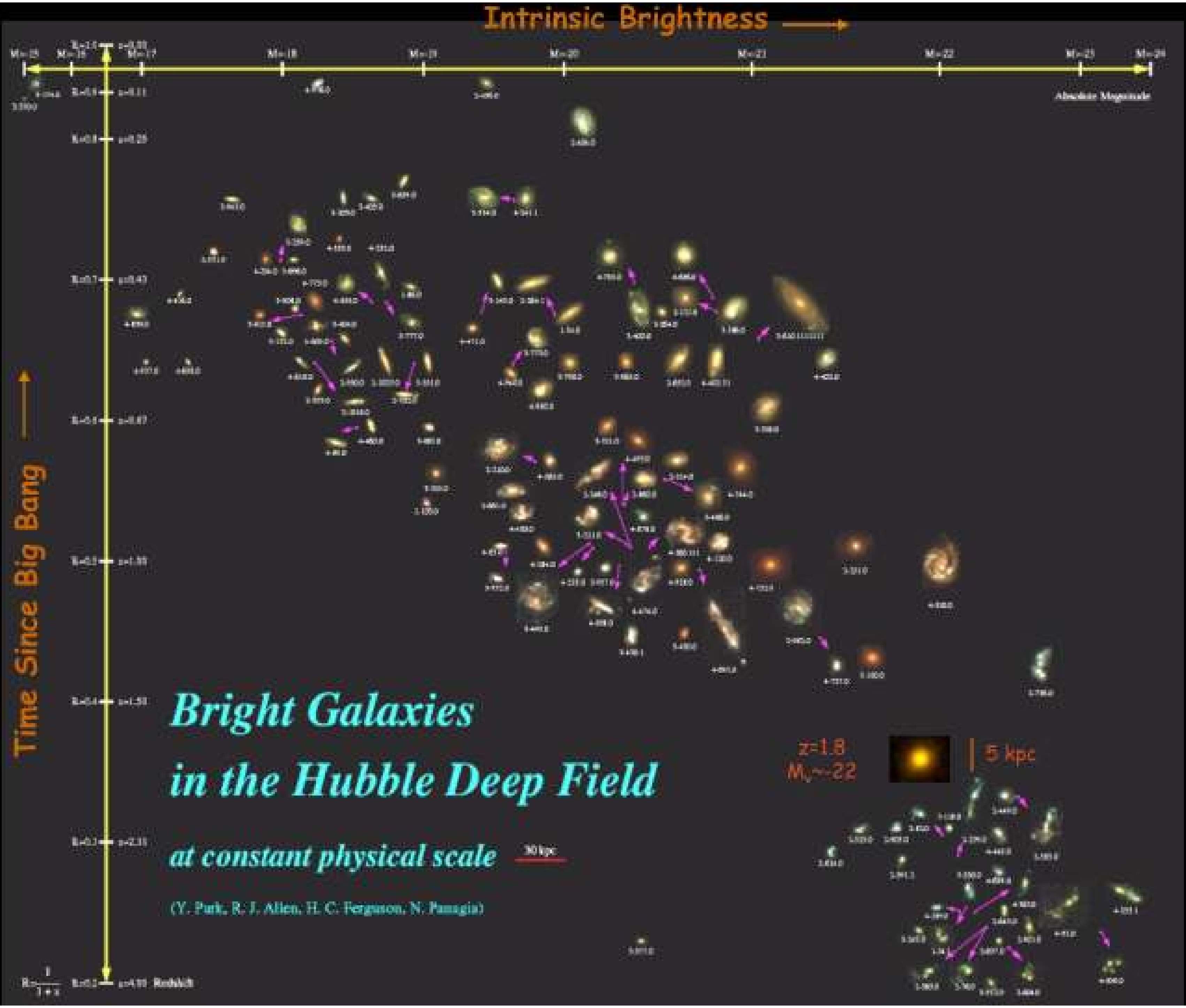
Bright Galaxies in the Hubble Deep Field

at constant physical scale

(Y. Park, R. J. Allen, H. C. Ferguson, N. Panagia)

HDF-S Flanking Fields



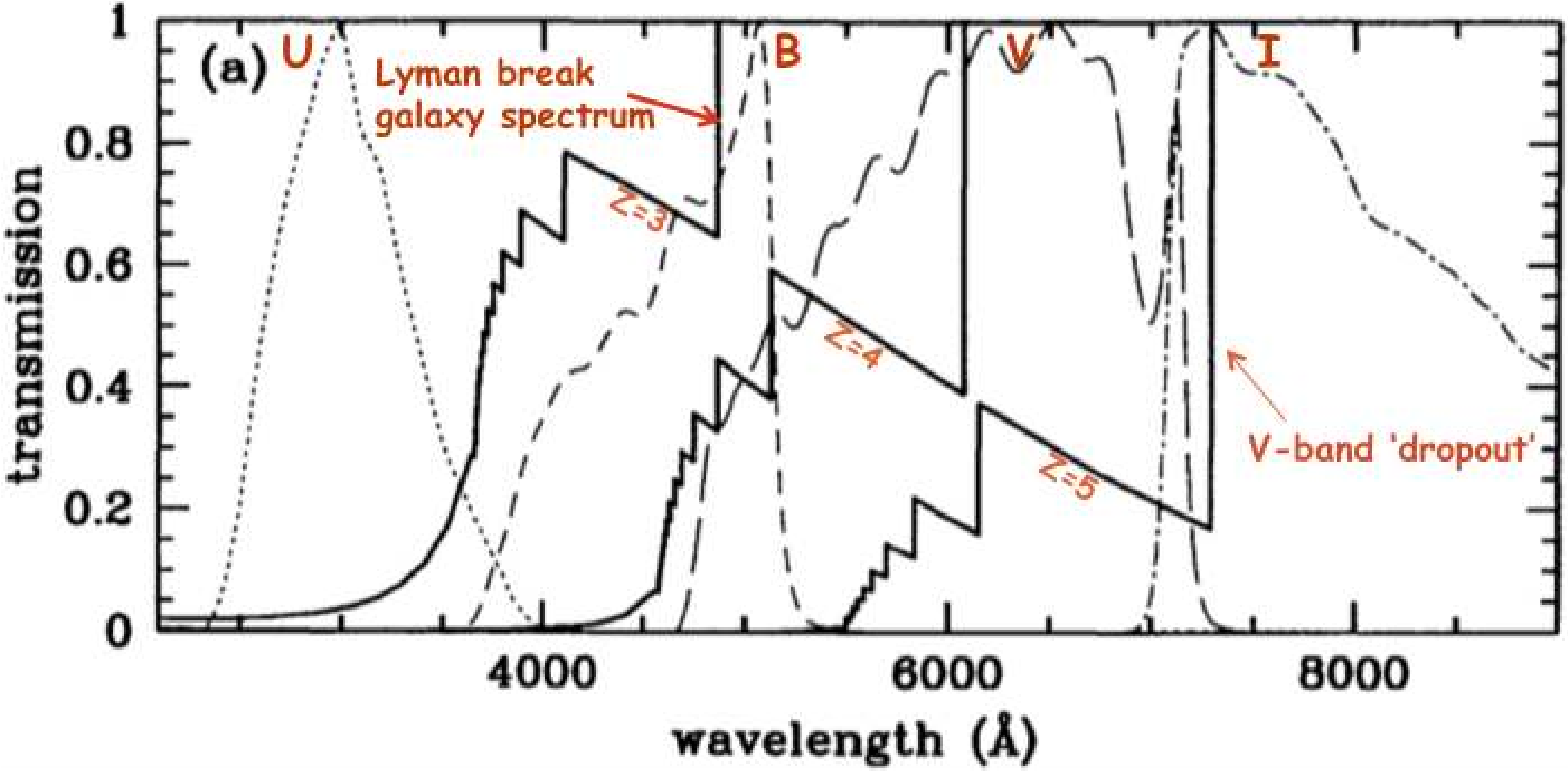


Bright Galaxies in the Hubble Deep Field

at constant physical scale

(Y. Park, R. J. Allen, H. C. Ferguson, N. Panagia)

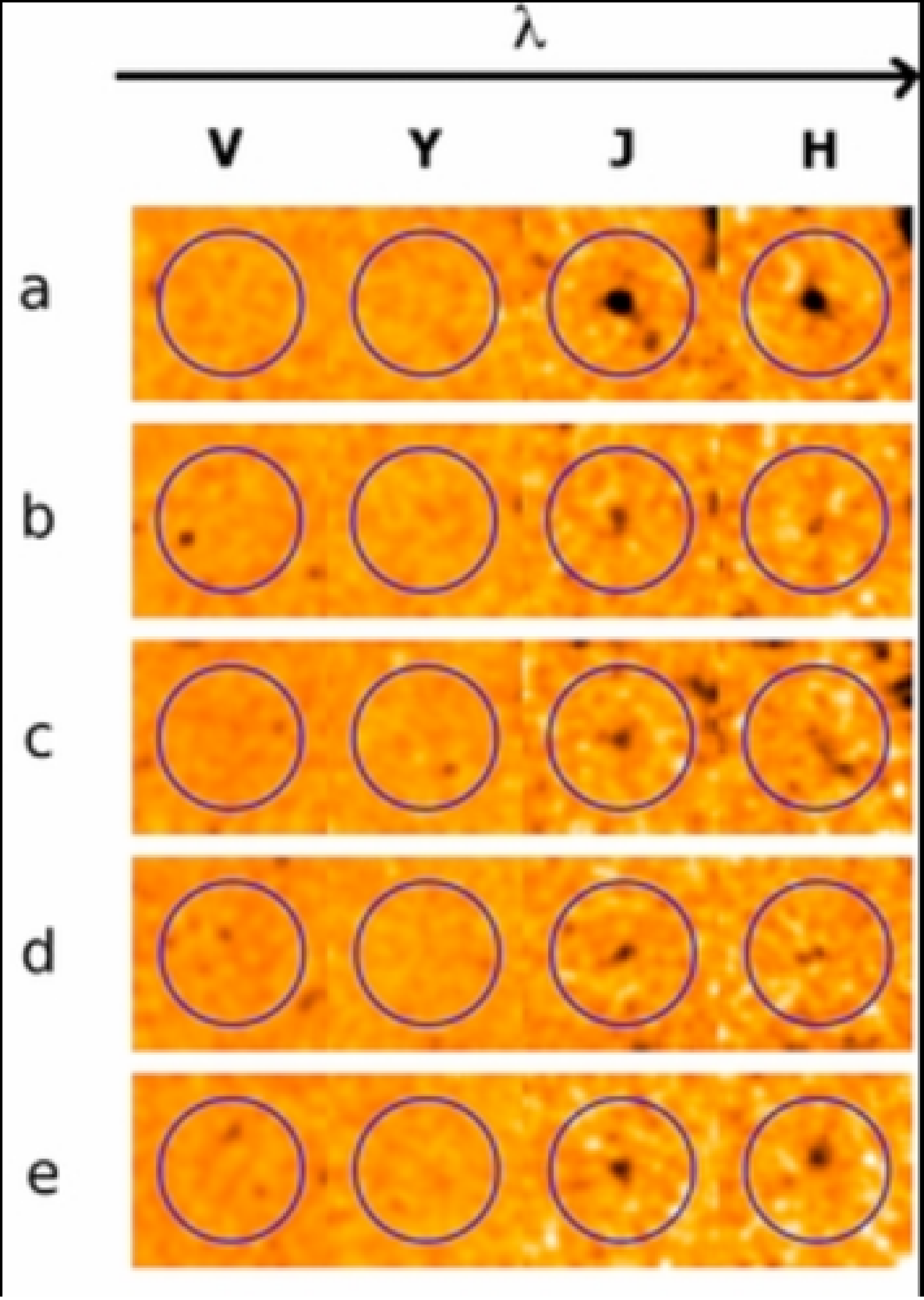
Galaxy Transmission Through 4 HDF Passbands



