Extragalactic Astronomy

Lecture 9: Galaxies at high z
Formation of spirals and ellipticals
Galaxy evolution

Definitions

- Redshift desert
- Lyman-break (UV drop-out)
- Photometric redshifts:
  - SEDs
  - Colors
- Distribution in z
- Comparison HST WFPC2 vs NICMOS

Redshift desert 1 < z < 2.5

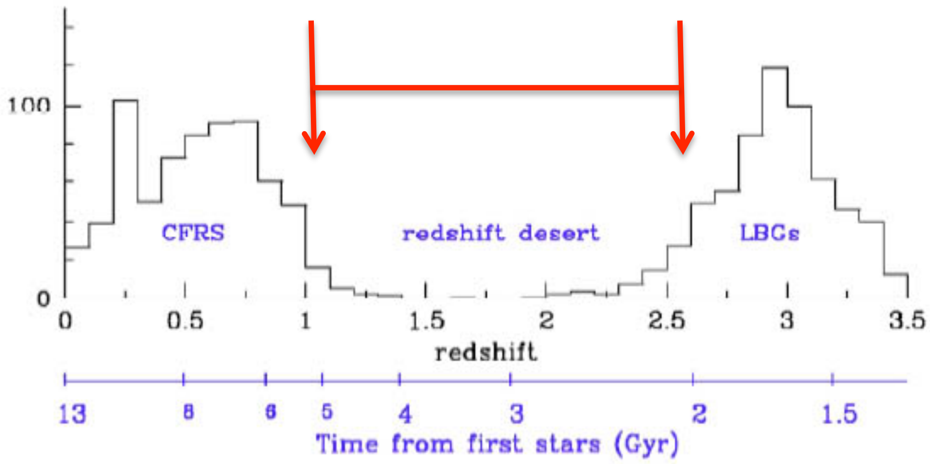
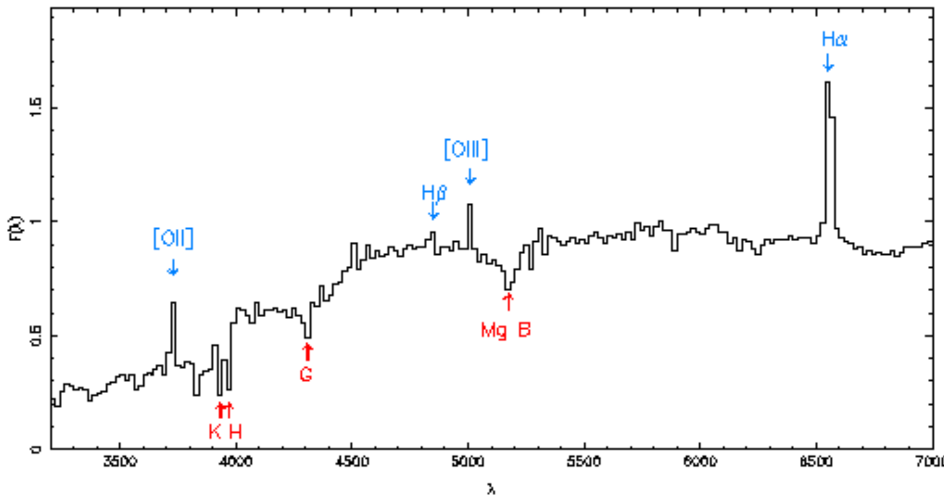


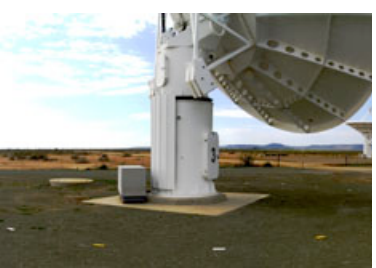
Fig.1: distribution of the number of galaxies as a function of redshift (2001). CFRS = Canada-France Redshift Survey.

- Term used in 1999-2000
- Disappeared in 2004 after the work of Steidel
- [OII] 3727 line in the IR
- Lyman-α line in the UV

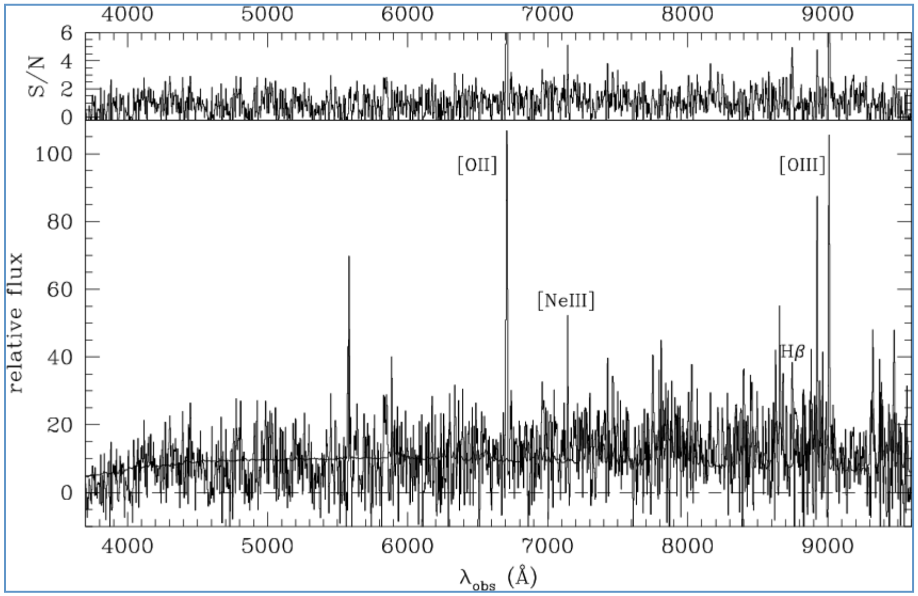
Optical Emission Lines

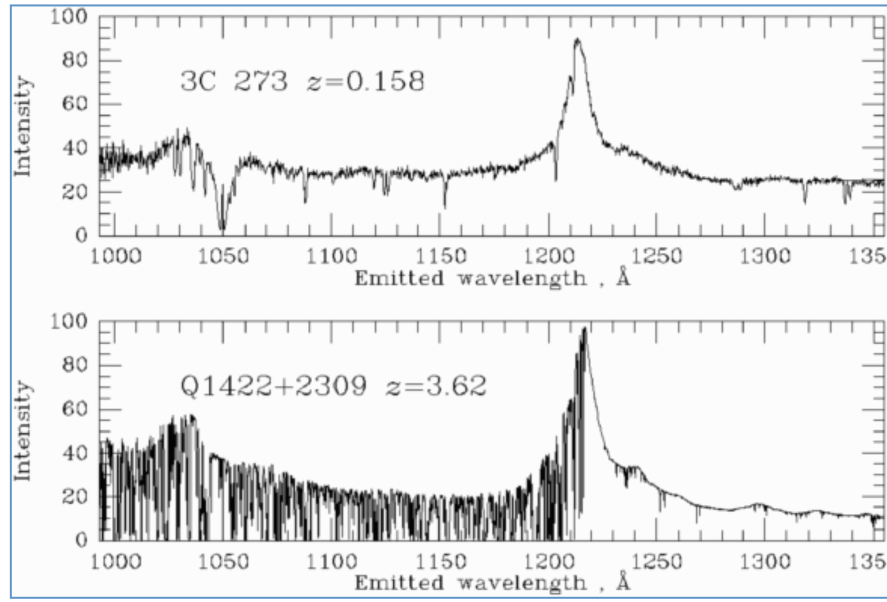


Emission Lines	
[OII]	3727Å
H-beta	4861Å
[OIII]	5007Å
H-alpha	6563Å
Absorption Lines	
Ca K	3933Å
Ca H	3969Å
Ca G	4303Å
Mg b	5174Å



Redshift desert 1 < z < 2.5

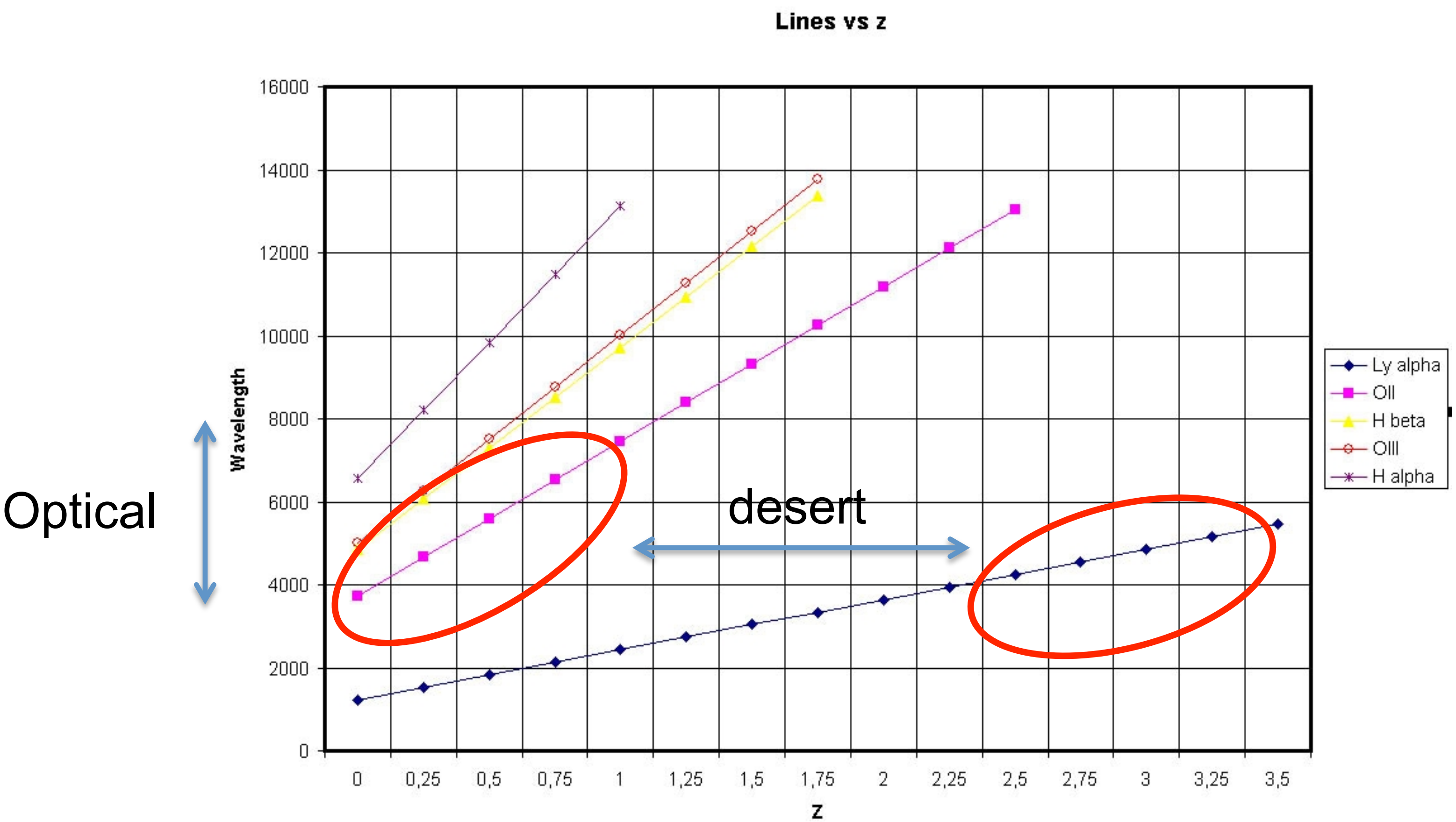




$[OII]_{3727}$ in the red – Hα in the nIR

Lα in the UV (rest frame)

Redshift desert 1 < z < 2.5



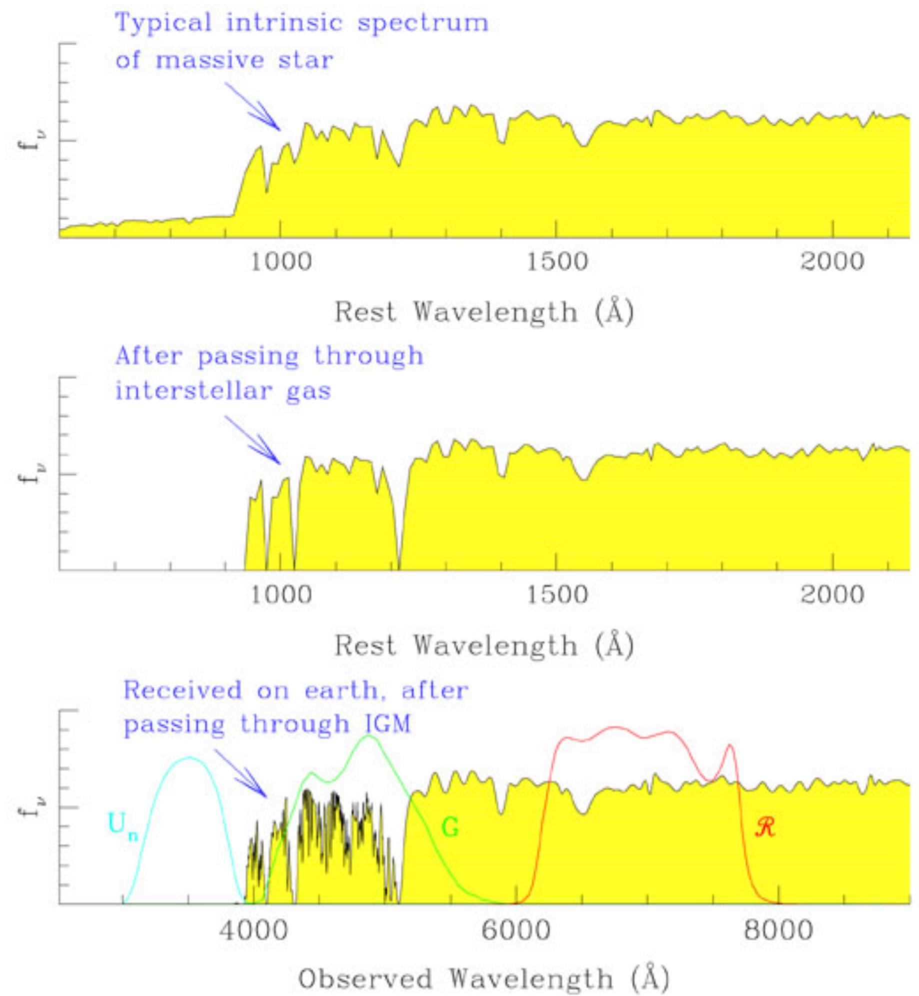
Observational selection effect

Lyman-break (UV drop-out)

