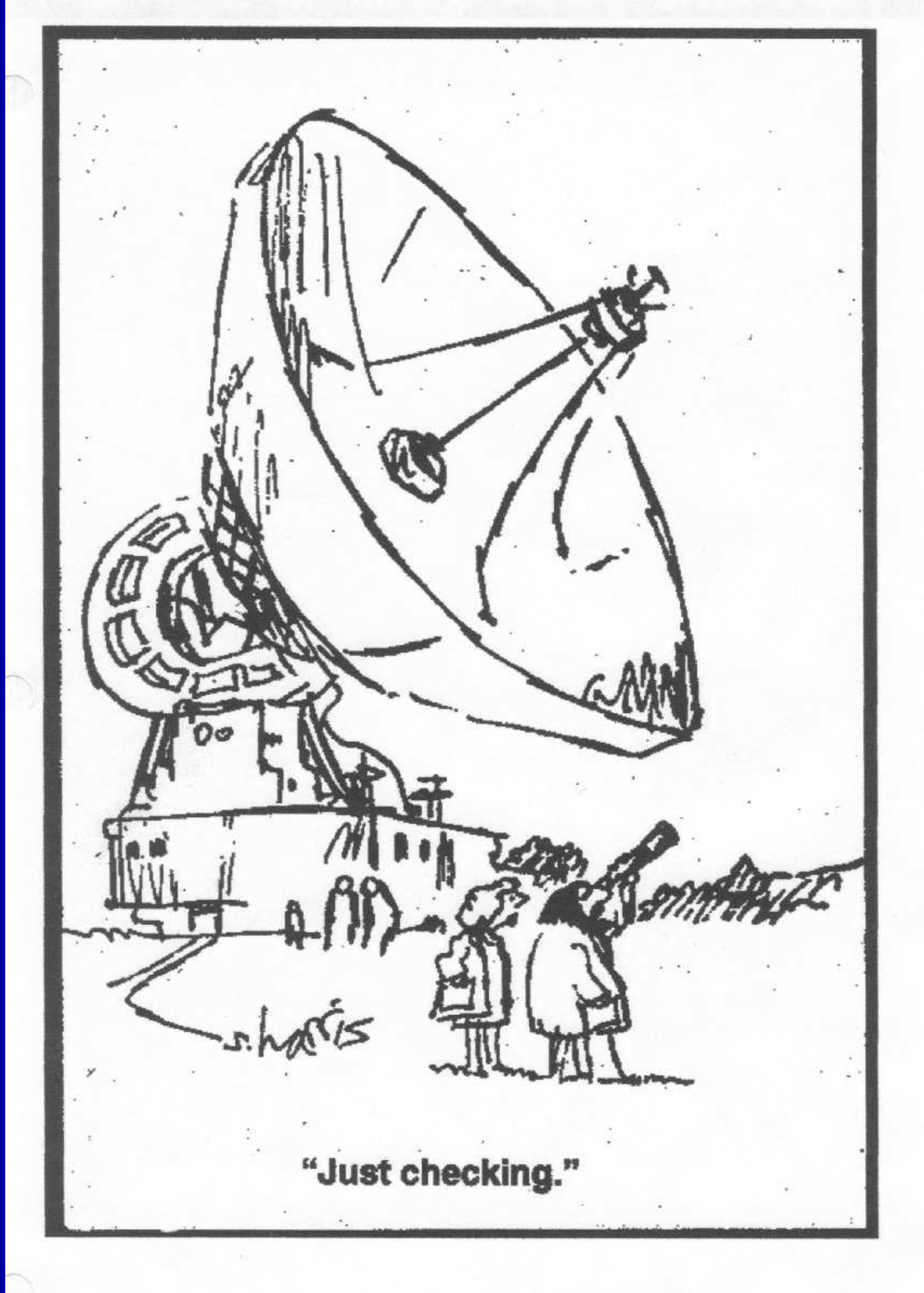
High Resolution Science with High Redshift Galaxies

Rogier Windhorst (Arizona State University)

36^{th} COSPAR Scientific Assembly, Beijing, China, July 17, 2006



For high res ($\equiv 1.22\lambda/D$ fwhm): concentrate on UV–Opt–near-IR & large D!

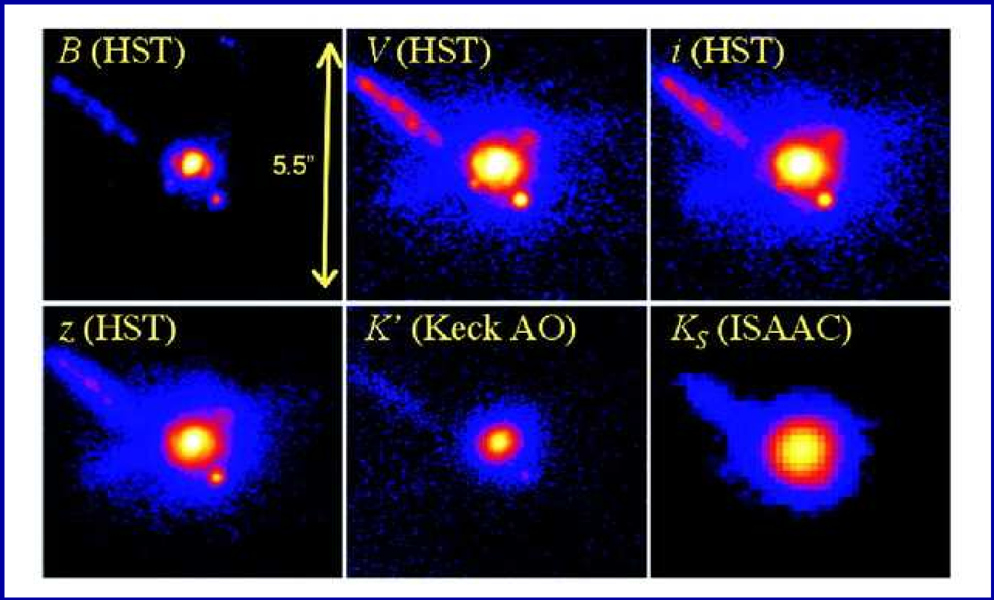
Outline: High resolution imaging of high redshift galaxies

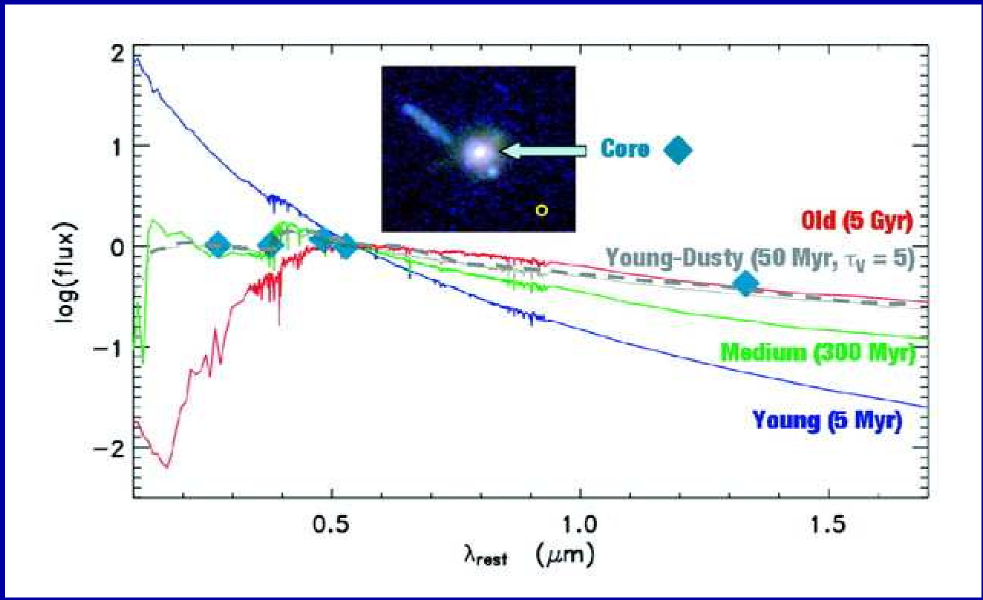
- (1) What can and has been done from the ground?
- (2) Why does high resolution imaging need to be done from space?
- (3) What has been done with the Hubble Space Telescope?
- (4) How can JWST measure First Light and Reionization?
- (5) How can JWST measure Galaxy Assembly?
- (6) Predicted Galaxy Appearance for JWST at $z \simeq 1$–15
- (7) Summary and Conclusions

Sponsored by NASA/JWST

Arizona State University

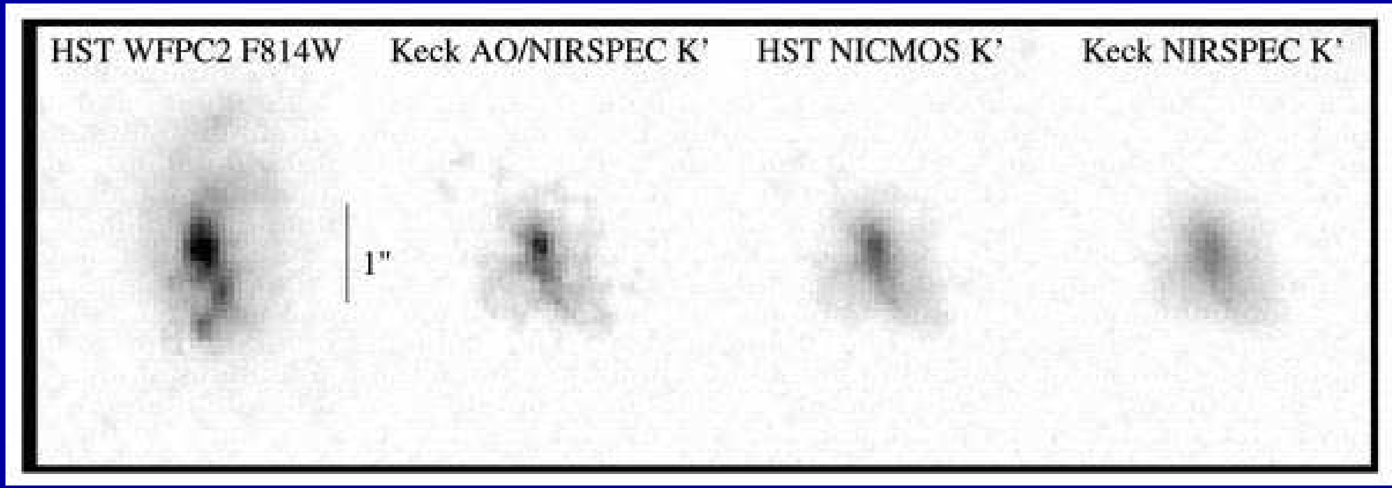
• (1) What can and has been done from the ground?

