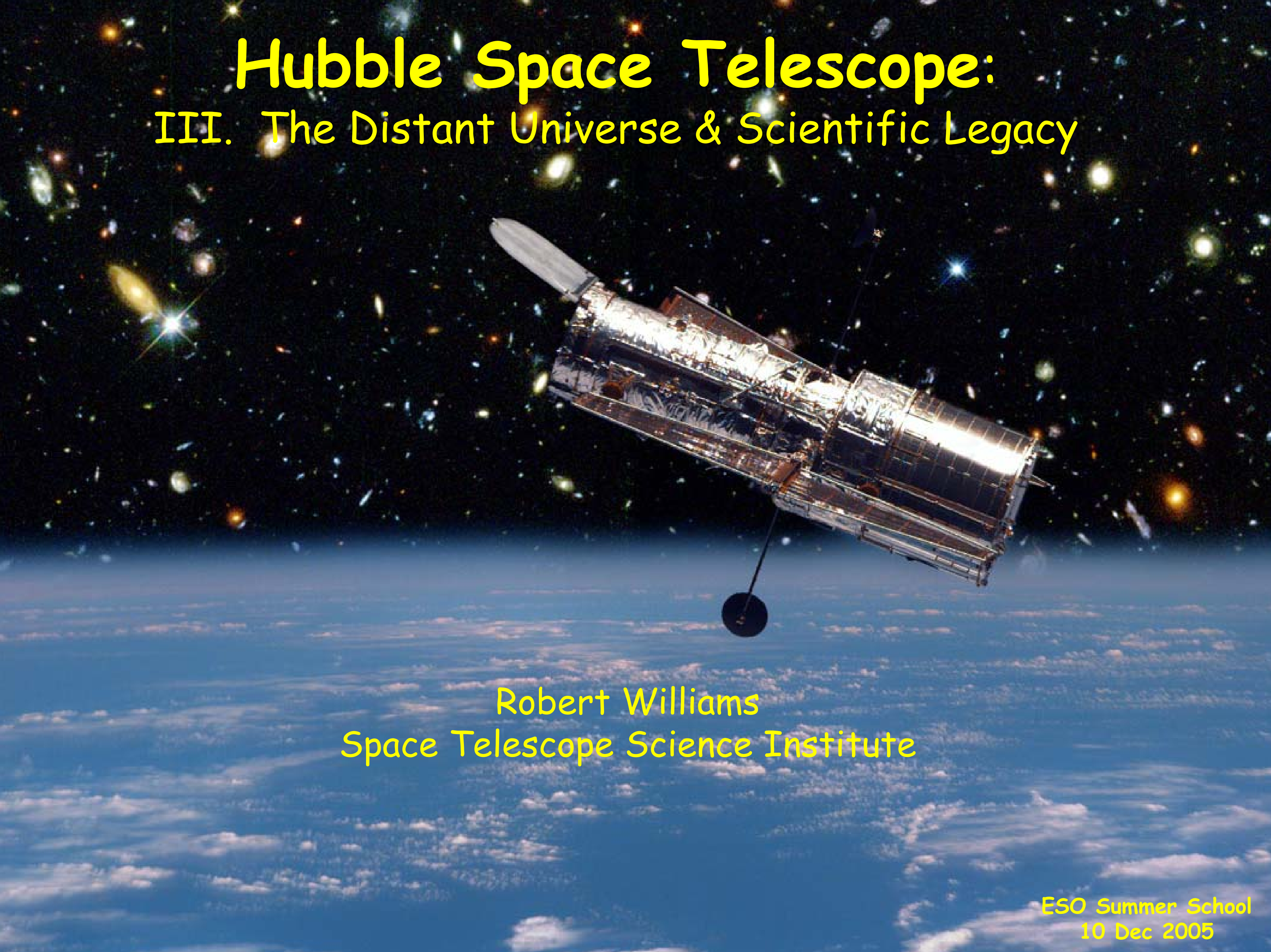
Hubble Space Telescope:

III. The Distant Universe & Scientific Legacy



Robert Williams
Space Telescope Science Institute

ESO Summer School
10 Dec 2005

Hubble Discoveries

Most Important Scientific Results

1) **Determined from SNe Ia supernovae distances that universe is accelerating**
2) Characterized (age & composition) previously unresolved stellar populations
3) **Detected distant galaxies at very high redshift before Hubble sequence formed**
4) Spectroscopic detection of atmosphere of planet around another star
5) Measured masses of black holes in centers of galaxies
6) **Characterized environment & optical properties of Gamma Ray Bursters**
7) **Mapped dark matter from gravitational arcs (associated with galaxies)**
8) Observations of unusual solar system phenomena
9) Resolved host galaxies of quasars
10) Demonstrated association between disks and jets, and that disks around young stars are common

Others: Evolution of IGM from QSO absorption lines
Determination of Hubble Constant (H_o = 75 km s^{-1} Mpc^{-1})
UV spectroscopy of the ISM, nebulae, winds, & galaxies

Host Galaxies of Gamma Ray Bursters

(greatest explosions since Big Bang)

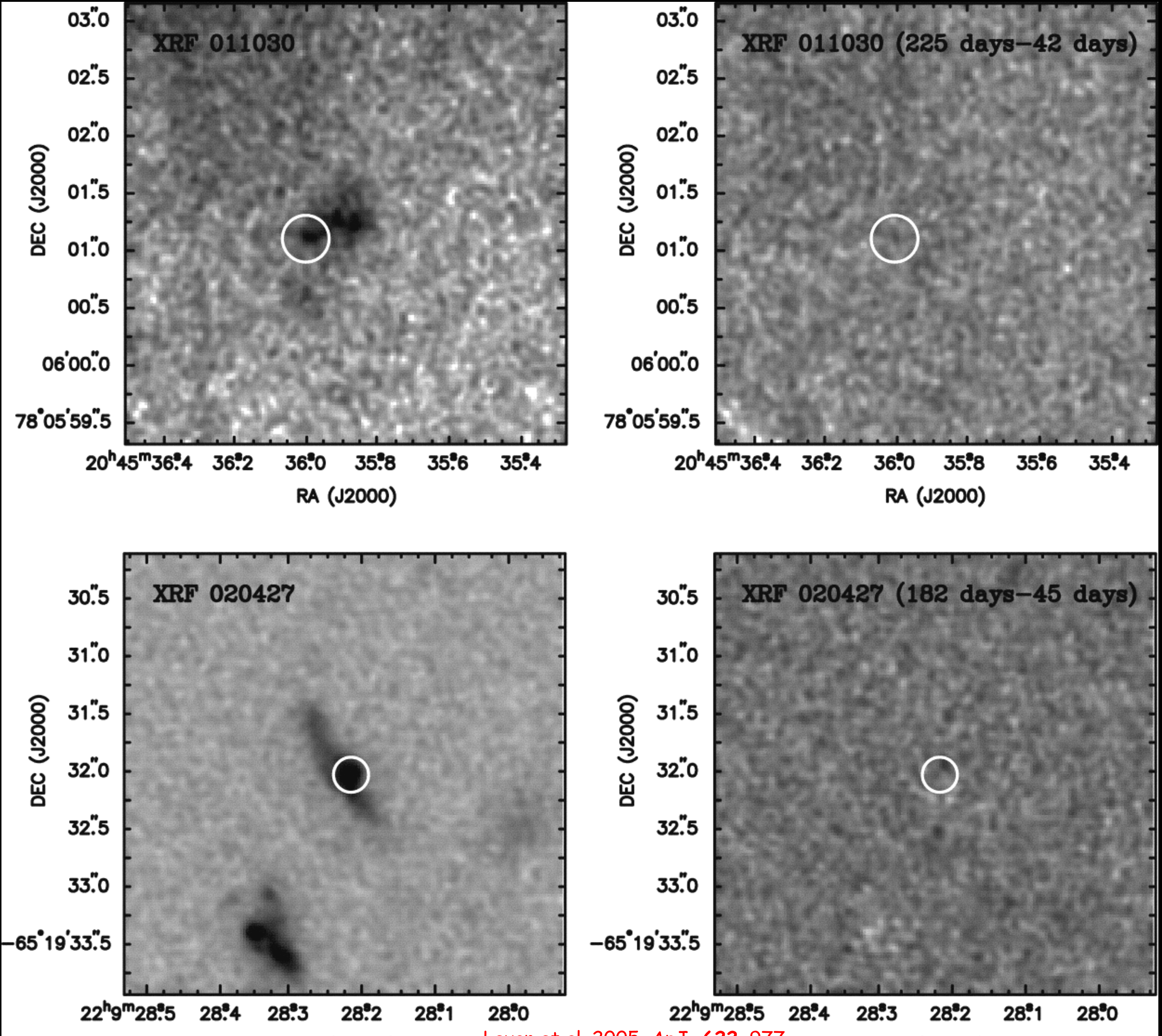
Gamma Ray Bursts

- 1-10 sec bursts of radiation from unresolved sources in distant galaxies. ~2/week detectable in visible universe.

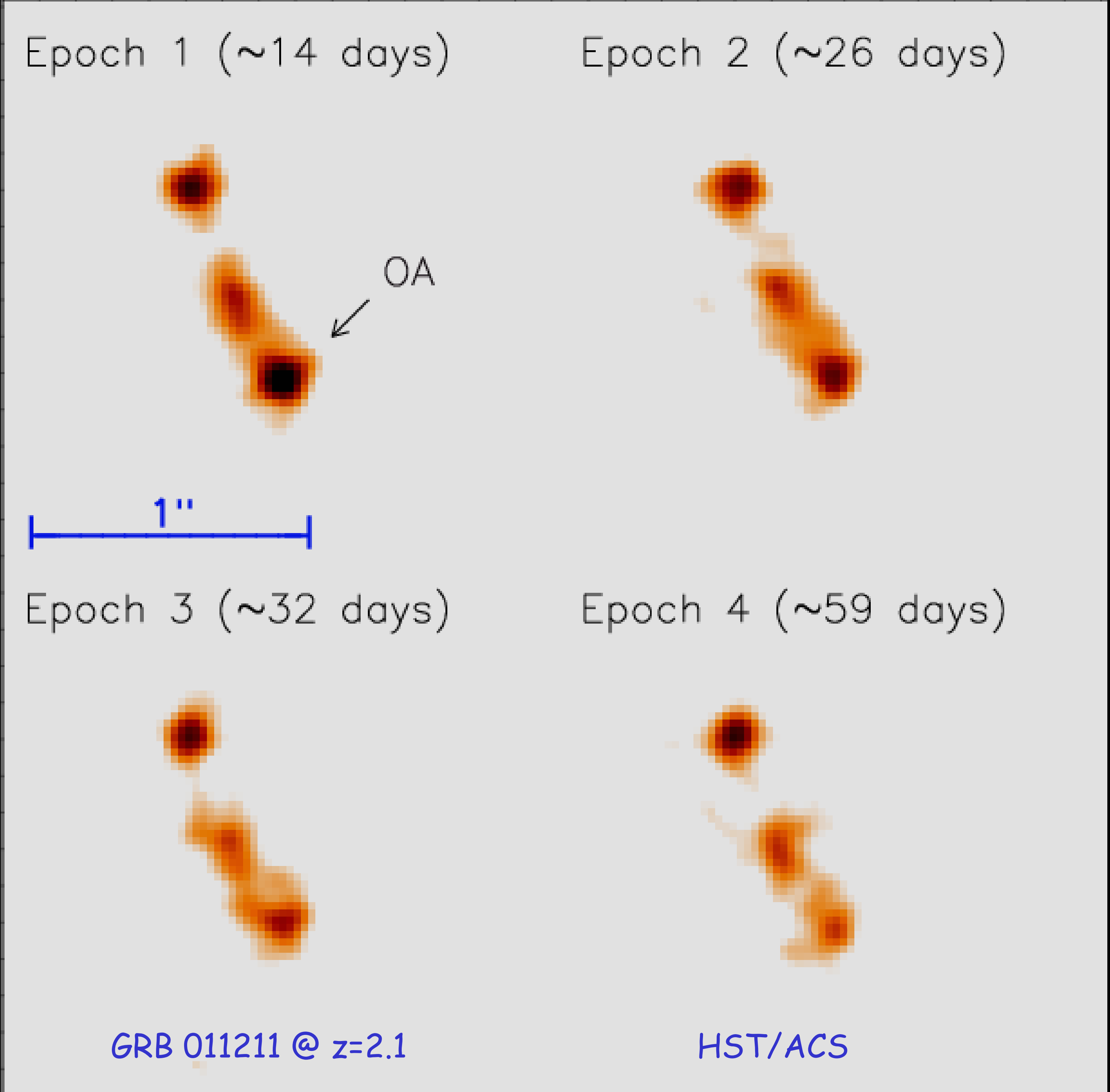
- Rare events. Extremely luminous: one GRB at z=1.6 achieved $m_V=9$ for seconds. Probably beamed radiation?