- Lyman-break galaxies have very active SF regions = tied to the number of massive stars
- Lyman-break galaxies: (U-G) > 1.0 and (G-R) < 1.2 & R < 25.5 (for spectroscopic follow-up)
- E.g.: In 1000 Mpc^3, @ z ~ 2.5, there are 10 Lyman-break galaxies with R < 25.5 (the number of galaxies goes down @ z ~ 3-4)

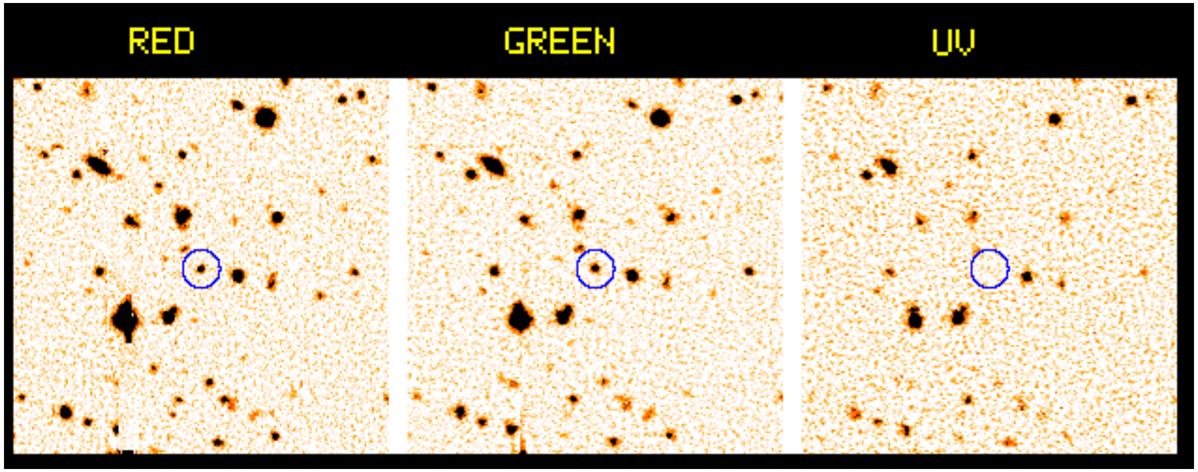
Lyman-break (UV drop-out)

The UV (rest frame) spectra of those galaxies is similar to a local starburst galaxy



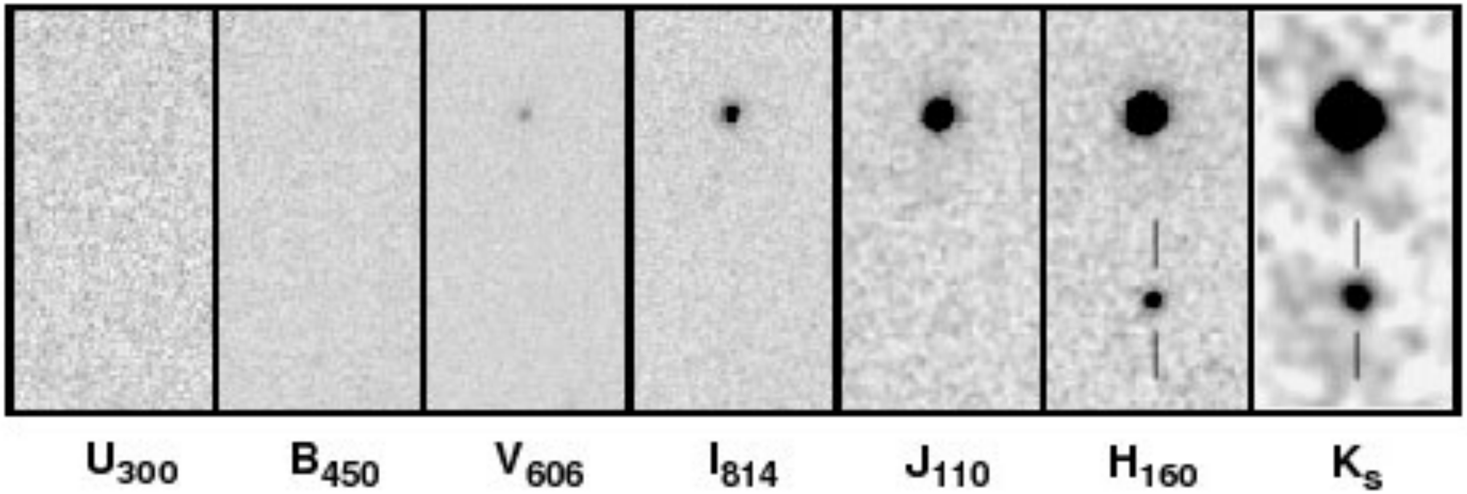
Lyman break galaxy @ z~3 from Pettini (2003)

Lyman-break (UV drop-out)



- Far UV, flux dominated by massive stars
- Red, green, UV used to find the galaxies at large z
- No UV flux

Lyman-break (UV drop-out)



Lyman-break galaxies

THE ASTROPHYSICAL JOURNAL, 522:L9–L12, 1999 September 1

AN EXTREMELY LUMINOUS GALAXY AT $z = 5.74$

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ABSTRACT

We report the discovery of an extremely luminous galaxy lying at a redshift of $z = 5.74$, SSA22-HCM1. The object was found in narrowband imaging of the SSA22 field using a 105 Å bandpass filter centered at 8185 Å during the course of the Hawaii narrowband survey using the Low-Resolution Imaging Spectrograph (LRIS) on the 10 m Keck II telescope, and it was identified by the equivalent width of the emission [W_λ(observed) = 175 Å, flux = 1.7×10^{-17} ergs cm^{-2} s^{-1}]. Comparison with broadband colors shows the presence of an extremely strong break (>4.2 at the 2 σ level) between the Z band above the line, where the AB magnitude is 25.5, and the R band below, where the object is no longer visible at a 2 σ upper limit of 27.1 (AB magnitudes). These properties are only consistent with this object's being a high-z Lyα emitter. An 18,000 s spectrum obtained with LRIS yields a redshift of 5.74. The object is similar in its continuum shape, line properties, and observed equivalent width to the $z = 5.60$ galaxy HDF 4–473.0, as recently described by Weymann et al., but is 2–3 times more luminous in the line and in the red continuum. For $H_0 = 65$ km s^{-1} Mpc^{-1} and $q_0 = (0.02, 0.5)$, we would require star formation rates of around (40, 7) $M_\odot$ yr^{-1} to produce the UV continuum in the absence of extinction.

Subject headings: cosmology: observations — early universe — galaxies: evolution — galaxies: formation

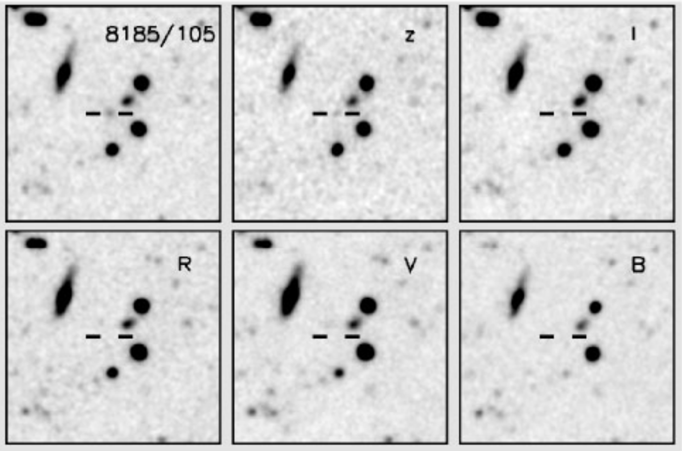
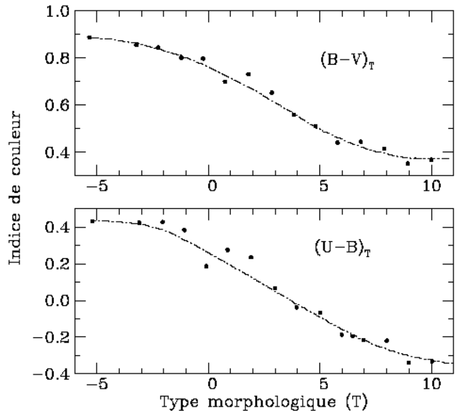
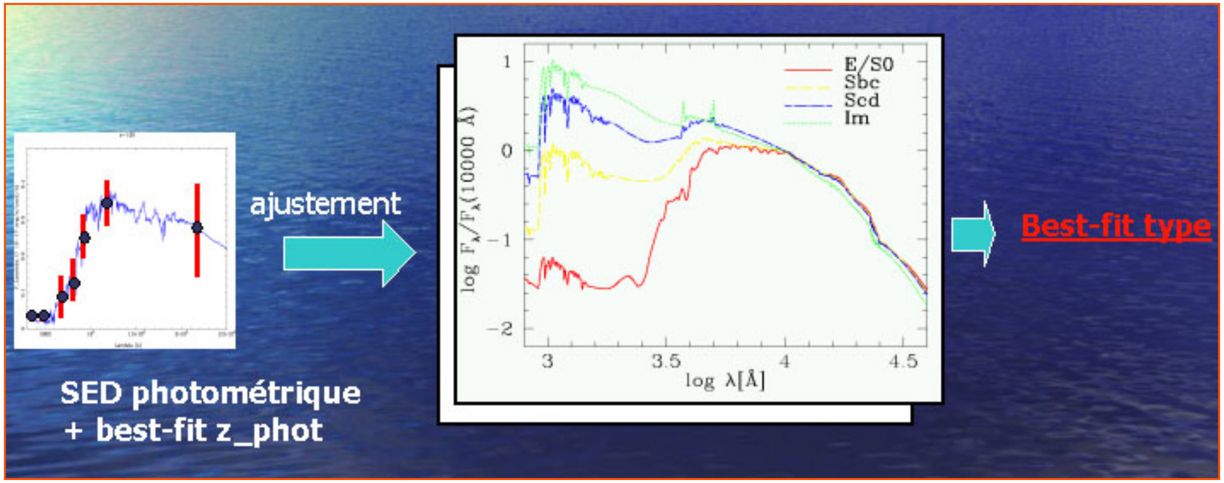


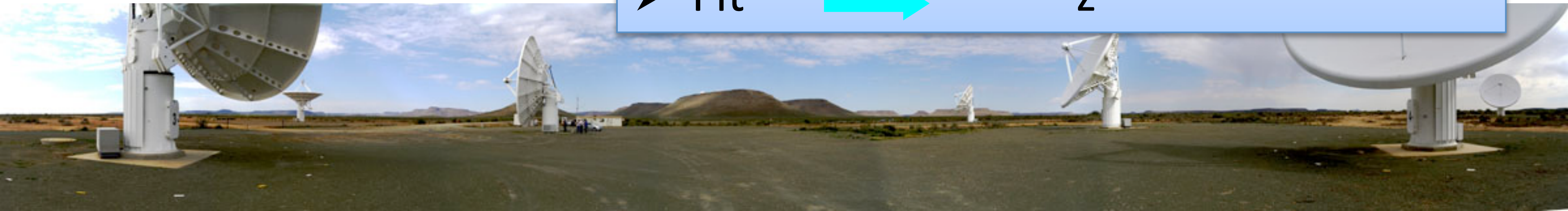
FIG. 1.—Multicolor B, V, R, I, Z, and narrowband 8185/105 Å images taken with LRIS on Keck of the $z = 5.74$ object, SSA22-HCM1 [R.A. (1950): $22^h15^m05^s.97$; decl. (1950): $-00°01'12''.9$]. Each panel is 30″ on a side. The positions of the sources are marked, with a separation of about 2″.5 between tick marks. The I-band image is weakly contaminated by line emission, but most of the light arises from the continuum, while the Z band is free of emission. The object is absent at B, V, and R in these extremely deep Keck LRIS images, which reach 1 σ limits of $B = 28.3$, $V = 28.2$, and $R = 27.8$ for a 2″ diameter aperture (magnitudes in the AB system). I(AB) for SSA22-HCM1 is 26.5, and Z(AB) is 25.5.

Photometric z (SEDs)

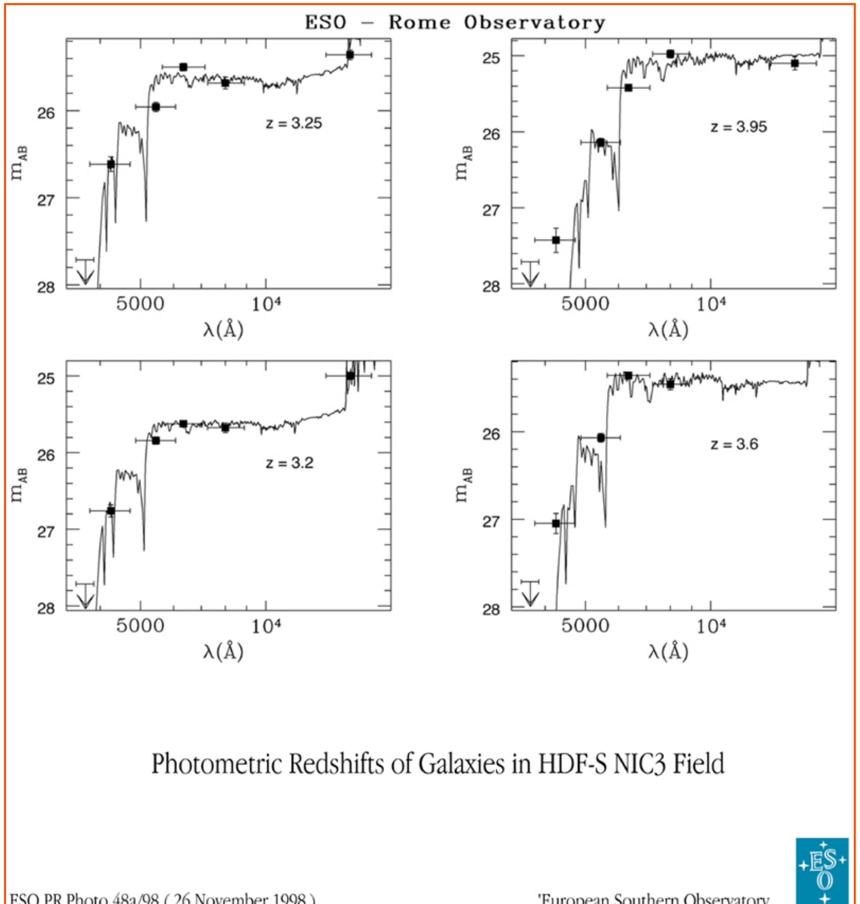


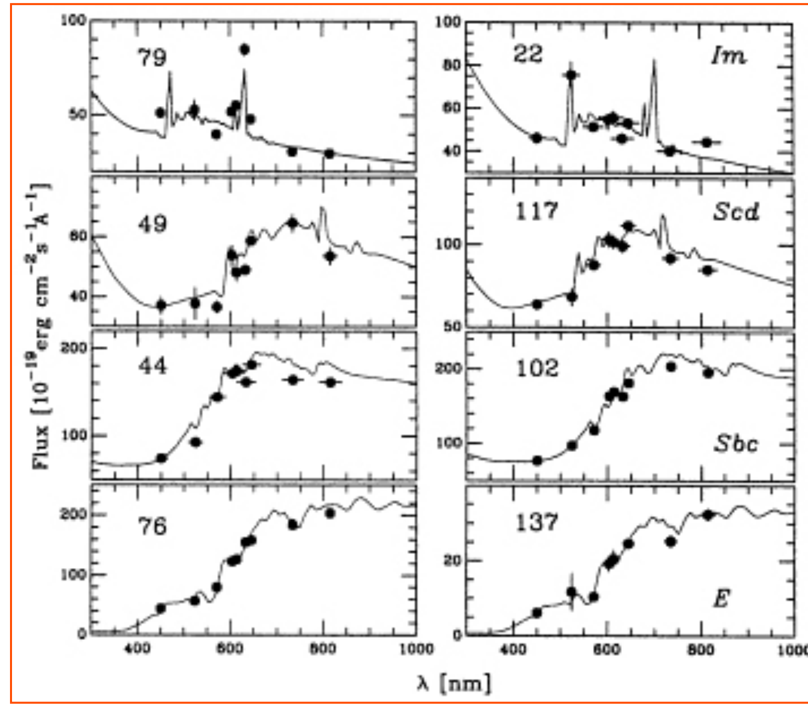


- Color → morphological type
- Morphological type → SED
- SED → photometric fit
- Fit → z