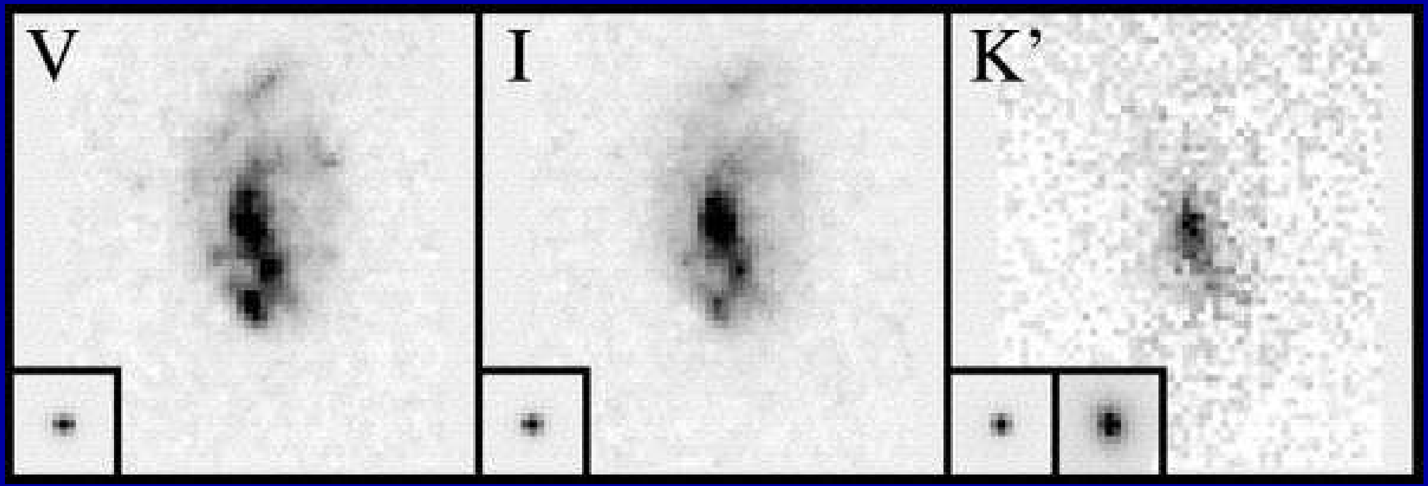




Ground-based AO in K-band with Keck (Melbourne et al. 2005 ApJL, 625, L27):

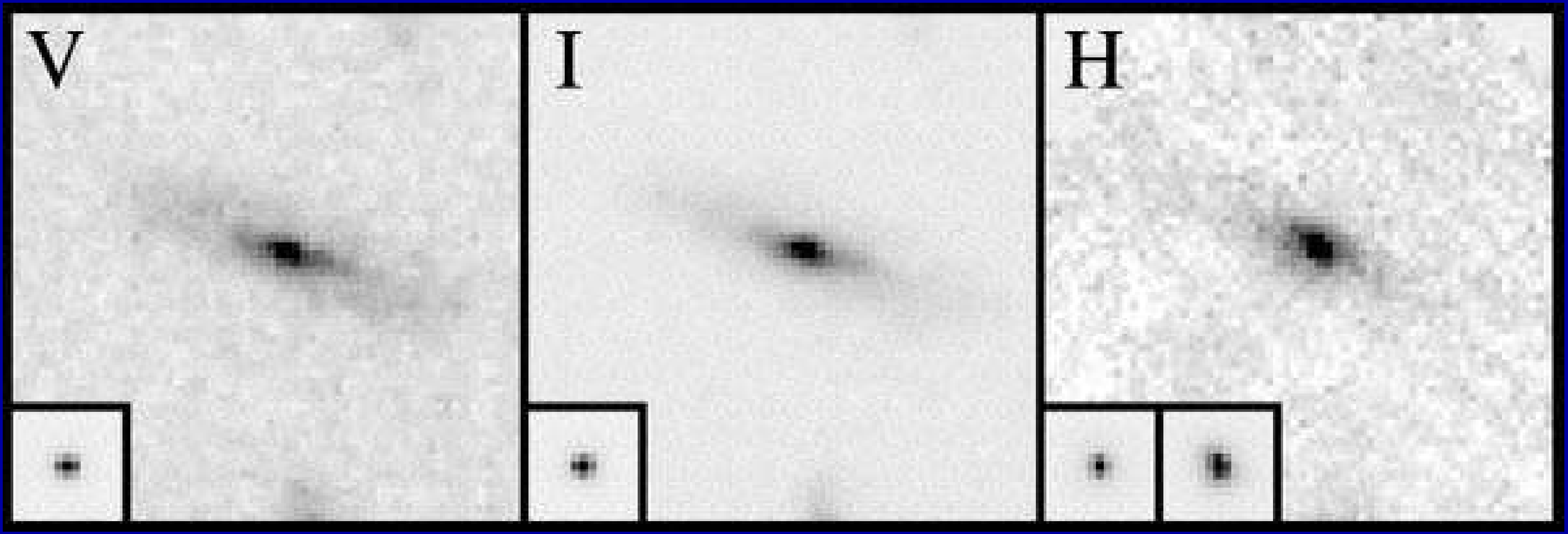
- Match or supersede HST resolution if have nearby AO guide star.
- But dynamic range, PSF stability, and sky-brightness no match to space.
- ⇒ Do brighter objects, but can get very high resolution from ground.
- Can decompose stellar populations, AGN and dust.

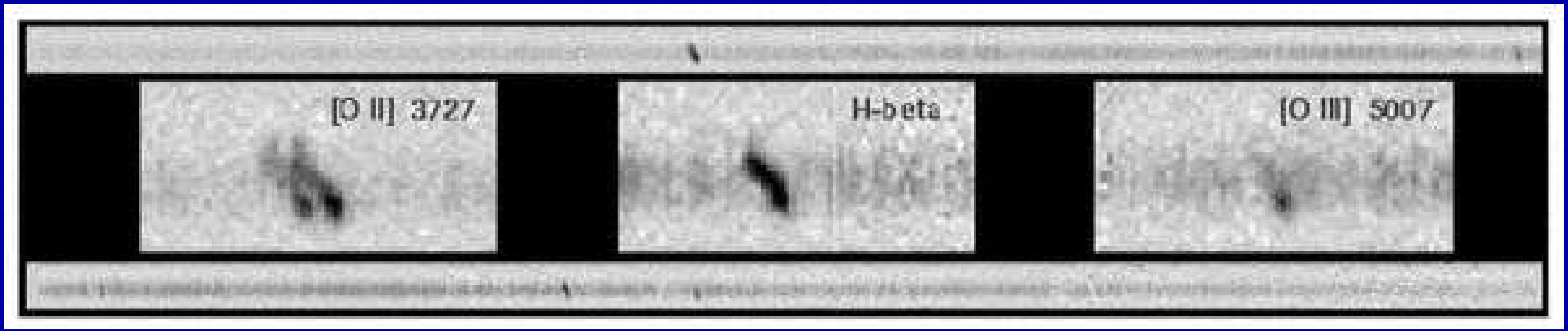




Ground-based AO in K-band with Keck (Steinbring ea. 2004 ApJ, 155, 15)

- Match or exceed HST resolution if have nearby AO guide star.
- But dynamic range, PSF stability and sky brightness no match to space.
- $\Rightarrow$ Do brighter objects, but can get very high resolution from ground.

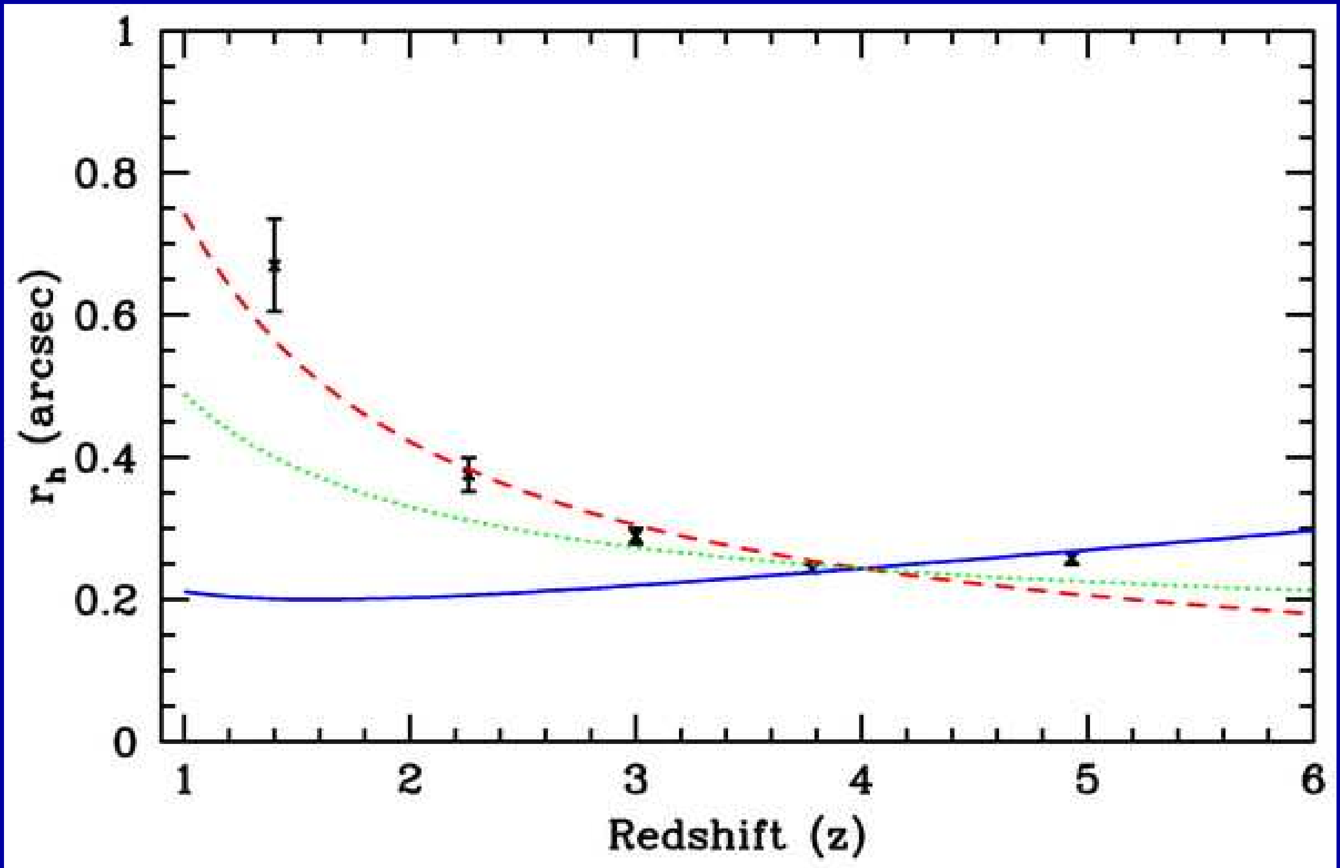




Ground-based AO in K-band with Keck (Steinbring 2004 ApJ, 155, 15):

- Much larger collecting area allows one to do high-resolution spectra.
- Can do rotation curves of faint galaxies $\longrightarrow$ masses etc. Match or exceed HST resolution if have nearby AO guide star.
- Low dynamic range & bright sky $\longrightarrow$ ground cannot go as faint and obtain as wide a field-of-view as HST.

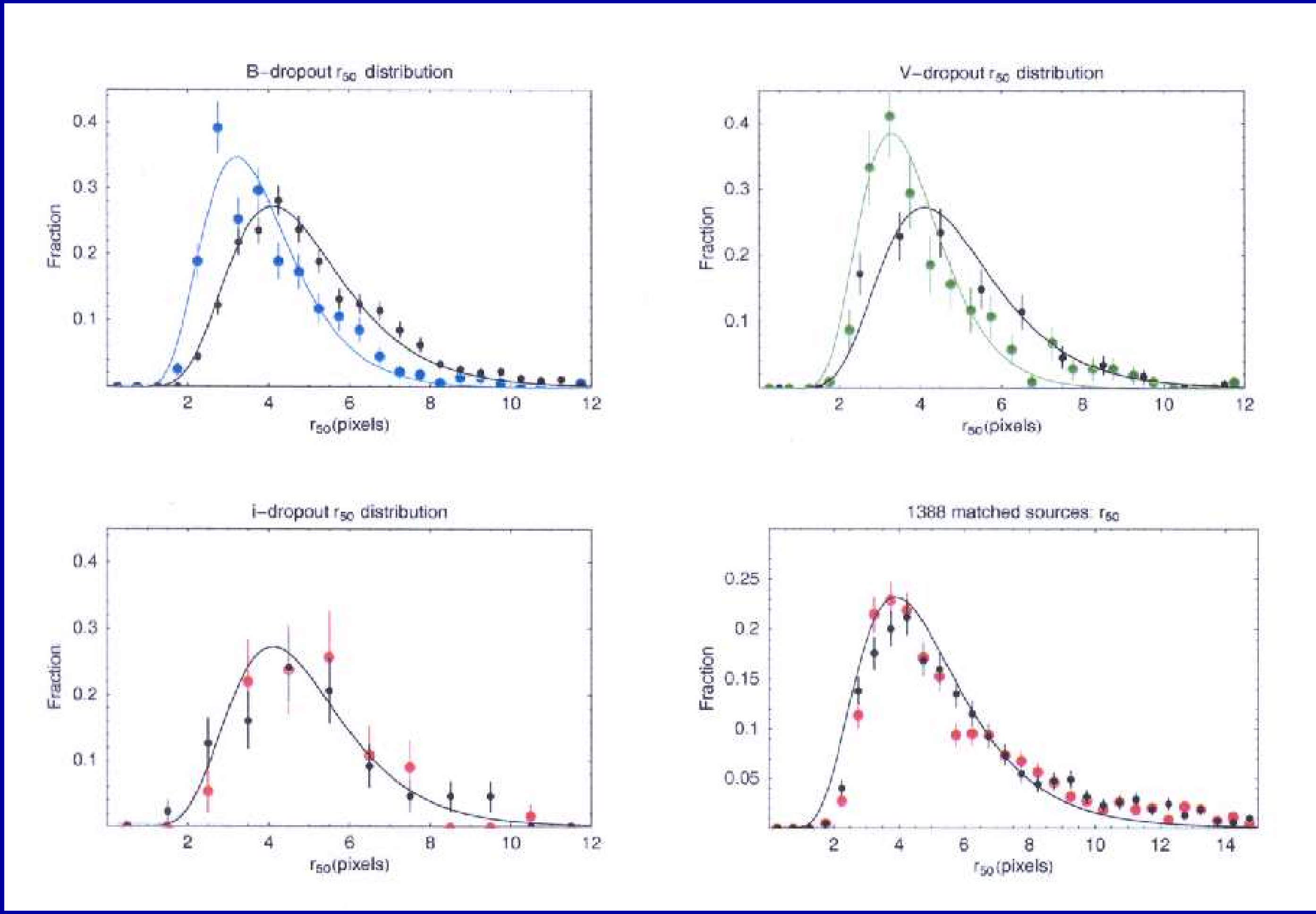
• (2) Why does high-res imaging need to be done from space?