Madau et al. 1996, MNRAS, 283, 1388

Nov 1995

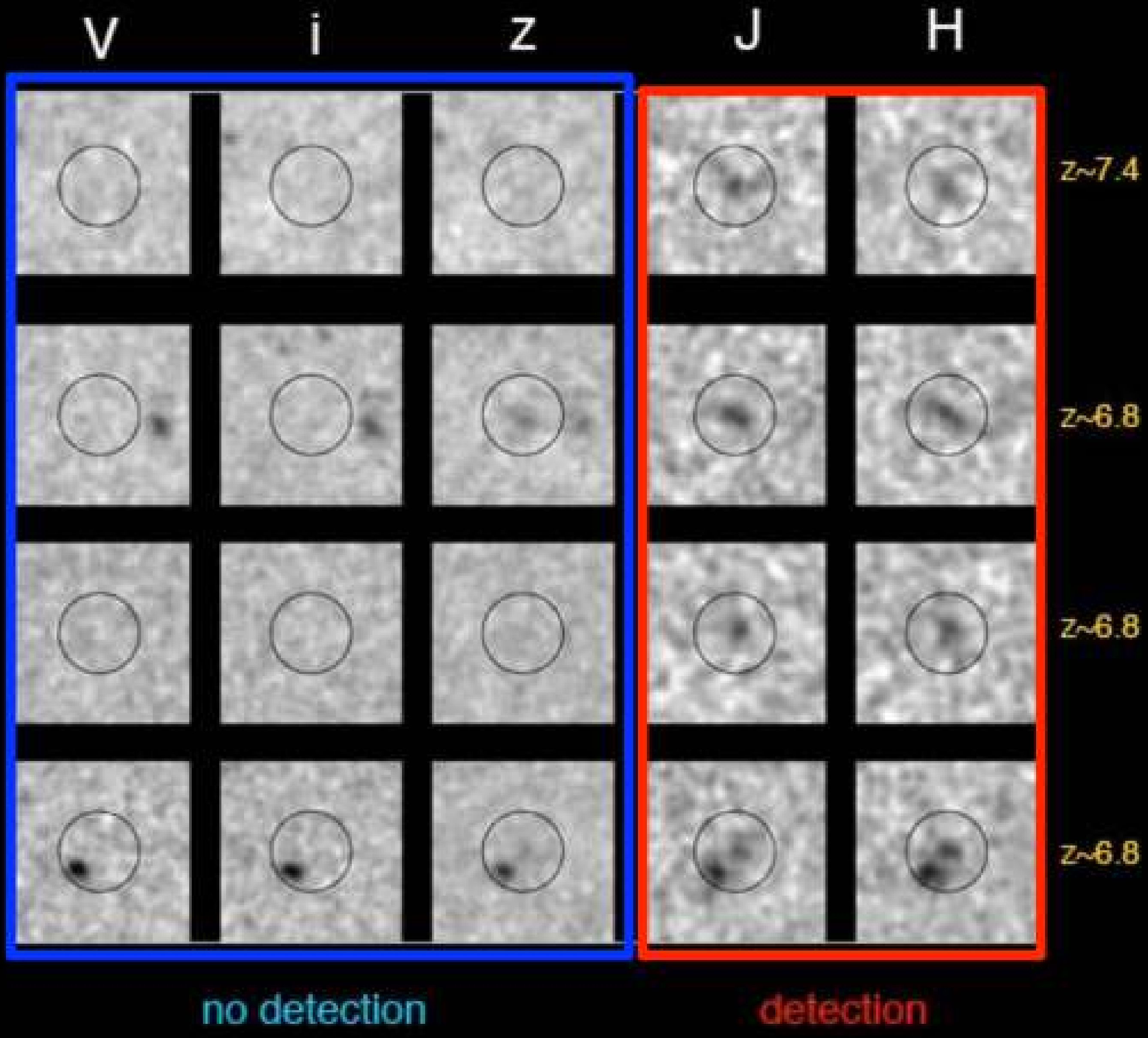
IR Dropouts (BoRG Survey)



(Z~8 candidates)

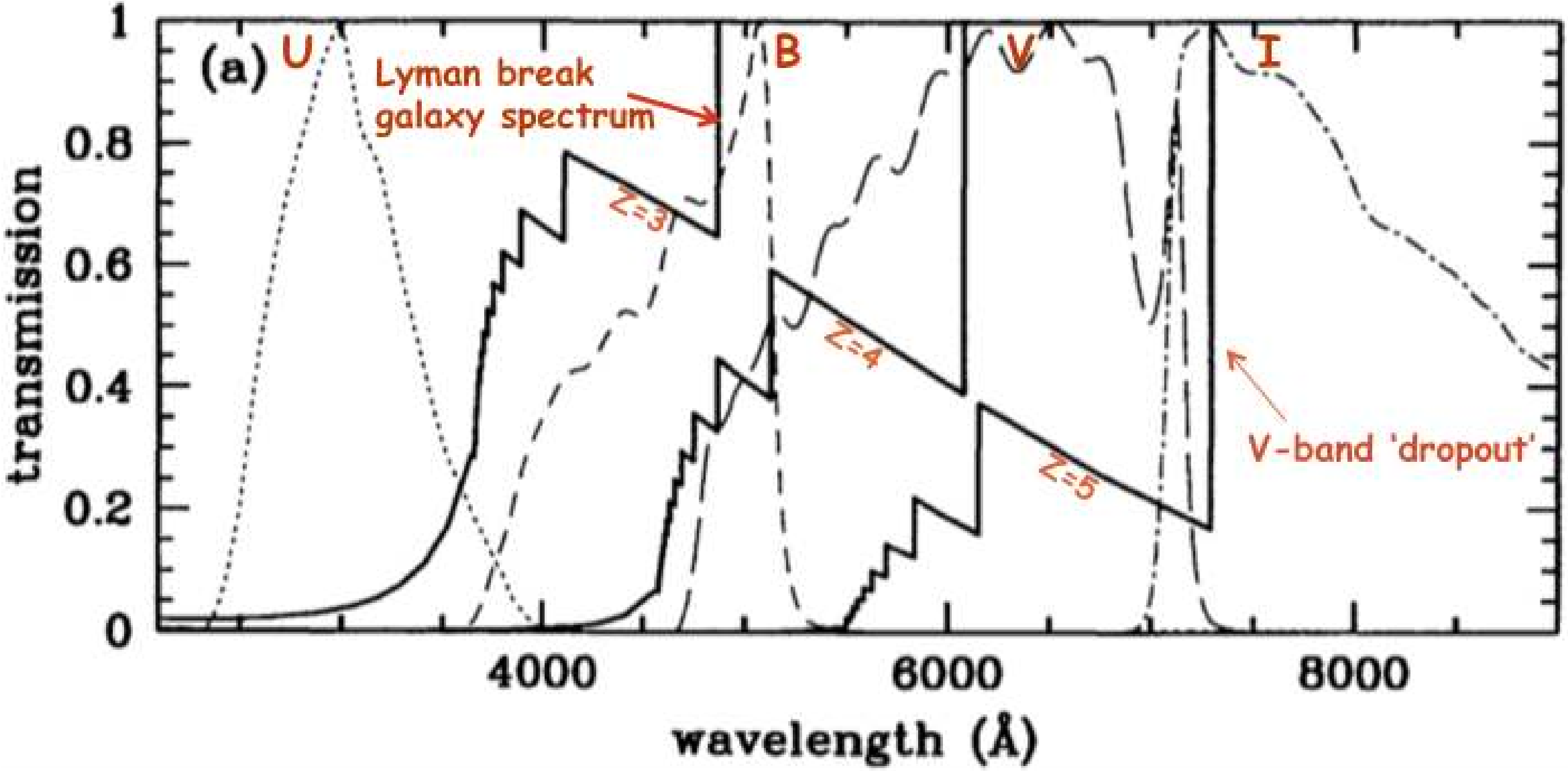
Trenti et al. 2012, ApJ, 746, 55

XDF Galaxy Dropouts



Bouwens & Illingworth, 2006, Nature, 443, 189

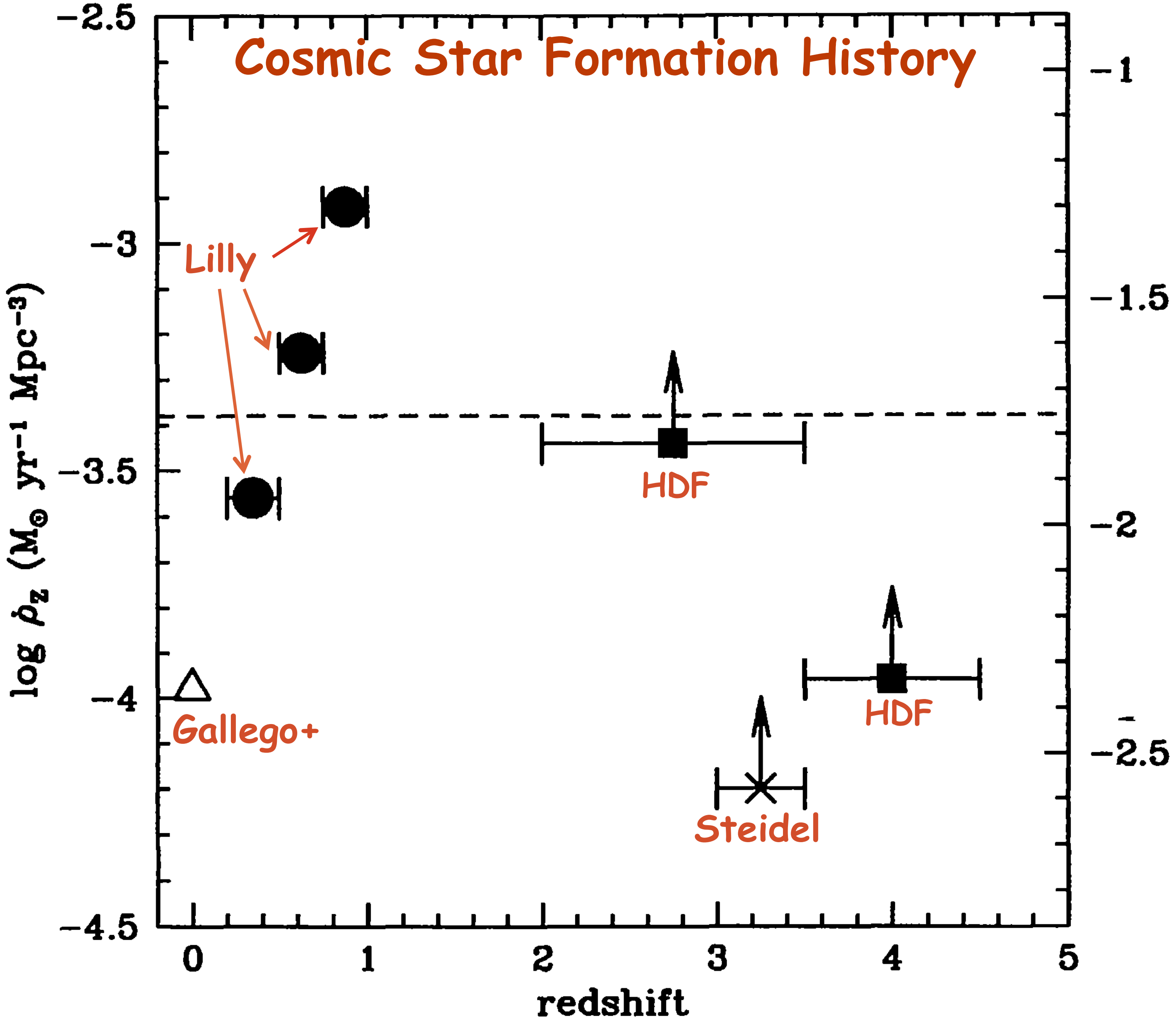
Galaxy Transmission Through 4 HDF Passbands