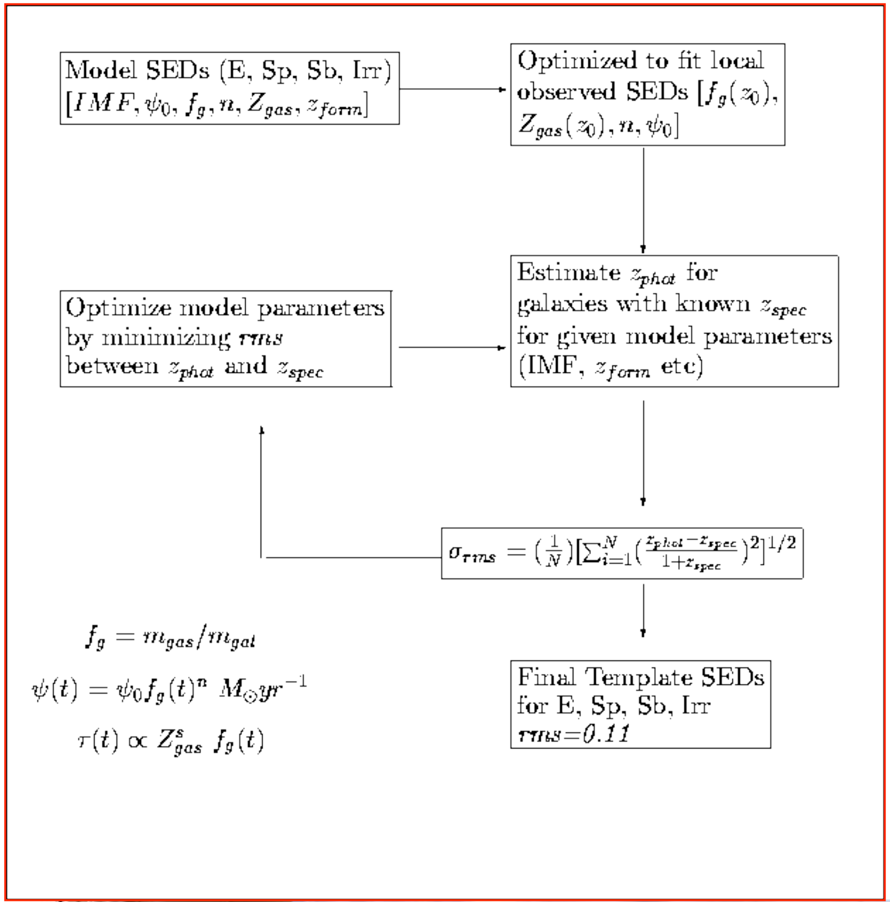
Photometric z (SEDs)

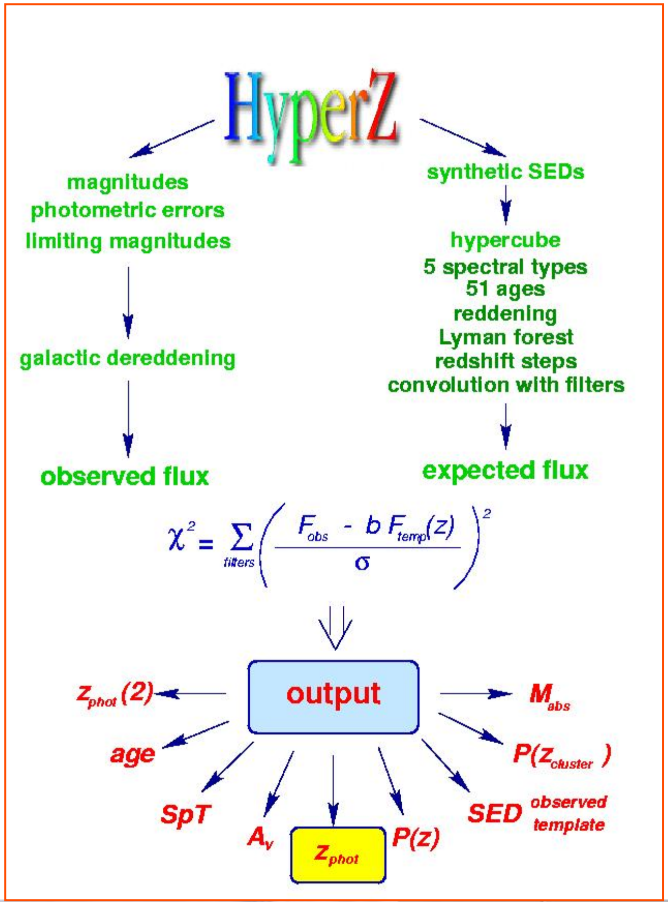




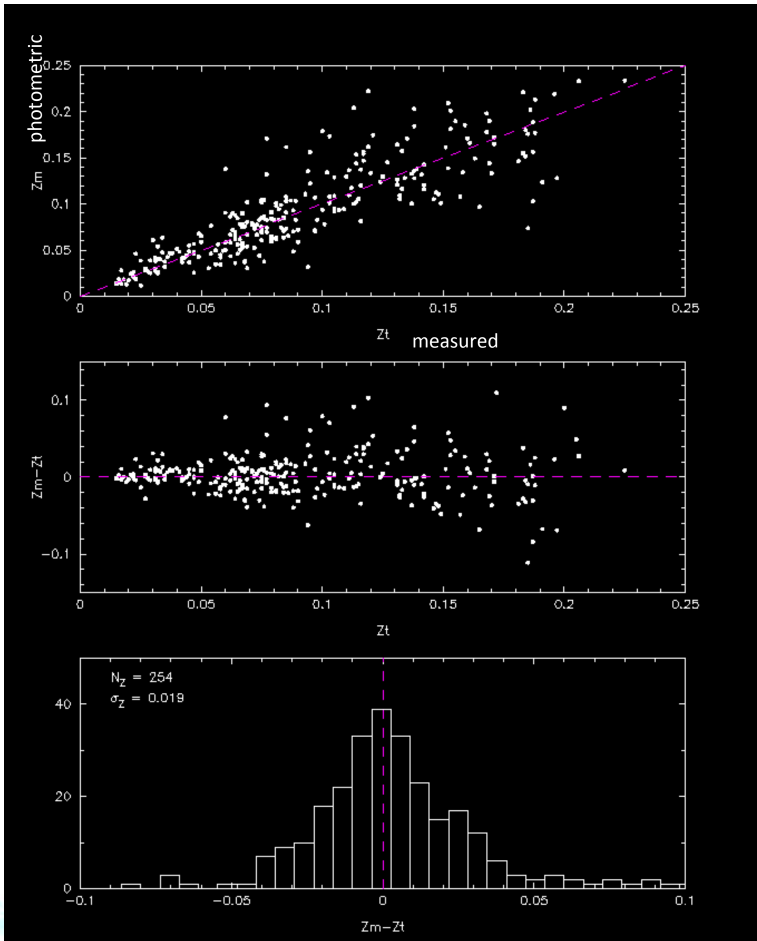
Examples in the HDF-S

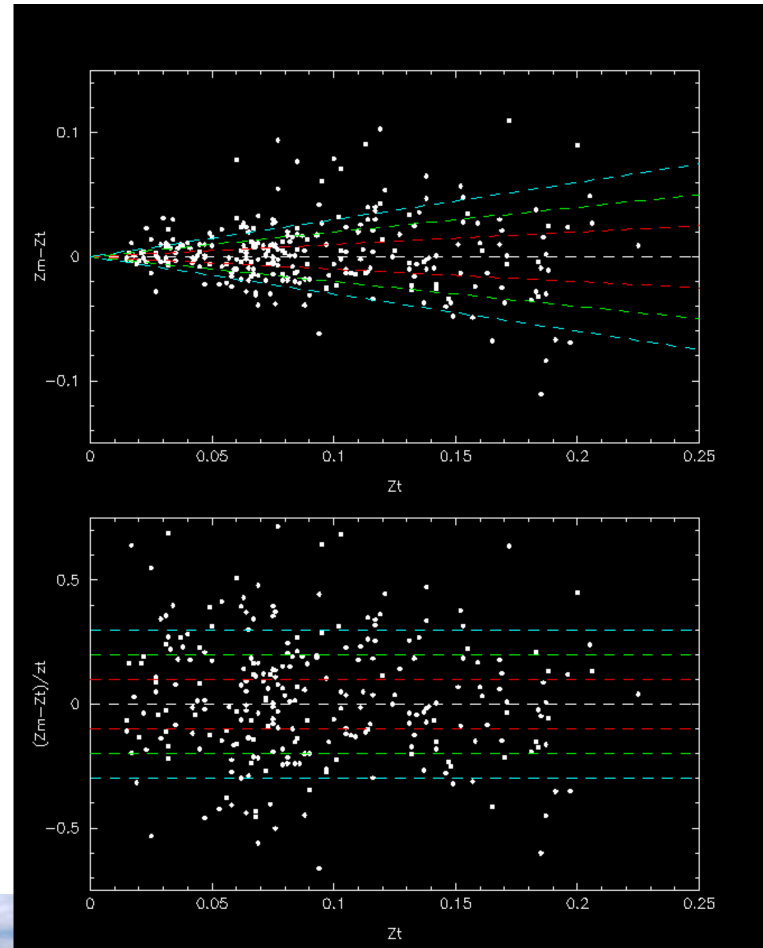
Photometric z (SEDs)



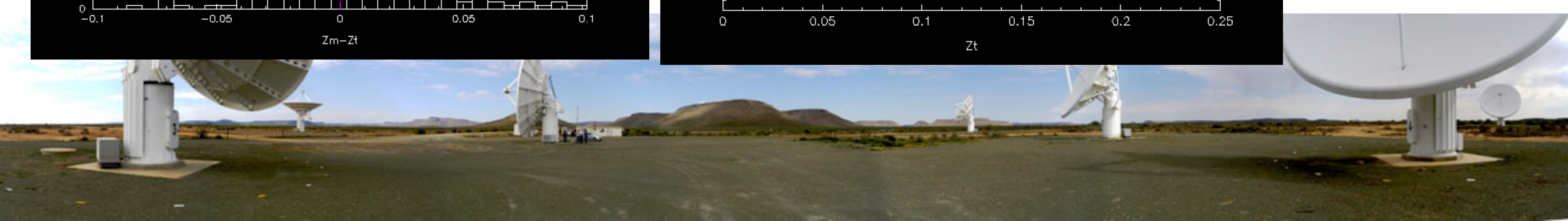


Photometric z (2MASS)