The HST/ACS GOODS survey (Ferguson et al. 2004 ApJL) showed:

- Median galaxy sizes decline steadily at higher redshifts, despite the cosmological Θ–z relation that minimizes at z$\simeq$1.6 for Λ-cosmology.
- Evidence of intrinsic size evolution: $\mathrm{r_{hl}(z)} \propto r_{hl}(0)\ .\ (1{+}\mathrm{z})^{-\mathrm{s}}$, s$\simeq$ 1.
- Caused by hierarchical formation of galaxies, leading to intrinsically smaller galaxies at higher redshifts, where fewer mergers have occurred.

- (2) Why does high-res imaging need to be done from space?



The HST/ACS Hubble UltraDeep Field (HUDF; Beckwith et al. 2006 AJ; http://www.stsci.edu/∼svwb/hudf.html) has similarly shown that:

- High redshift galaxies (B-drops at z≃4; V-drops at z≃5; and i-drops at z≃6) are intrinsically very small:
- Galaxies at z≃4–6 have: $r_{\rm hl} \simeq 0\farcs12 \simeq$ 0.7–0.9 kpc intrinsically.

• (2) Why does high-res imaging need to be done from space?

Combination of ground-based and space-based HST surveys have shown (Odewahn et al. 1996; Cohen et al. 2003, Windhorst et al. 2006):

(1) Apparent galaxy sizes decline steadily from RC3 to HUDF limits.

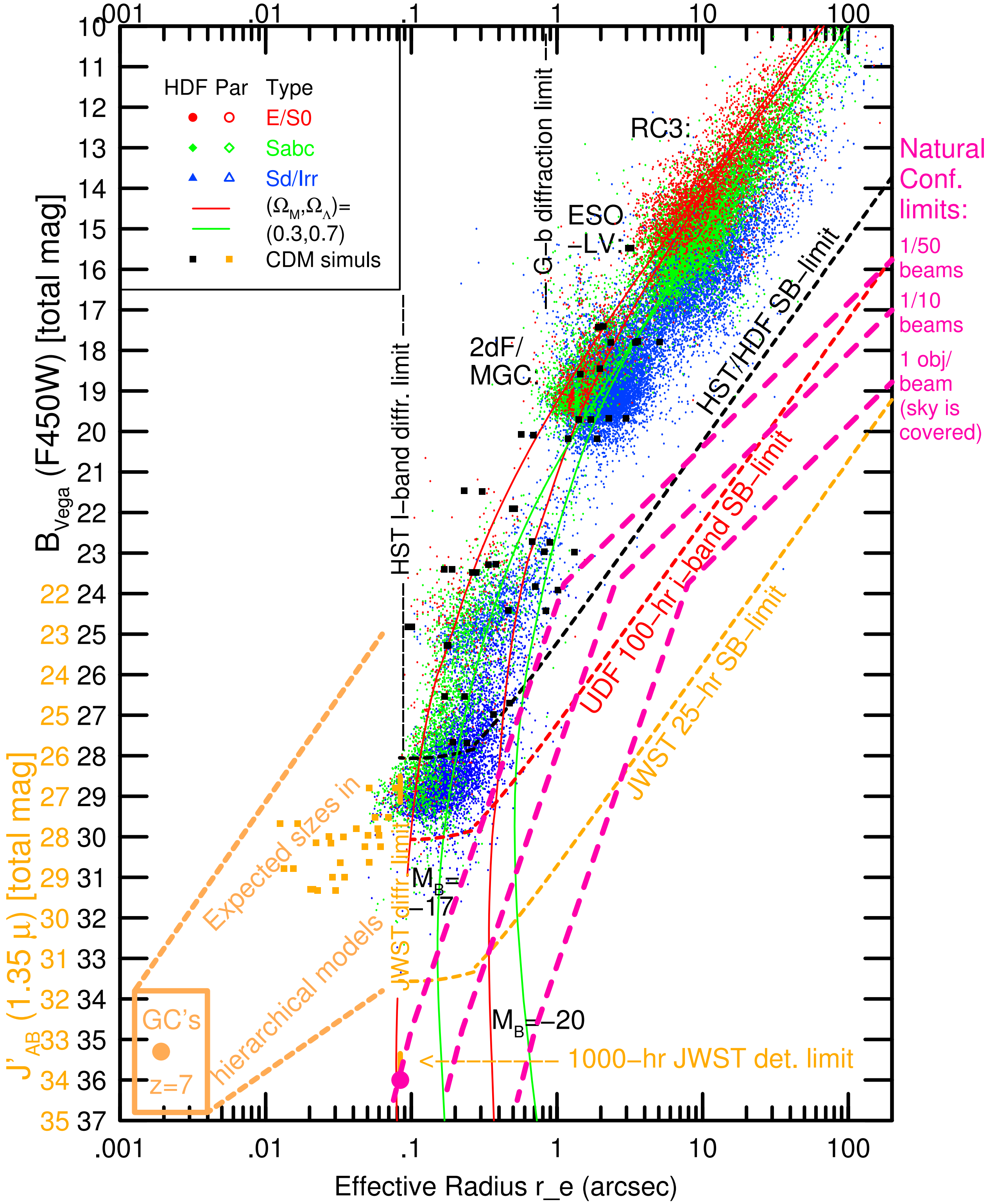
(2) This is *not* due to surface brightness selection effects (cosmological $(1+z)^4$-dimming), but instead due to:

• (a) the hierarchical formation of galaxies, which causes galaxy sizes to evolve as: $r_{hl}(z) \propto r_{hl}(0) \cdot (1+z)^{-s}$, $s \simeq 1$.

• (b) Fluxes at AB$\gtrsim$26 mag sample the faint end of the LF at $z_{med} \gtrsim 2$–3, resulting in intrinsically smaller galaxies.

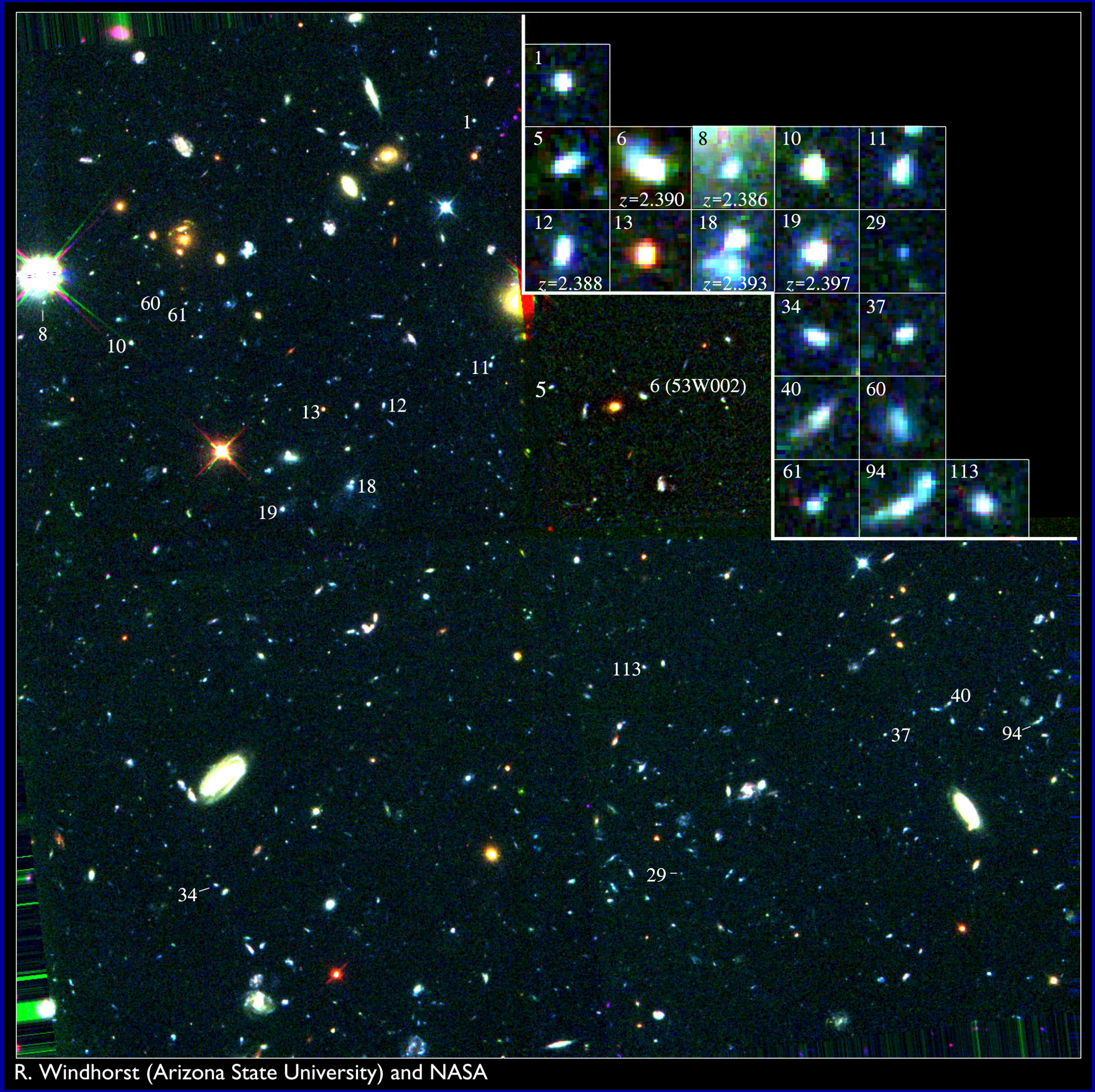
(3) Most galaxies seen by JWST at AB$\gtrsim$27 mag will be unresolved ($r_{hl} \lesssim 0\farcs1$ fwhm). Since $z_{med} \gtrsim 2$, this mitigates the $(1+z)^4$-dimming.

$\Rightarrow$ Most galaxies seen by JWST will be point sources at FWHM $\lesssim 0\farcs1$!



HDF Par Type
E/S0
Sabc
Sd/Irr
$(\Omega_M,\Omega_\Lambda)$=
(0.3,0.7)
CDM simuls
RC3:
ESO -LV:
2dF/ MGC:
G–b diffraction limit
HST I–band diffr. limit
HST/HDF SB–limit
UDF 100–hr i–band SB–limit
JWST 25–hr SB–limit
Natural Conf. limits:
1/50 beams
1/10 beams
1 obj/ beam (sky is covered)
Expected sizes in hierarchical models
JWST diffr. limit
M_B= –17
M_B=–20
GC's z=7
1000–hr JWST det. limit
B_{Vega} (F450W) [total mag]
J'_{AB} (1.35 μ) [total mag]
Effective Radius r_e (arcsec)

- (3) What has been done with the Hubble Space Telescope?



One of the remarkable discoveries of HST was how numerous and small faint galaxies are — the building blocks of the giant galaxies seen today.

• (3) What has been done with the Hubble Space Telescope?