Madau et al. 1996, MNRAS, 283, 1388

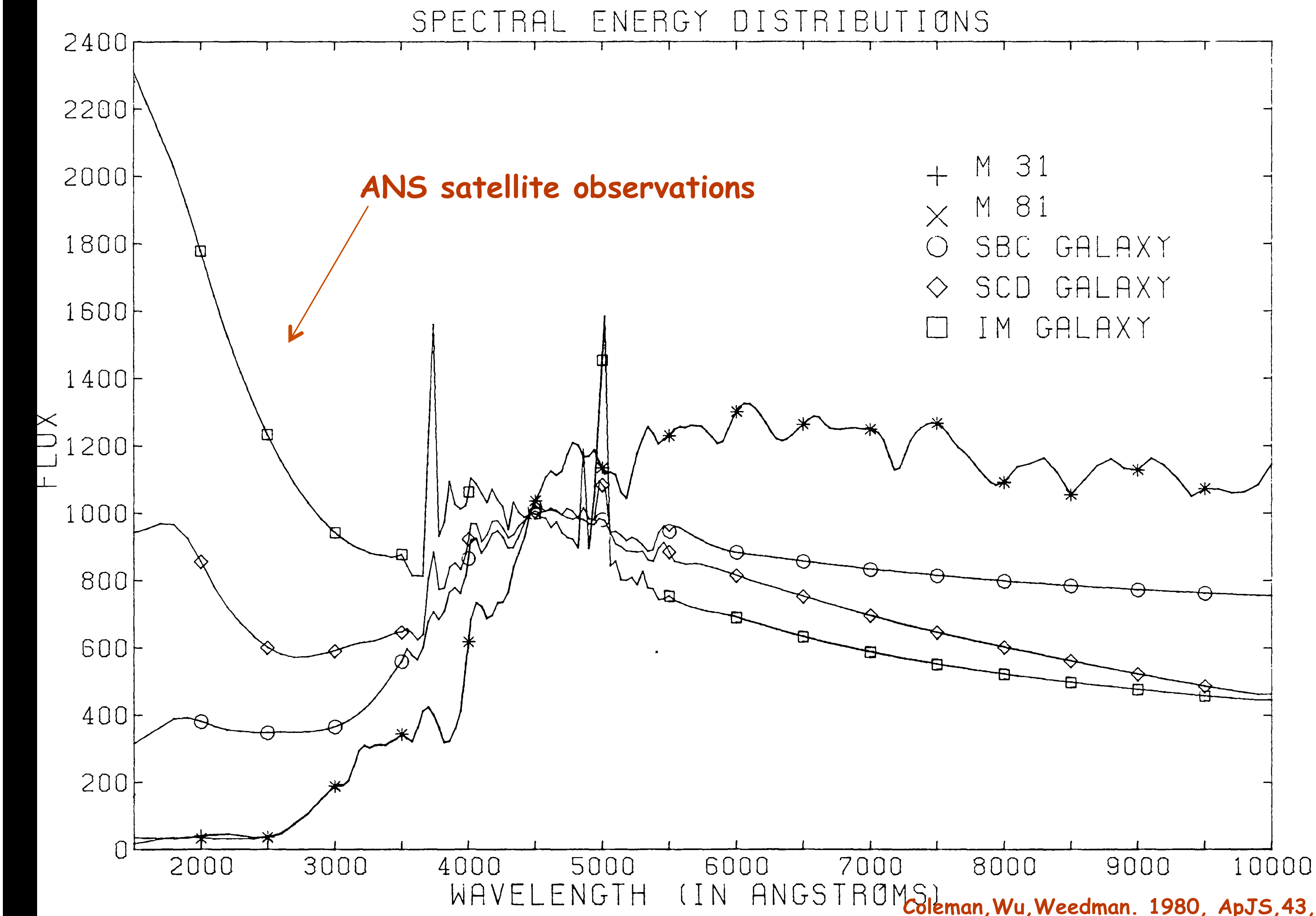
Nov 1995

Cosmic Star Formation History



Madau, P. et al. 1996, MNRAS, 283, 1388

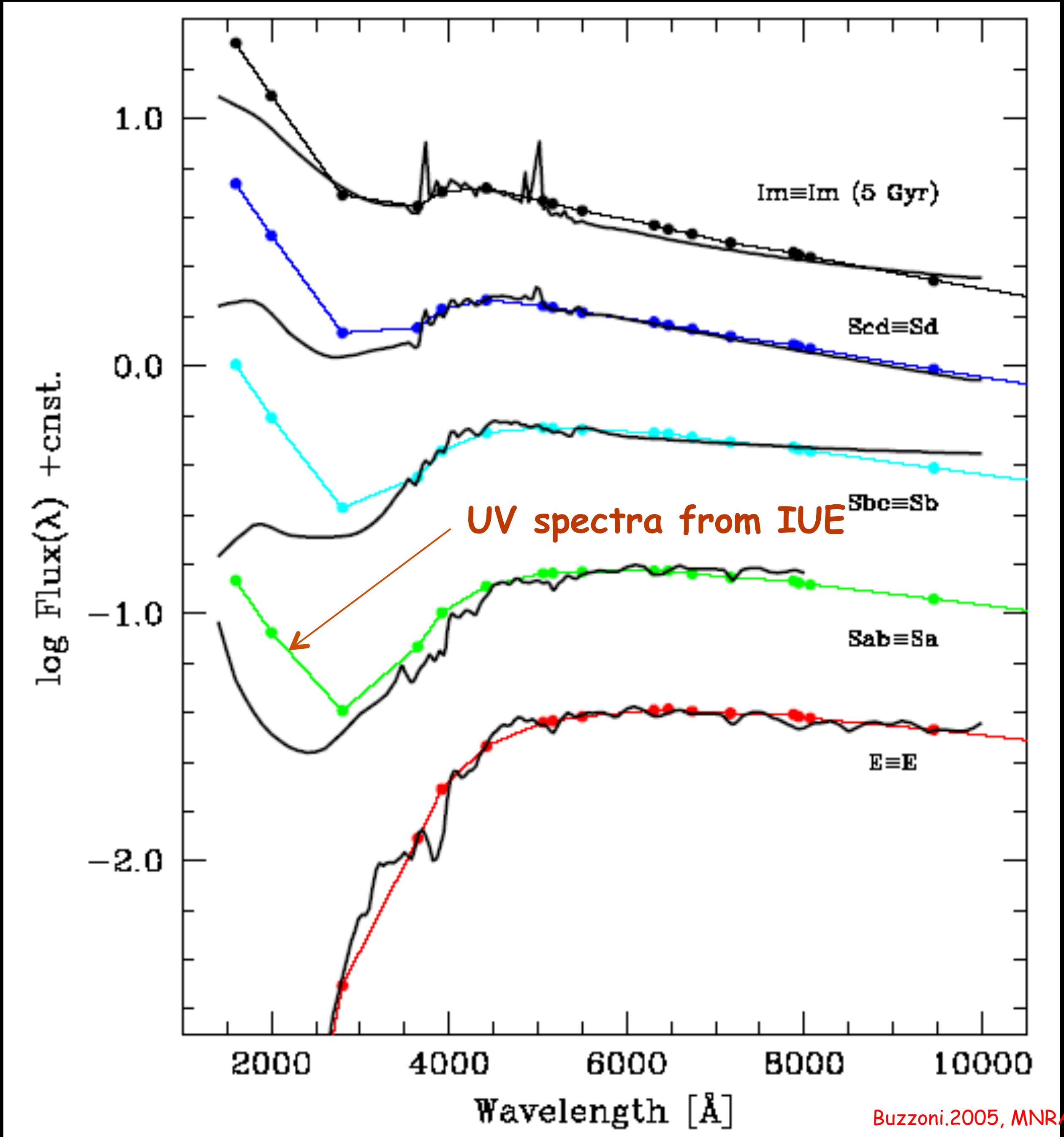
Observed Template Galaxy Spectra



ANS satellite observations

Coleman, Wu, Weedman. 1980, ApJS, 43, 393

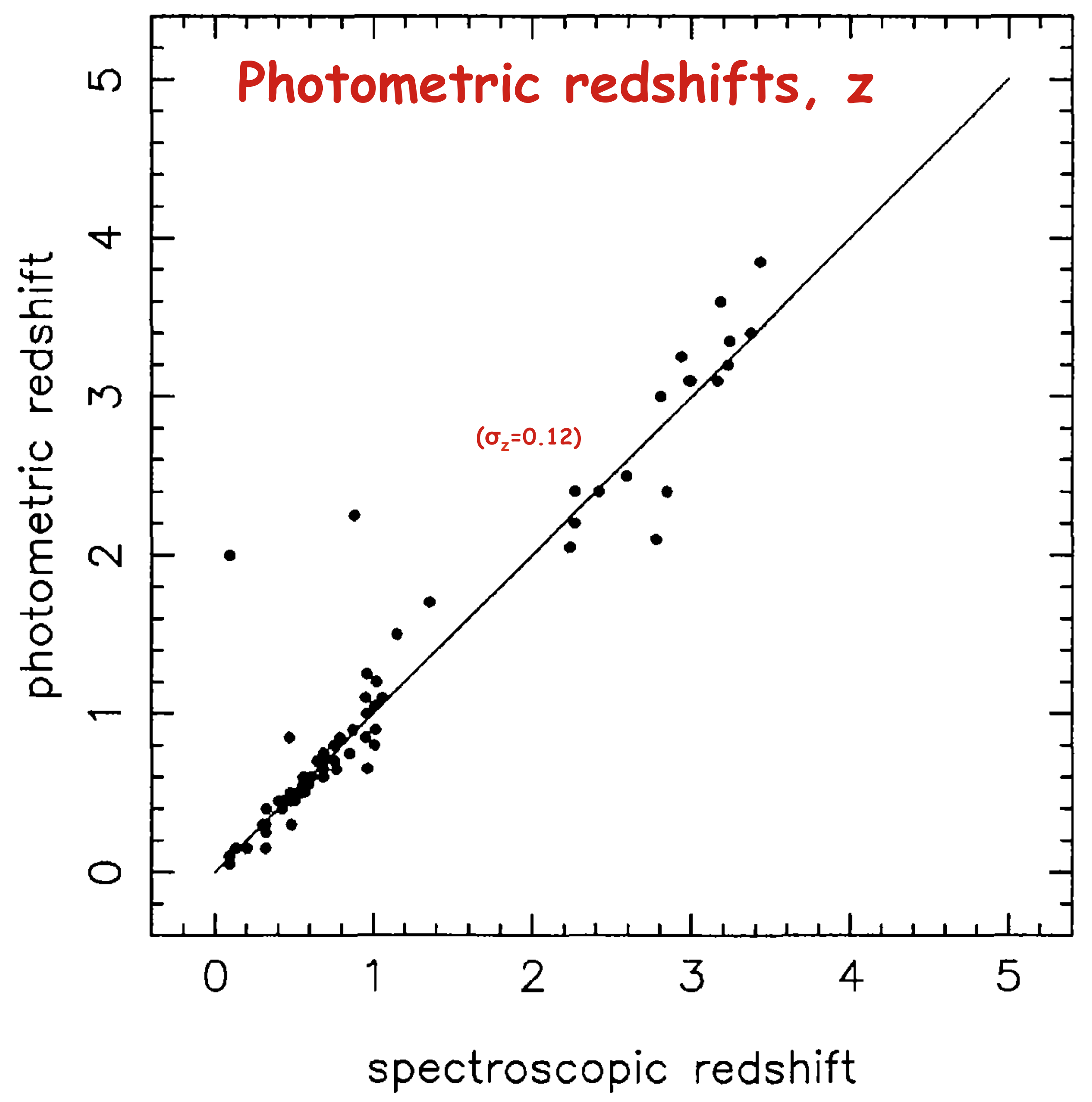
Galaxy Spectral Templates



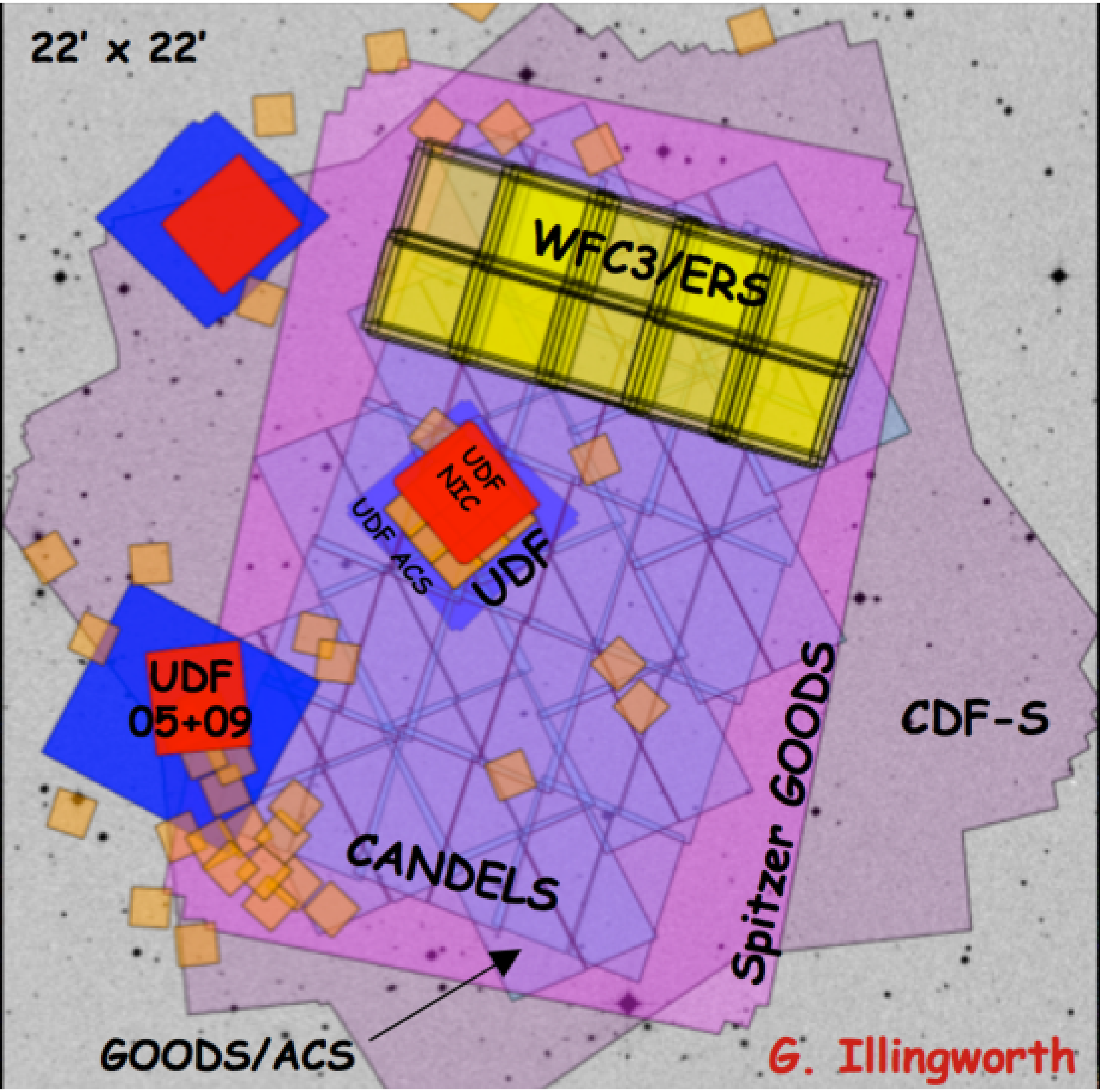
UV spectra from IUE

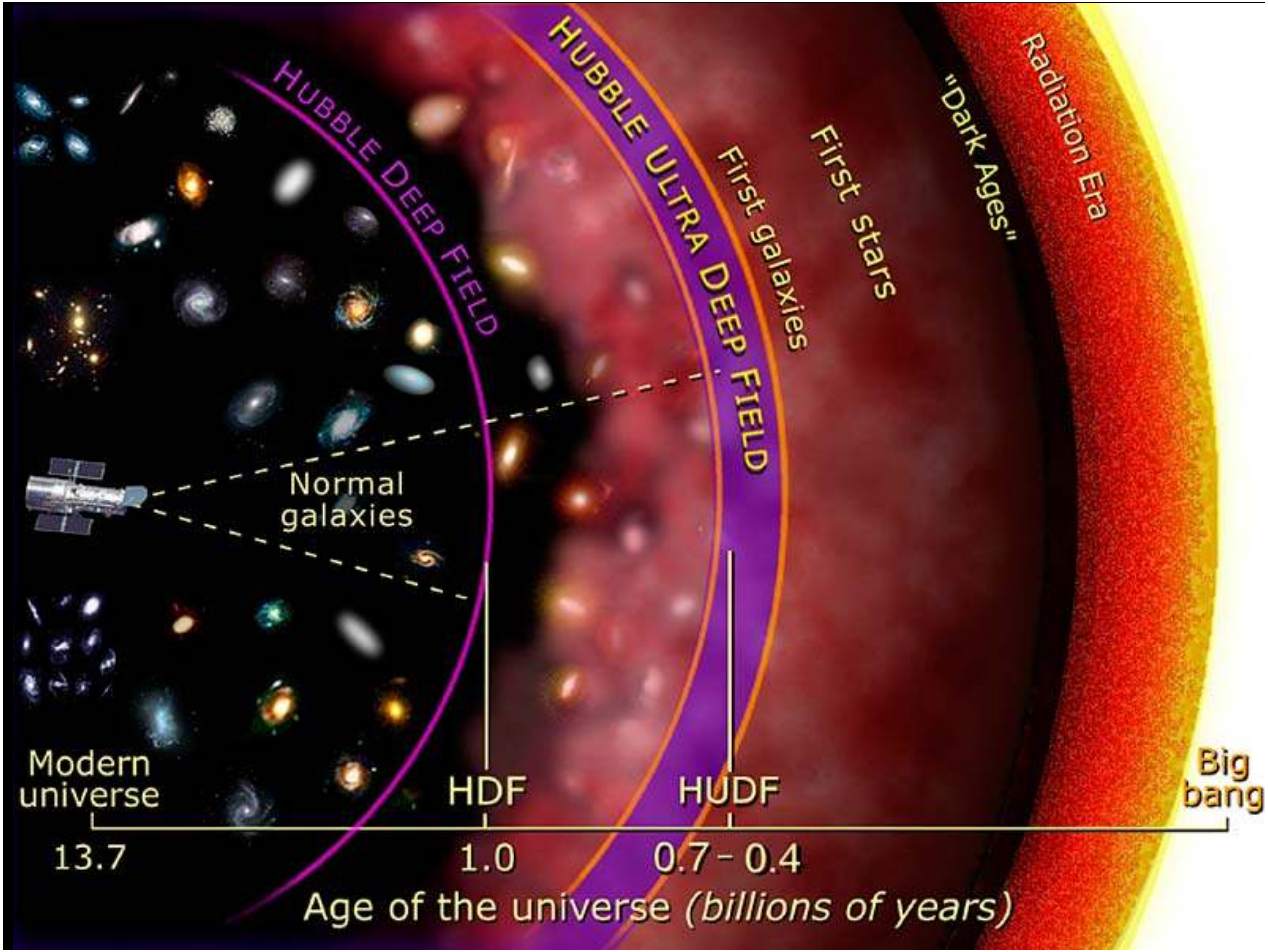
Buzzoni.2005, MNRAS, **361**, 725

Photometric redshifts, z



Sawicki, Lin, & Yee. 1997, AJ, 113, 1


22' x 22'
WFC3/ERS
UDF NIC
UDF ACS
UDF
UDF 05+09
CANDELS
Spitzer GOODS
CDF-S
GOODS/ACS
G. Illingworth


HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

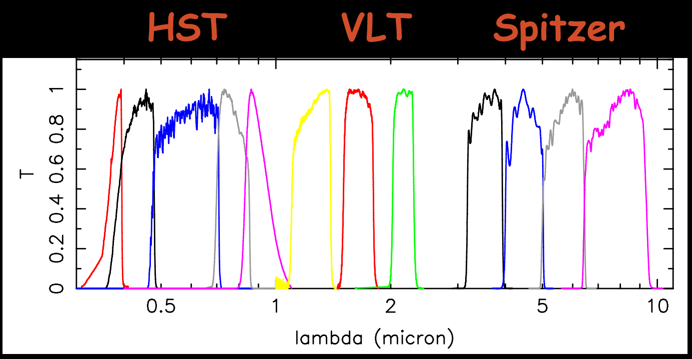
SYNOPSIS OF HST DEEP SURVEYS

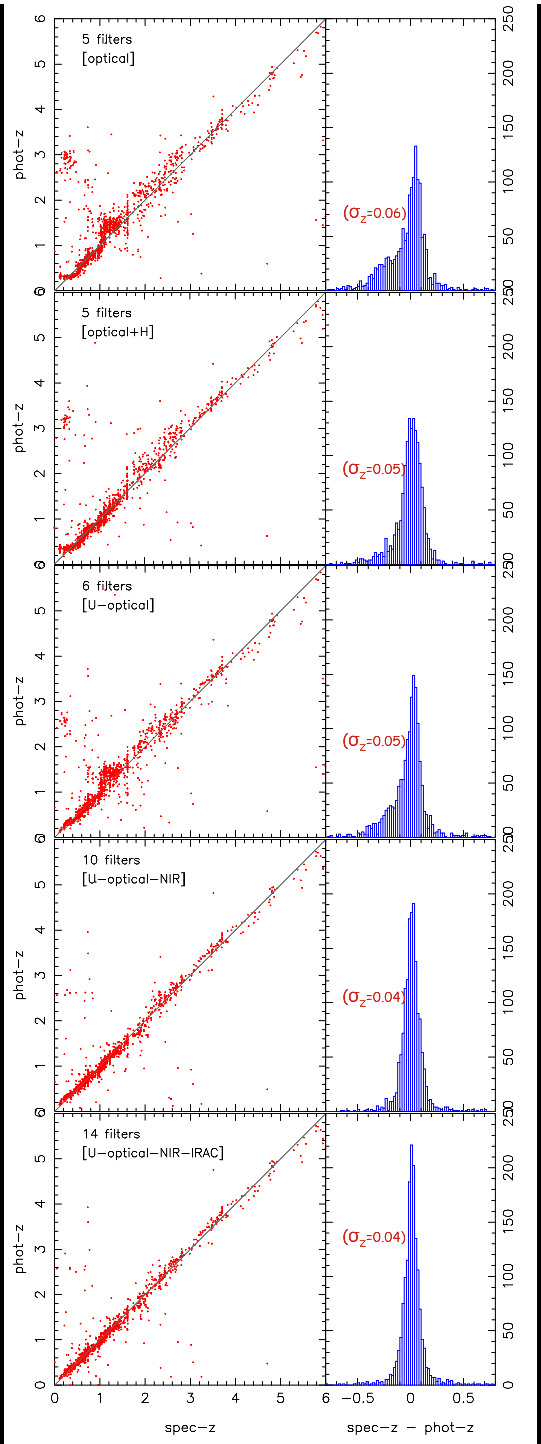
(created by Anton Koekemoer)

Date	Survey	Facility	Field/ Location	Chandra	HST				Spitzer, Herschel	Area (arcmin^2)	Epochs	No. of Opt/IR Spectra	Primary Results / Discovery Space
				Xray	V	I	Z	NIR	MIR/FIR				
1995-97	HDF(-N)	HST/ WFPC2	CVZ 12h +54°		28.2	28.2		27.5		4.3	1	130	•With Keck spectroscopy validated concept of photometric redshifts •Star formation rates for 1<z<3 •Quantitative morphologies
1998	HDF-S	HST/ WFPC2	23h -60°		28.2	28.2		27.0		4.3	1		•Account for cosmic variance •IGM metallicities
2000	CDF-N	Chandra	HDF (-N)	3.0 x 10^{-17}						450	1	~300	•Resolved X-ray background •Probed faint AGN up to z~6 •Spectroscopic redshifts for large homogeneous AGN samples
2000	CDF-S	Chandra	03h -27°	1.9 x 10^{-17}						450	1	~300	