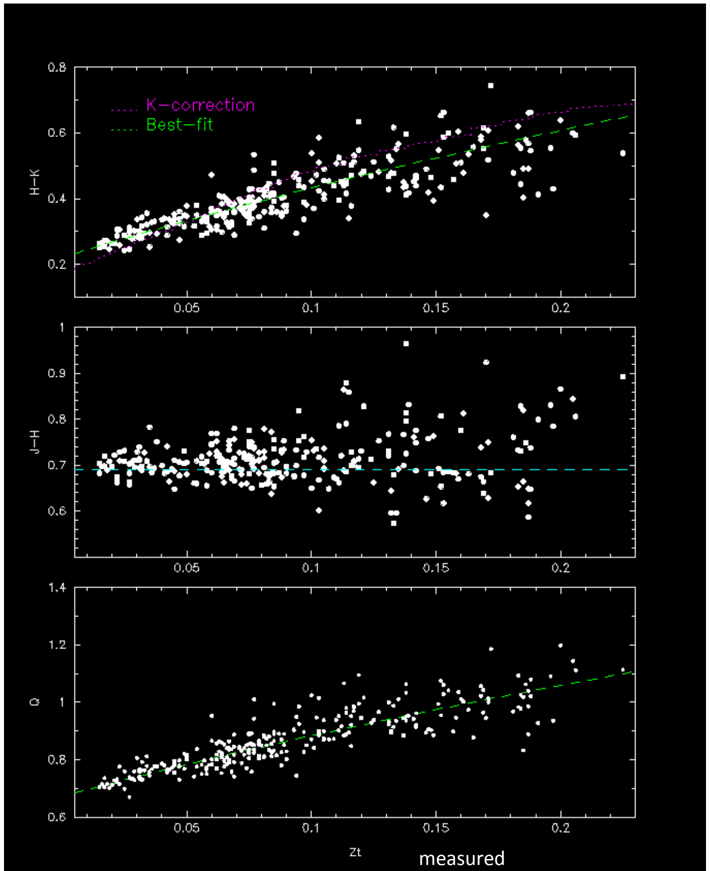




10%
20%
30%



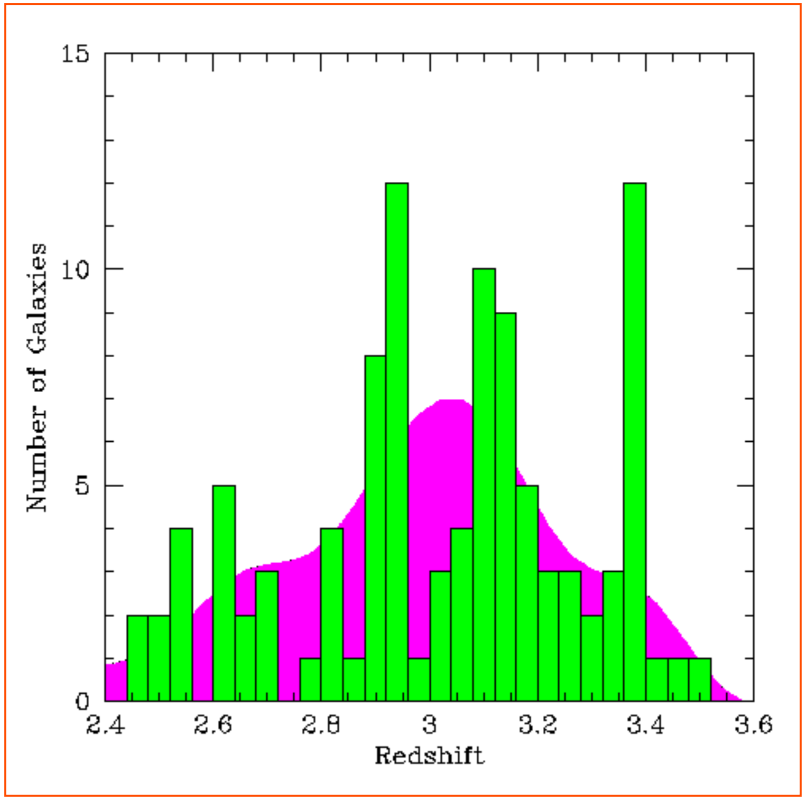
Photometric z (2MASS)



- z_m = photometric z
- Z_t = measured z (true)
- Q = (H-K) + f * (J-H)
- f = 0.644 = free parameter

Zm = -0.1677954 + (0.08079361 * Q) + (0.2517542 * Q^2)

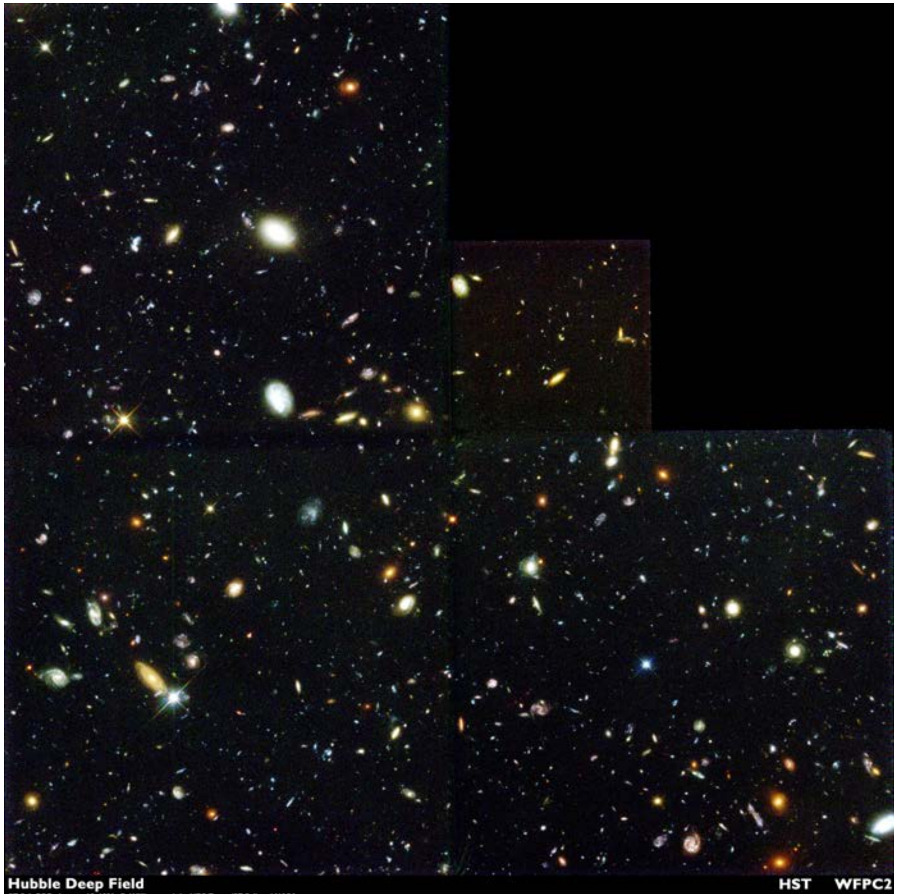
z distribution



Expected
Observed

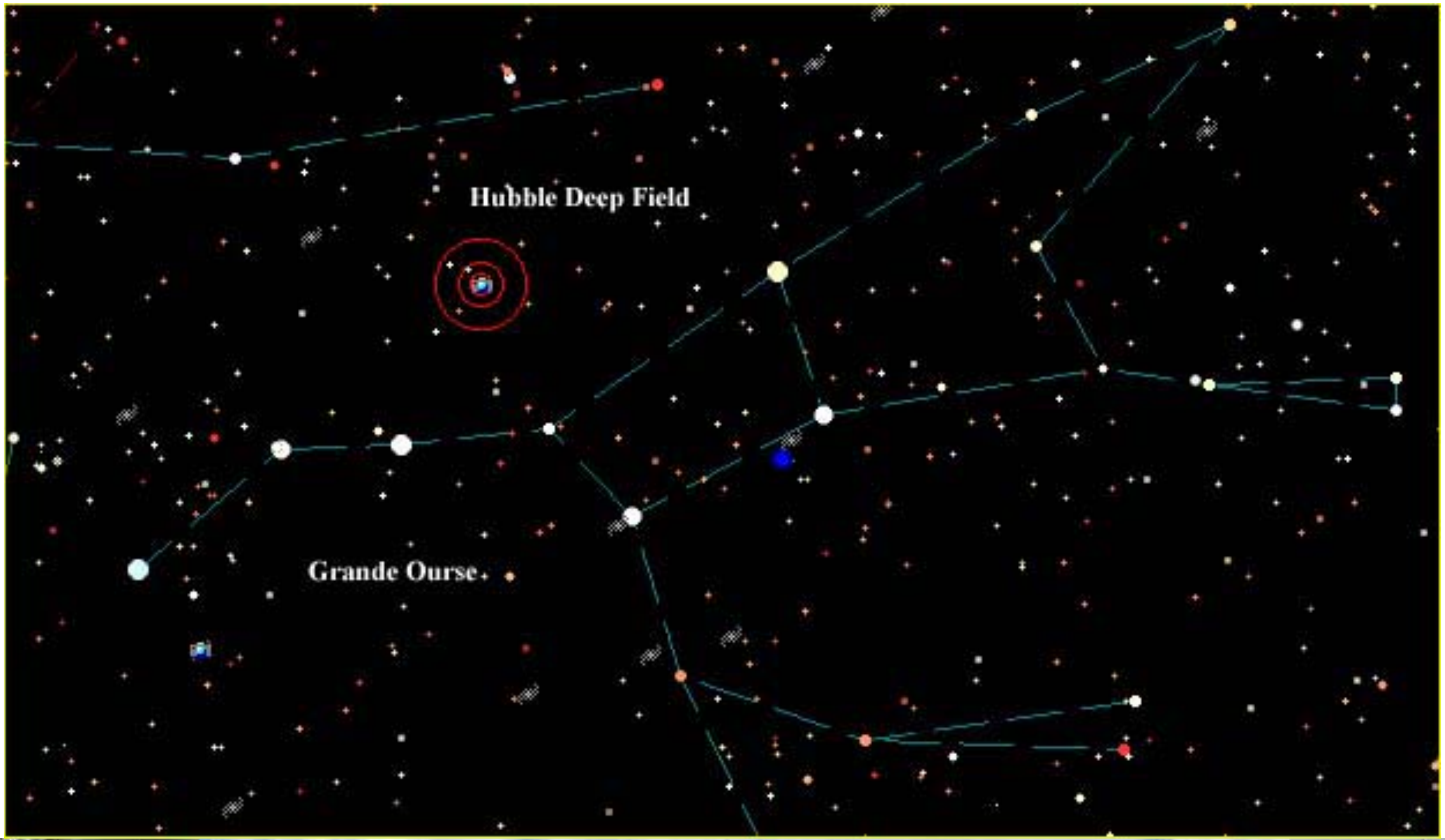
- The difference shows a strong clustering of galaxies at large z
- The presence of a so large clustering at large z shows that galaxies formed on the matter peaks
- With time, gravity amplified those dense regions (rich clusters)

HDF – Hubble Deep Field

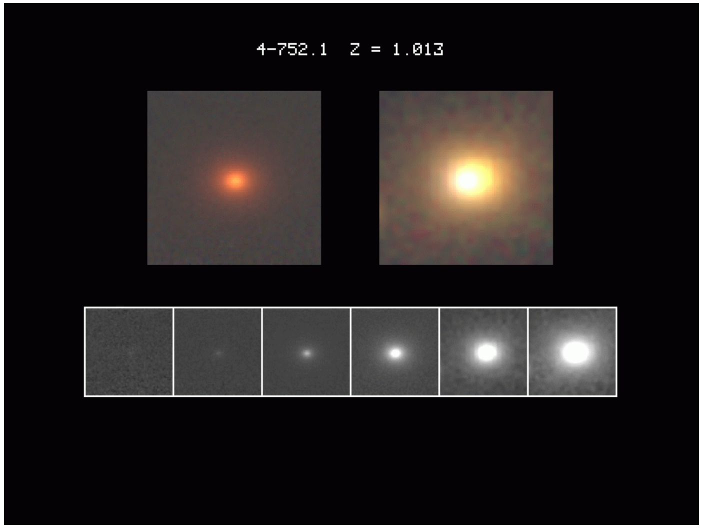


- Field ~ 2 arcmin
- 342 exp.s from december 18 to 28, 1995 with WFPC2
- 42.7 hours (300 nm), 33.5 hours (450 nm), 30.3 hours (606 nm), 34.3 hours (814 nm)
- 3000 objects (almost all galaxies)

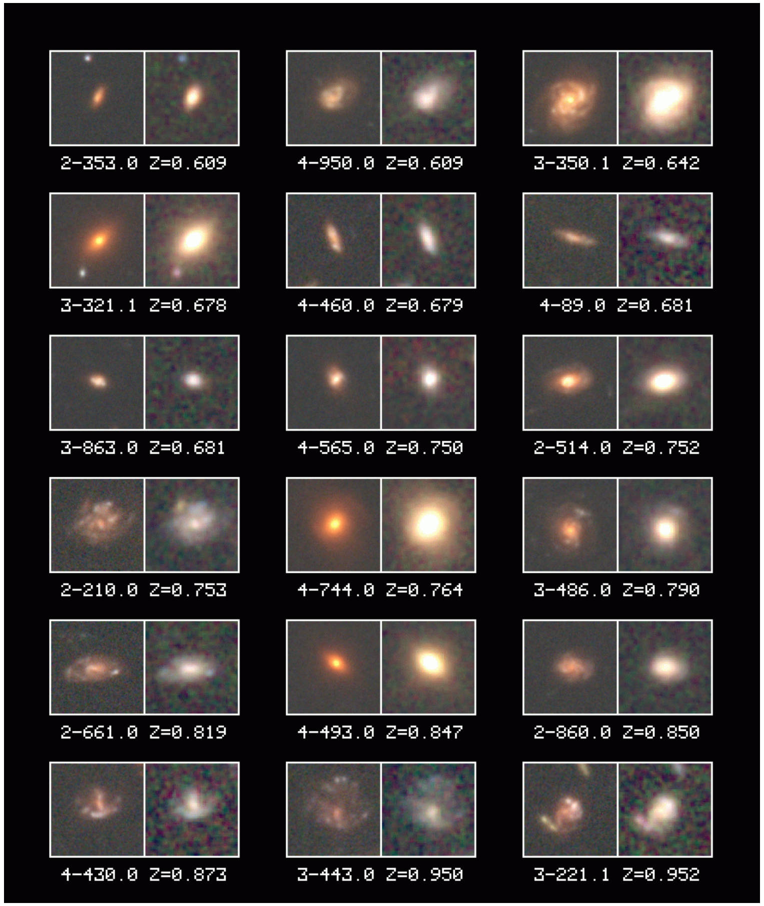
HDF – Hubble Deep Field

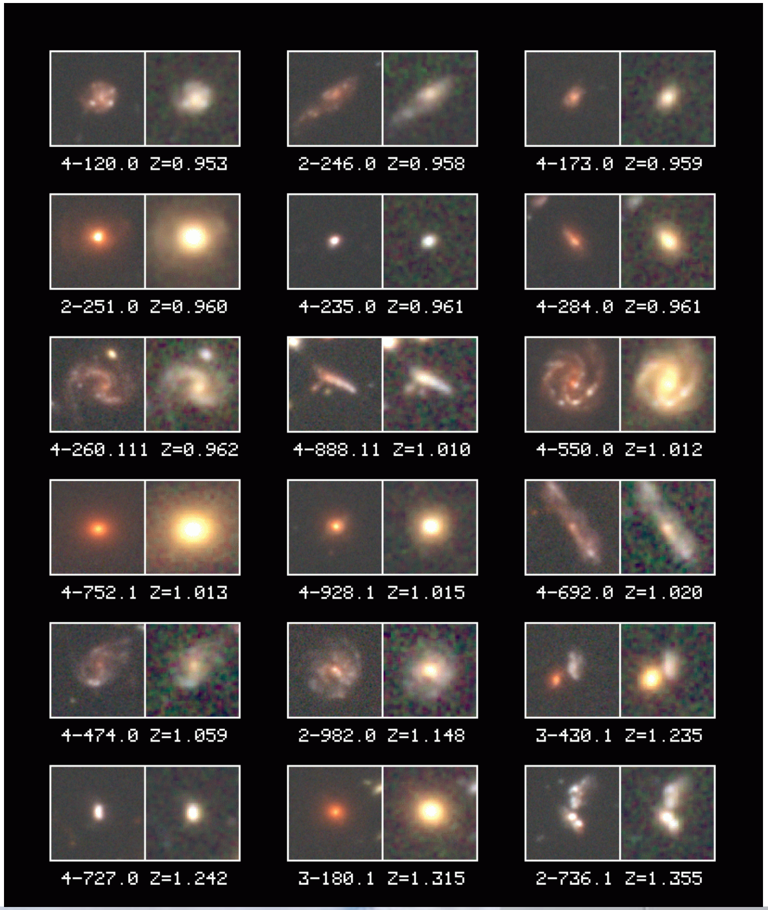


HST WFPC2 (optical) vs NICMOS (IR)