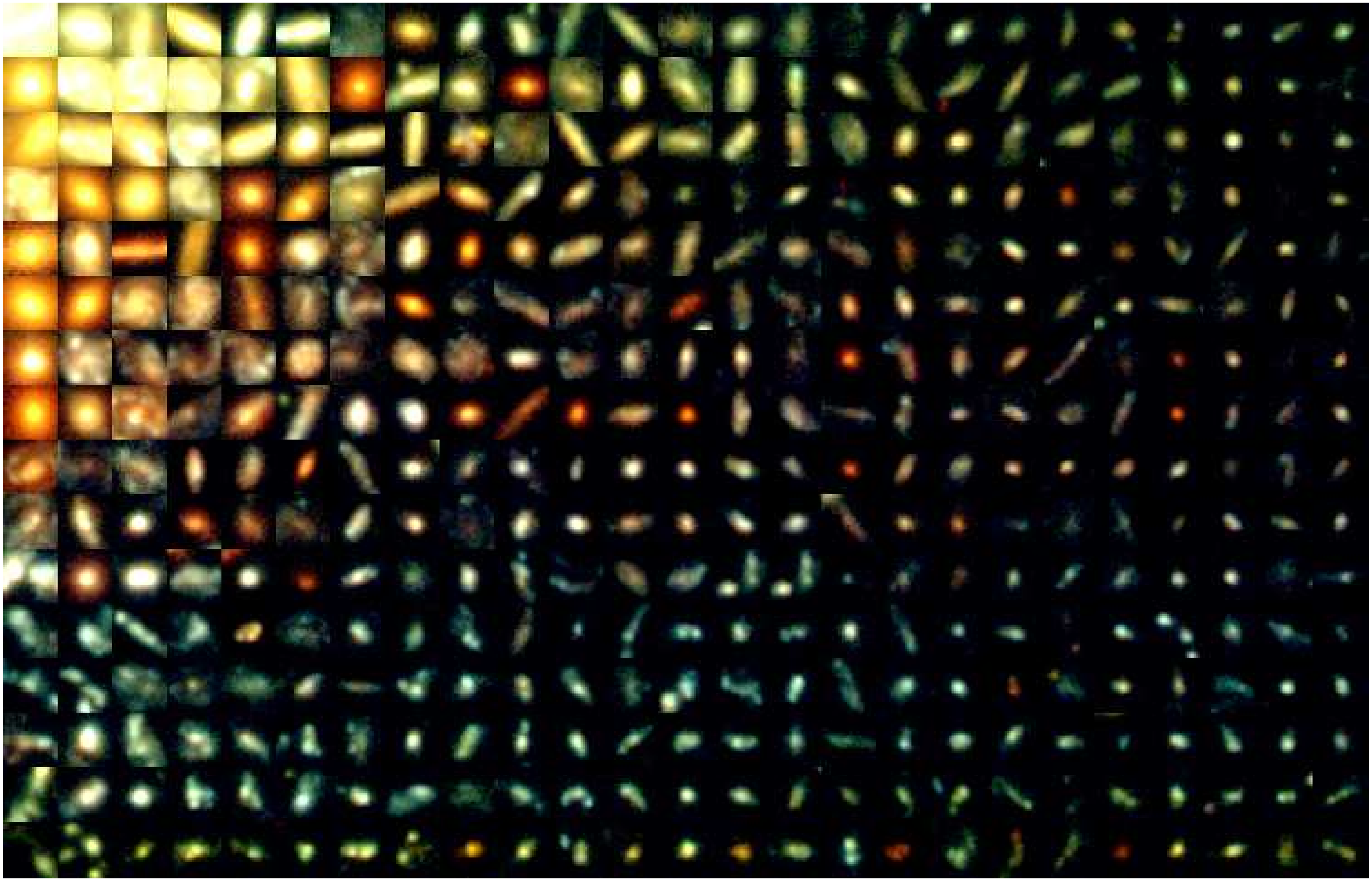
• Galaxies of Hubble types formed over a wide range of cosmic time, but with a notable phase transition around redshifts $z \simeq 0.5$–1.0:

(1) Subgalactic units rapidly merge from $z \simeq 7 \rightarrow 1$ to grow bigger units.

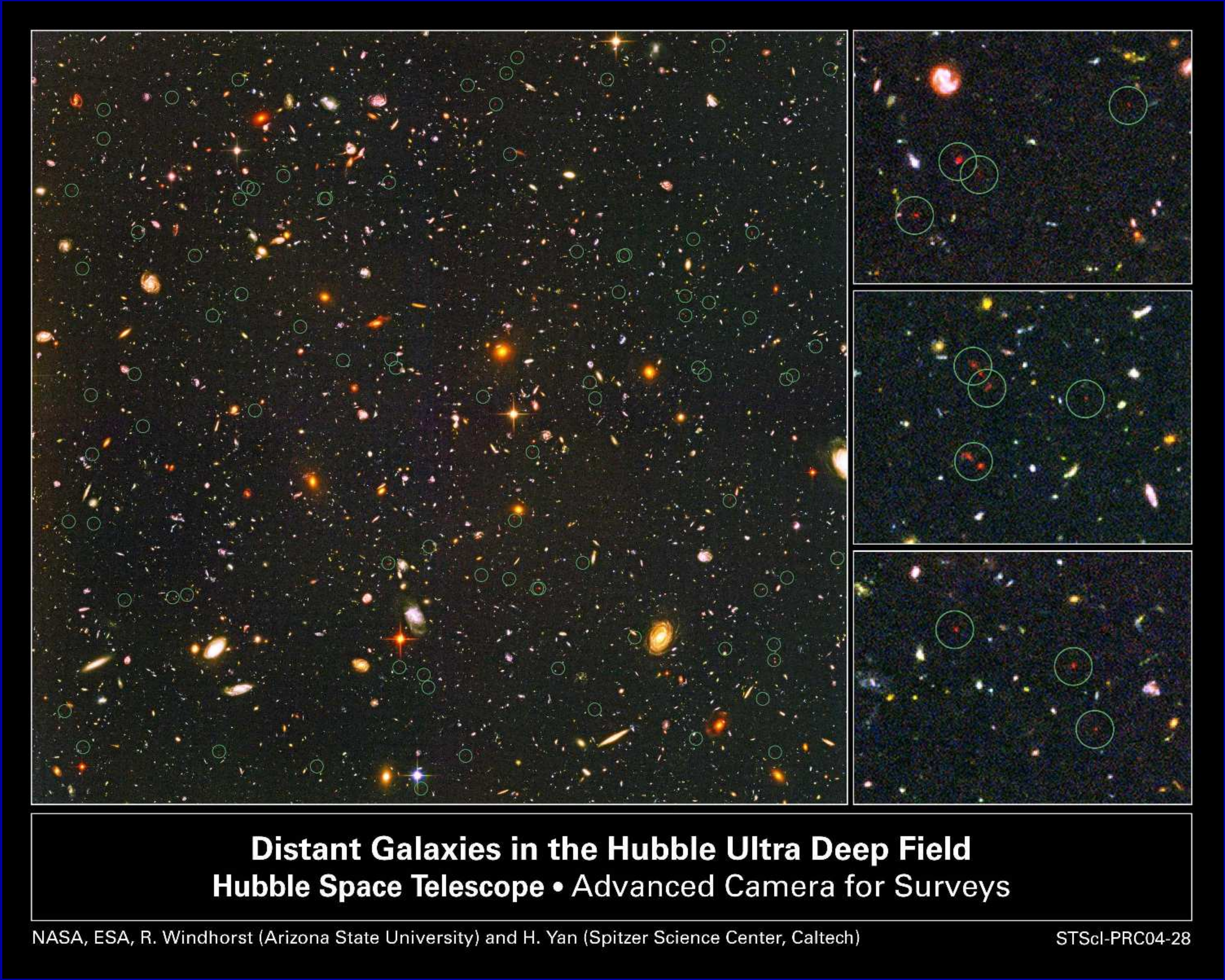
(2) Merger products start to settle as galaxies with giant bulges or large disks around redshifts $z \simeq 1$. These evolved mostly passively since then (their mergers tempered by the Cosmological Constant), resulting in the giant galaxies that we see today.

• JWST can measure how galaxies of all types formed over a wide range of cosmic time, by accurately measuring their distribution over rest-frame structure and type as a function of redshift or cosmic epoch.

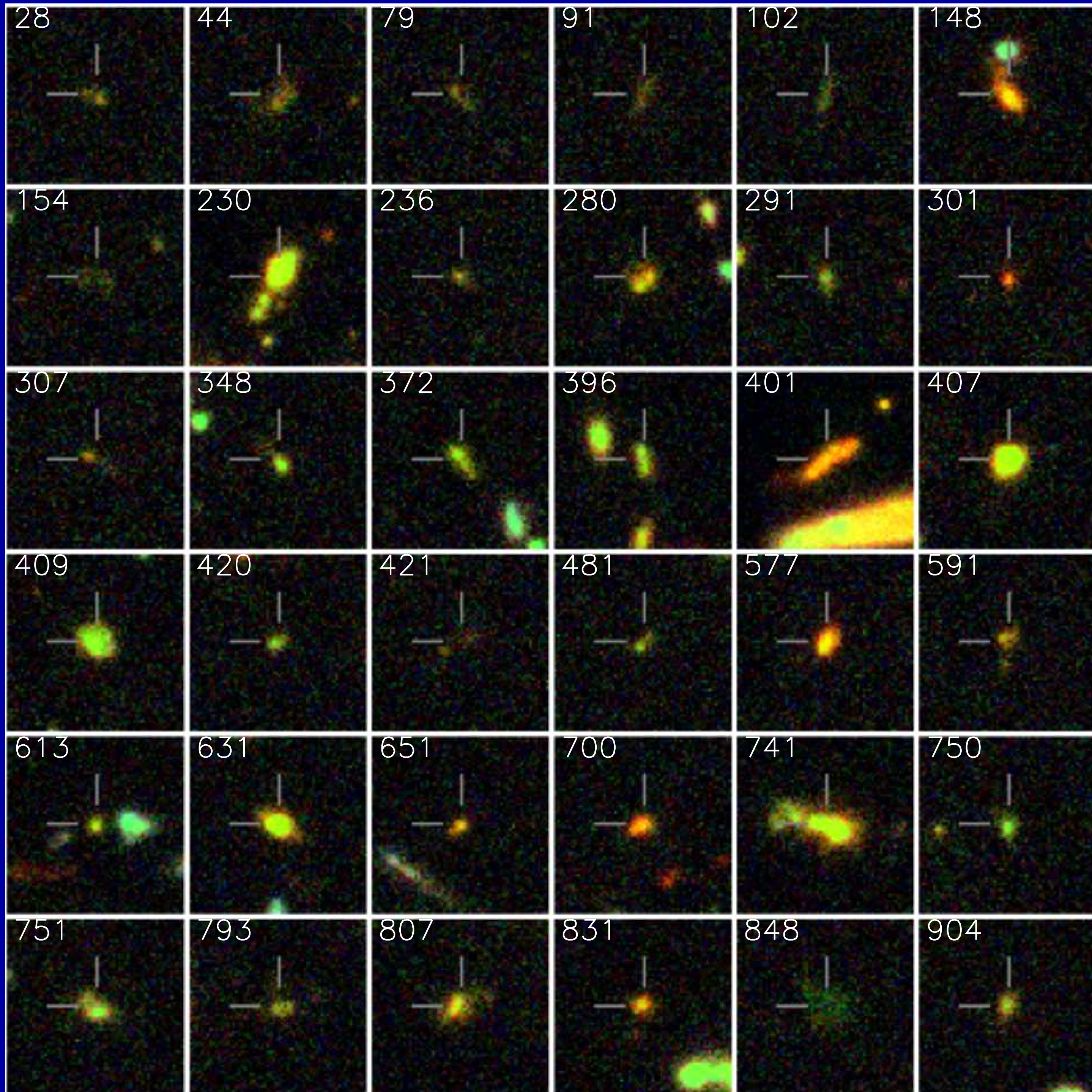
THE HUBBLE DEEP FIELD CORE SAMPLE ($I < 26.0$)