2002	GOODS-N ACS	HST/ ACS	HDF-N		27.7	27.2	27.1			150	10	~500	•Galaxy LF to z~5 (I-dropouts) •SN / Dark Energy to z~1.5 •Galaxy size evolution •SFR evolution z~0 - 1 •Red sequence evolution to z~1.5
2002	GOODS-S / GEMS ACS	HST/ ACS	CDF-S		27.7	27.2	27.1			150	10	1500 + COMBO-17	
2003	GOODS Spitzer	Spitzer	HDF-N CDF-S		27.7	27.2	27.1		24.0 (3 μm) 3-160 μm	600	1	2000 + COMBO-17	•Dusty star formation / SFR-Σ relation at high z •Obscured AGN at the peak of galaxy evolution (z~2-3)
2004	UDF	HST/ ACS	CDF-S		29.3	28.7	29.2	27.0	24.0 (3 μm)	10	1	106 (ACS grism)	•Galaxy LF to z~6 (z-dropouts) •Detection of galaxies at z~7 •"Clump" morphological class
2005	UDF05	HST/ ACS	CDF-S		29.0	28.4	28.9	27.5	24.0 (3 μm)	20	1		•Account for cosmic variance •Galaxy LF to z~6 •Detection of galaxies at z~7
2005	AEGIS/EGS	HST/ ACS	14h +53°	5.3 x 10^{-17}	27.4	27.0				700	1	~20,000 (DEEP2)	•Galaxy mass / metallicity / morphology relations to z~1.5 •Blue/red sequence, AGN quenching
2005	COSMOS	HST/ ACS	10h +02°	1.9 x 10^{-16}		26.7				7200	1	~20,000 (VIMOS)	•Dark matter map (from weak lensing)
2009	UDF09	HST/ WFC3	CDF-S		29.3	28.7	29.2	28.8	24.0 (3 μm)	15	1	106 (ACS grism)	•Galaxy LF to z~7 •Detection of galaxies at z~8
2010-13	CANDELS (+ WFC3 ERS2)	HST/ WFC3	HDF-N, CDF-S, AEGIS, COSMOS, UKIDSS/ UDS		27.4 – 27.7	26.7 – 27.2	27.1	27.0		770	10	~4000 + HST grism	•Galaxy evolution z~1.5-8 •Confirm steep slope of low-L end of LF. Re-ionization due to dwarf galaxies •Detect SNe Ia with z>1.5/EOS to z~2.5 •Tracing the merger sequence
2011	GOODS-H	Herschel							100–500 μm				•Cold dust / SFR at all redshifts