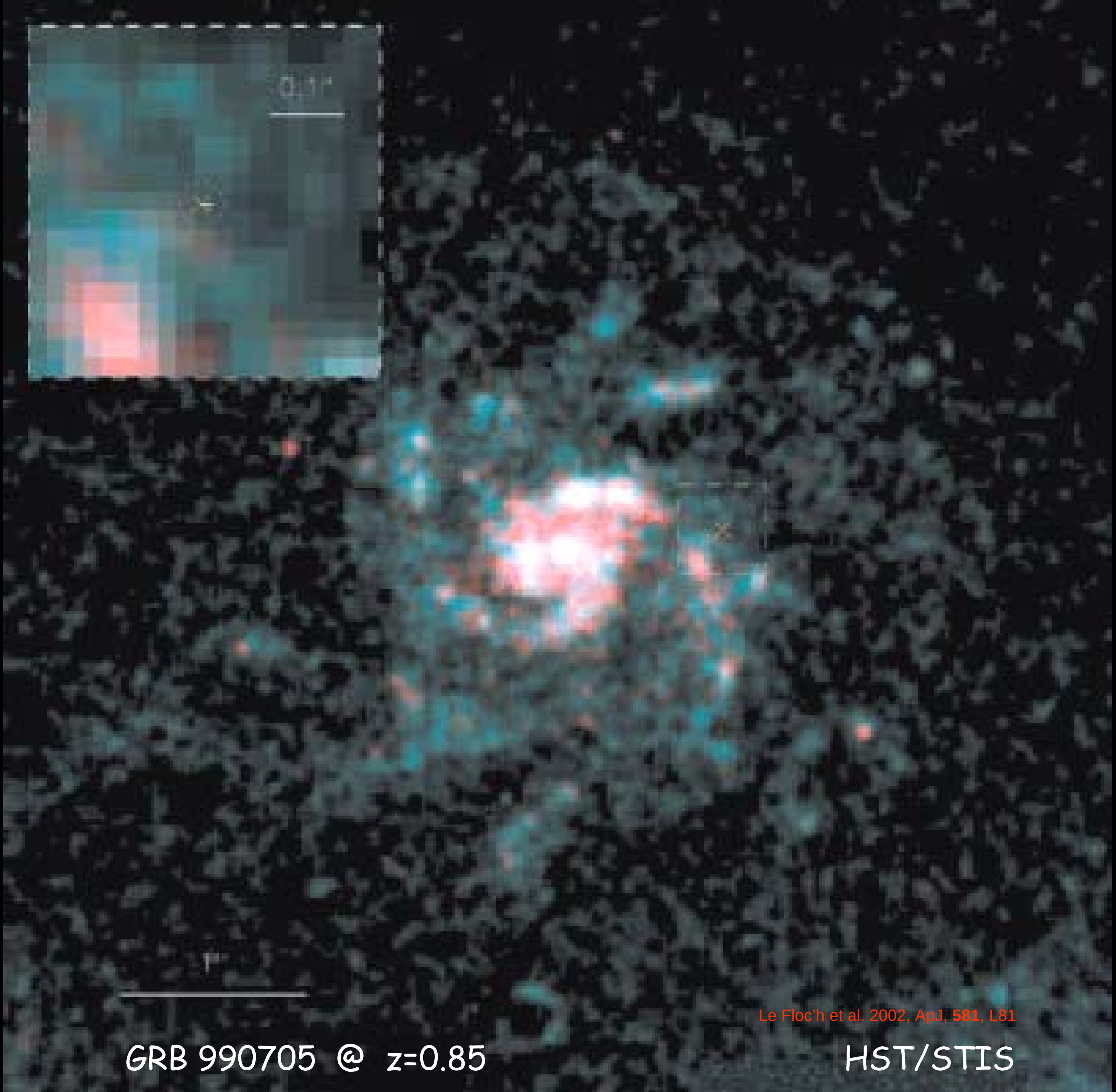
- Energies ~ 10^{53} ergs (~10 x SNe) emitted in seconds, primarily in γ-rays. Some in X-ray, radio, & optical. SNe connection?

- Models include massive star collapse → Black Hole, or merging neutron stars → Black Hole, etc.



Levan et al. 2005, ApJ, **622**, 977


Epoch 1 (~14 days)
Epoch 2 (~26 days)
OA
1''
Epoch 3 (~32 days)
Epoch 4 (~59 days)
GRB 011211 @ z=2.1
HST/ACS



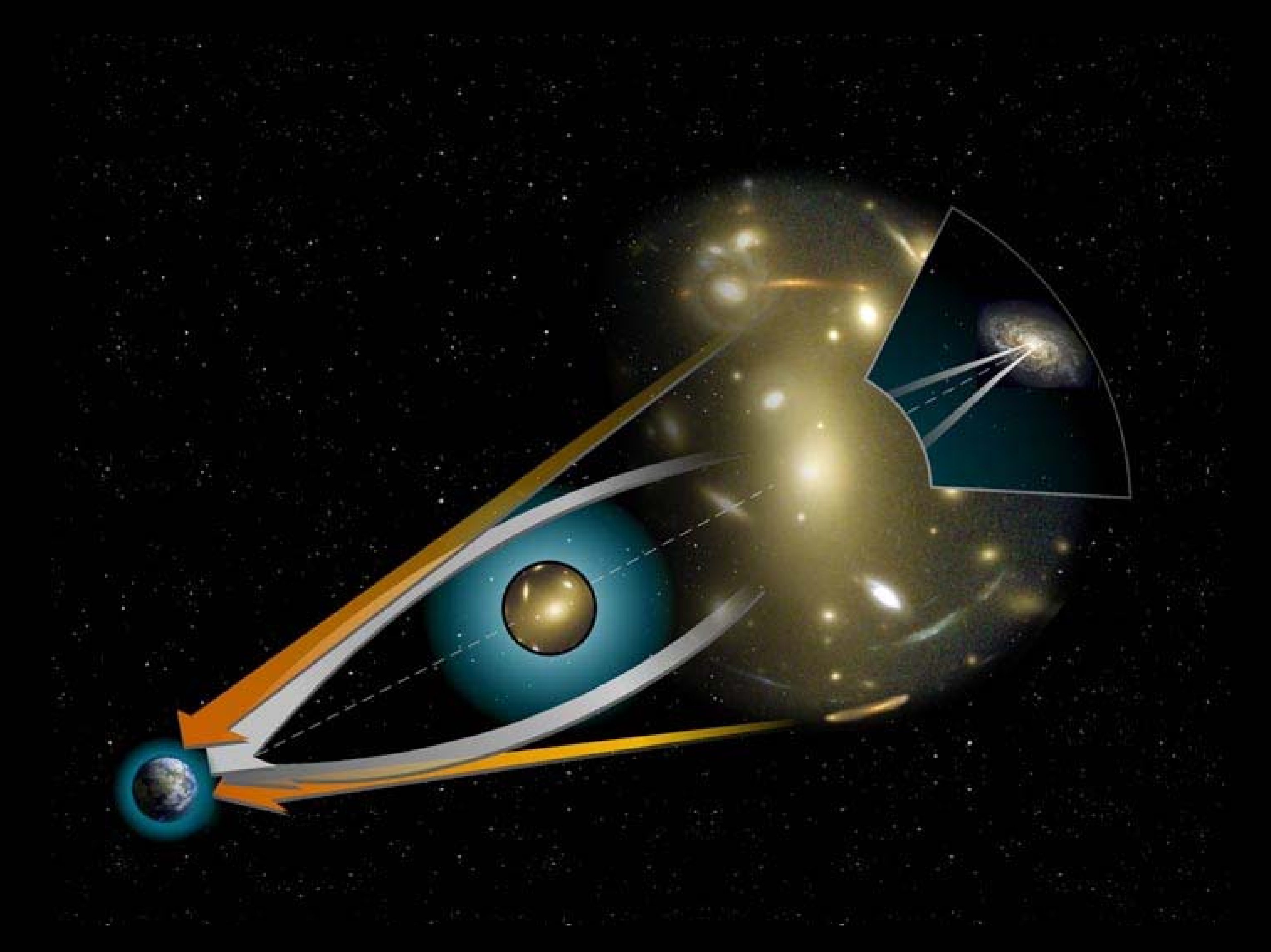
Le Floc'h et al. 2002, ApJ, **581**, L81

GRB 990705 @ z=0.85

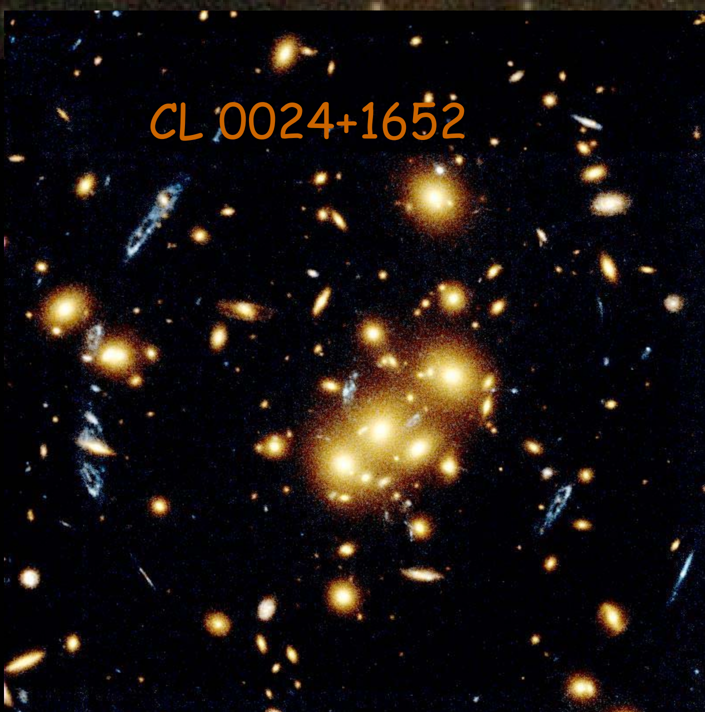
HST/STIS

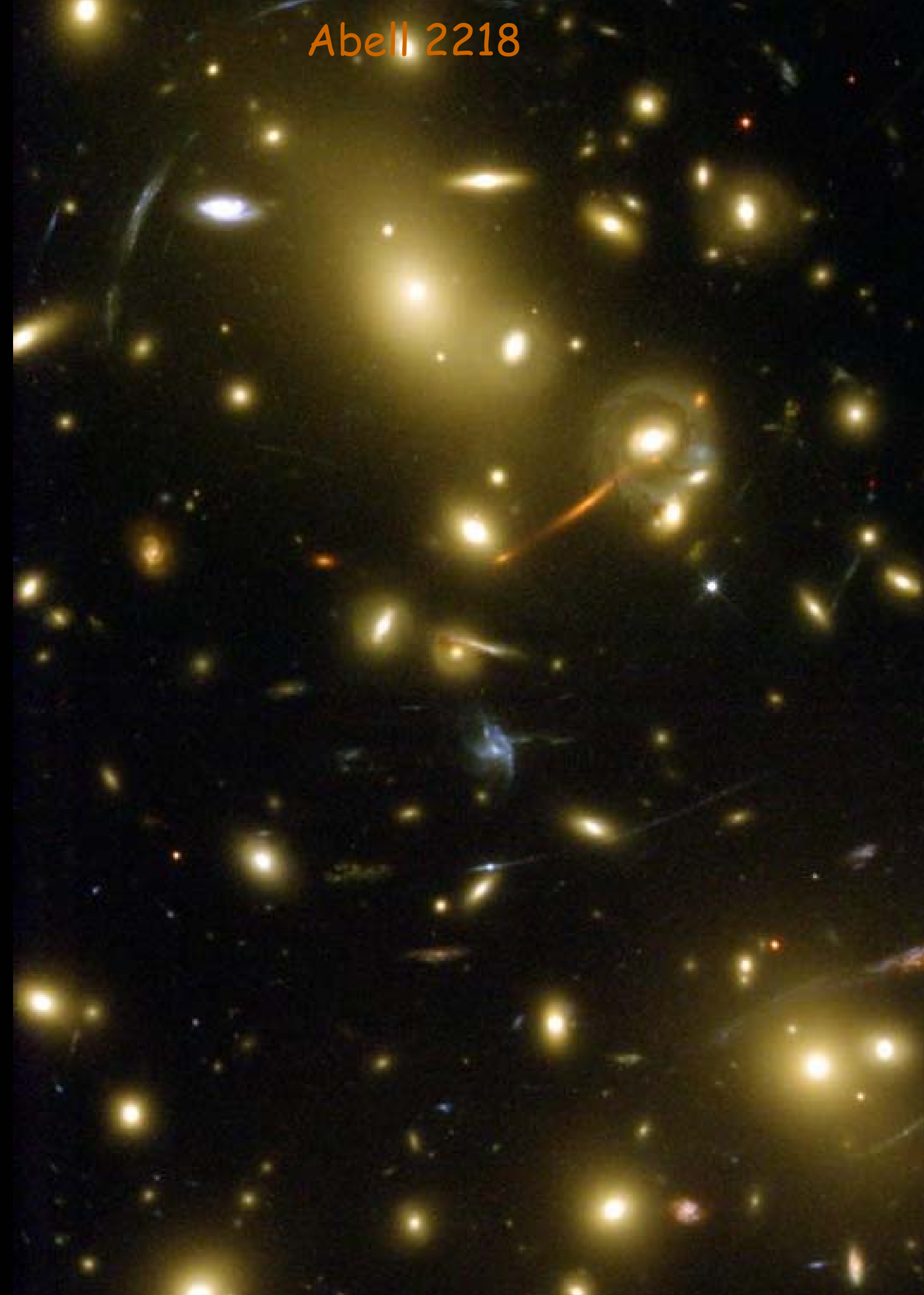
Gravitational Lensing

(Mapping Dark Matter)