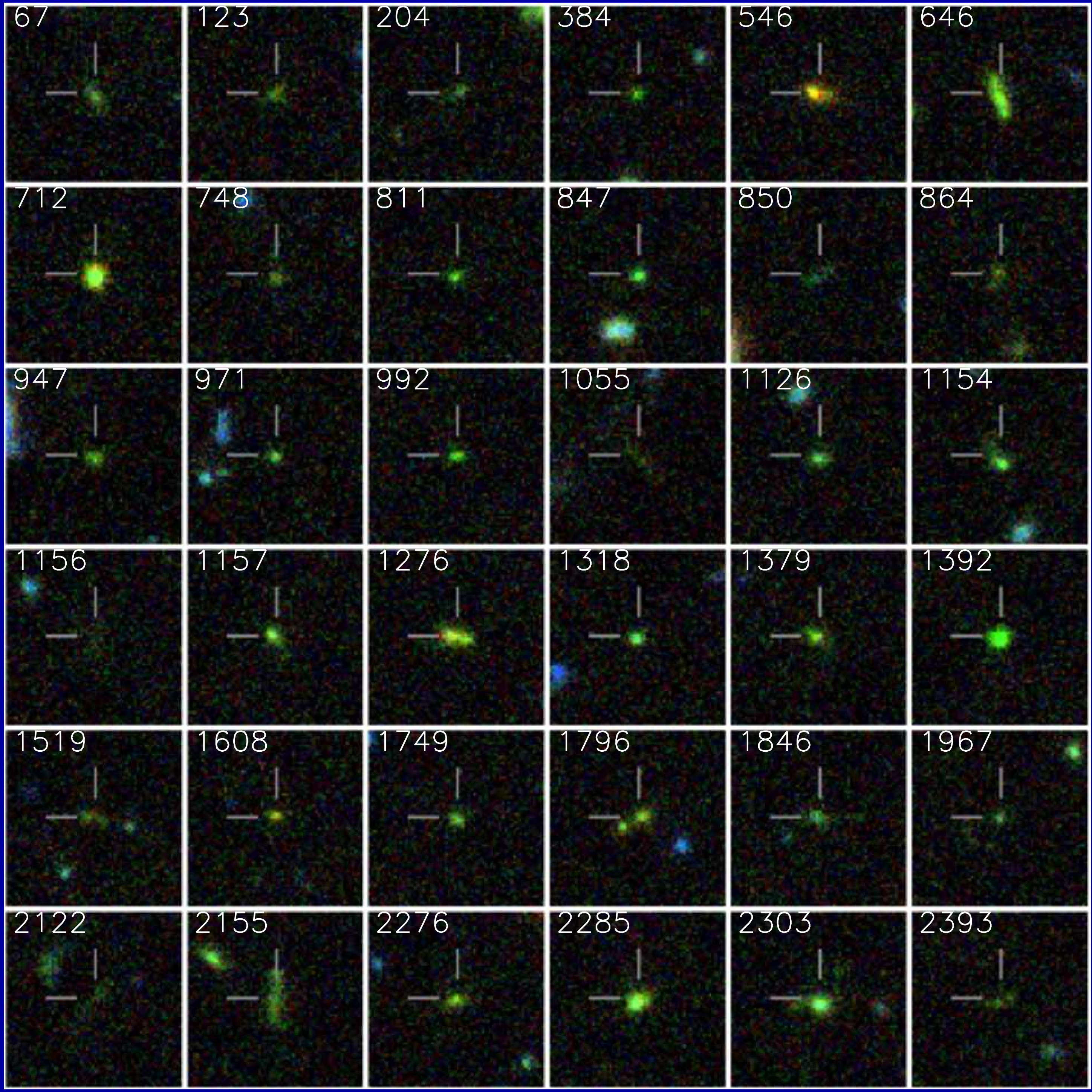
z	Age ($q_o = 0.5$)
0.19	77%
0.44	58%
0.54	52%
0.64	48%
0.74	44%
0.87	39%
0.97	36%
1.03	35%
1.14	32%
1.24	30%
1.41	27%
1.61	24%
1.76	22%
2.05	19%
2.57	15%
3.59	10%



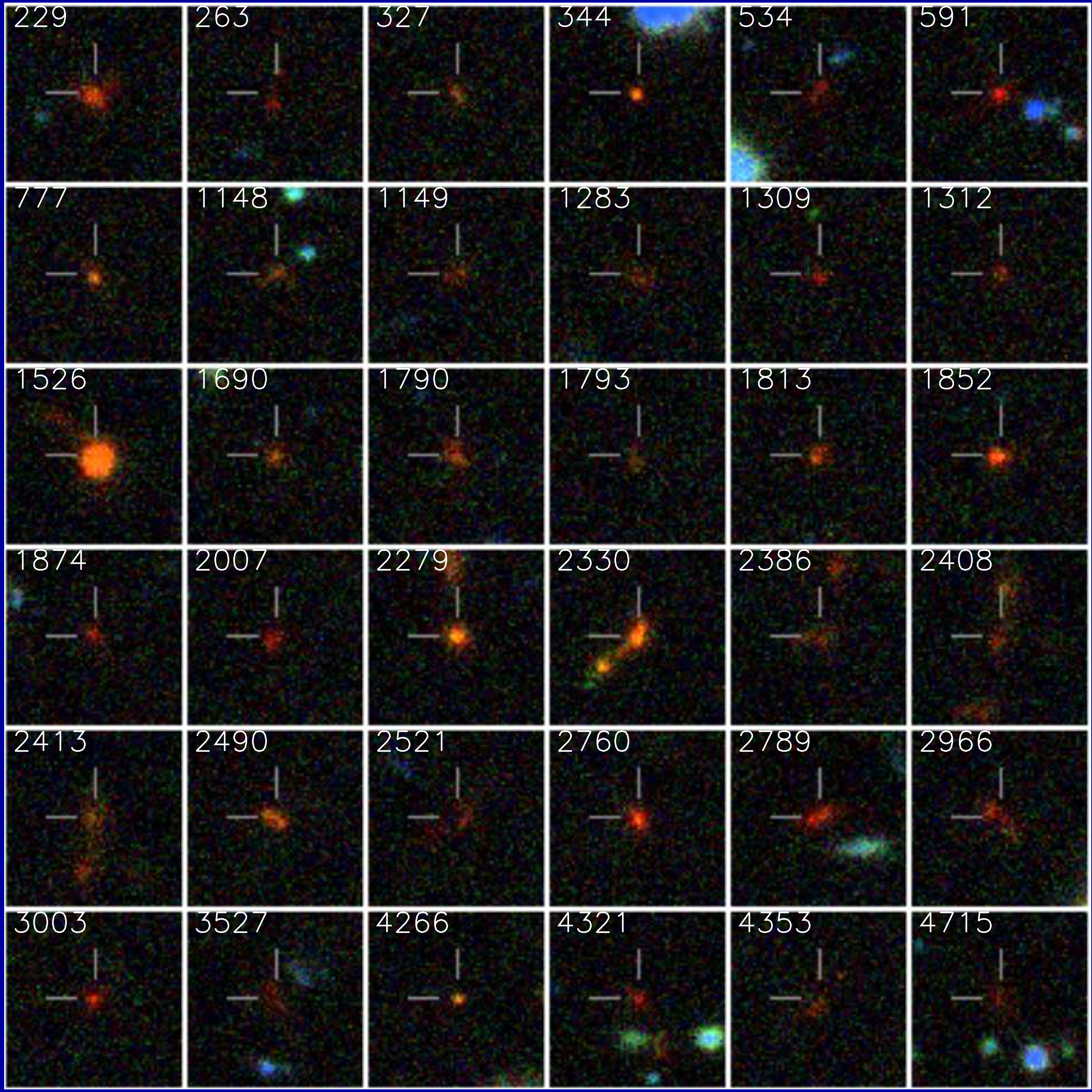
i-band drops in the HUDF: Most confirmed at $z \simeq 6$ (Malhotra et al. 2005)



B-drops in the HUDF (Beckwith et al. 2006 AJ): 504 $z \sim 4$ candidates.



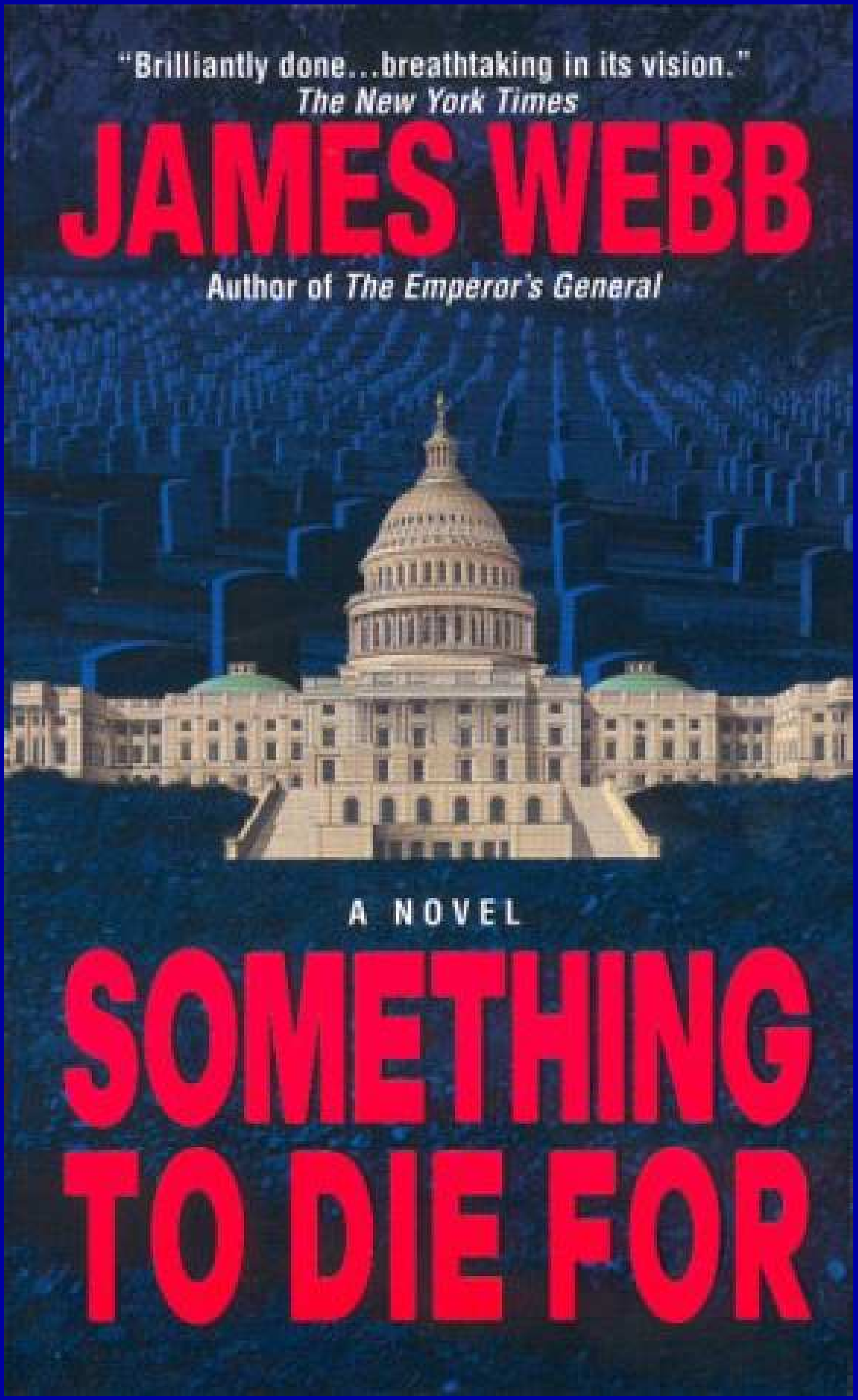
V-drops in the HUDF (Beckwith et al. 2006 AJ): 204 z∼5 candidates.