Photometric Redshifts From CANDELS GOODS-S

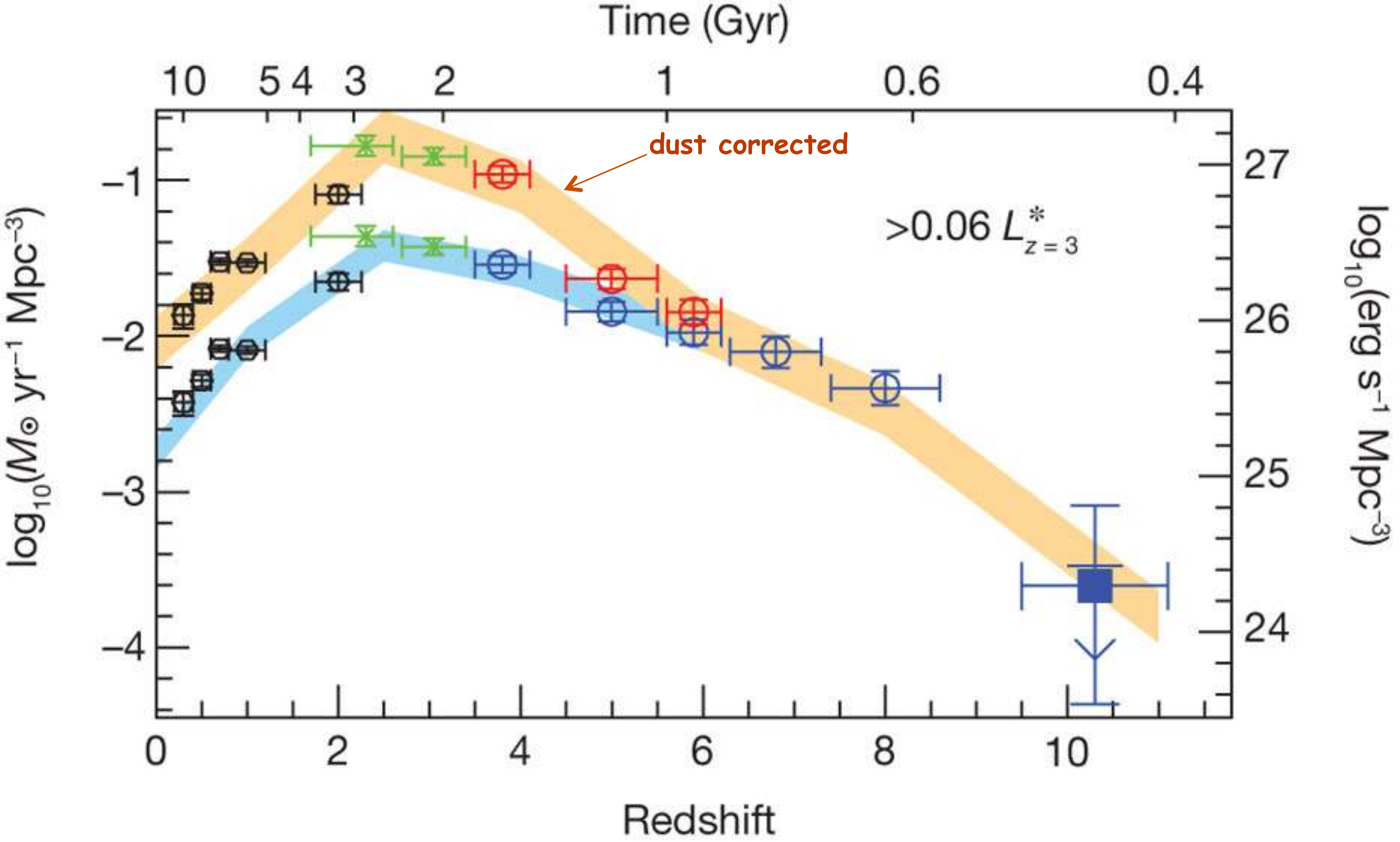
(1570 galaxies)