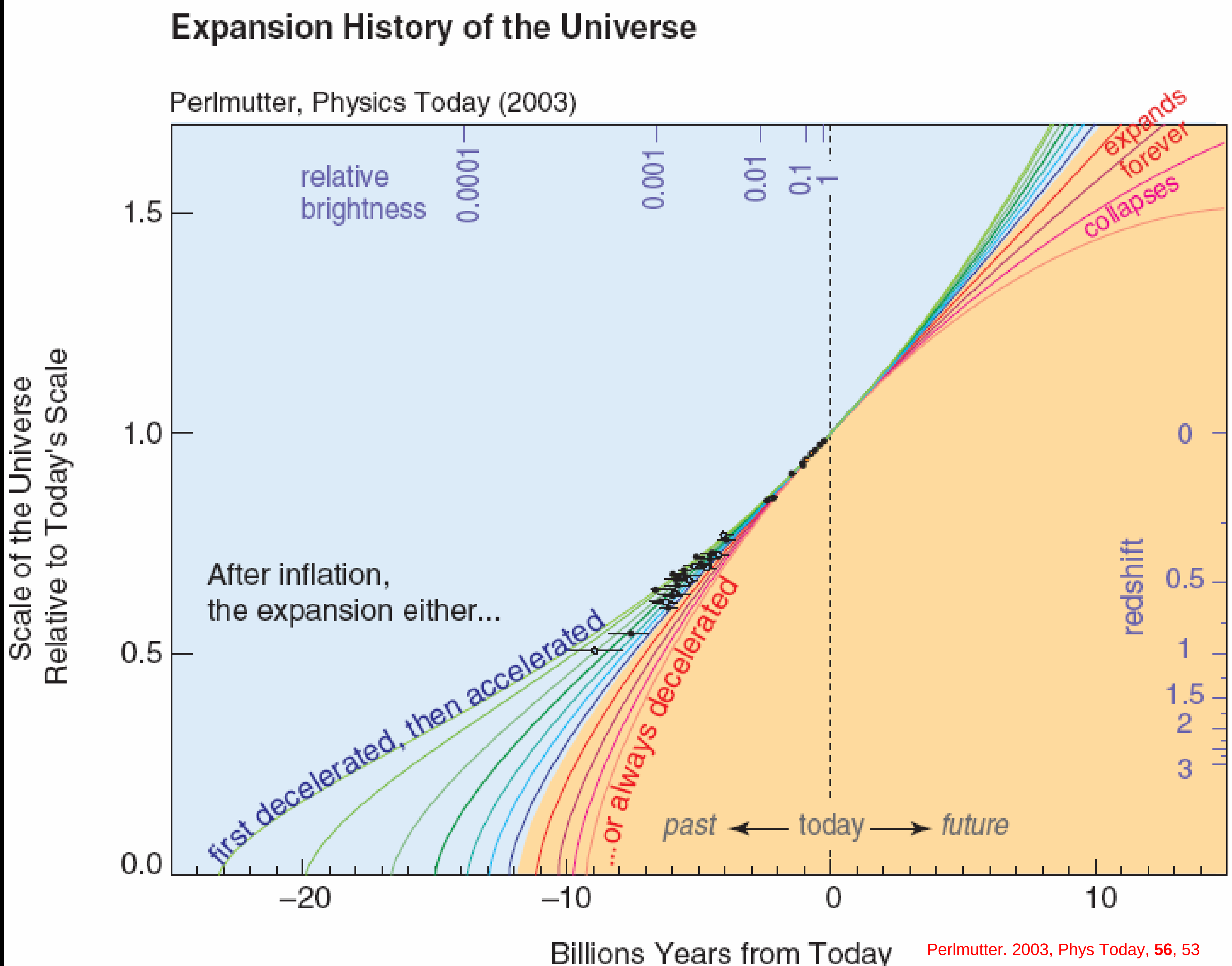

Abell 1689


CL 0024+1652

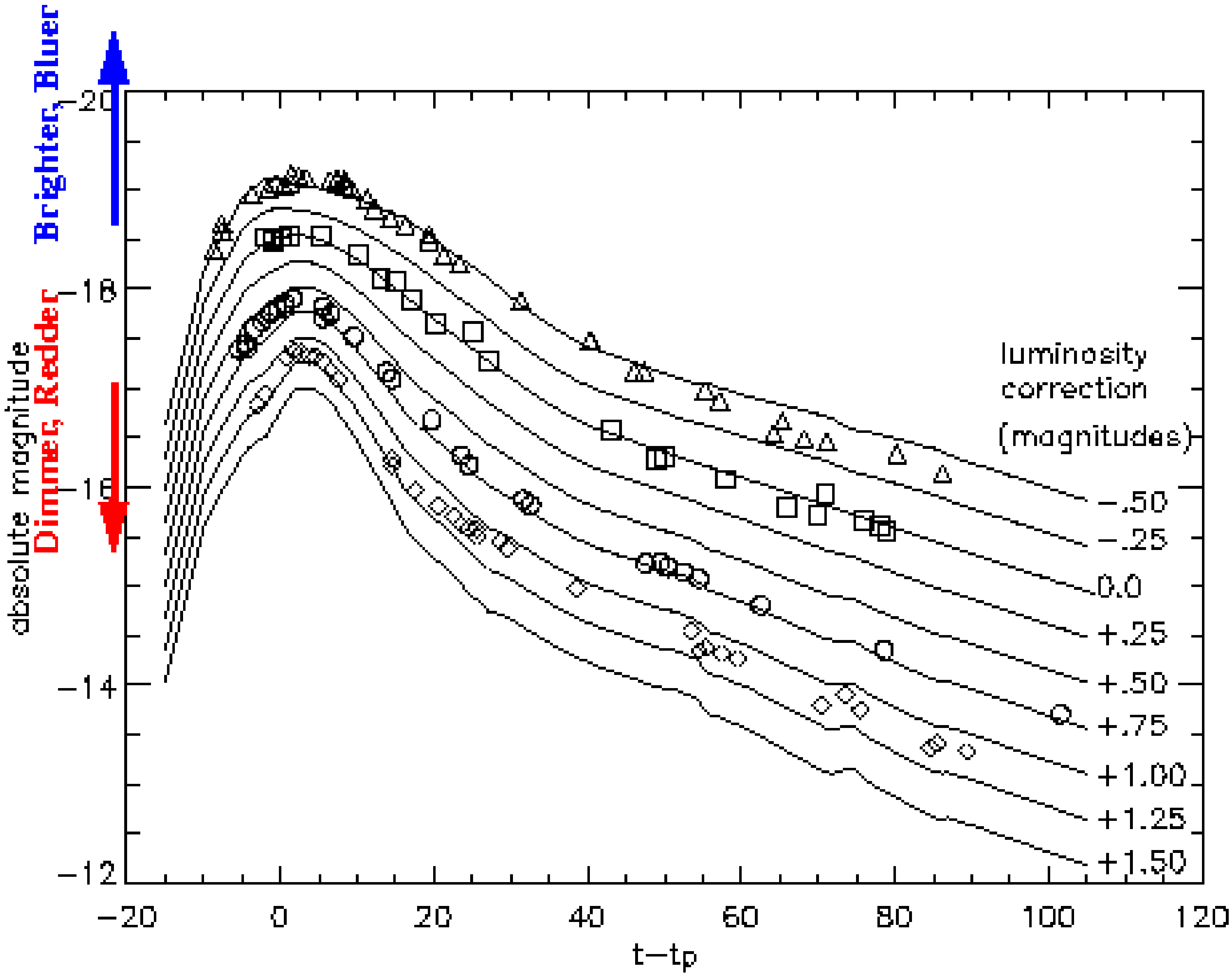

Abell 2218

Accelerating Expansion of the Universe

(Dark Energy)