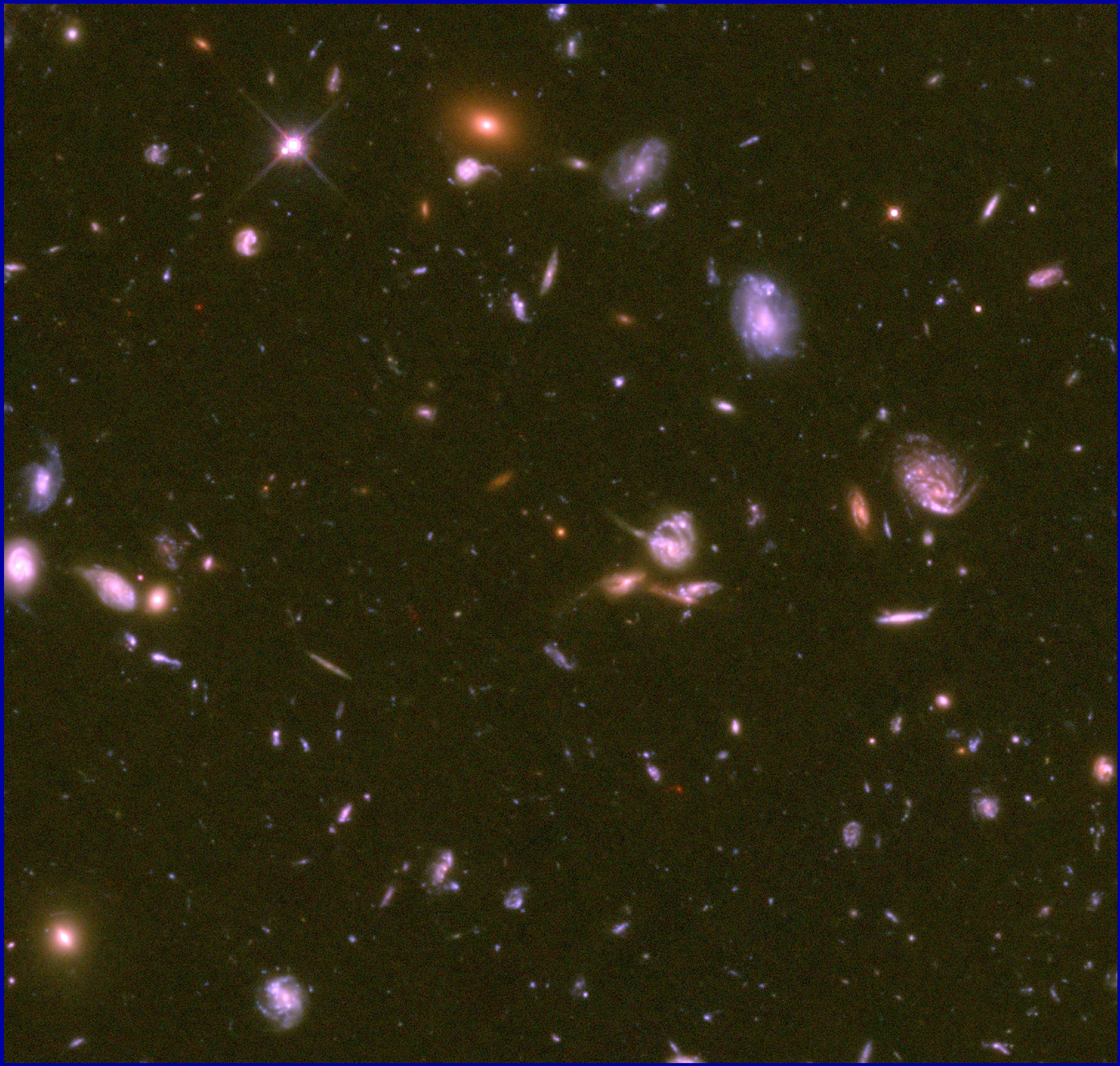
i-drops in the HUDF (Beckwith et al. 2006 AJ): 54–108 z∼6 candidates.

• (4) How can JWST measure First Light and Reionization?

See Dr. Mark Clampin's JWST talks this session and elsewhere at COSPAR.

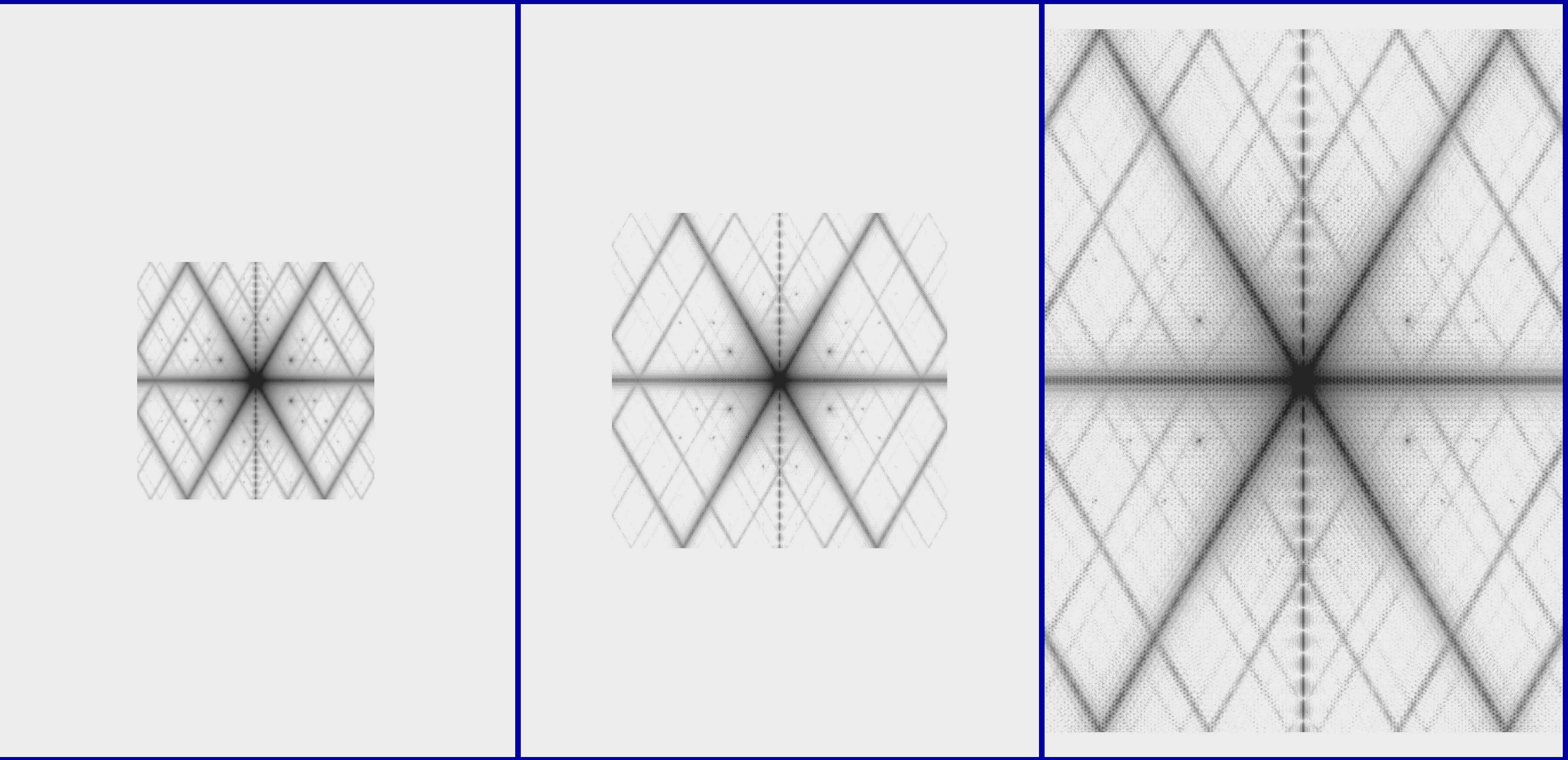


Need hard-working grad students & postdocs in $\gtrsim$2013 ... It'll be worth it!

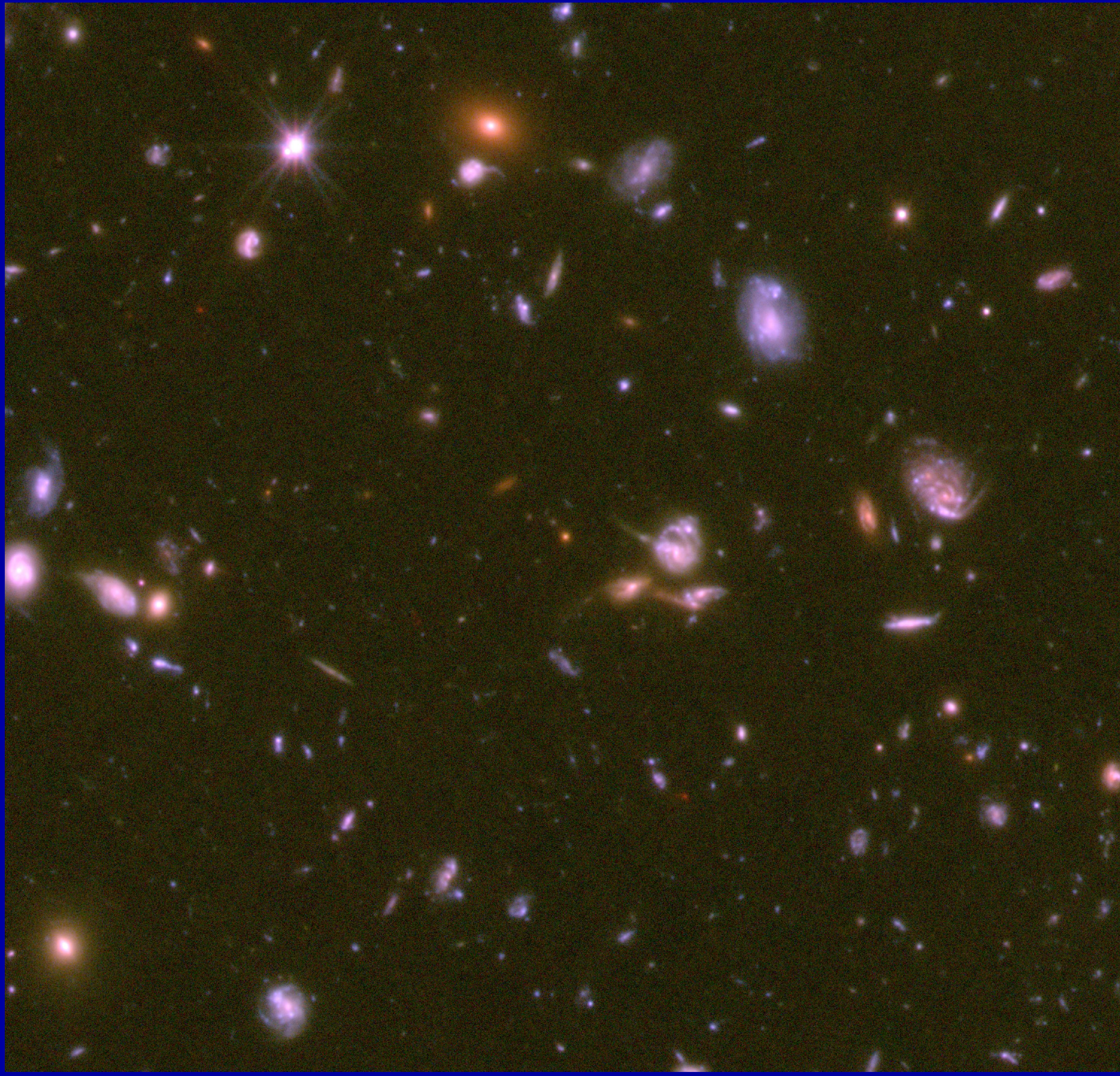


240 hrs HST/ACS in Vi'z' in the Hubble UltraDeep Field (HUDF)

6.5m JWST PSF's models (Ball Aerospace and GSFC):