Dahlen, T. et al. 2010, ApJ, 724, 425

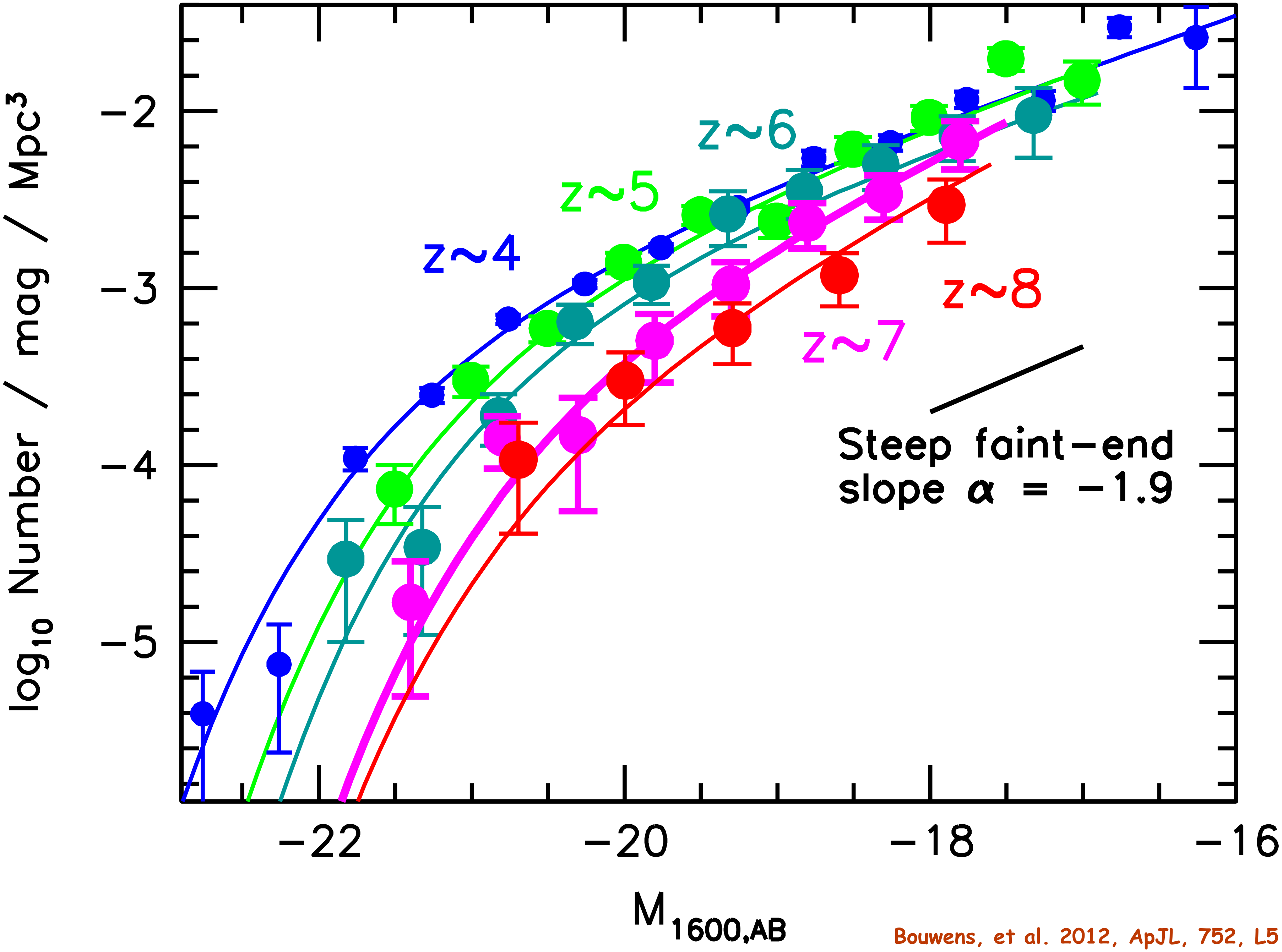
Star Formation Rate History



dust corrected

Bouwens, R. et al. 2011, Nature, 469, 504

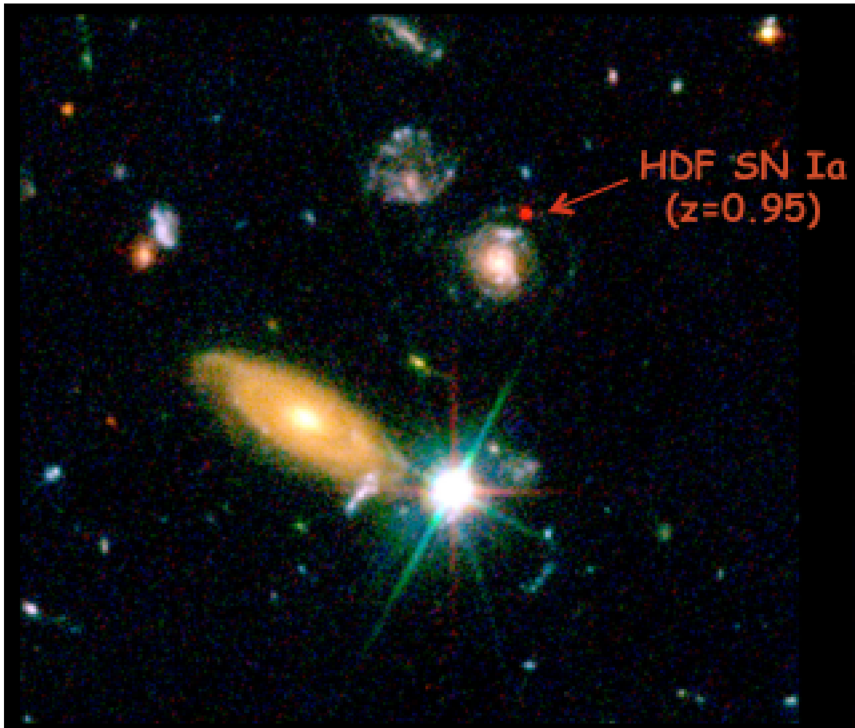
Galaxy Luminosity Fuction

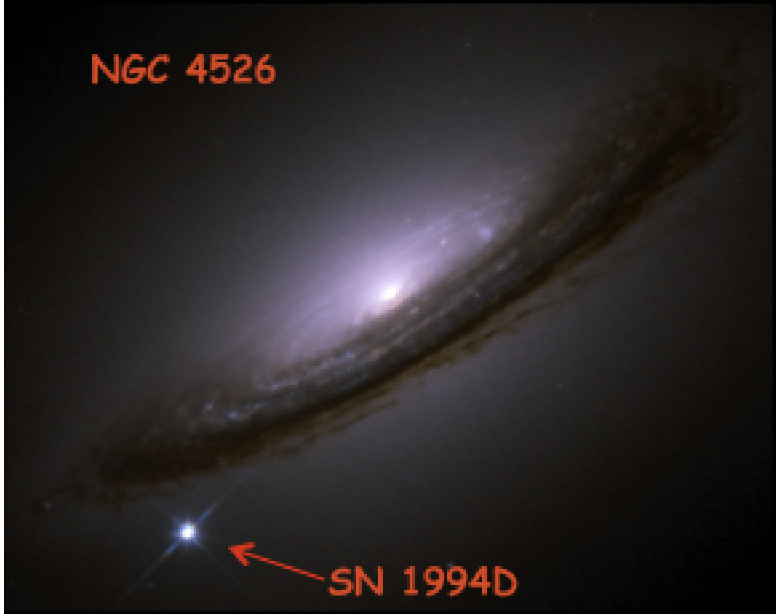


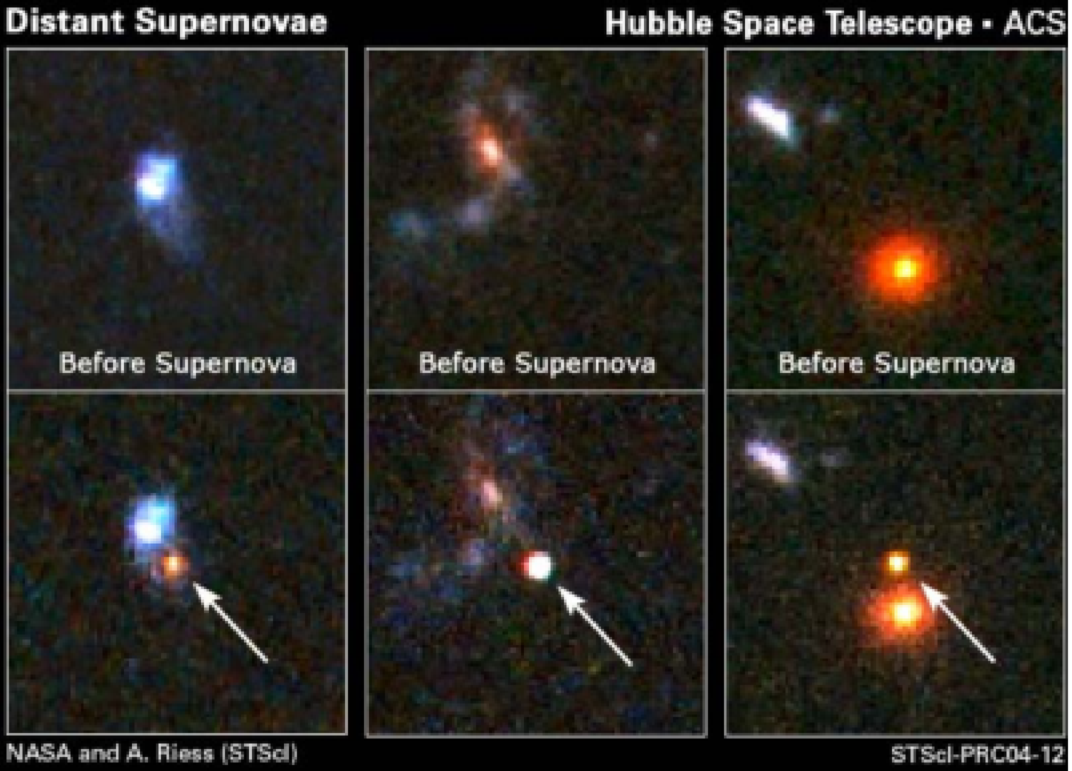
Steep faint-end slope α = −1.9

Bouwens, et al. 2012, ApJL, 752, L5

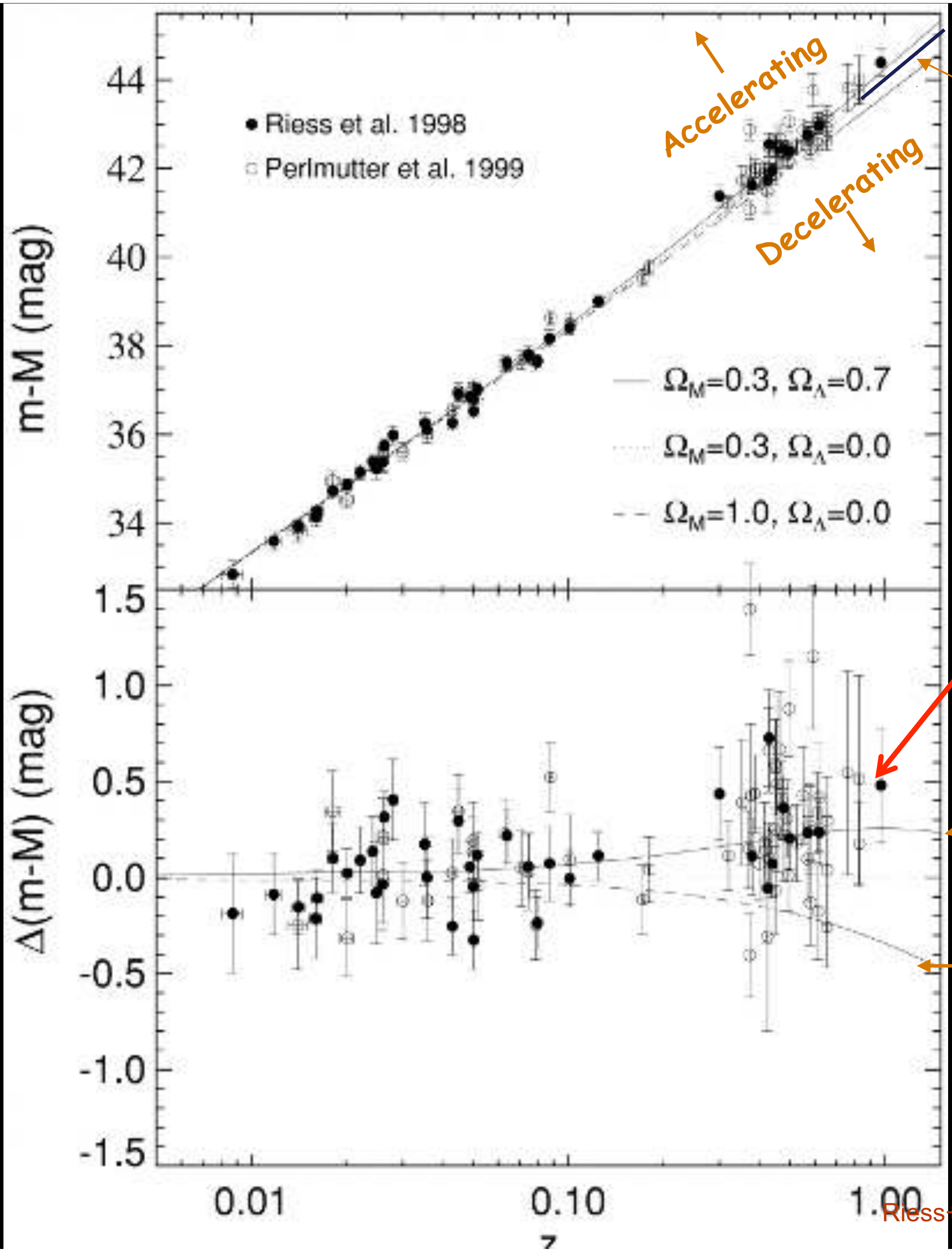
Distant Supernovae







Deep Fields: *GOODS + CLASH + CANDELS*



Constant Expansion
(‘Hubble Law’)

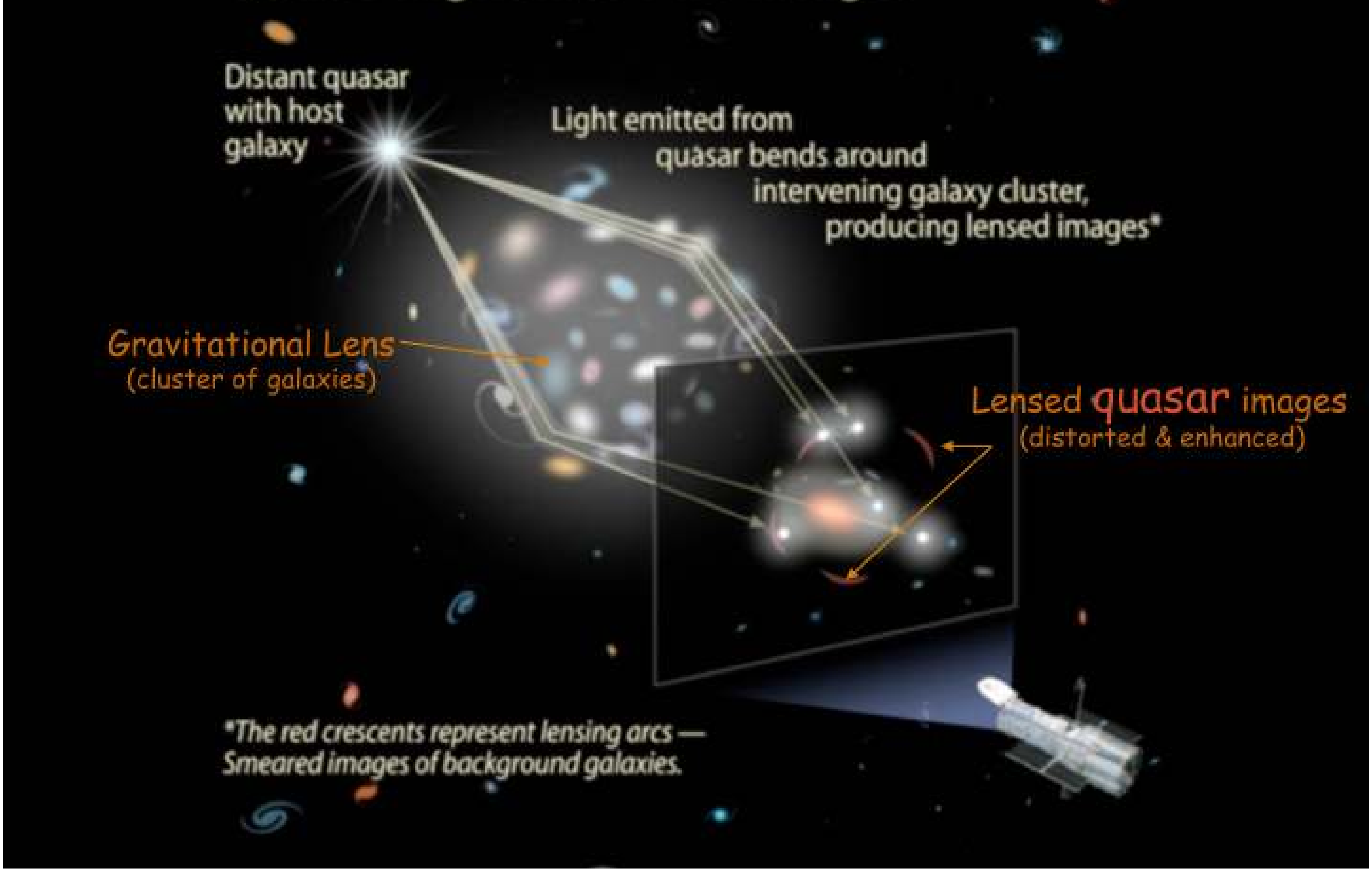
Cosmological Acceleration

Deceleration

Riess 2000, PASP, 112, 1284

Riess+. 2007, ApJ, 659, 98

Gravitational Lensing Splits Quasar Light into Five Images



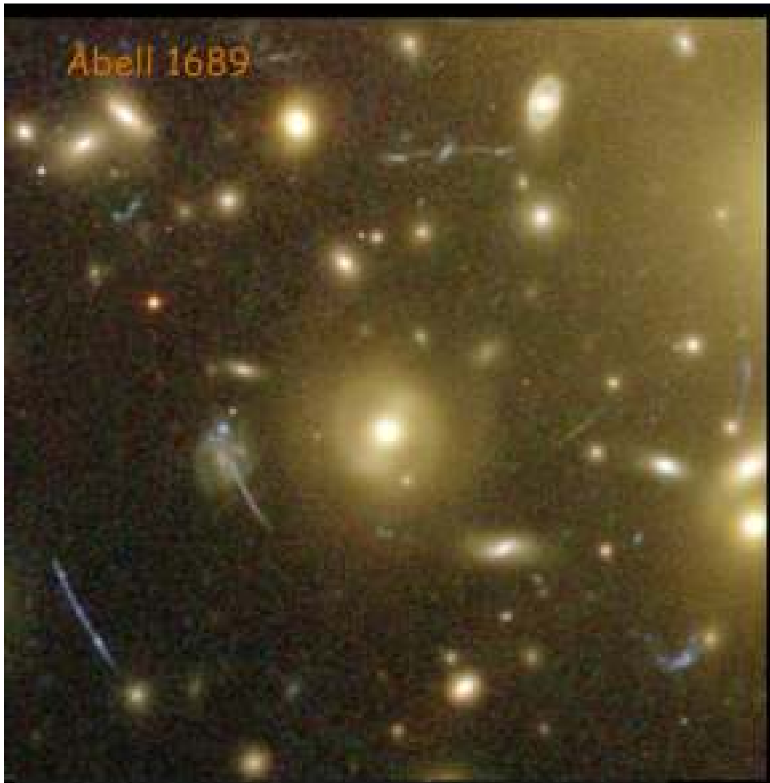
Distant quasar
with host
galaxy

Light emitted from
quasar bends around
intervening galaxy cluster,
producing lensed images*