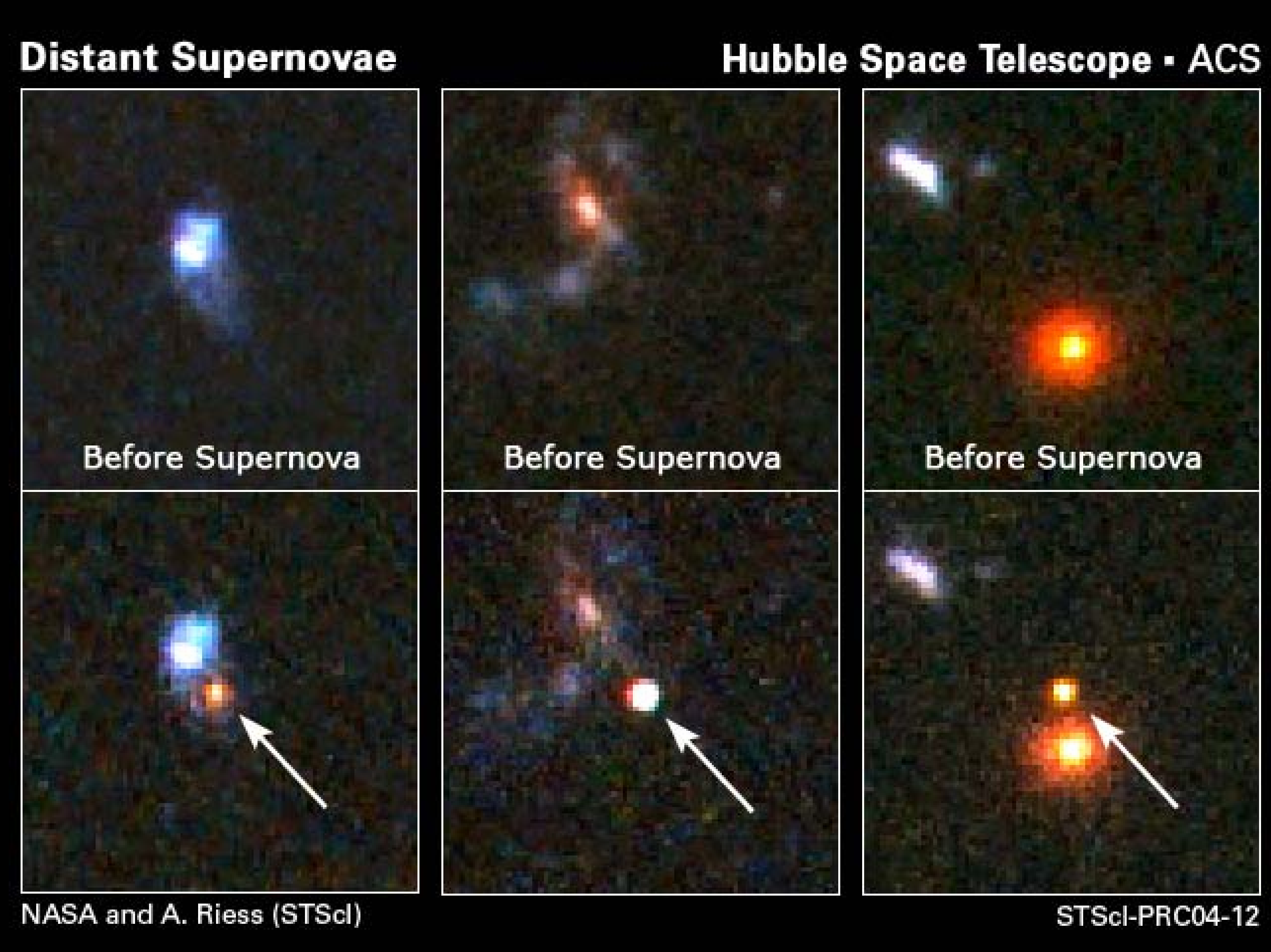


Perlmutter. 2003, Phys Today, **56**, 53



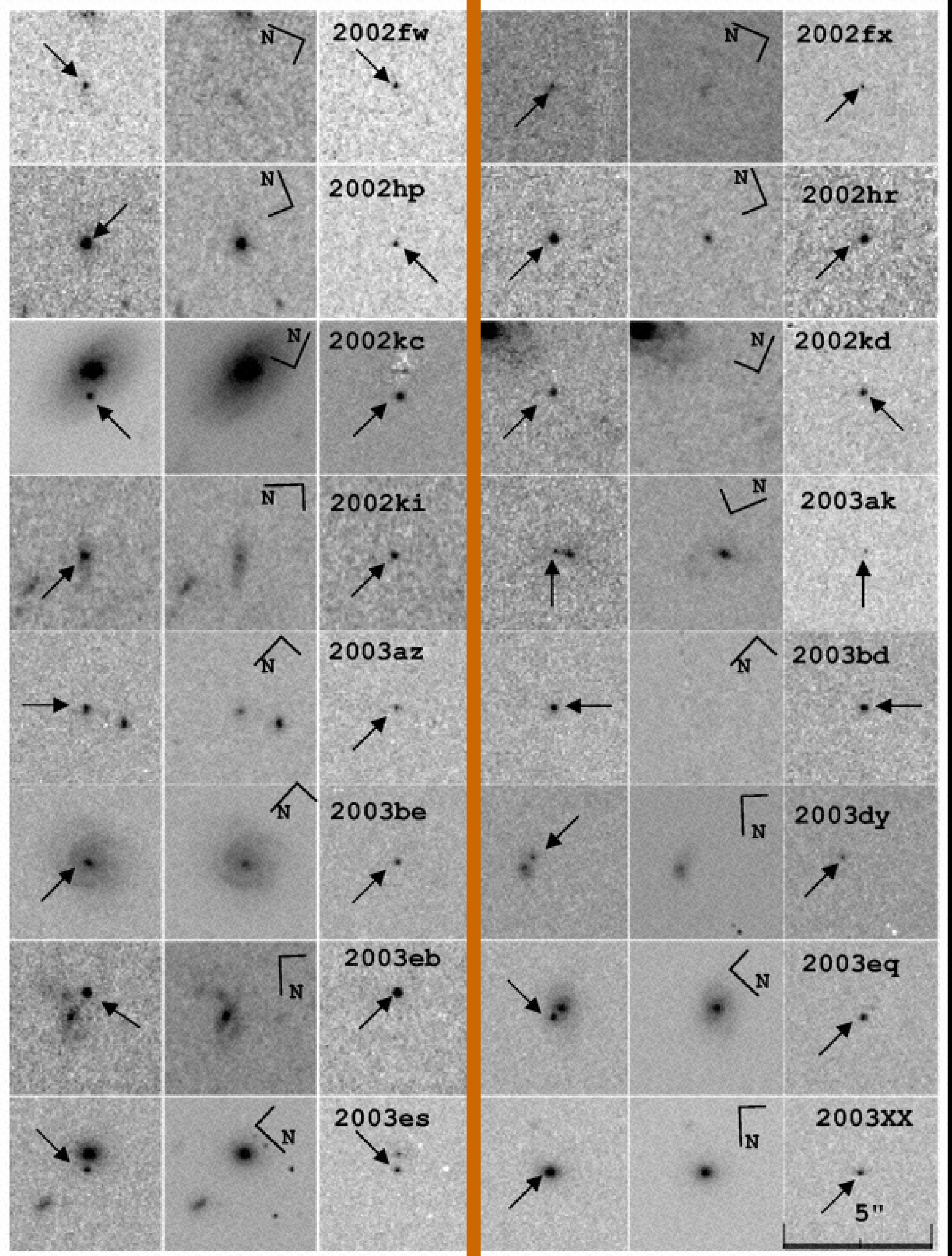
Phillips. 1993, ApJL, **413**, L105

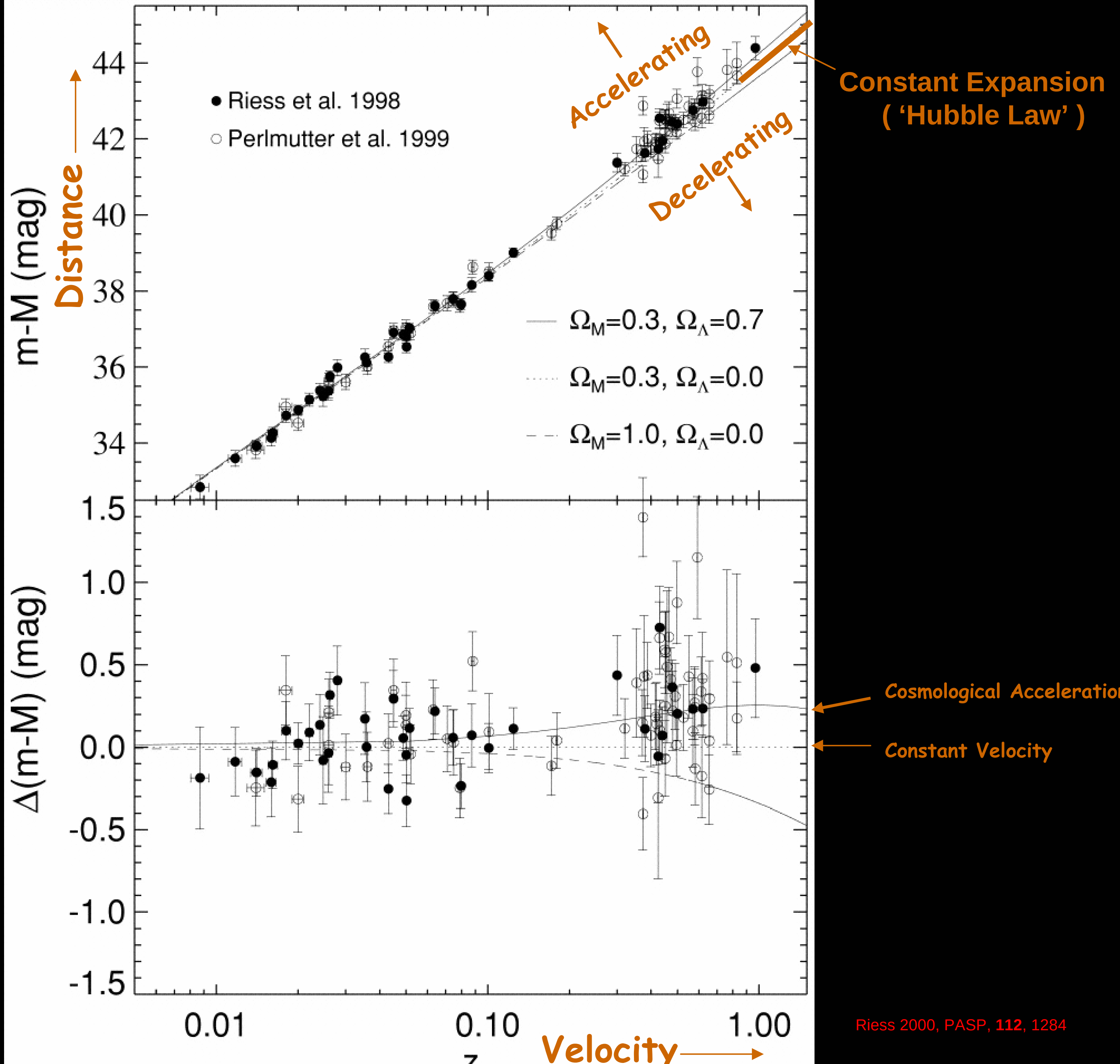

Galaxy NGC 4526
Supernova



Distant Supernovae
Hubble Space Telescope ▪ ACS
Before Supernova
Before Supernova
Before Supernova
NASA and A. Riess (STScI)
STScI-PRC04-12

Before/After Images of SNe Ia





Riess 2000, PASP, **112**, 1284

The Distant Universe:

Evolution of Galaxies

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 ($\sim$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 $\sim$0″.2) with HST in the longest planned exposures by guaranteed time observers (GTOs) (*4, 5*). For a given luminosity, the more compact the object the easier it is to detect. To escape detection from the ground but still be observed with HST, the faintest galaxies ($V > 27$) must have angular radii of less than $\sim$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

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 discovery would imply, contrary to some theoretical ideas (*8–9*), that the majority of the halo brown dwarfs have not yet cooled beyond the limiting sensitivity of HST. For the simplest case in which all of the brown dwarfs have the same absolute luminosity and mass, the number with an apparent infrared magnitude (m_{IR}) brighter than I is:

$$n(m_{IR} \leq I) = 100\left(\frac{\rho}{0.01\ M_\odot\ pc^{-3}}\right)\left(\frac{0.08\ M_\odot}{M_{brown\ dwarf}}\right) \times 10^{0.6[(I-26)-(M_I-15)]} \quad (1)$$

for the area of a WFC field (7.1 arc min^2). Here ρ is the halo density in the form of brown dwarfs in solar masses per cubic parsec and M_I is the absolute I band magnitude of the brown dwarfs. Possible values of these quantities are also indicated: $\rho_{halo} \sim 0.01\ M_\odot\ pc^{-3}$ (*7*), $I_{limiting} \sim 26$ (a conservative limit for a moderately long exposure), and $M_I \geq 15$ (the greatest source of uncertainty). The number of brown dwarfs in the disk could be of order ten or so per deep WFC field if the missing matter in the disk is all brown dwarfs. Some of these objects may be young enough to appear on deep WFC images. Brown dwarfs will be visible either by the rapid increase in the total star counts due to the appearance of the new population (see the $10^{0.6I}$ factor in Eq. 1) or by the discovery of very red objects with $V - I > 4$.

The longest HST exposures will also provide important new information on the number of faint quasi-stellar objects, quasars. The most accurate ground-based determinations of quasar numbers (*10*) do not reach fainter than blue magnitude $B = 21$, a limit which could be extended by a factor of more than a thousand in brightness by HST images. A naive extrapolation of the ground-based observations would suggest that the quasar number density at faint 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 galaxy parameters, we have been forced to extrapolate quantities that have been measured accurately only for relatively bright galaxies ($V \leq 15$), even though the vast majority of galaxies in the simulated images (and those expected to be detected in the WFC deep images) are much fainter ($V > 22$).