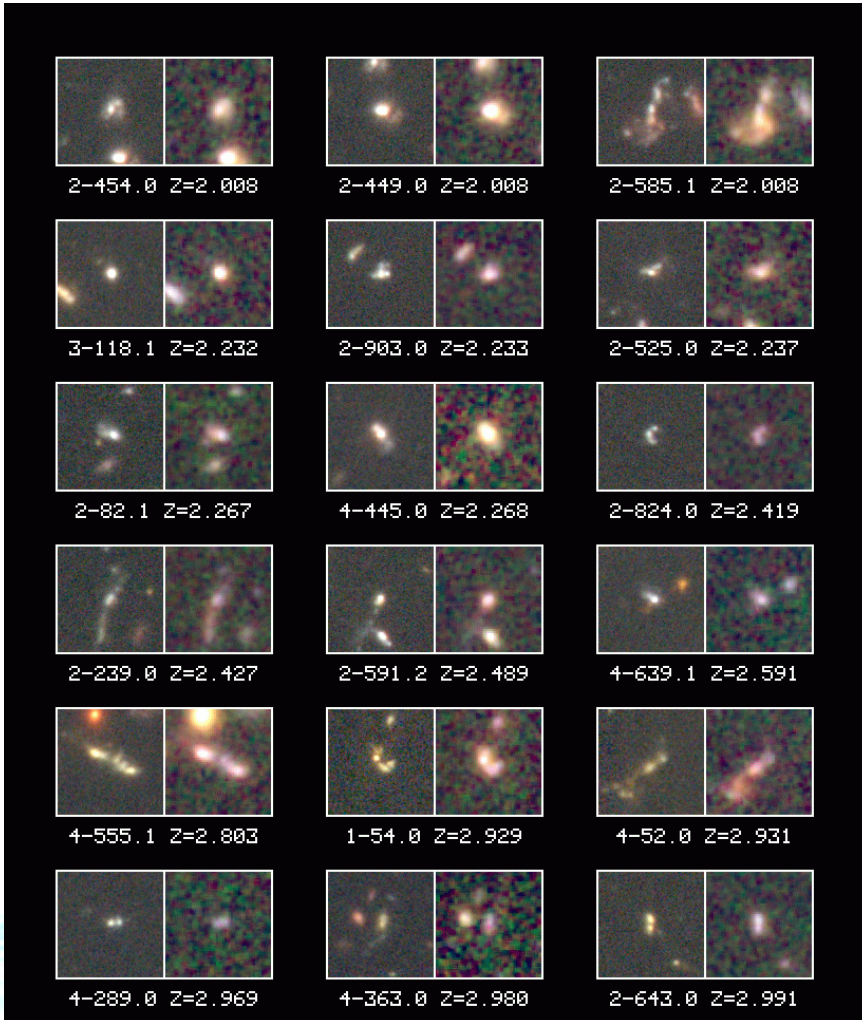


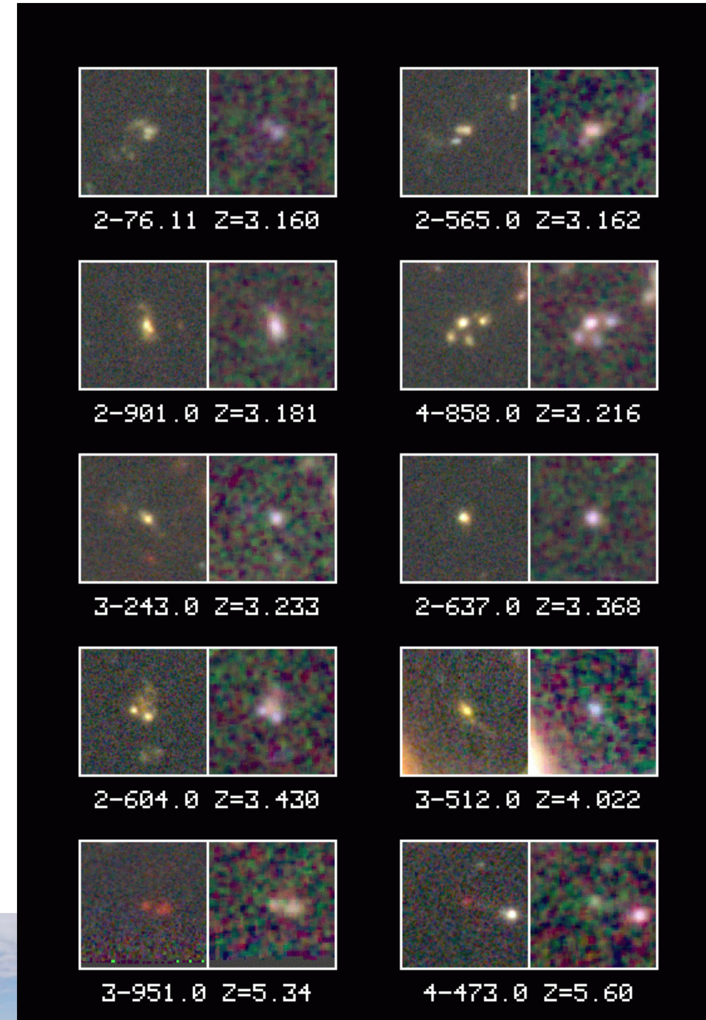
HST WFPC2 (optical) vs NICMOS (IR)



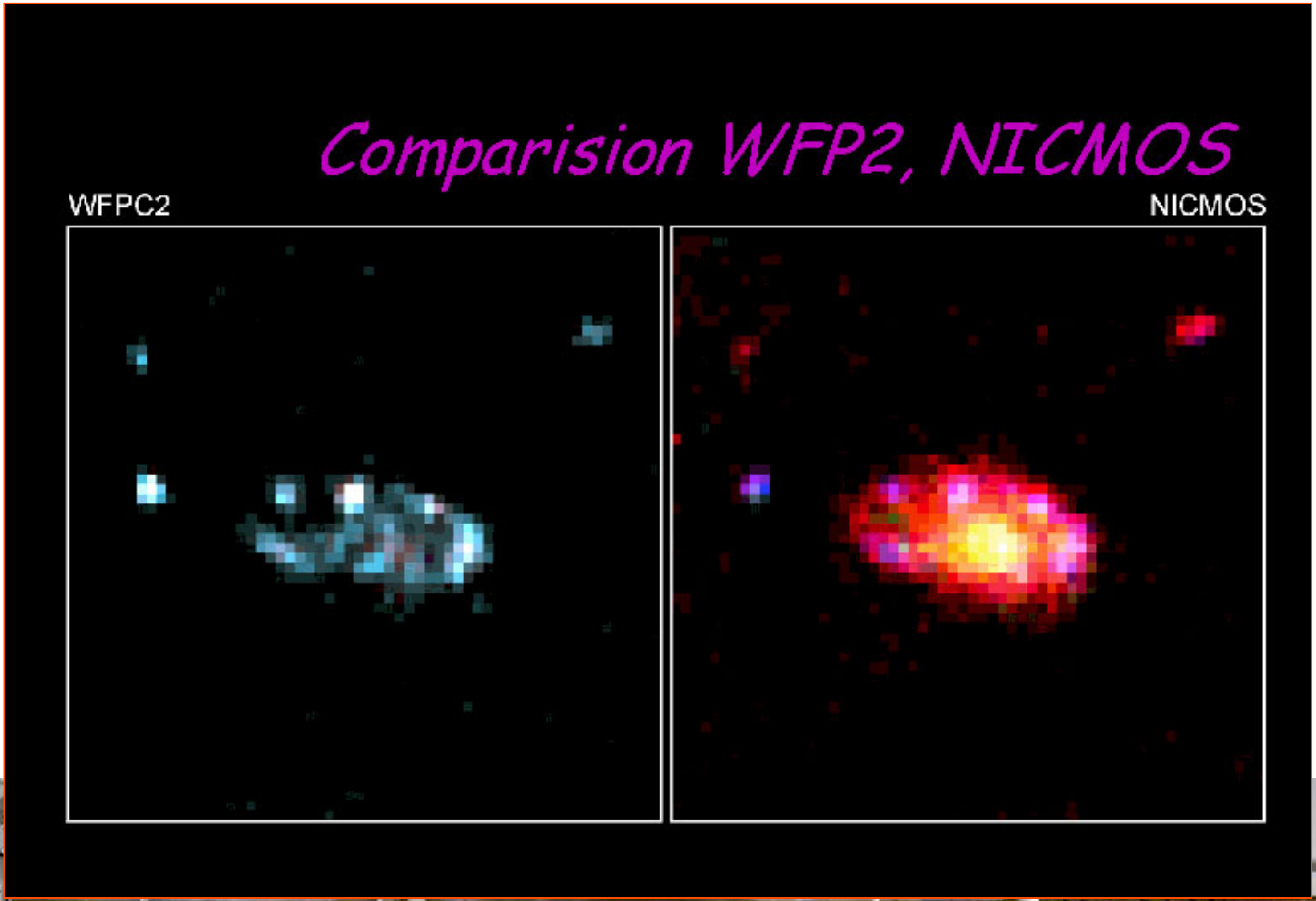


HST WFPC2 (optical) vs NICMOS (IR)

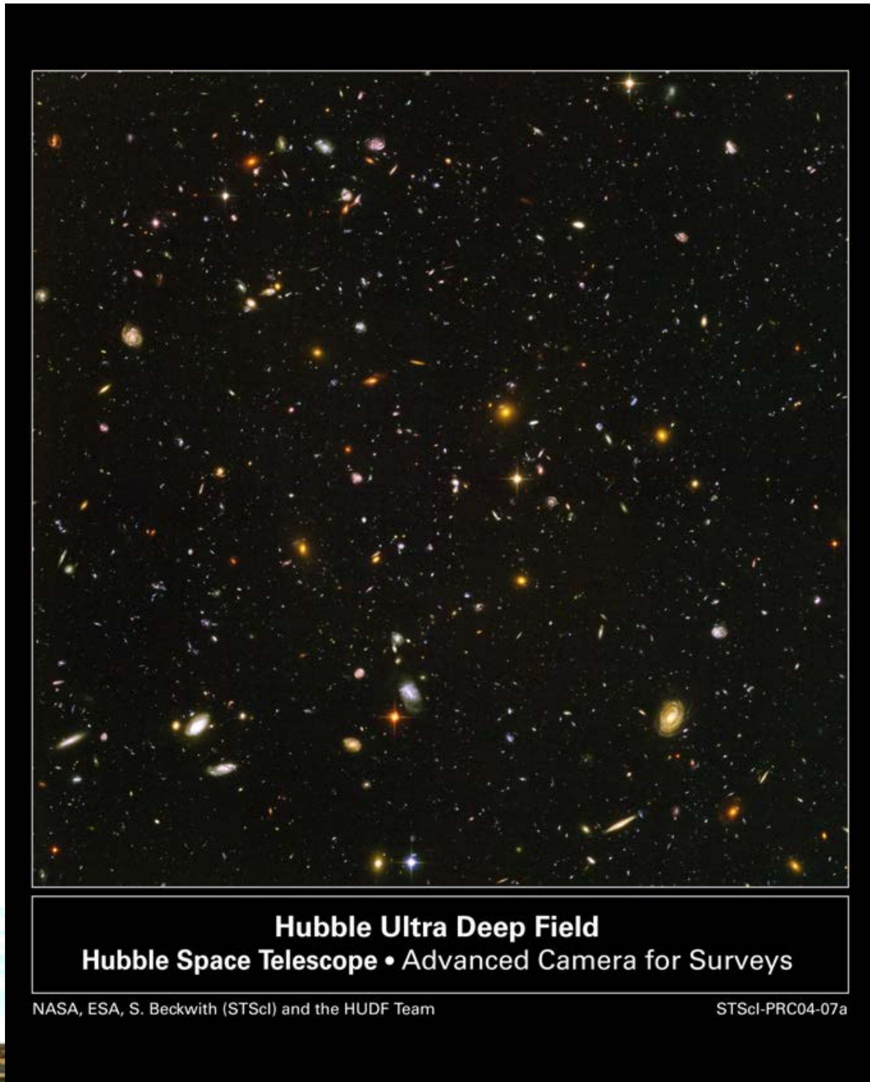




HST WFPC2 (optical) vs NICMOS (IR)