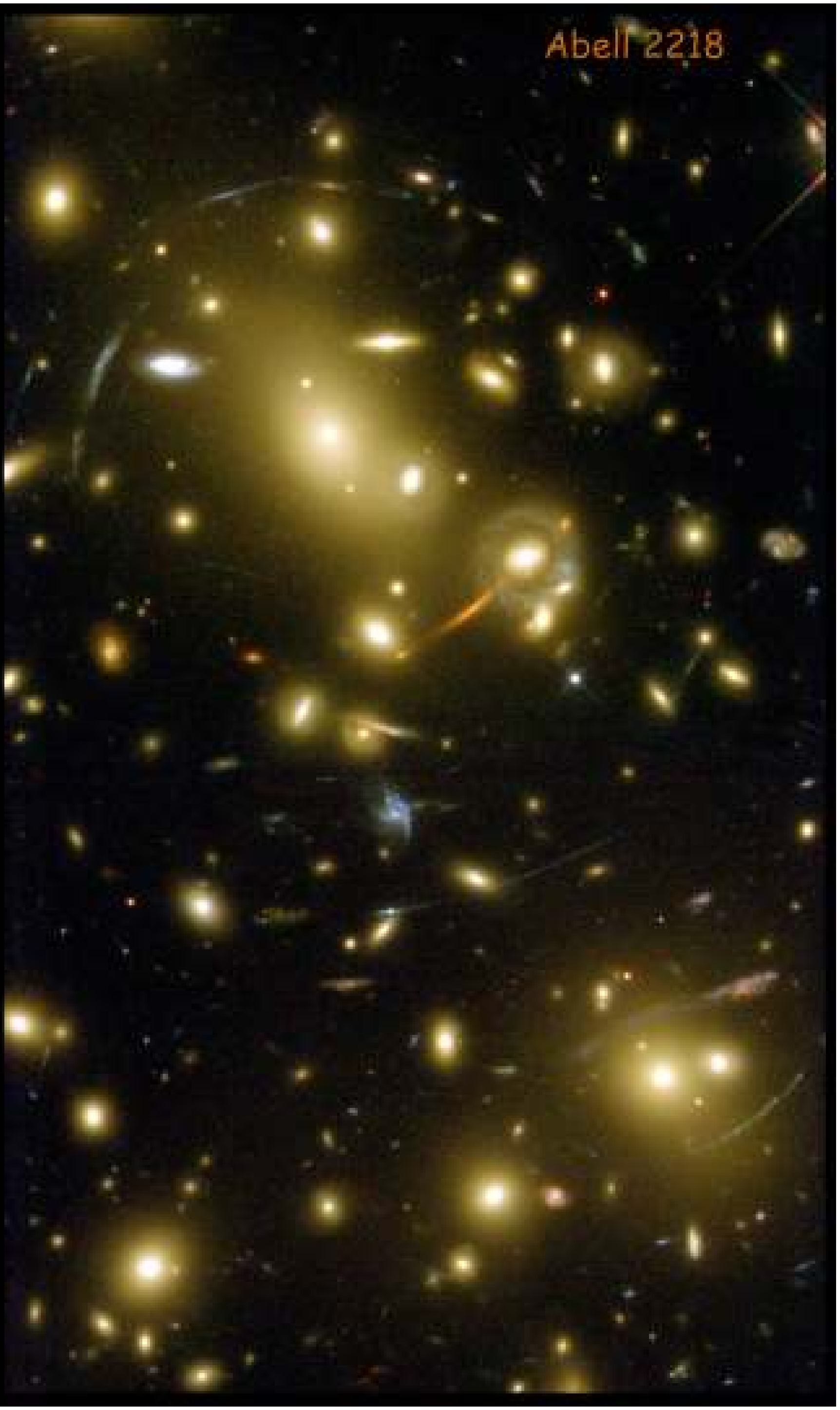
Gravitational Lens
(cluster of galaxies)

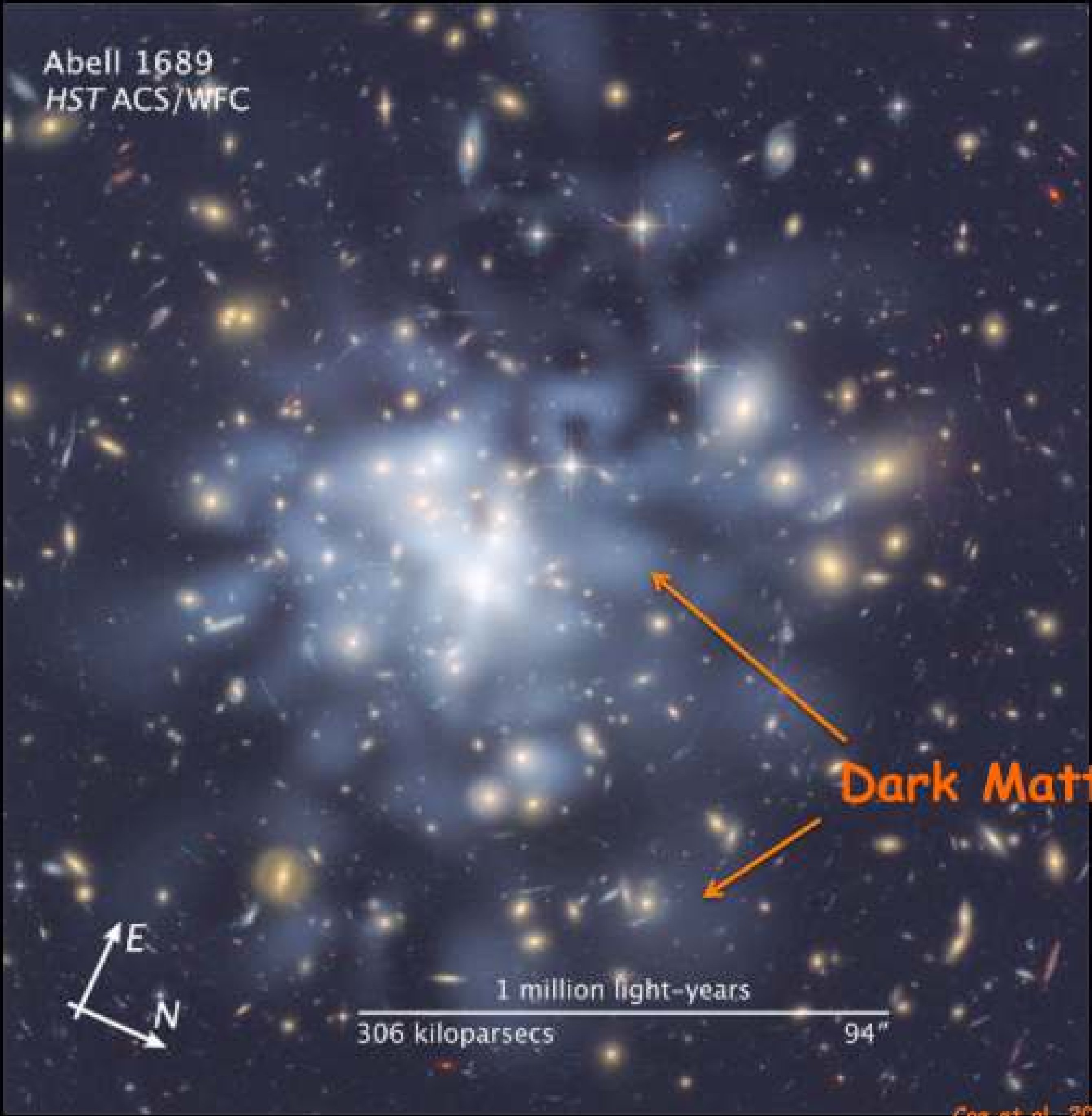
Lensed quasar images
(distorted & enhanced)

*The red crescents represent lensing arcs —
Smeared images of background galaxies.