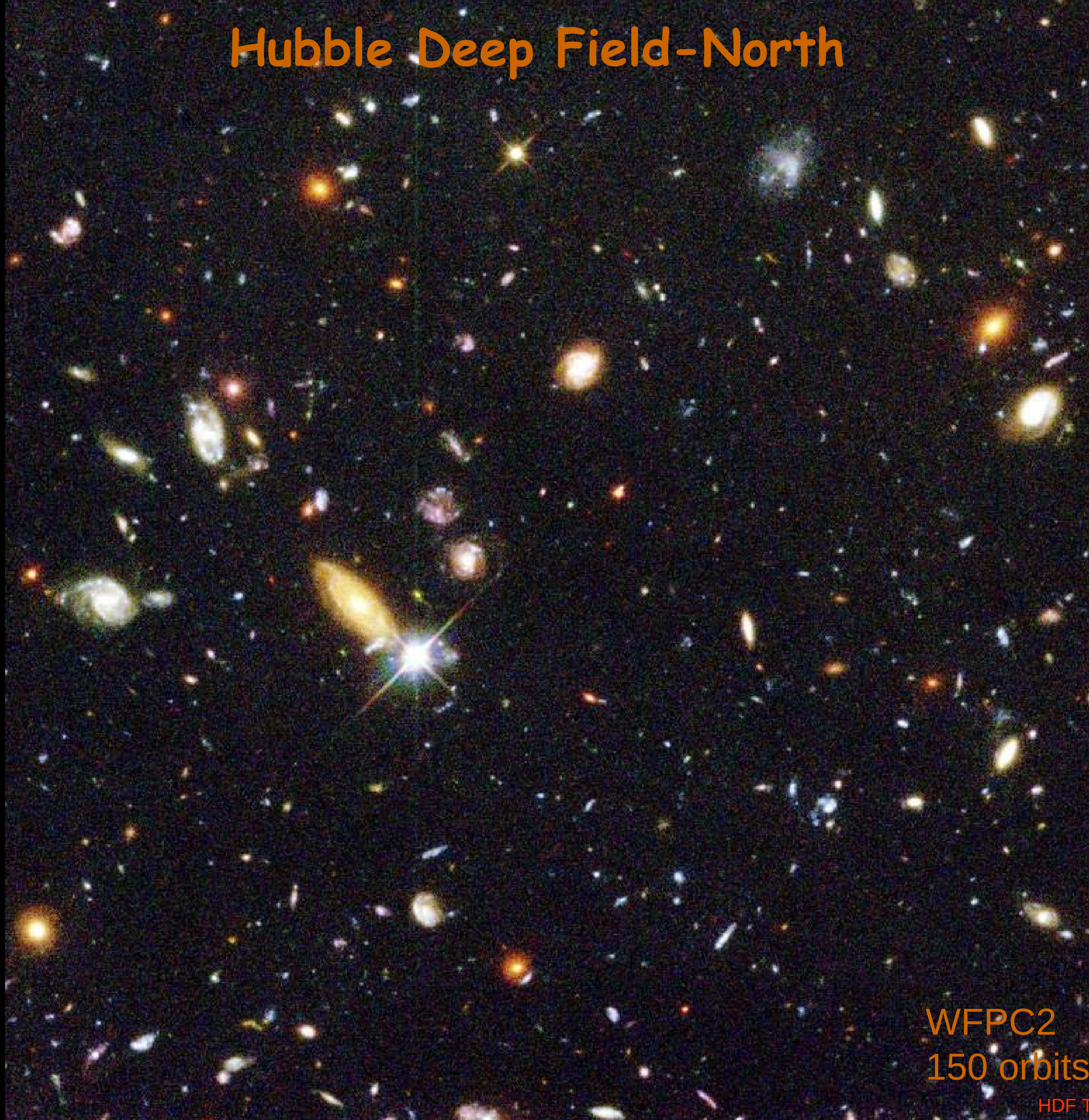
Our results show that the most sensitive exposures achieved so far from the ground reveal more galaxies per unit area than will be seen by planned HST observations unless galaxy sizes decrease with apparent brightness at the maximum rate consistent with existing ground-based observations. In this, the most favorable case for HST, the space exposures will show almost as many galaxy images as have been observed so far in the most sensitive ground-based data.

Figure 1 is constructed with simulation software (*11*) that embodies the characteristics of the HST, the WFC, and the expected number density of galaxies and stars as a function of apparent magnitude. Each frame represents one quarter of a WFC field (80″ by 80″). These pictures are in some sense "ideal" images; the effects of cosmic rays and detector systematics are presumed to be removed perfectly from the images.

A simulation of a moderately long exposure, one orbit or 2300 seconds, made with the wide band visual (V) filter (F555W) is shown in Fig. 1A. This simulation suggests that HST images of high-latitude random fields will not contain many objects unless extremely long exposures are taken.

Our best estimates of what will be observed on very long exposures in which data from eleven orbits are co-added are shown in Fig. 1, B and C. Figure 1B simulates observations made with the wide band visual filter (same as for Fig. 1A except that the exposure time is 11 times longer) and Fig. 1C simulates observations made with the broad band I filter (F785LP). The simulations refer to the longest broad band observations (slightly more than 7 hours) on a