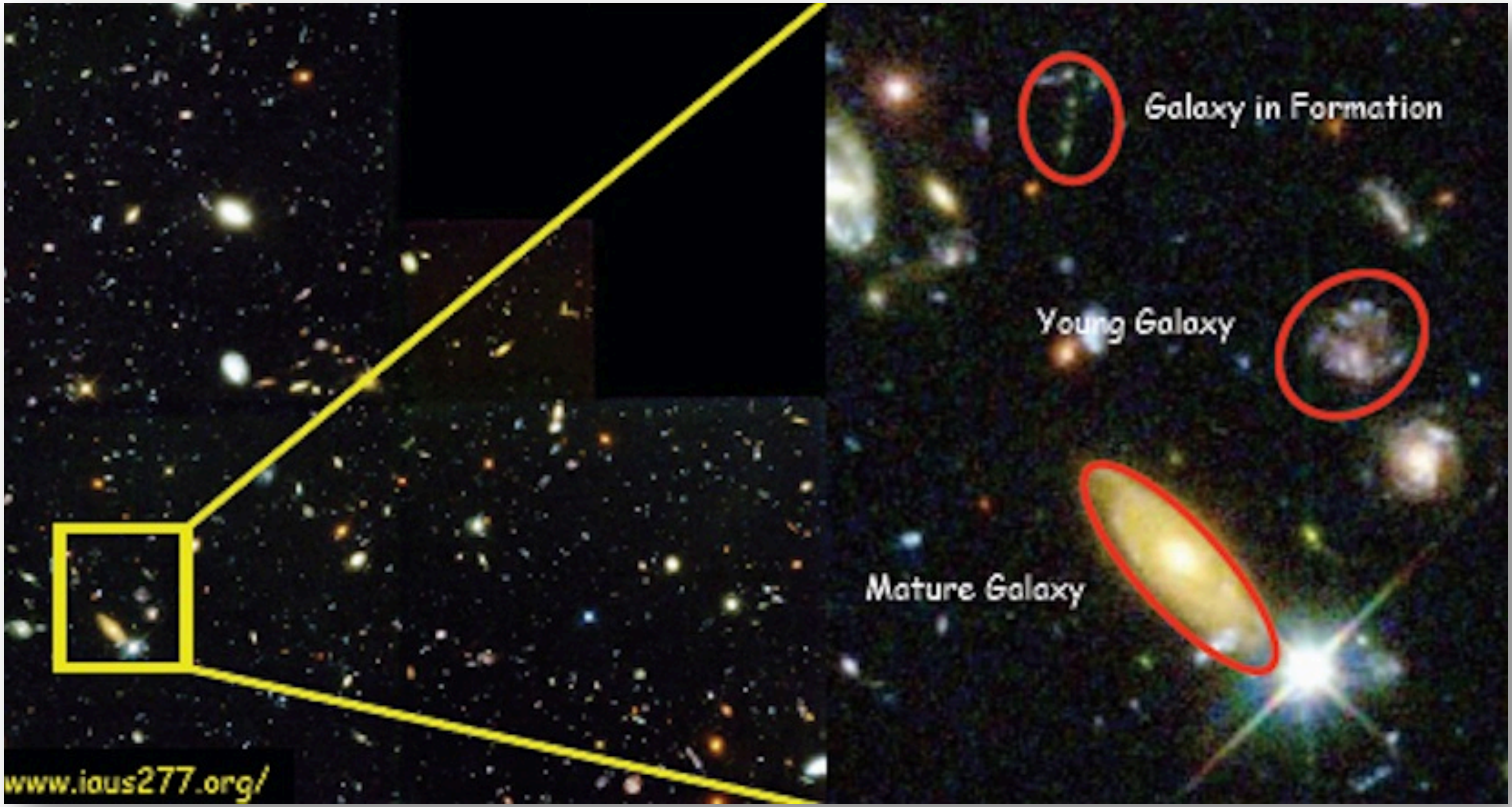


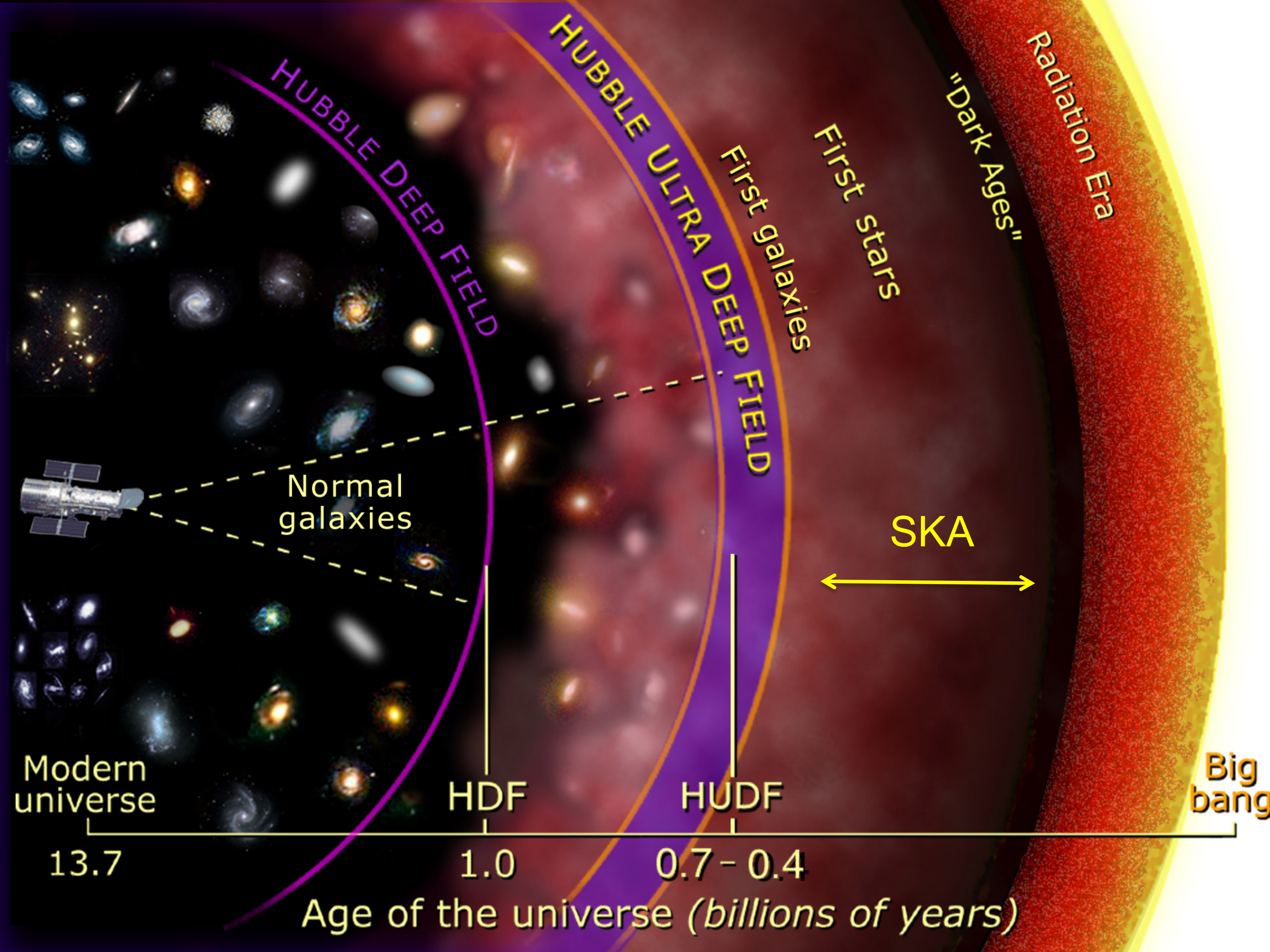
HUDF



HUDF
Hubble Ultra
Deep Field
2003-2004
400 orbits
2 X HDF
Exp. ~ 11.3 days
09/03 – 01/04

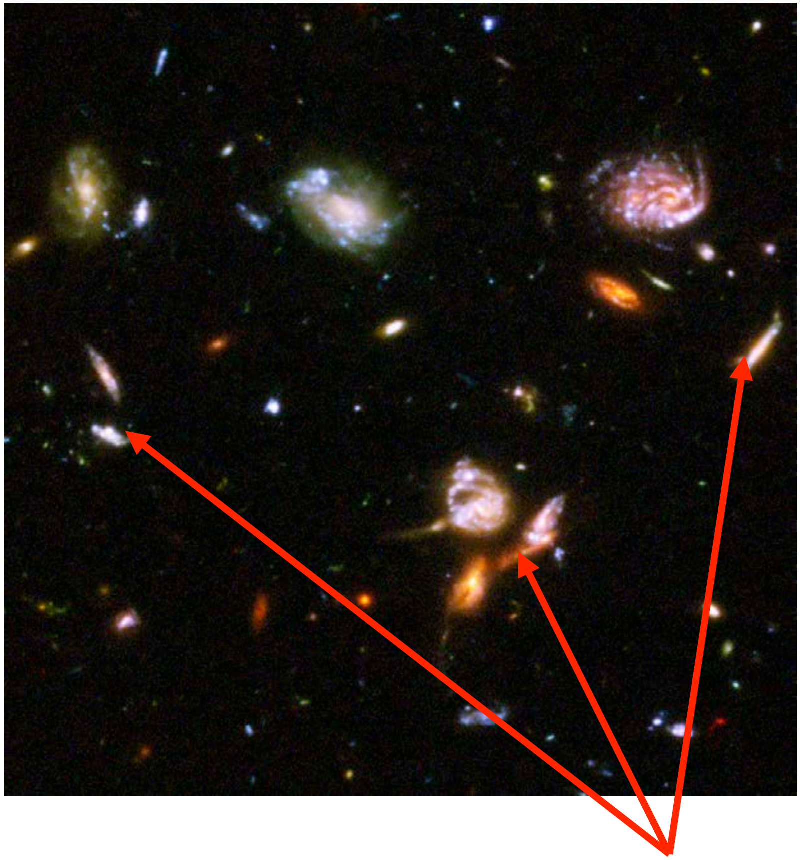
HUDF

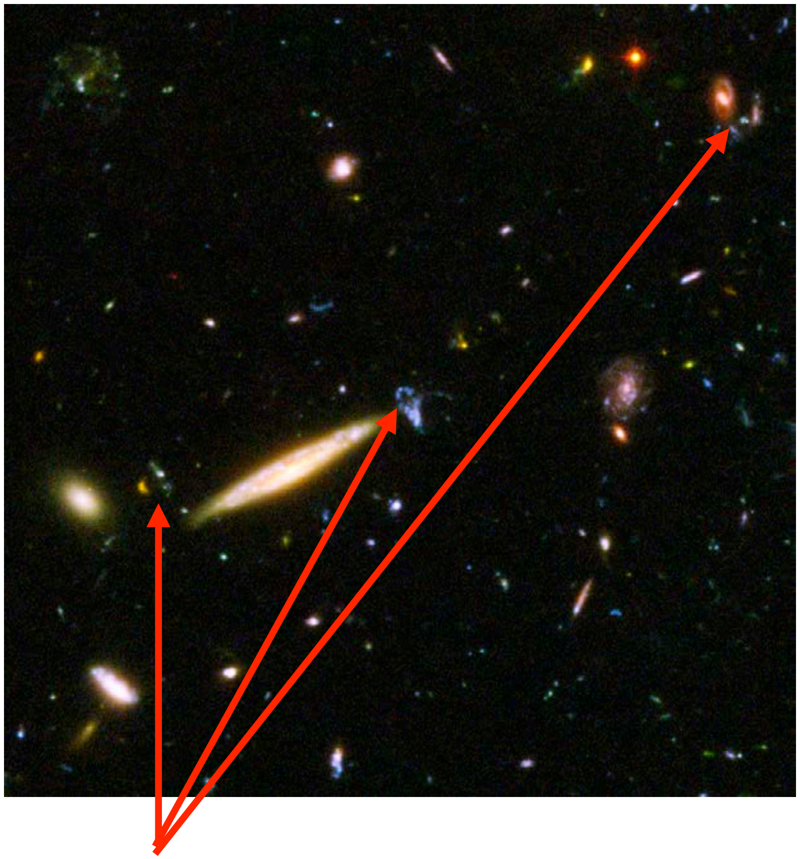

Galaxy in Formation
Young Galaxy
Mature Galaxy
www.iaus277.org/



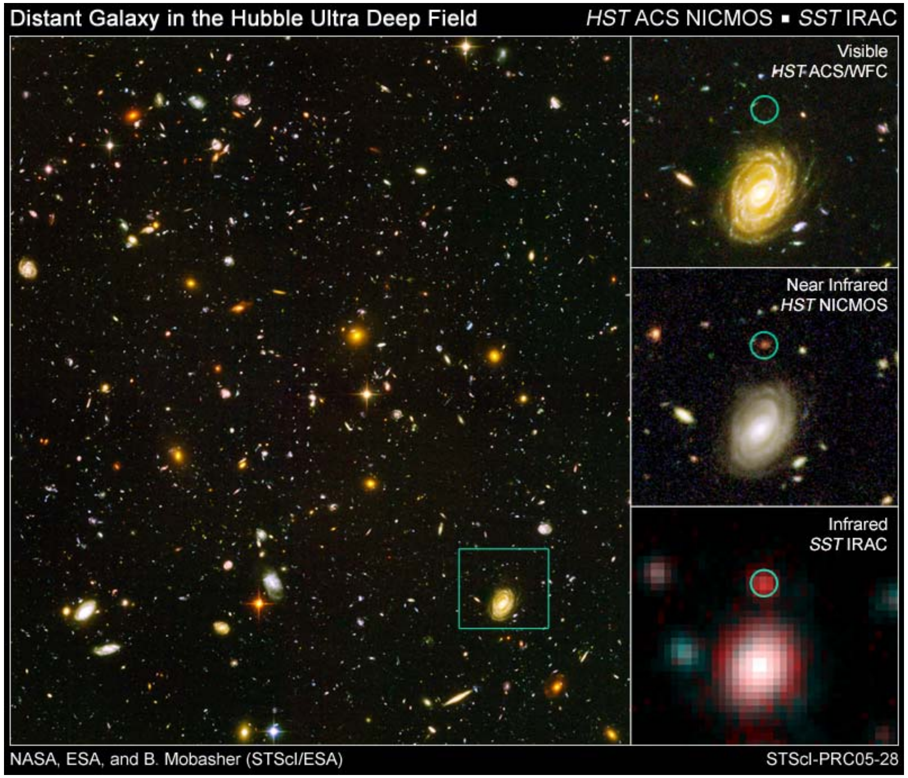
HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
SKA
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

HUDF - mergers





HUDF – JD2



- HUDF- JD2 / z ~ 6.5 corresponds to t ~ 0.7 Gy
- Could be z ~ 2.5 with a lot of dust !