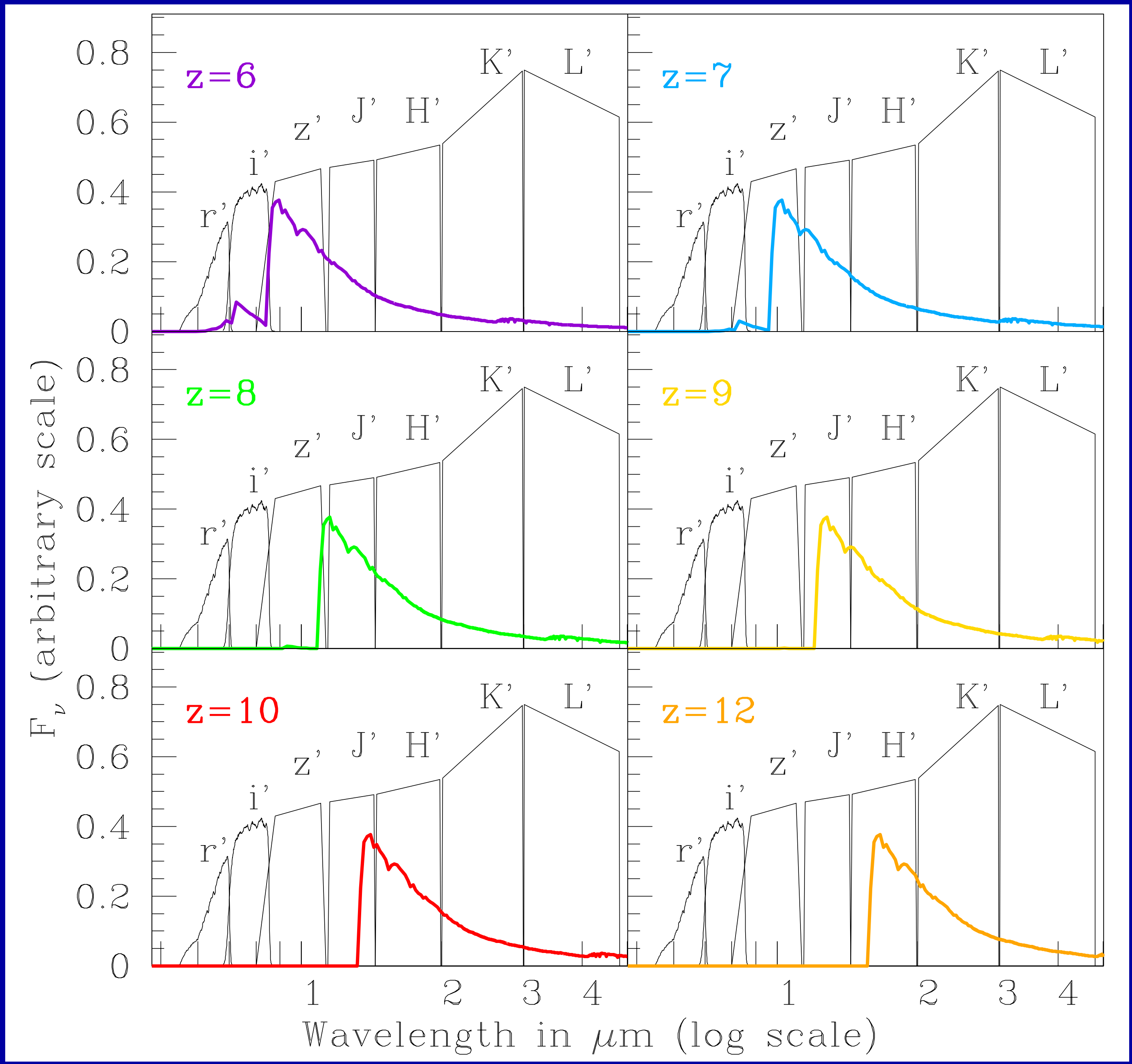


NIRCam 0.7 μm 1.0 μm (<150 nm WFE) 2.0 μm (diffr. limit)



$\lesssim$20 hrs JWST NIRCam at 0.7, 0.9, 2.0 μm in the HUDF

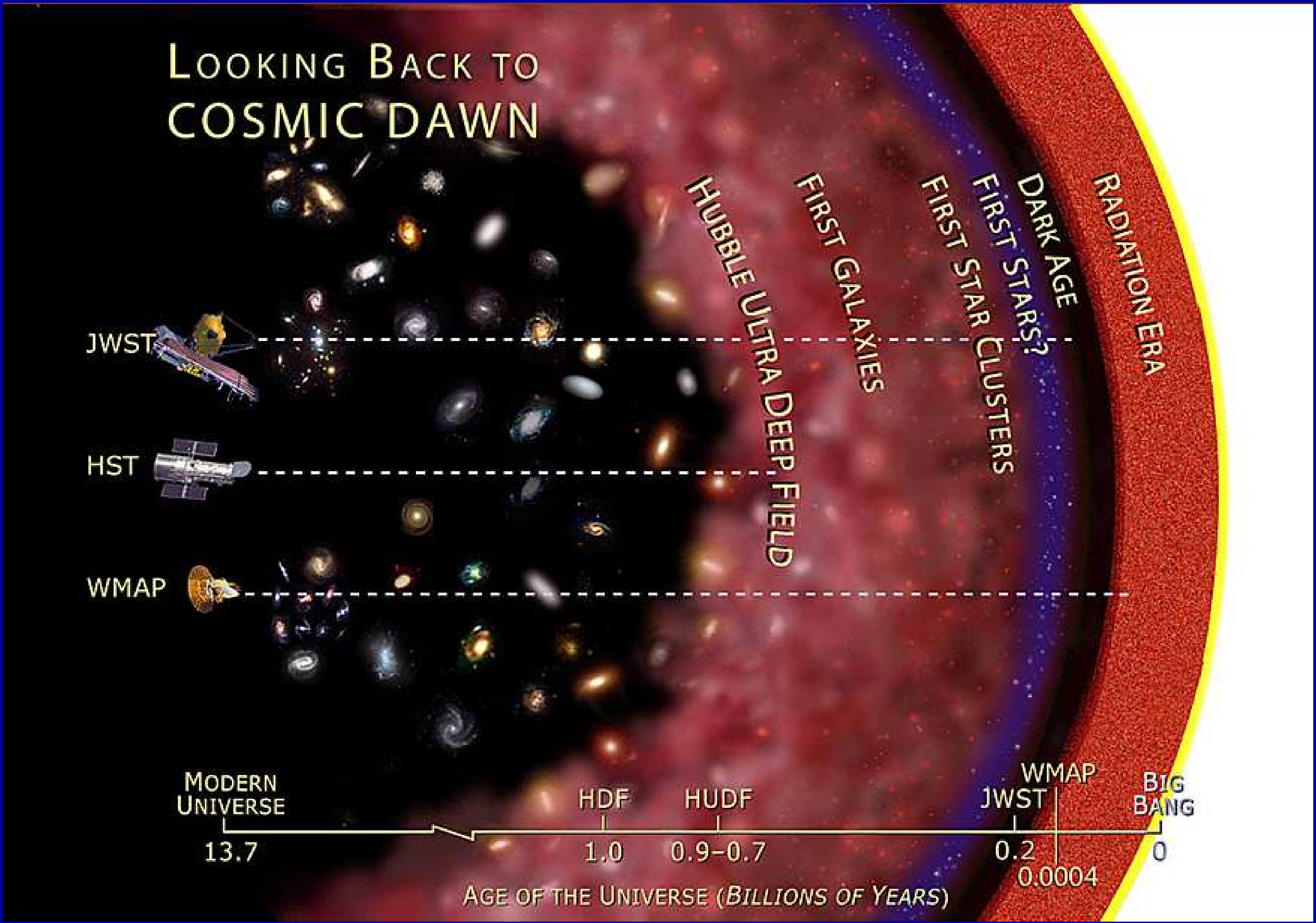
Truth≡240 hrs HUDF Vi'z' $\lesssim$20 hrs JWST 0.7, 0.9, 2.0 μm



• Can't beat redshift: to see First Light, must observe near–mid IR.

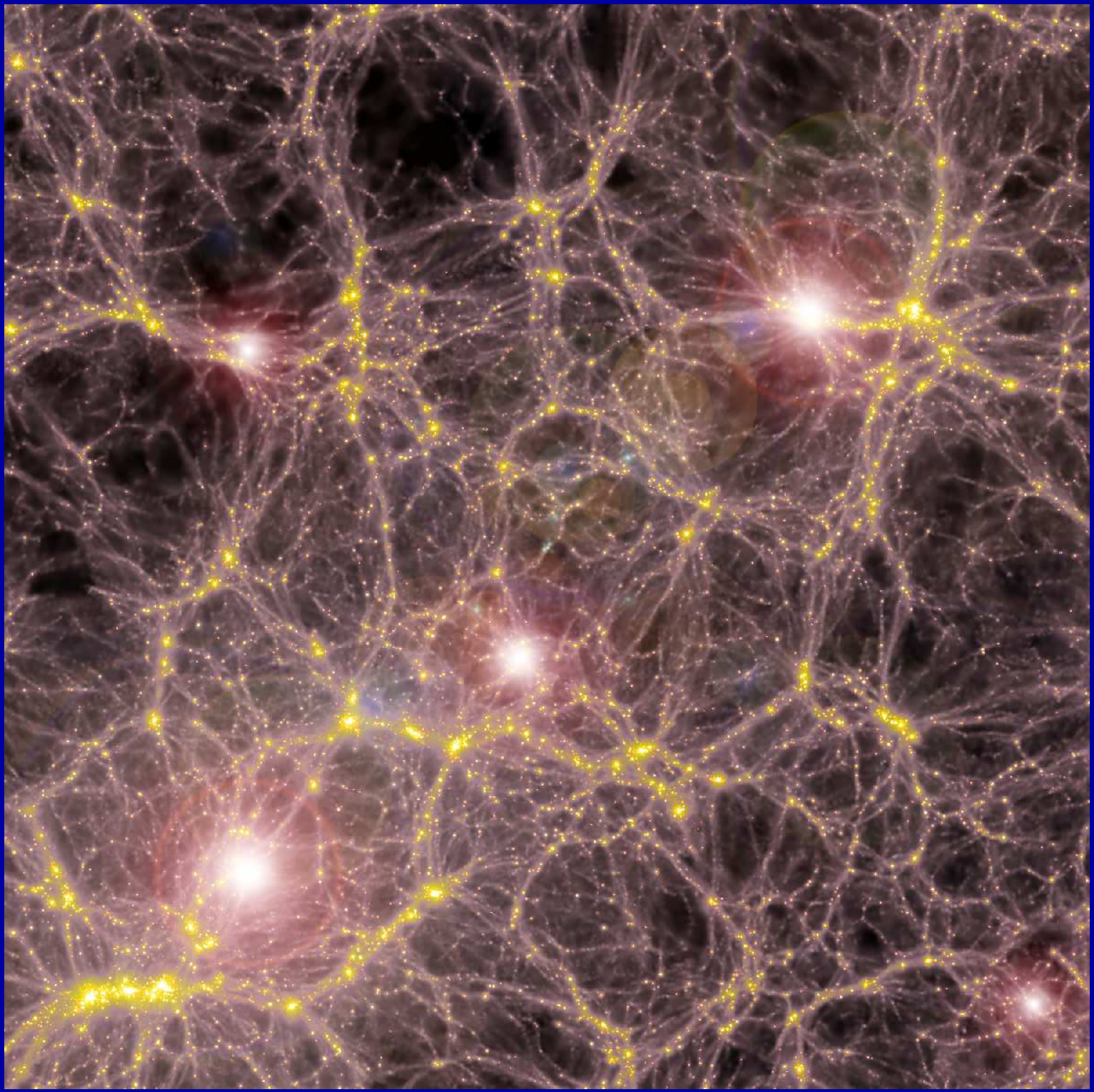
⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

(4a) What is First Light, Reionization, and Galaxy Assembly?

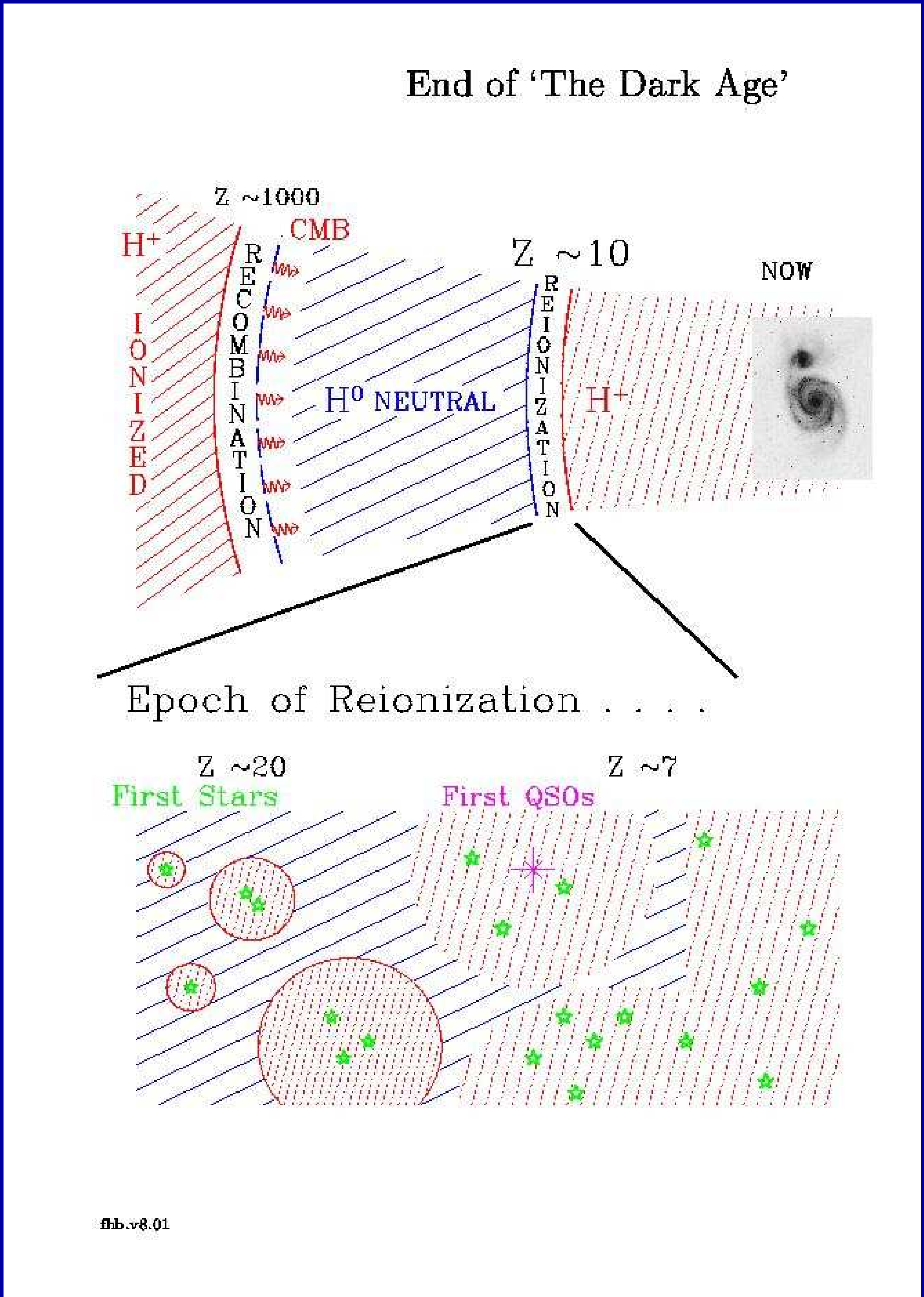


NASA telescopes penetrating Cosmic Dawn, First Light, & Recombination

• (4a) What is First Light and Reionization?