Hubble Deep Field-North

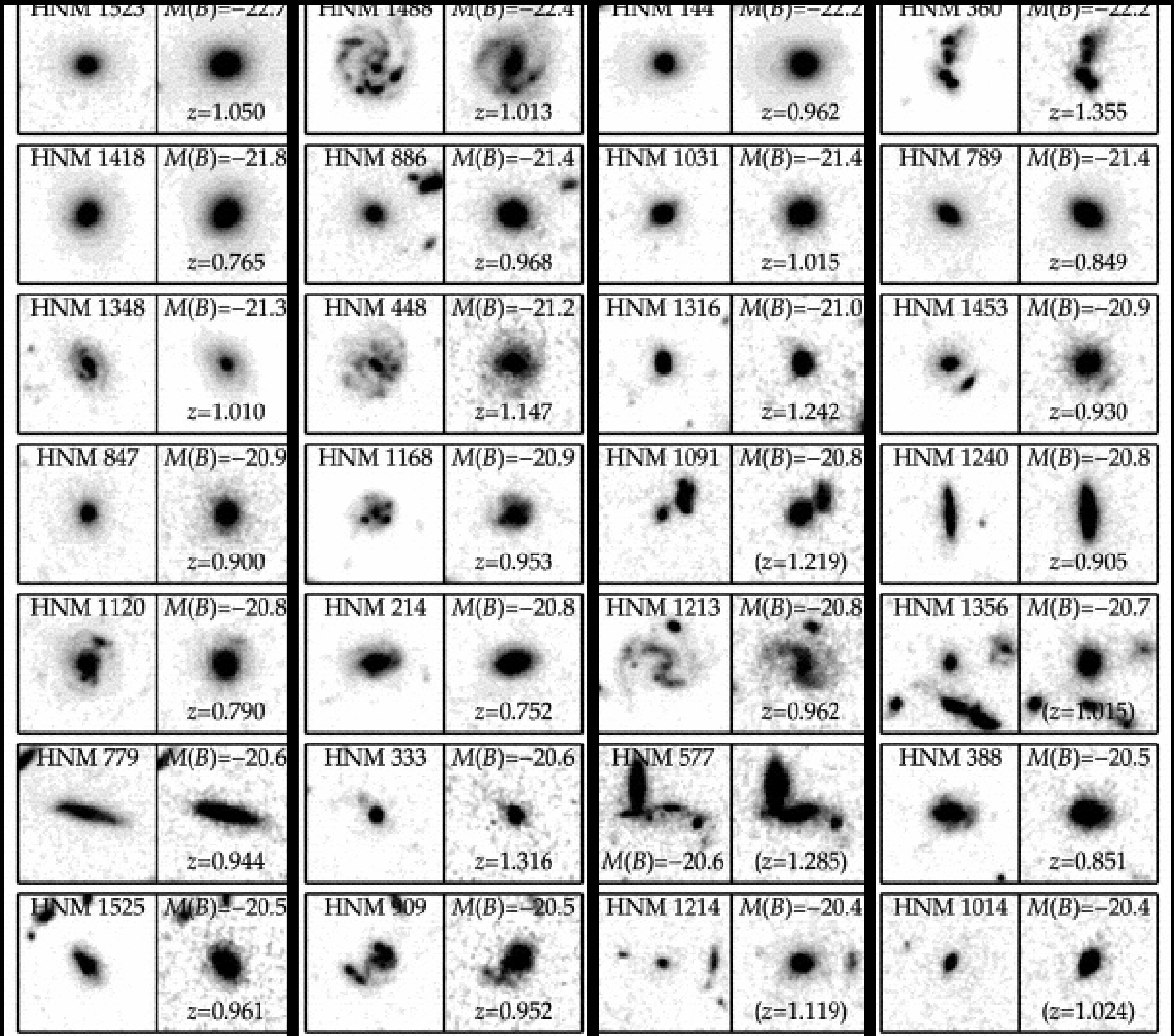


HDF Team

Hubble Deep Field-North with Keck Redshifts

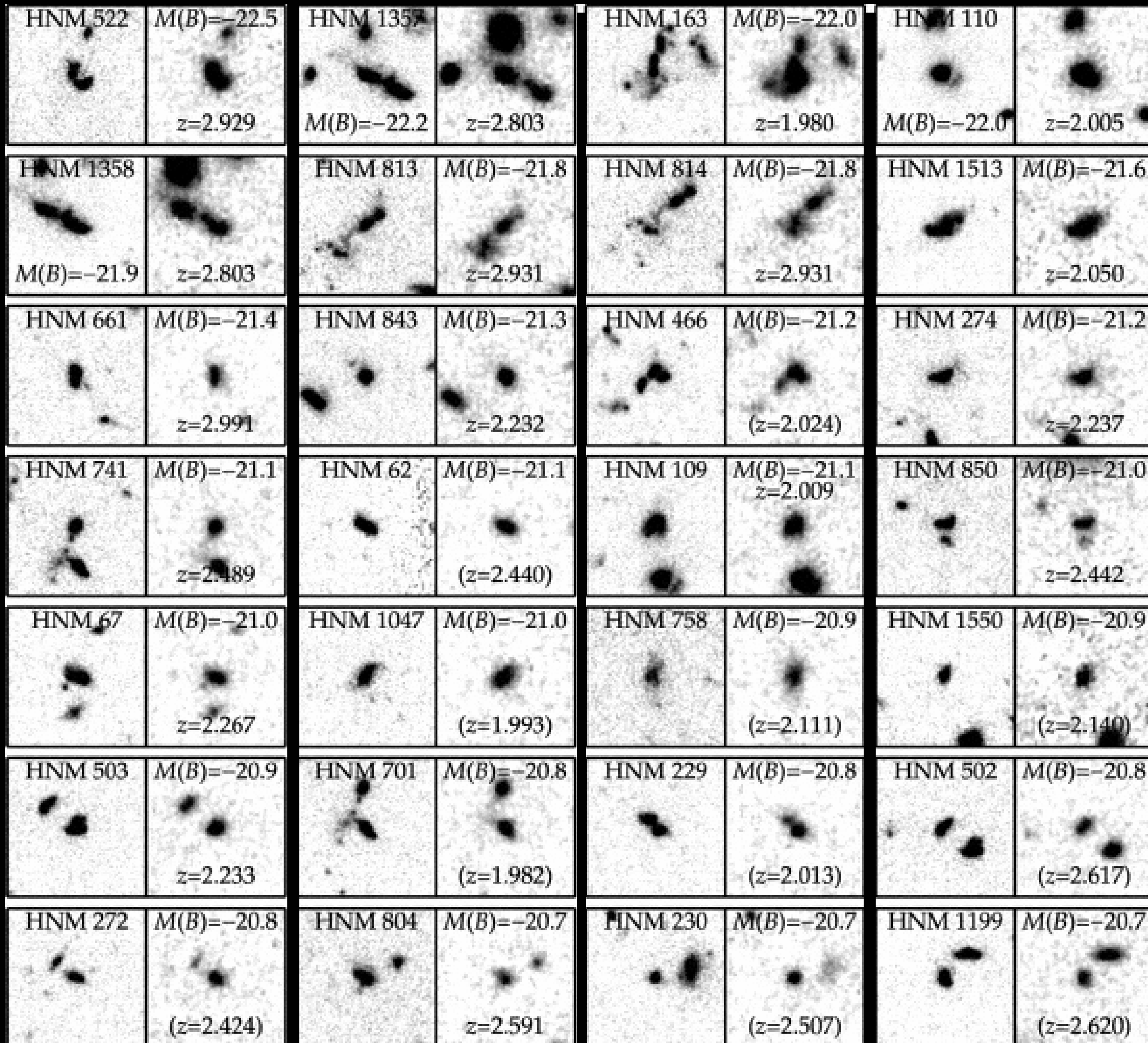
Papovich et al. 2005, ApJ, **631**, 101

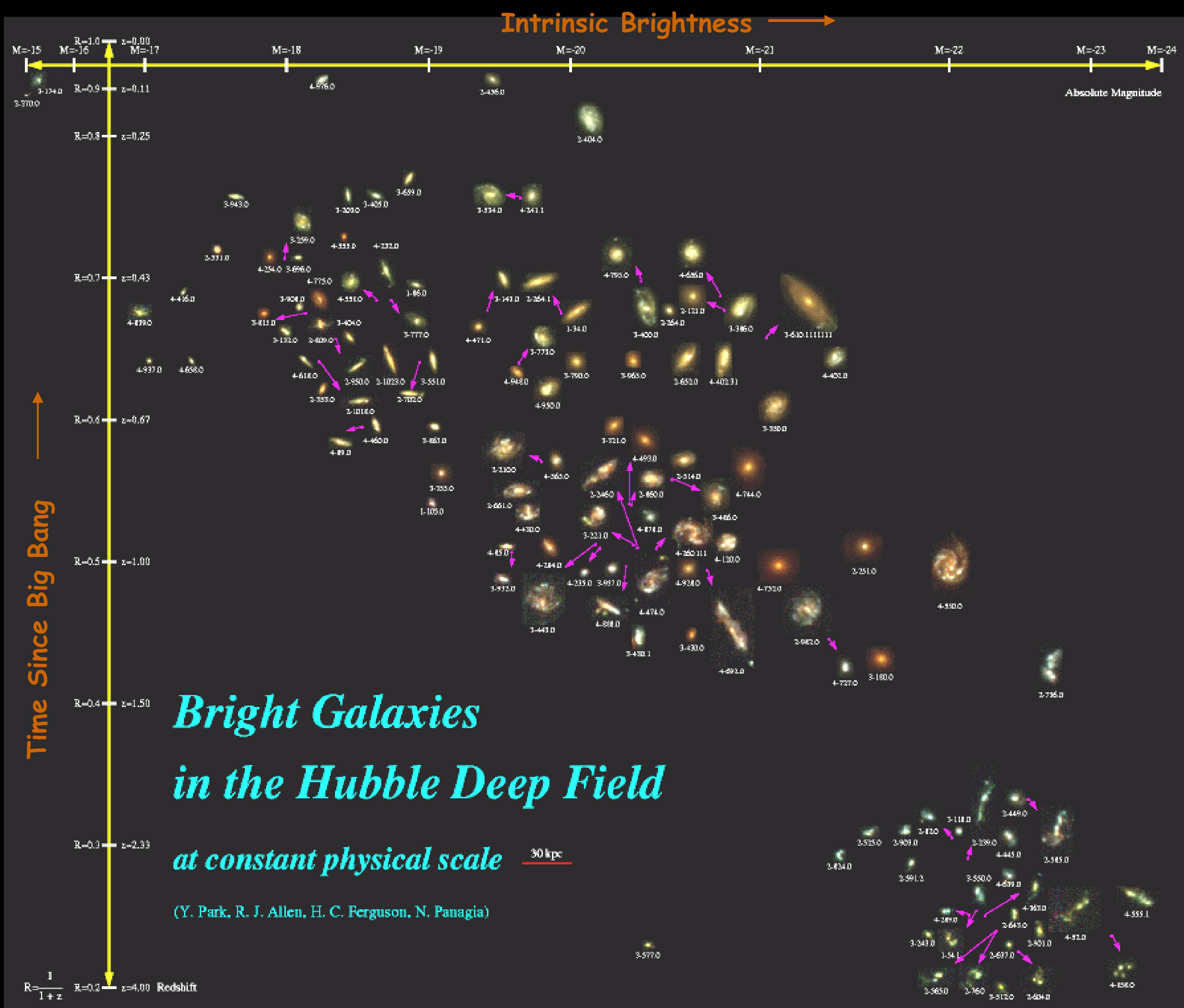
HDF-N z=1 Galaxies



Papovich et al. 2005, ApJ, **631**, 101

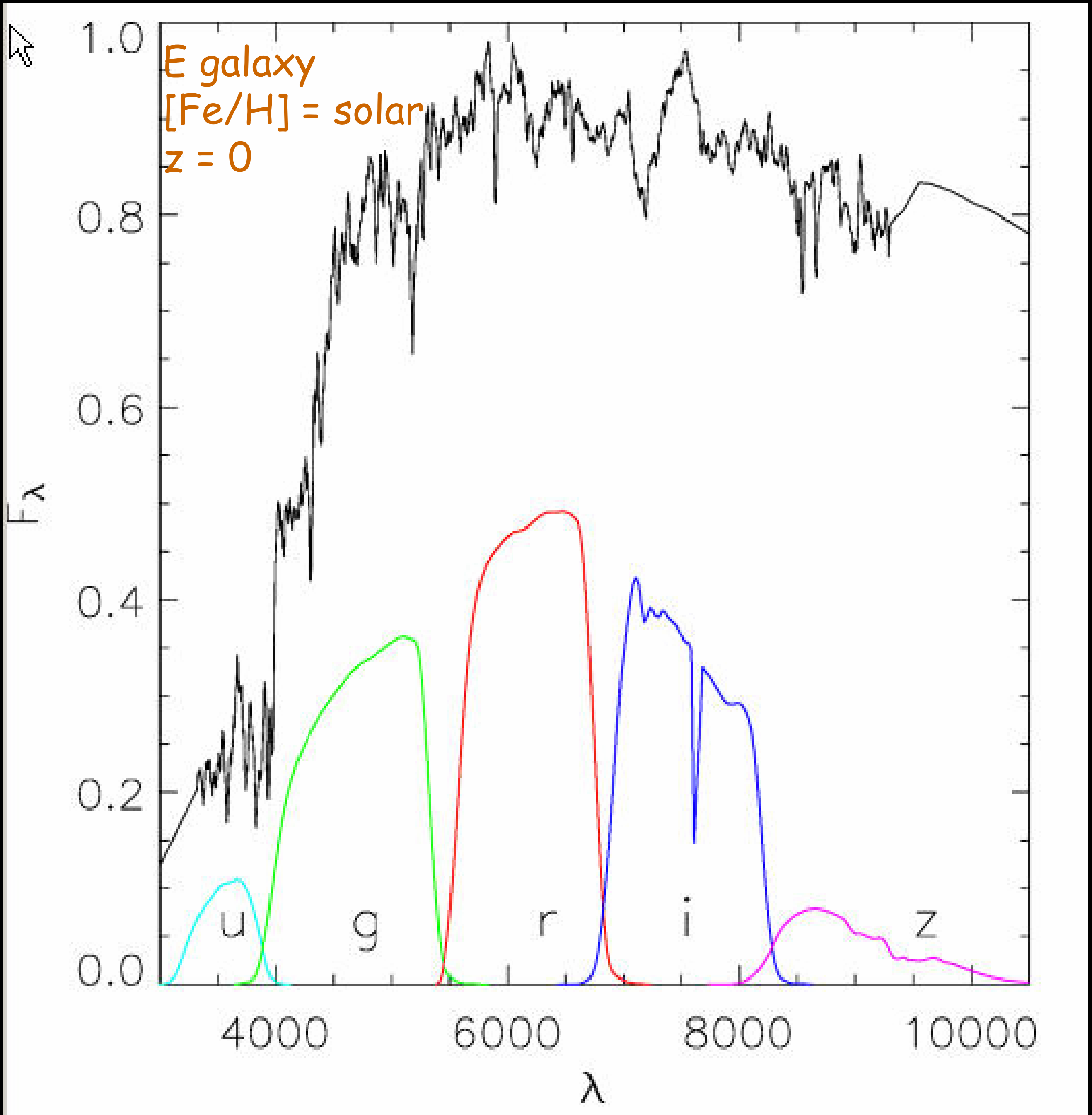
HDF-N z=2.4 Galaxies



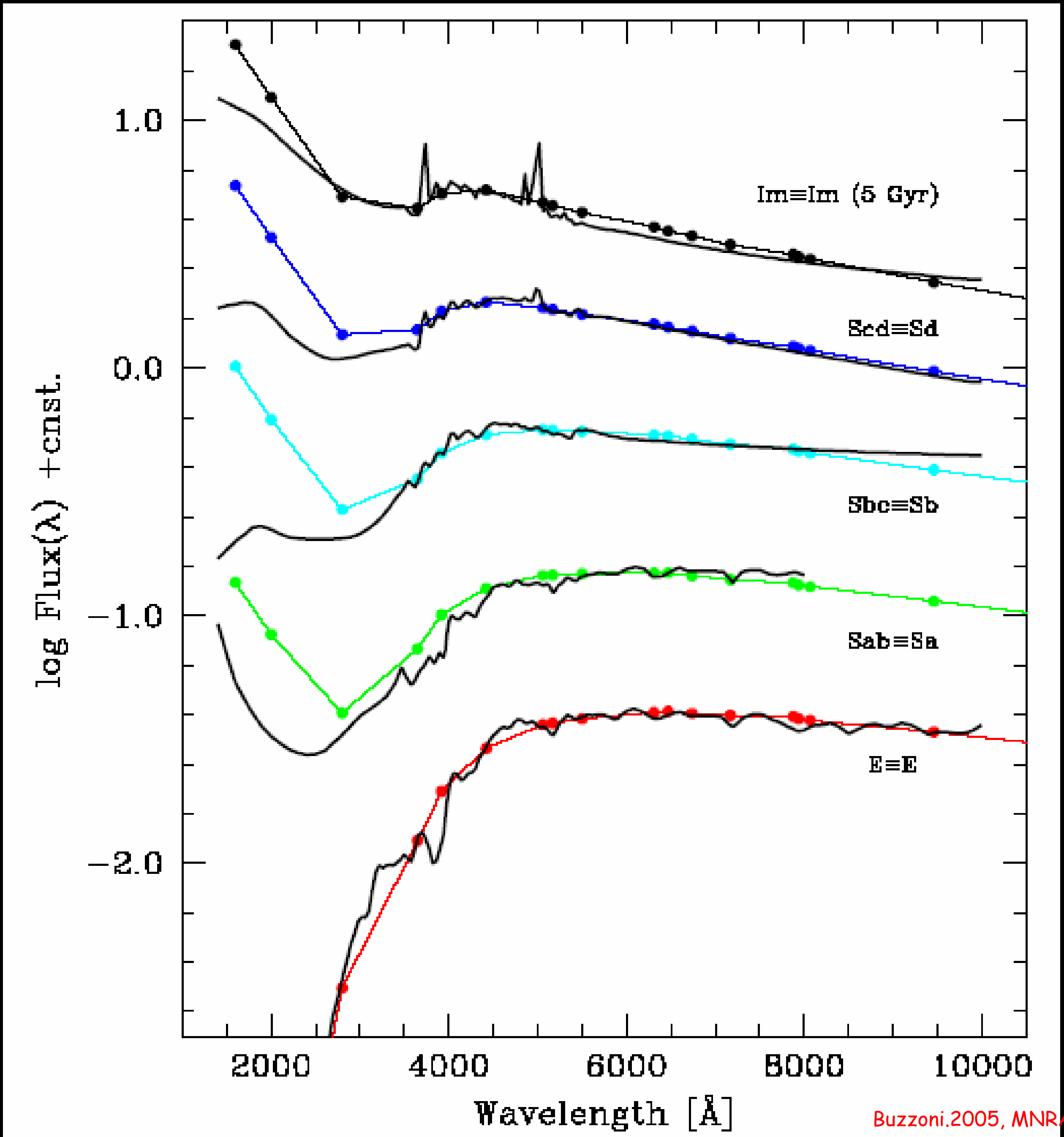


Intrinsic Brightness
M=-15 M=-16 M=-17 M=-18 M=-19 M=-20 M=-21 M=-22 M=-23 M=-24
Absolute Magnitude
R=1.0 z=0.00
R=0.9 z=0.11
R=0.8 z=0.25
R=0.7 z=0.43
R=0.6 z=0.67
R=0.5 z=1.00
R=0.4 z=1.50
R=0.3 z=2.33
R=0.2 z=4.00 Redshift
R=1/(1+z)
Time Since Big Bang
Bright Galaxies
in the Hubble Deep Field
at constant physical scale
30 kpc
(Y. Park, R. J. Allen, H. C. Ferguson, N. Panagia)