HUDF – JD2

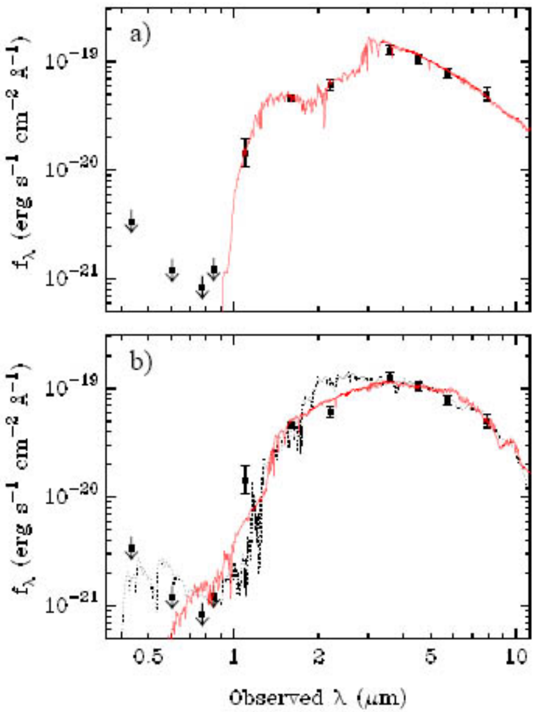


Fig. 3.— Observed and model SED of HUDF-JD2. *Top panel:* The red line is the model SED based on the best fit Bruzual & Charlot model (see Table 2) at a redshift $z = 6.5$. *bottom panel:* Alternative, lower redshift models. The solid line shows the best fit for a dusty model galaxy at $z = 2.5$, the best fit from the secondary χ^2 minimum seen in Figure 4. The parameter values are given in Table 2. The dotted line shows the SED for an old population with $z = 3.4$ and an age of 2.4 Gyr (Table 2). (Table 2)

Z ~ 6.5

Z ~ 2.5 + dust

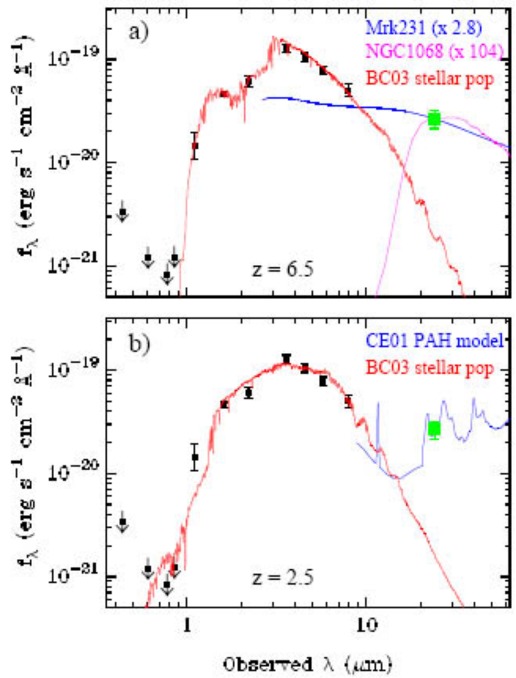
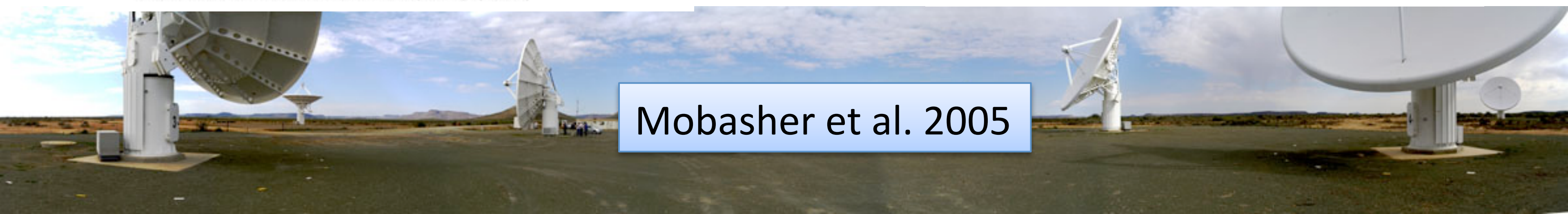


Fig. 6.— Observed and model spectral energy distributions for HUDF-JD2, extended to include the 24μm measurement. The models which best fit the data at $\lambda \leq 8\mu$m (see Figure 3 and Table 2) are shown as red lines in both panels. *Top panel:* The $z = 6.5$ solution. Two models of obscured, infrared-luminous AGN are shown, normalized to the observed 24μm point: the ultraluminous infrared AGN Mrk 231, scaled in luminosity by a factor of 2.85, and the highly obscured Seyfert 2 nucleus NGC 1068, scaled by a factor of 105. *Bottom panel:* The $z = 2.5$ solution. A model starburst galaxy template from Chary & Elbaz 2001, with $L_{IR} = 2 \times 10^{12} L_\odot$, is shown, normlaized to the 24μm photometry.



Mobasher et al. 2005

HUDF – JD2

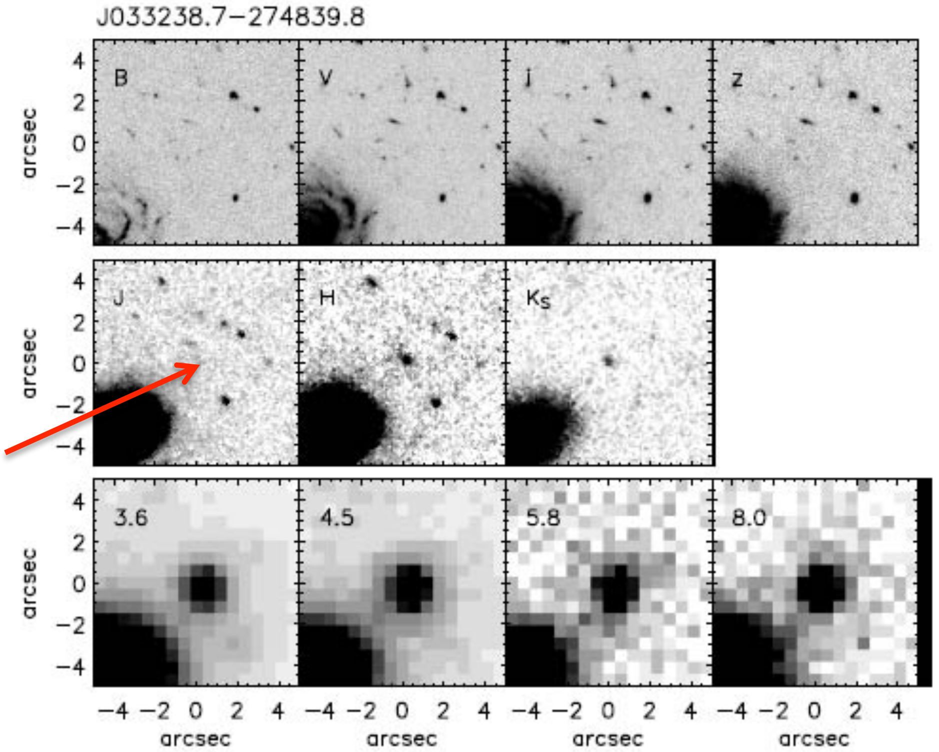


Fig. 1.— Images of the J–dropout candidate HUDF–JD2 (α =3:32:38.74; δ = −27:48:39.9 J2000) from HST/ACS ($B_{435}V_{606}i_{775}z_{850}$), HST/NICMOS ($J_{110}H_{160}$), VLT/ISAAC ($K_s$) and Spitzer/IRAC (3.6-8.0 μm). The K_s ISAAC image is from deep FIRES observations.

Formation of disks

Current Estimated Cosmological Parameters

Description	Symbol	Value	±
Total density	Ω_{tot}	1.02	0.02
Eqn. state quint.	w	< -0.78	
Dark energy density	Ω_Λ	0.73	0.04
Baryon density	Ω_b	0.044	0.004
Matter density	Ω_m	0.27	0.04
Light neutrino density	Ω_ν	< 0.015	
Fluctuation amplitude	σ_8	0.84	0.04
Power spectrum index	n_s	0.93	0.03
Hubble constant	h	0.71	0.04
Age of Universe (Gyr)	t_0	13.7	0.2

Taken from *WMAP* results (Bennett et al. 2003)

Formation of disks

Timetable for Structure Formation	
Gravitational potential fluctuations	$z \gtrsim 10^3$
The first stars	$z \sim 20$
Dark halos of galaxies	$z \gtrsim 10$
Intergalactic medium	$z \sim 10$
First engines of AGN	$z \sim 10$
Angular momentum of galaxy rotation	$z \sim 5$
Spheroids of galaxies	$z \gtrsim 5$
Thick disks of galaxies	$z \gtrsim 5$
First 10% of heavy elements	$z \gtrsim 3$
Rich clusters of galaxies	$z \sim 1$–2
Thin disks of galaxies	$z \gtrsim 1$
Superclusters, walls, and voids	$z \sim 1$

Formation of disks

- How do protogalaxies acquire their angular momentum ?
- In the hierarchical clustering scenario, protogalaxies form by the merging of smaller units by the effect of gravity
- The ***tidal torques*** from the other protogalaxies will create the angular momentum
- Spin parameter (Peebles 1971, Fall & Efstathiou 1980)

Formation of disks

Spin parameter:

$$\lambda \equiv \frac{J\,|E|^{1/2}}{G M^{5/2}}$$

J = total angular momentum
E = energy of the system
M = mass of the system
G = grav, constant

- λ = measure the degree of gravitational support of the system by the rotation
- λ = ratio of the centrifugal acceleration $g_\phi \sim v_c^2/r$ over the gravitational acceleration $g \sim GM/r^2$

Formation of disks

- Formation of disks
  1. Protogalaxy forms by the agglomeration of smaller entities (initial fluctuations)
  2. Spin is acquired by the torque exerted by the neighboring protogalaxies
  3. Gas collapses in the pre-existing dark matter halos (collapse factor ~10)

Hierarchical clustering

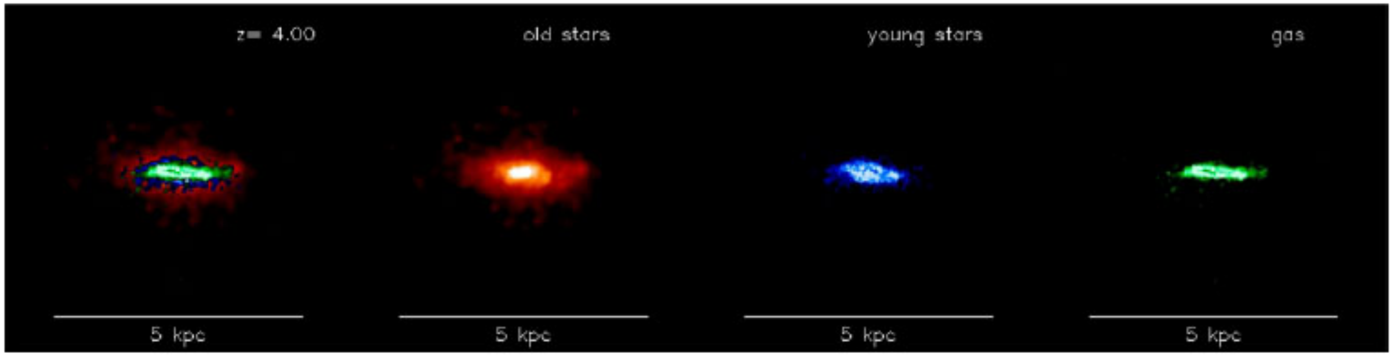
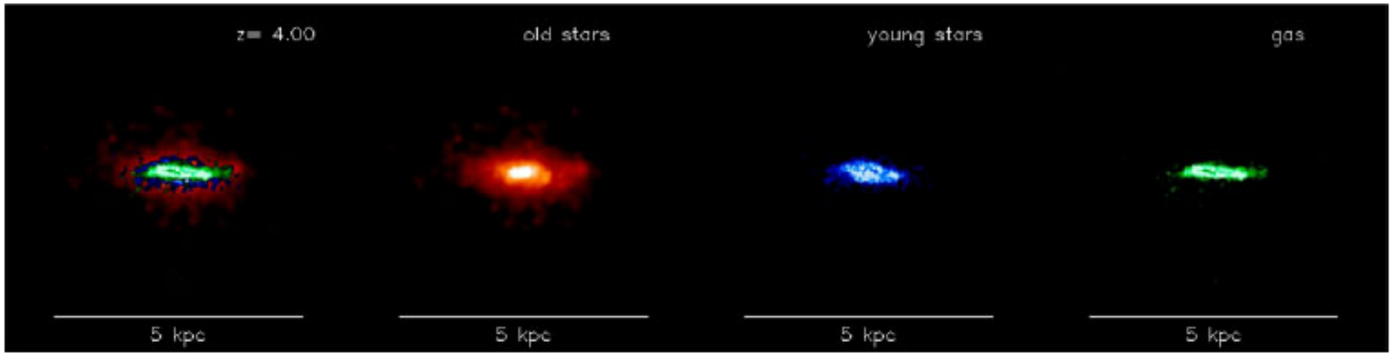


Fig. 1. The most massive progenitor at $z = 4$ shown edge-on. Gas particles are shown in green, 'young' (i.e. less than 200 Myr old) stars in blue and older stars in red. Horizontal bars in each panel are 5 (physical) kpc long.

- Cosmological simulations: N-body + gas + SF + feedback
- Sufficient resolution to determine the morphological type of galaxies
- Presence of the different components: disk, bar, spheroid → determine by the gas accretion and the mergers (small or large)

Steinmetz & Navarro 2002, New Astronomy, 7, 155

Hierarchical clustering



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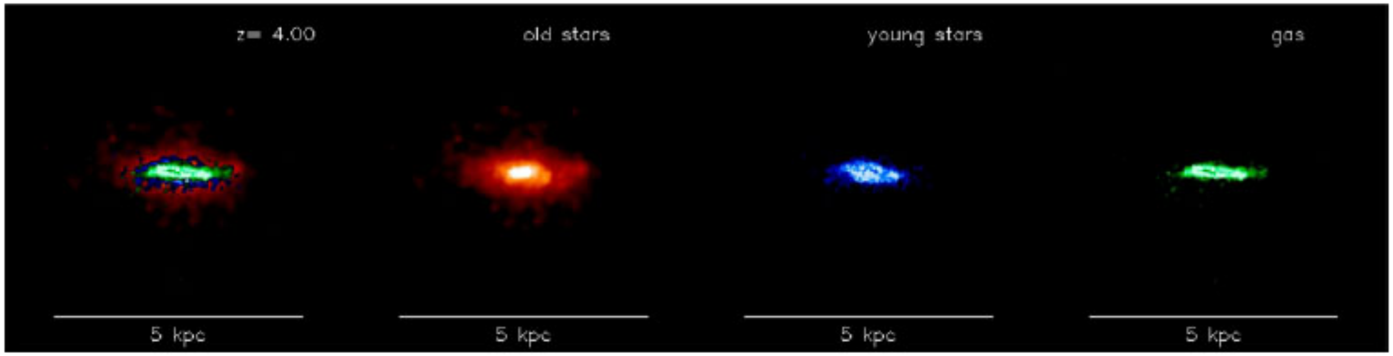
- Disks form by the slow collapse of the gas in the center of the dark halos
- Spheroids form by the mix resulting of mergers of comparable masses
- Bars form by the tidal forces generated by the satellites

Steinmetz & Navarro 2002, New Astronomy, 7, 155

Hierarchical clustering



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- Dark halo ~ 2.5×10^{12} M_{sun} at z = 0
- ΛCDM with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.019h^{-2}$
- $h = H_0/(100\ km/s/Mpc) = 0.65$
- Evolution z = 4 → z=0 (mergers at z ~ 3.3 & z ~ 0.6)

Steinmetz & Navarro 2002, New Astronomy, 7, 155

Hierarchical clustering

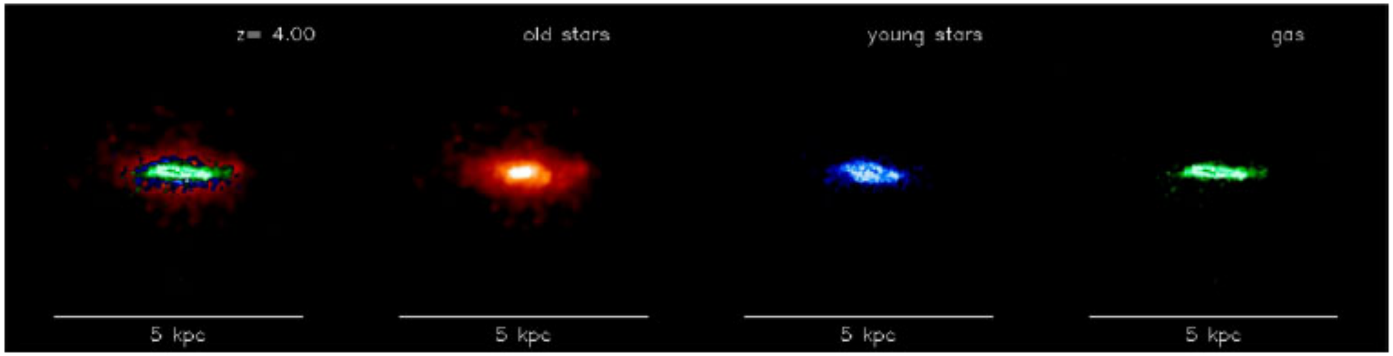

Fig. 1. The most massive progenitor at $z = 4$ shown edge-on. Gas particles are shown in green, 'young' (i.e. less than 200 Myr old) stars in blue and older stars in red. Horizontal bars in each panel are 5 (physical) kpc long.