Abell 1689


CL 0024+1652

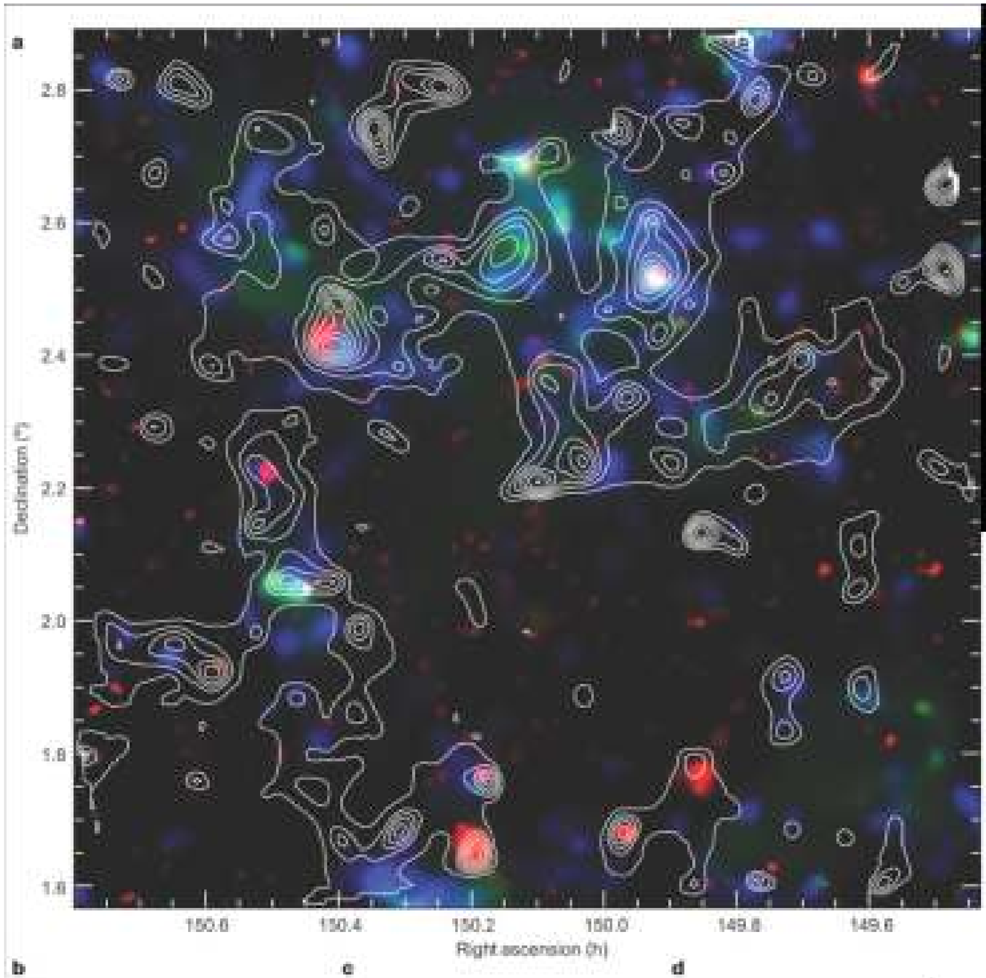

Abell 2218



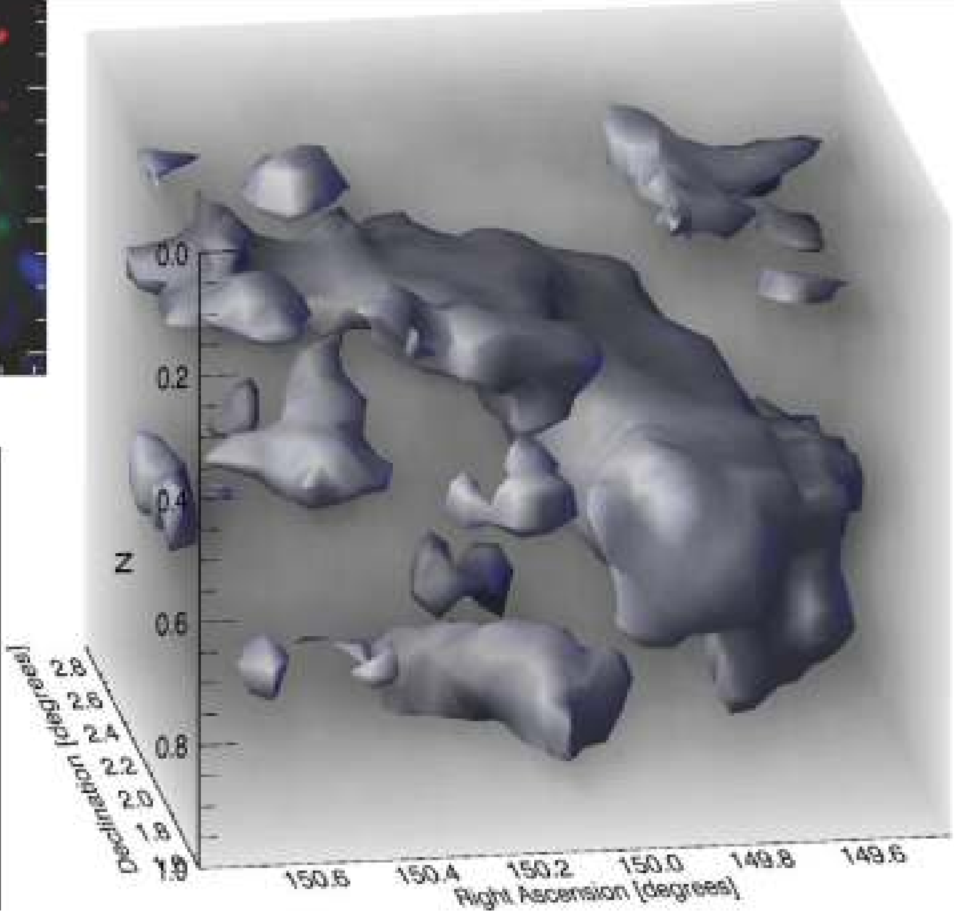
Dark Matter

Coe et al. 2010, ApJ, 723, 1678

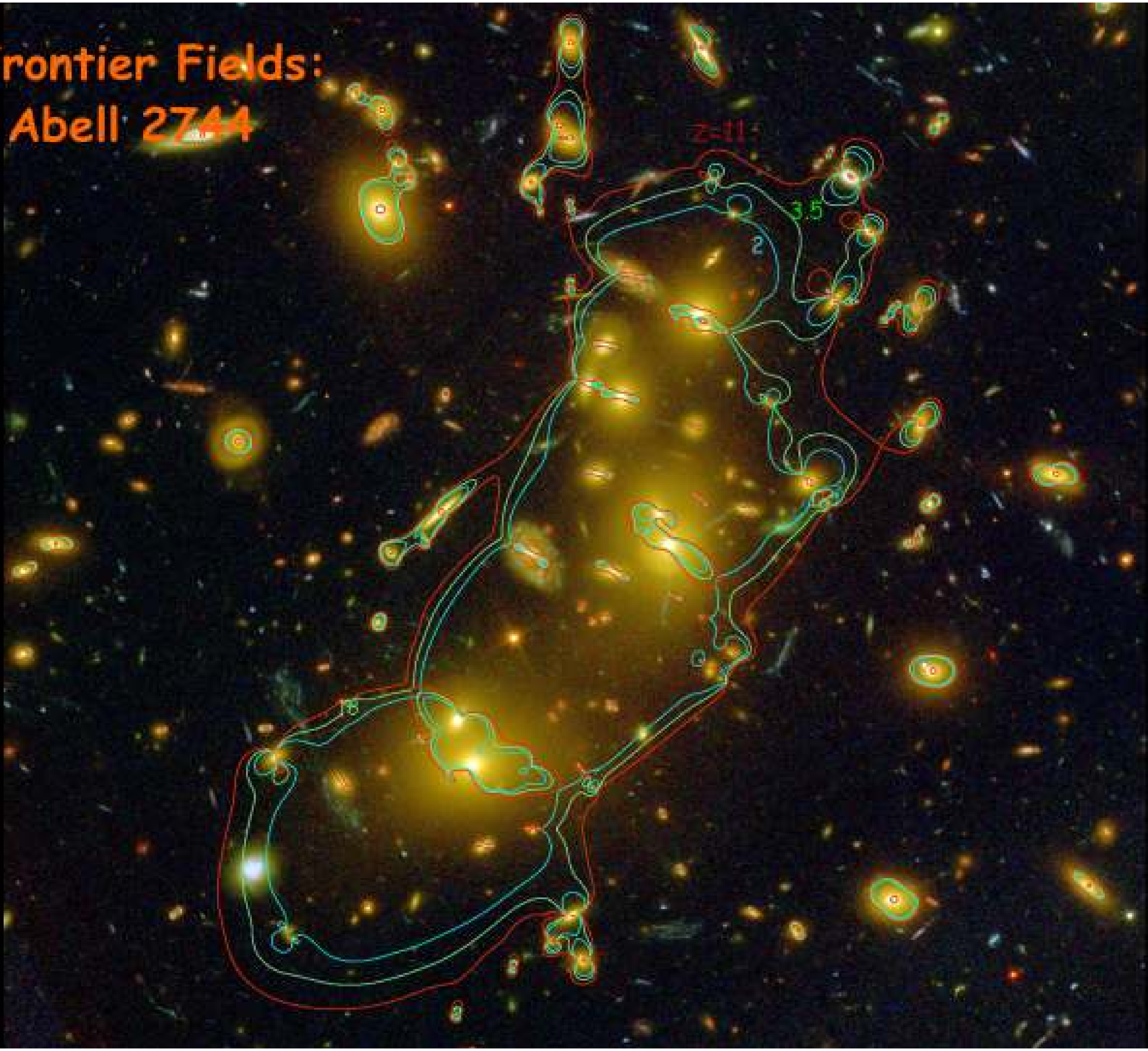
Dark Matter Map From COSMOS 1°x2° Survey



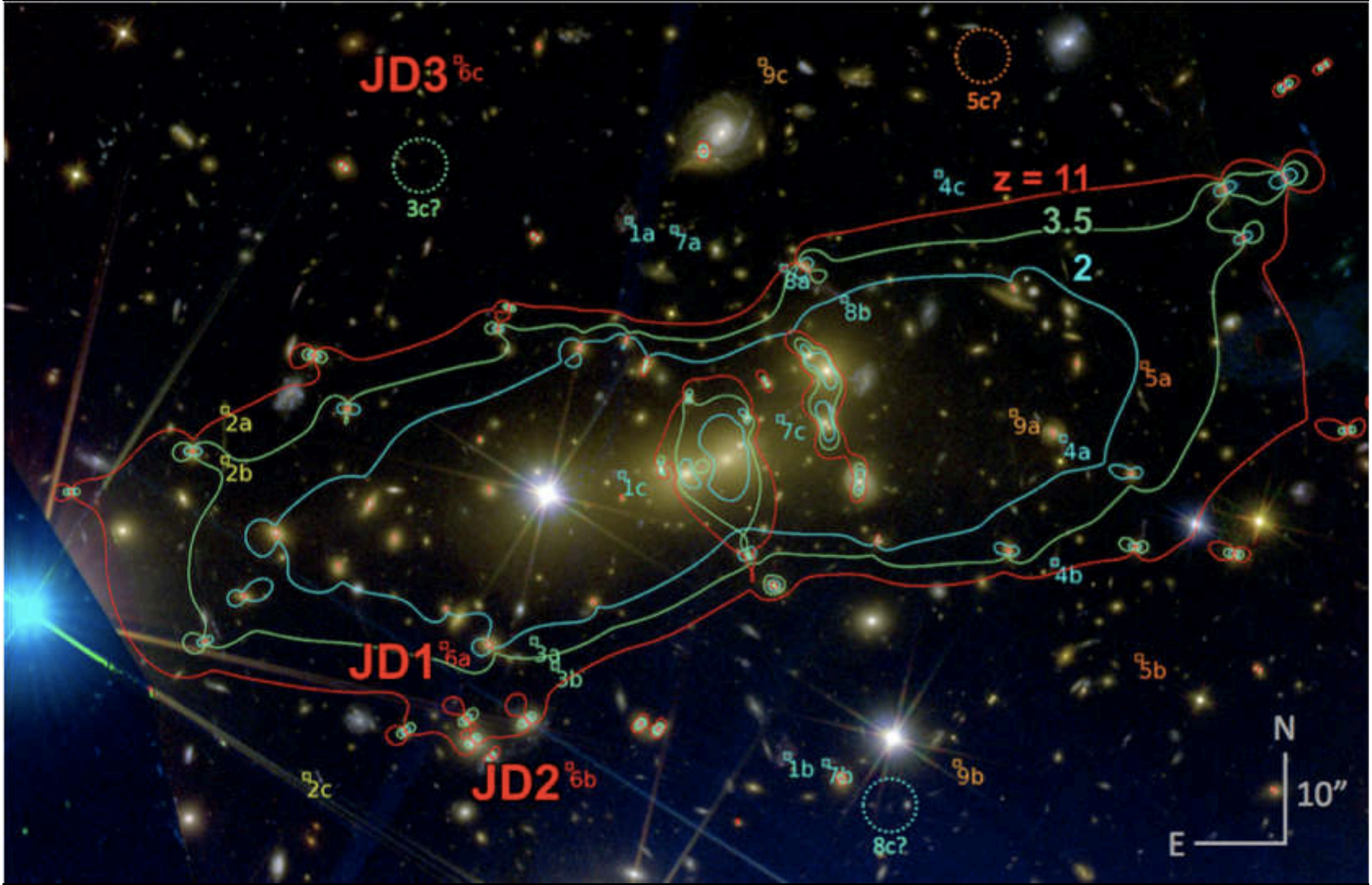
Massey, R. et al. 2007, Nature, 445, 286



Frontier Fields: Abell 2744



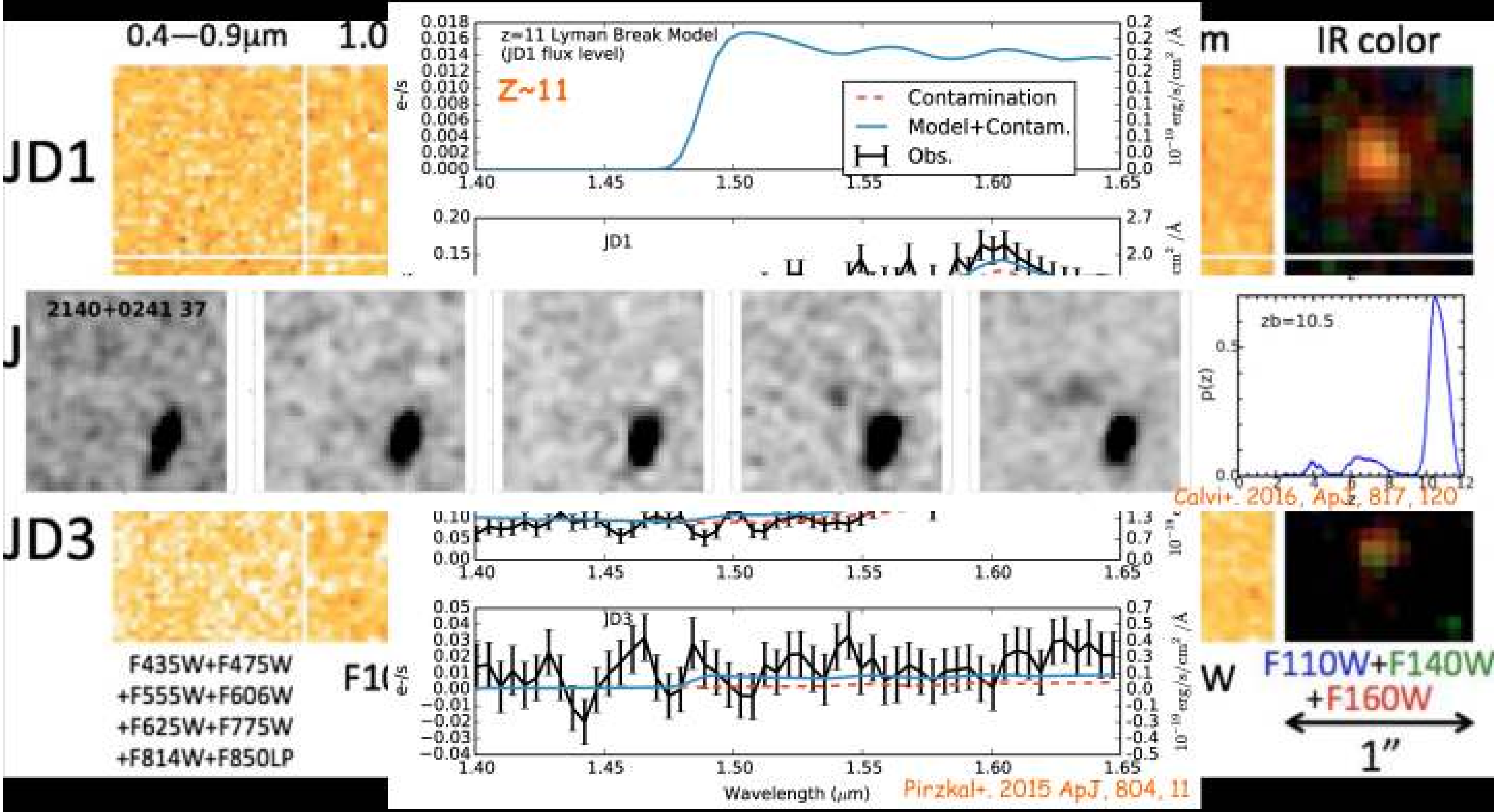
CLASH → Frontier Fields



MACSJ0647.7+7015

Coe, D. et al. 2013,ApJ,762, 32

z≈11.7 Candidate



Calvi+. 2016, ApJ, 817, 120

Pirzkal+. 2015 ApJ, 804, 11

Coe et al. 2013 ApJ 762 32

James Webb Space Telescope