Photometric Redshifts

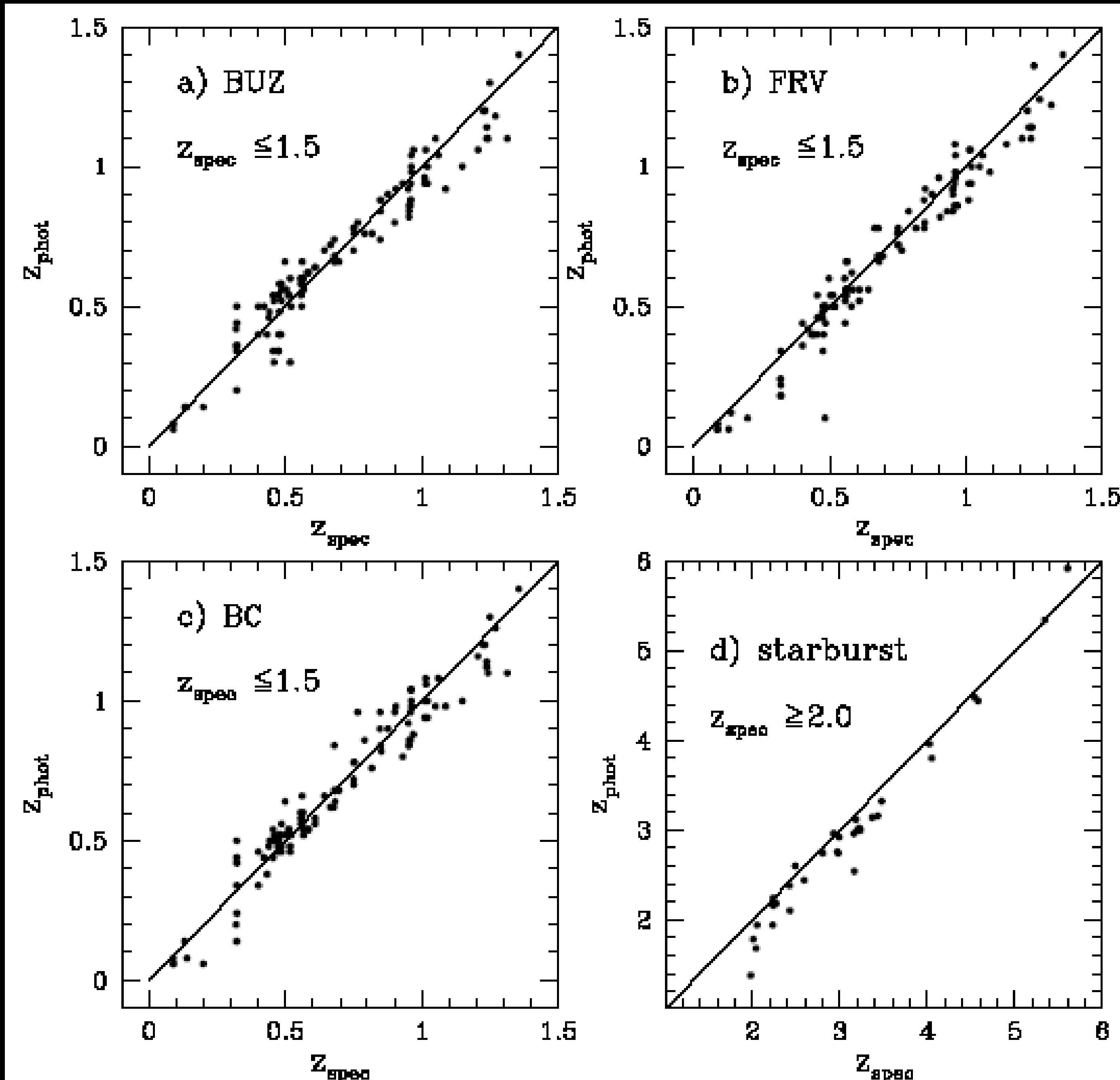


Galaxy Spectral Templates

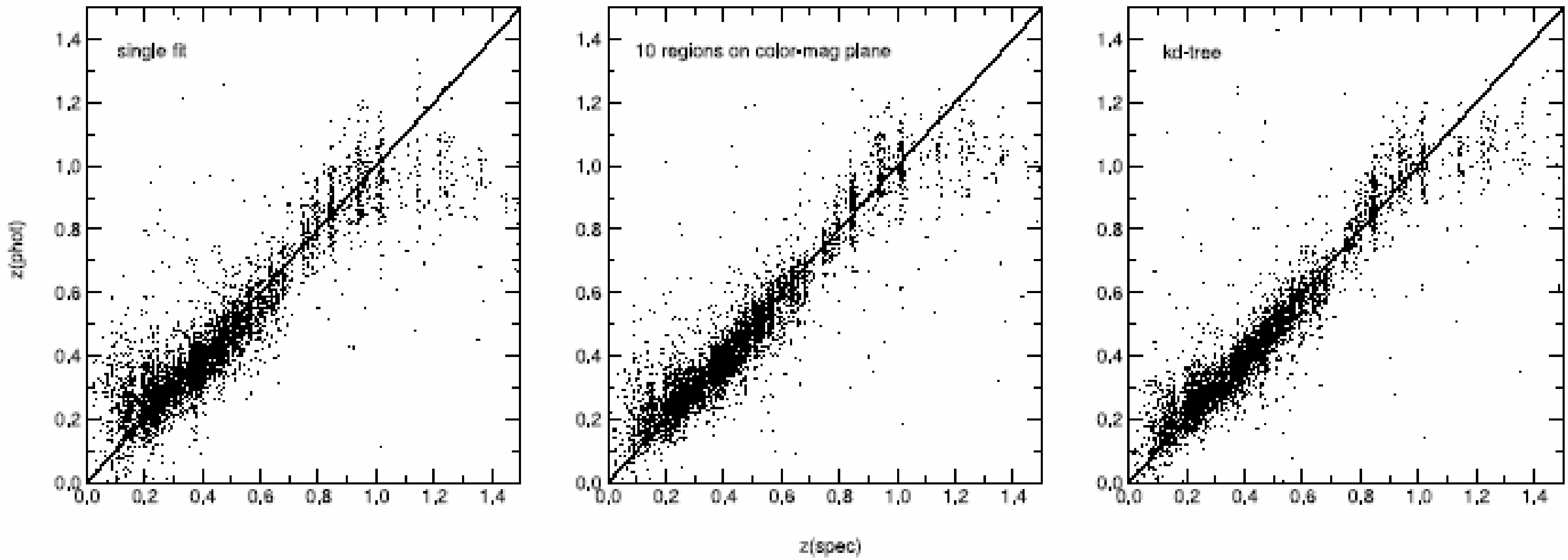


Buzzoni.2005, MNRAS, **361**, 725

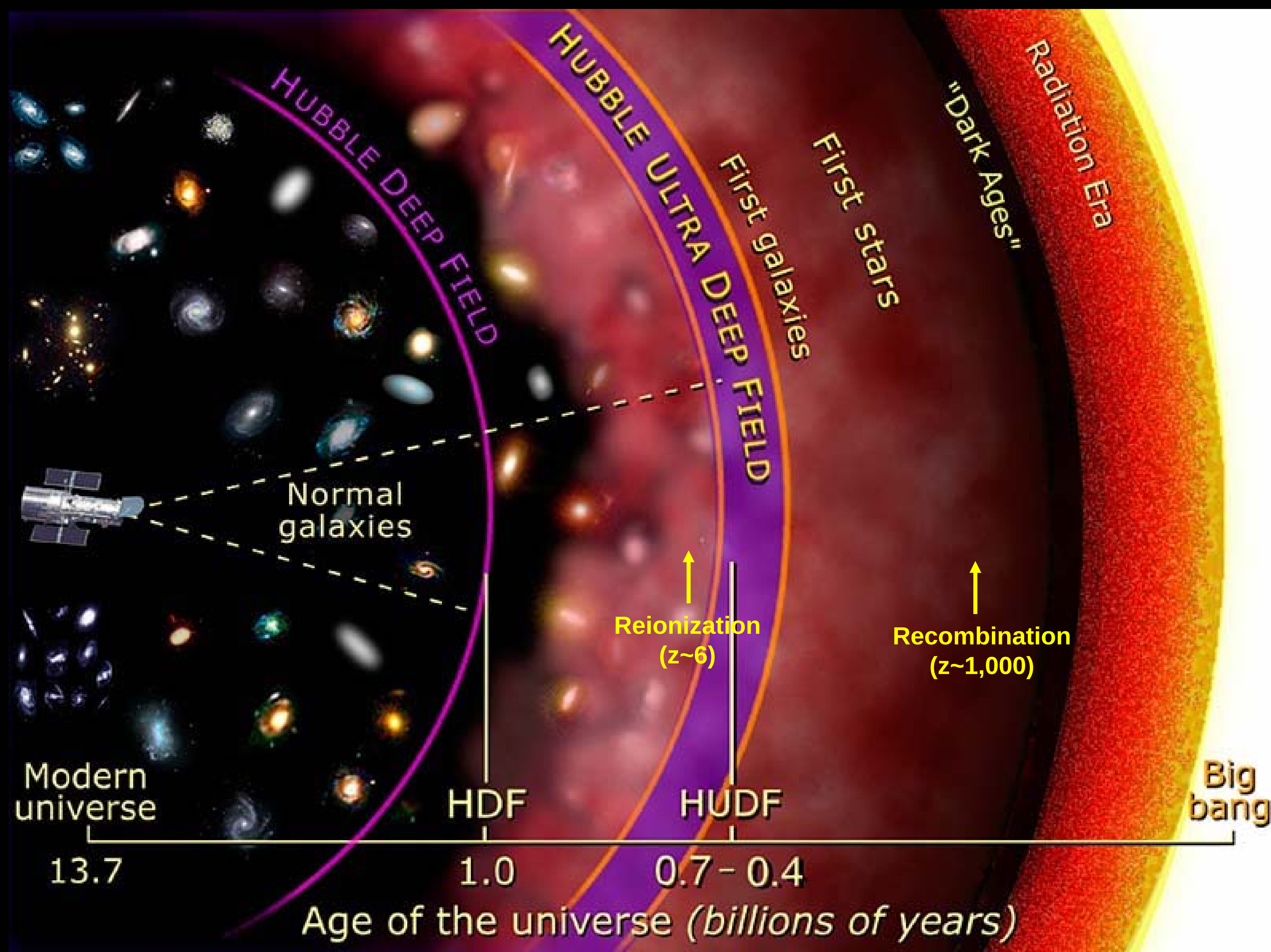
Accuracy of Photometric vs. Spectroscopic Redshifts



Massarotti et al. 2001, **380**, 425



Hsieh, 2005, ApJ Supp, **158**, 161



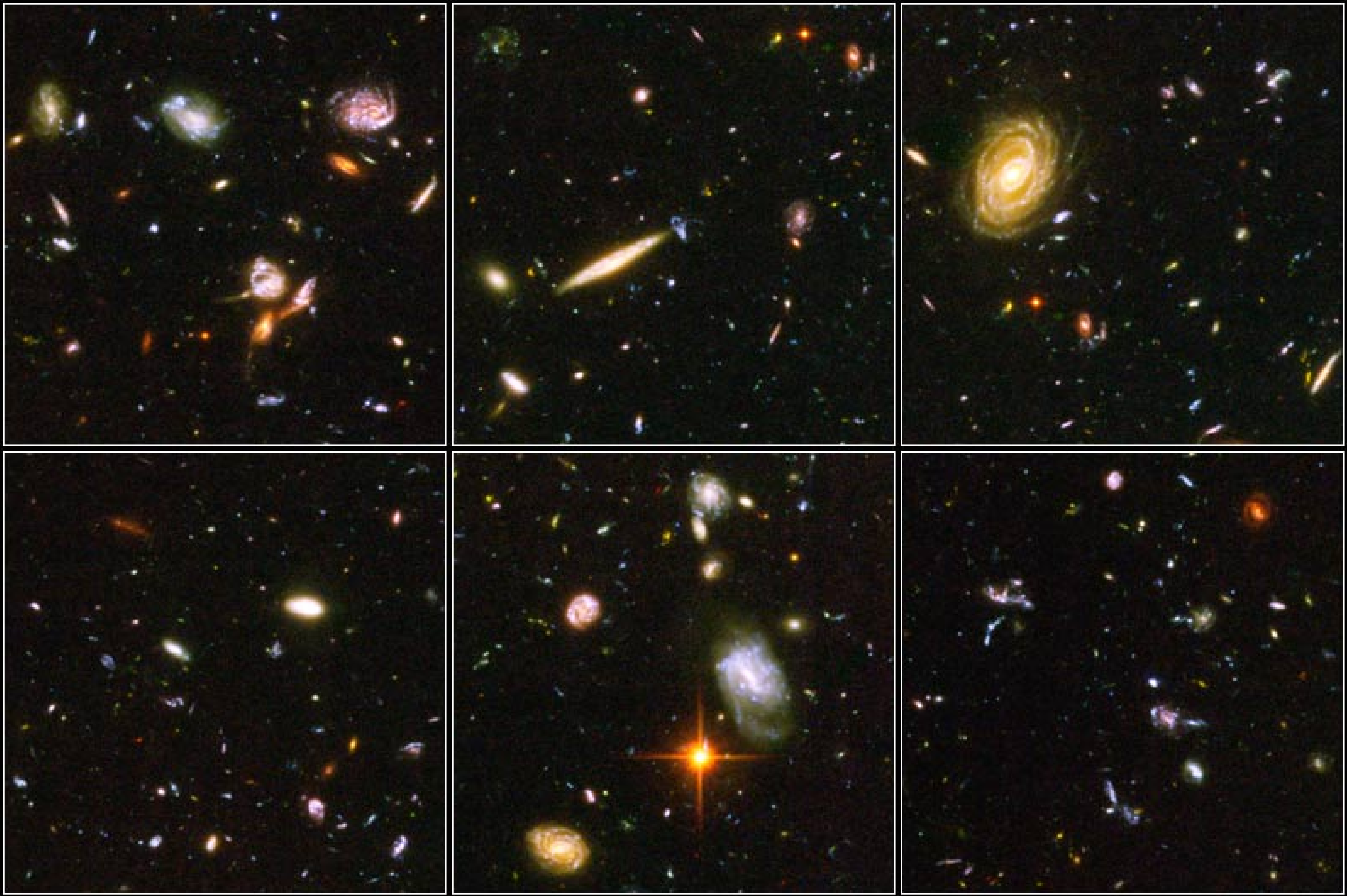
Hubble Deep Field
Hubble Ultra Deep Field
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Reionization (z~6)
Recombination (z~1,000)
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