- Z = 4, $M_b \sim 3 \times 10^{10}$ M_{sun} (gas & stars)
- Disk: diam. (small) ~ 3 kpc / V_{rot} ~ 180 km/sec
- SF started at z ~ 10 with SFR ~ 30 M_{sun}/year
- Young stars (blue) < 200 X 10^6 years

Steinmetz & Navarro 2002, New Astronomy, 7, 155

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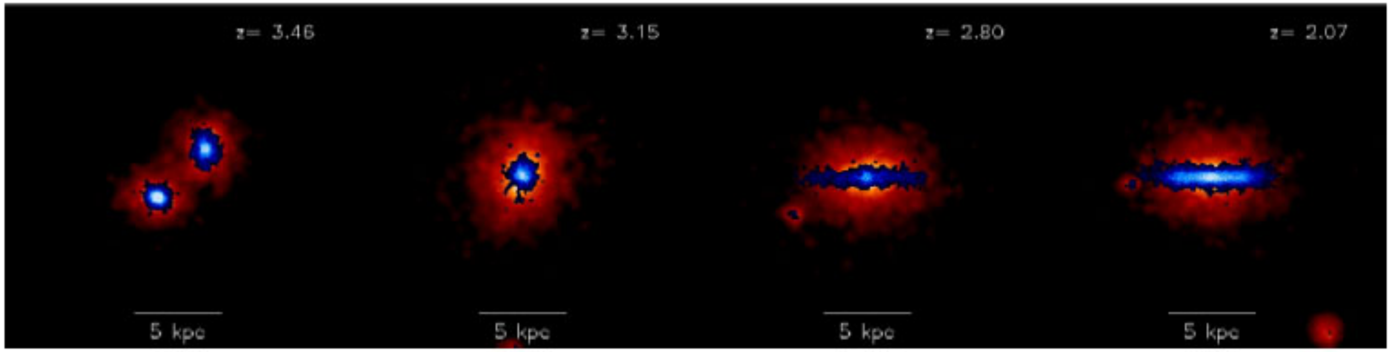

Fig. 2. The formation of a bulge and the rebirth of a disk. The sequence shows the formation of a bulge by the merger of two almost equal mass 'pure disk' systems at $z \sim 3$. After $z = 3$ smooth accretion of gas regenerates the disk component around the bulge. Blue is used in each panel to denote stars formed since the preceding frame (since $z = 4.2$ for the first panel), red for older stars. Horizontal bars in each panel are 5 (physical) kpc long.

- Z = 3.3, merger of 2 similar size disks
- Z = 3.15, already the progenitor of a bulge with a burst of SF (1.6 X 10^{10} M_{sun} gas ⟶ stars in 300 x 10^6 years)
- During the burst, M_R ~ -25 (compatible with Lyman-break)

Steinmetz & Navarro 2002, New Astronomy, 7, 155

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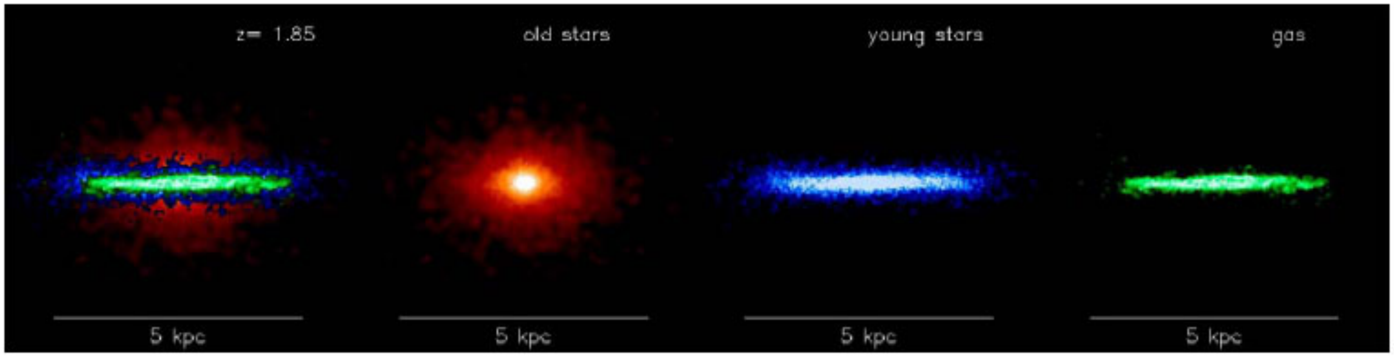

Fig. 3. The appearance of the galaxy at $z = 1.8$, seen edge-on. Green is used for the gas, blue for 'young' stars (i.e. formed since $z = 3$), red for older stars. At this time, the morphology of the galaxy is reminiscent of early type spirals, with a dense bulge surrounded by a disk of gas and young stars. Horizontal bars in each panel are 5 (physical) kpc long.

- From z = 3 to z = 1.8, baryonic mass increases by 50 %
  (accretion of IGM → formation of the disk
  SFR: 20 M_{sun}/y (z=3) → 8 M_{sun}/y (z=1.8)
- Z = 1.8, M_R = -22 → Sa/Sb (70% exp disk – 30% bulge)
- Disk α^{-1} = 1.5 kpc – bulge $r^{1/4}$ r_{eff} ~ 1 kpc

Steinmetz & Navarro 2002, New Astronomy, 7, 155

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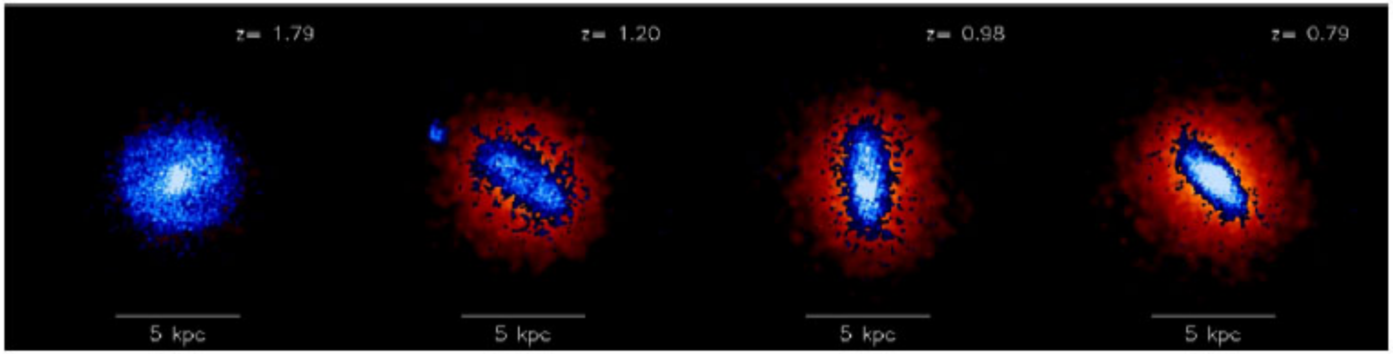

Fig. 4. The tidal triggering of bar instability by a satellite. At $z = 1.6$ the disk develops a well defined, long-lasting bar pattern as a result of tidal forcing by the satellite shown in the $z = 1.2$ panel. The satellite is finally disrupted at $z = 1.18$ after 7 pericentric passages. The bar pattern, however, survives for several Gyr, as shown in the picture. Stars less than 1.5 Gyr old are shown in blue, older stars in red. Note that the bar is most prominent in the young component. Horizontal bars in each panel are 5 (physical) kpc long.

- From z = 1.8 to z = 0.7, accretion of a satellite (e.g. Sagittarius & MW)
- Main effect: formation of a bar at z ~ 1.62
- Bar ~ 2.5 kpc stable on 30 orbits
- $M_{baryons}$ ~ 70% for r < 3kpc (maximum disk)

Steinmetz & Navarro 2002, New Astronomy, 7, 155

Hierarchical clustering

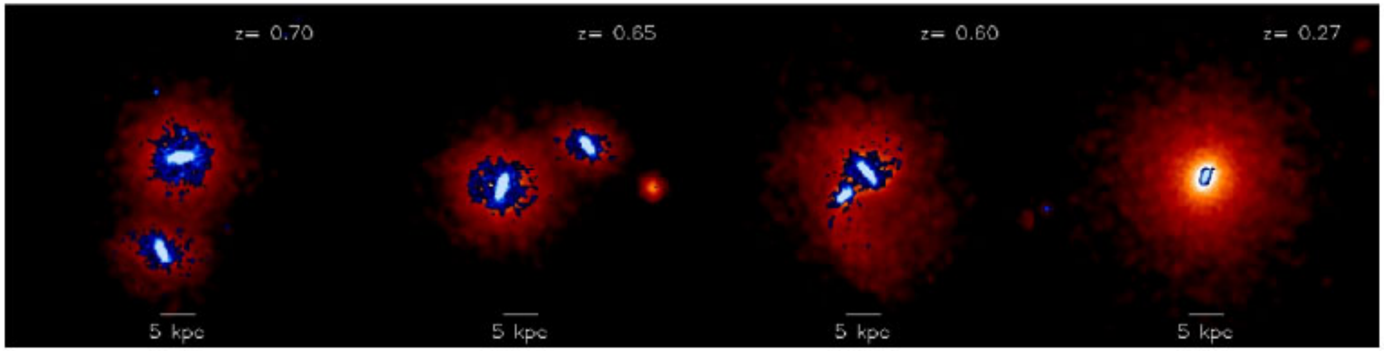

Fig. 5. A major merger and the formation of an elliptical galaxy. The disk merges with another system of about half its mass at $z = 0.7$ to form a spheroidal system of stars resembling an elliptical galaxy. All remaining gas is driven to the center of the remnant and consumed in a burst of star formation lasting 600 Myr. Stars less than 1.5 Gyr old are shown in blue, older in red. A movie illustrating the whole evolution of the galaxy can be found in the supplemental material (Annex) associated with this manuscript.

- At z = 0.7, major merger with a galaxy ½ mass
- At z = 0.6, 2 Sp ⇒ E, triaxial system & 10% of the remaining gas fall in the center ⇒ burst of SF
- Z = 0, Normal E, σ_v ~ 310 km/s, r_{eff} ~ 1.3 kpc, (B-V) ~1

Steinmetz & Navarro 2002, New Astronomy, 7, 155

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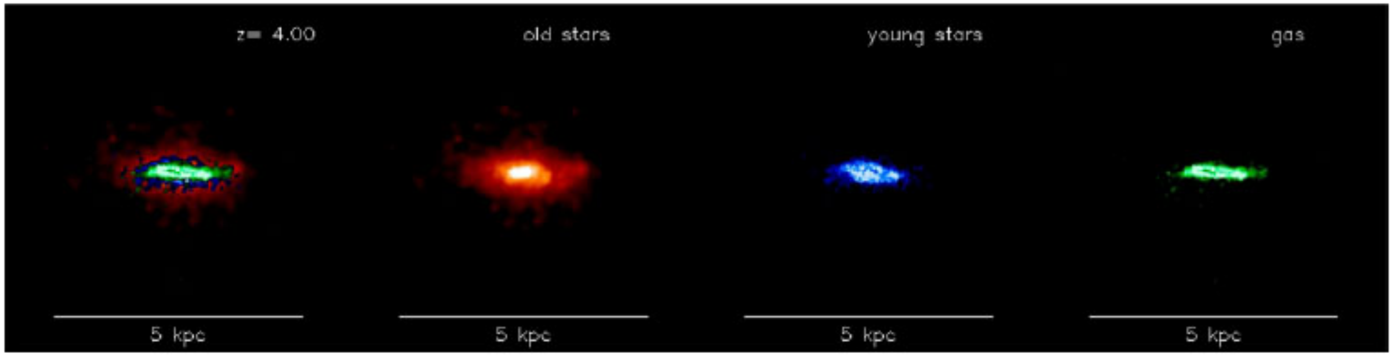

Fig. 1. The most massive progenitor at $z = 4$ shown edge-on. Gas particles are shown in green, 'young' (i.e. less than 200 Myr old) stars in blue and older stars in red. Horizontal bars in each panel are 5 (physical) kpc long.

- This demonstrates that the morphological type is a transitory phenomenon during the life of a galaxy
- The Hubble sequence is a signature of the accretion history of galaxies in the hierarchical clustering scenario
- A system bulge/disk may build and rebuild itself by slow accretion of gas and/or the result of a merger

Steinmetz & Navarro 2002, New Astronomy, 7, 155