Hubble Ultra Deep Field HST ▪ ACS

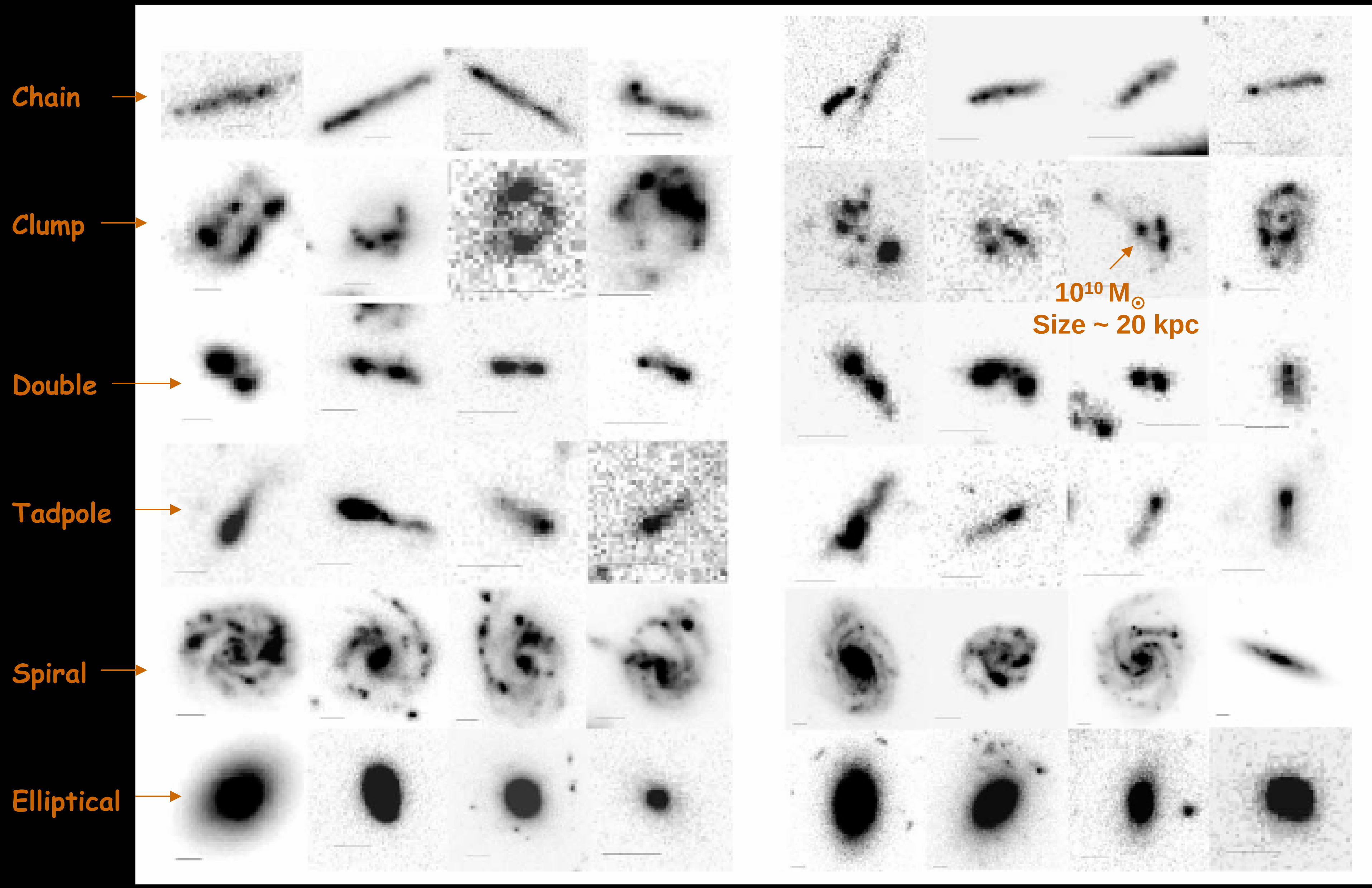
S. Beckwith+HUDF Team

Hubble Ultra Deep Field Details

HST ▪ ACS

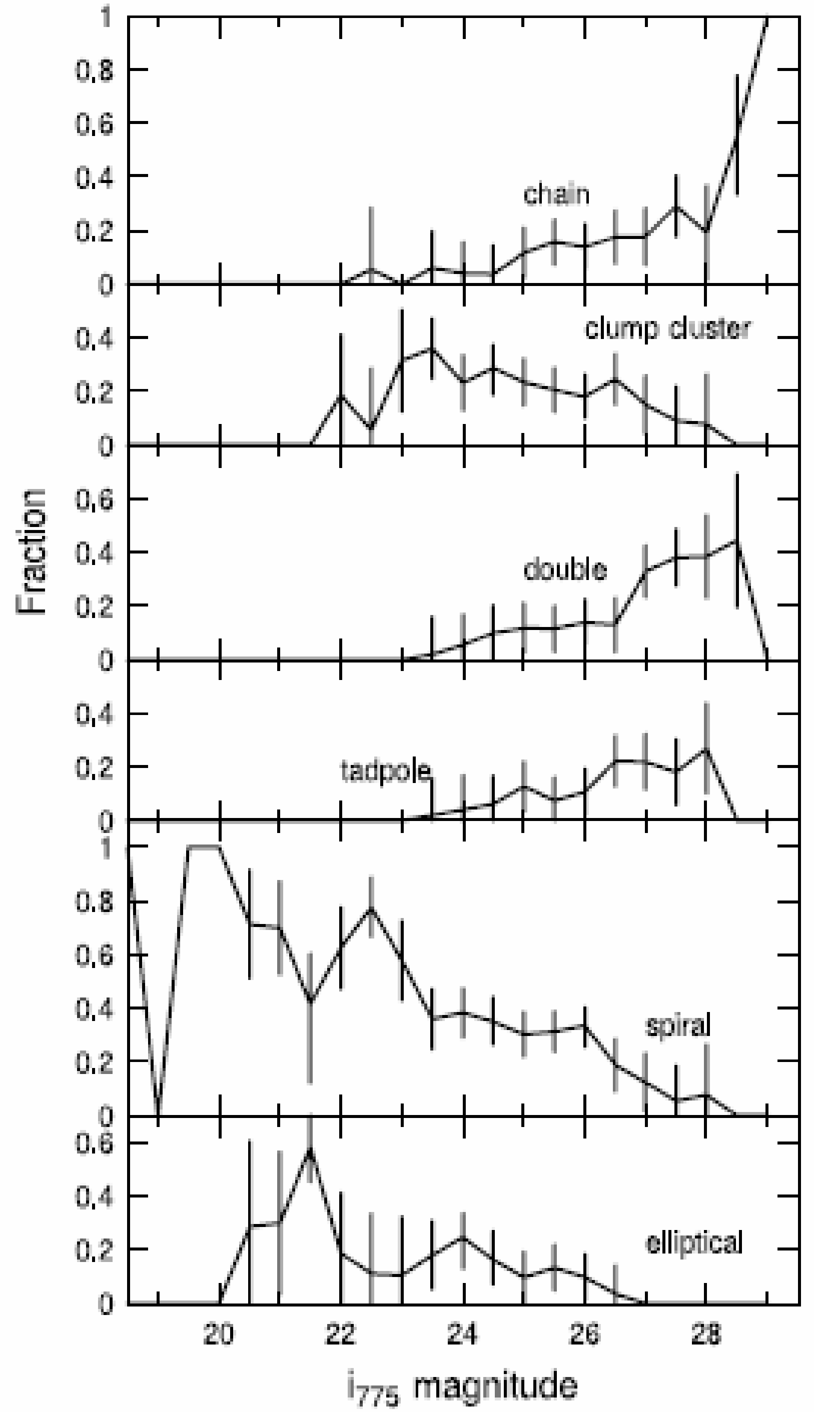


S. Beckwith+HUDF Team



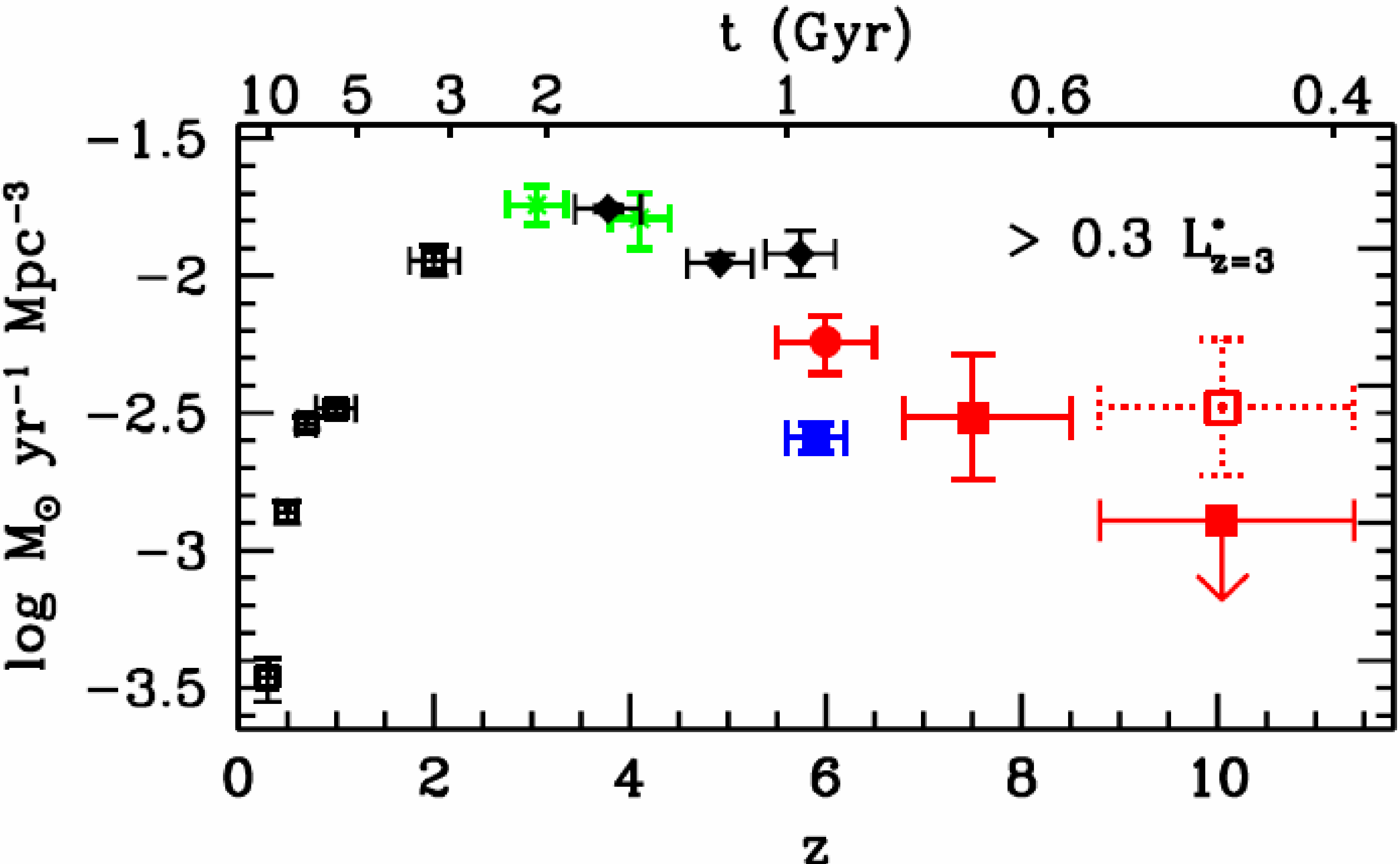
Galaxies in the HUDF

Elmegreen et al. 2005, ApJ, **631**, 85



Elmegreen et al. 2005, ApJ, **631**, 85

Cosmic Star Formation History



Bouwens et al. 2005 , astro-ph 0510697

Hubble's Legacy

- **Scientific Results**

  -Detected acceleration of the universe

  >>>> *Affirmed existence of 'dark energy'*

  -Detected distant galaxies before the Hubble sequence had formed

  >>>> *Validated the concept of photometric redshifts*

  -First direct detection of planetary atmosphere constituent outside solar system

  >>>> *Na I D line absorption in transiting planet around HD 209458*

  -Characterized supermassive black holes in centers of galaxies

  -Demonstrated that disks around young stars are common

  >>>> *Other solar systems may be very common*

  -Resolved and characterized previously unresolved stellar systems

  >>>> *Made H-R Diagrams possible for extragalactic systems*

  -Observed rare solar system phenomena

- **Impact on Science Culture**

  -Importance of Director's Discretionary time in defining science program

  -Importance of archival data with finite proprietary time for data

  -Importance of multi-wavelength, coordinated observations on other telescopes

  -Value of data reduction funding

  -Value of large public outreach program, i.e., engaging the public