- Detailed Hydrodynamical models (V. Bromm) show that formation of Pop III stars reionized universe for the first time at $z \lesssim 10$–30 (First Light).
- A this should be visible to JWST as the first Pop III star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10 \rightarrow 30$.

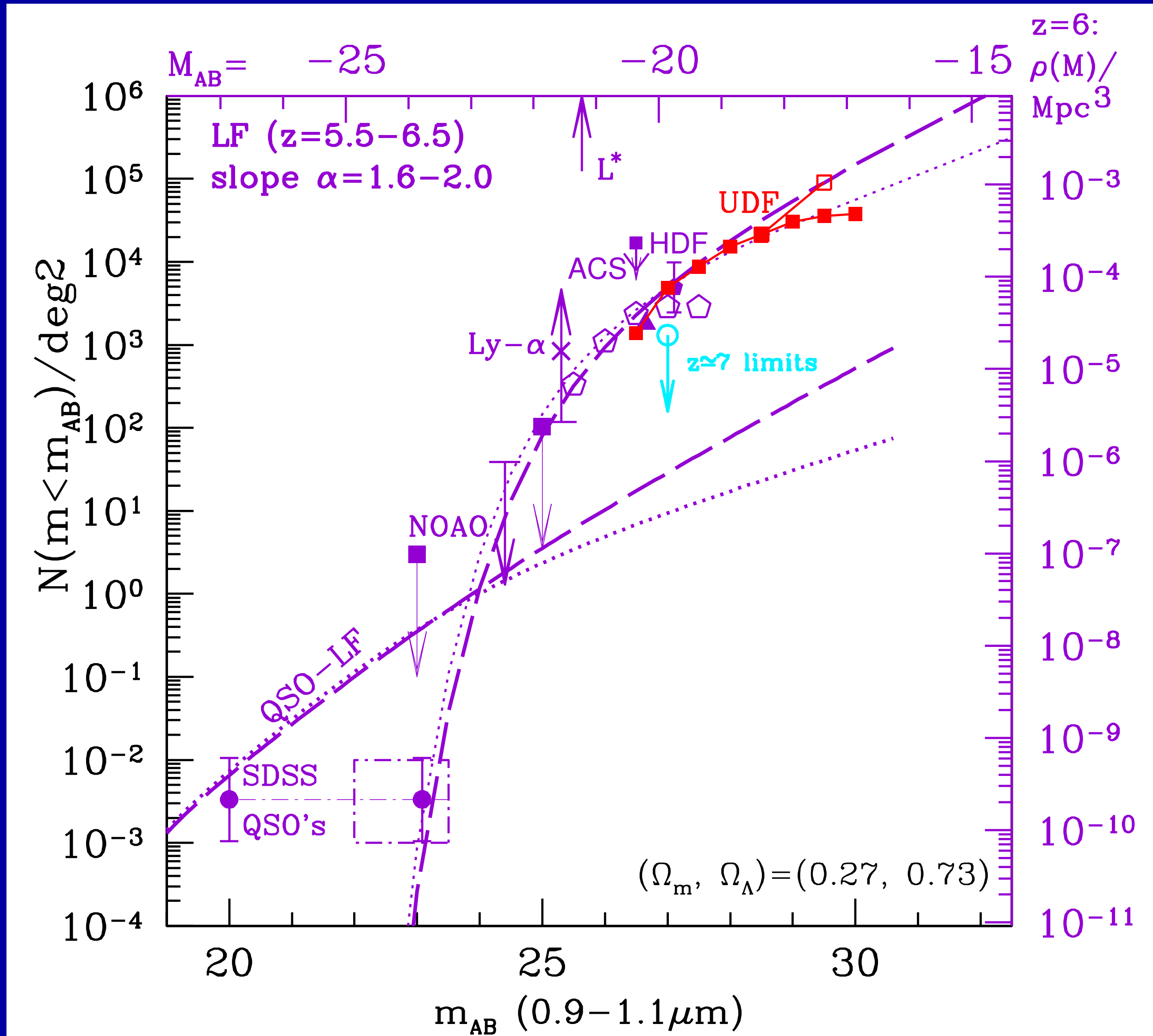


WMAP: First Light may have happened as following:

- (0) First Dark Ages since recombination (z=1089) until first light objects started shining (z=11–20)
- (1) First Light when Population III stars start shining with mass=200-1000 $M_\odot$ at z≃11–20
- (2) Second Dark Ages since Pop III supernovae heated gas which could not cool and form normal Pop II halo stars until z≃9–11.
- (3) This is followed by Pop II stars forming in dwarf galaxies (mass≃10^7–10^9 $M_\odot$) at z≃6–9, ending the epoch of reionization.

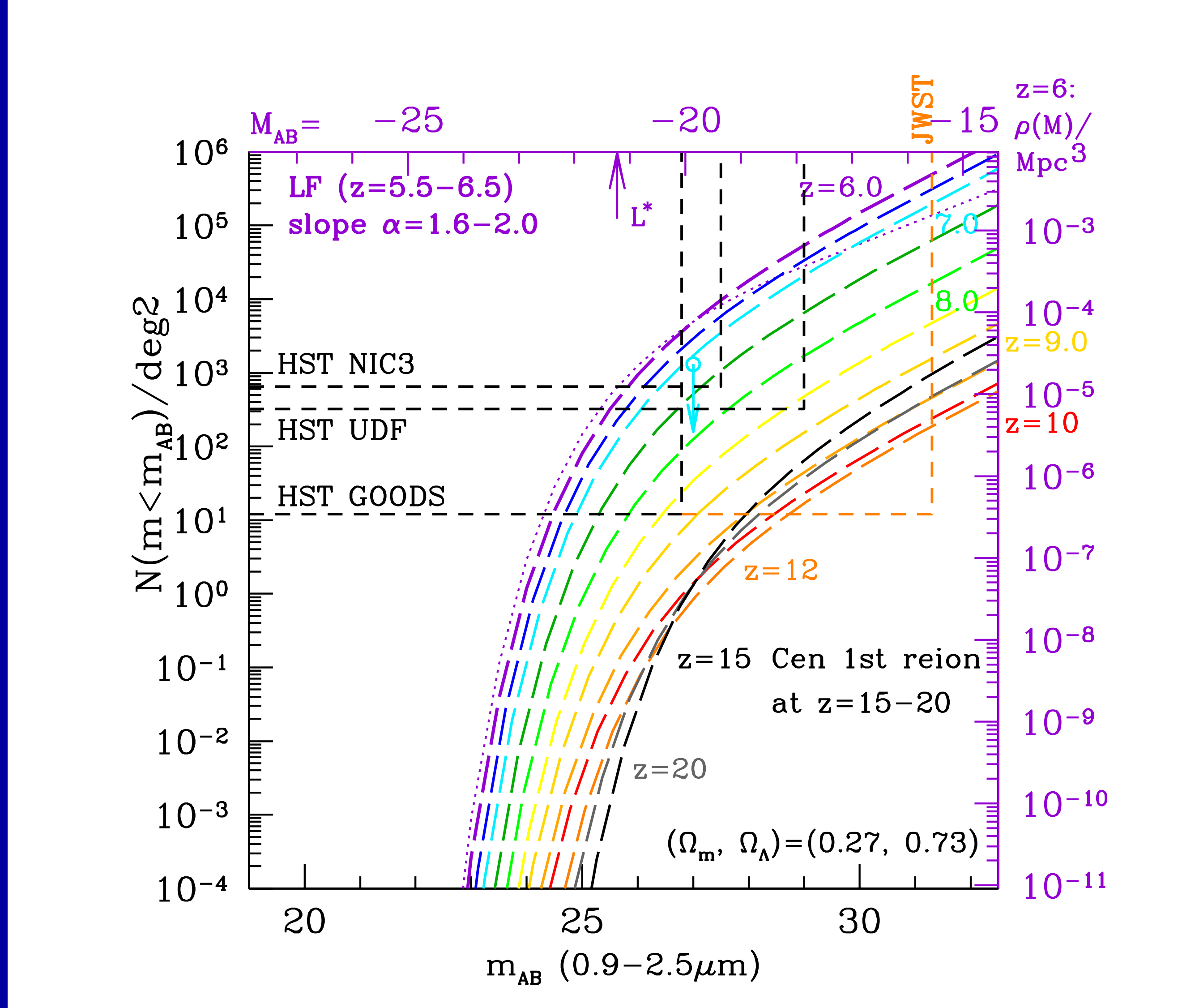
(Fig. courtesy of Dr. F. Briggs)

• (4b) How JWST can measure First Light and Reionization

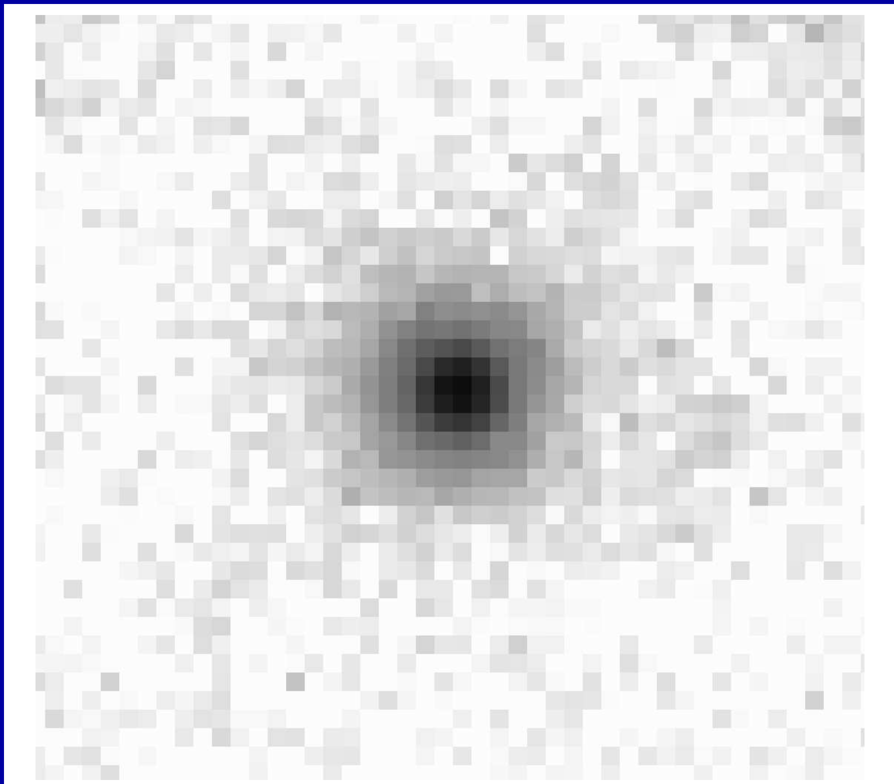


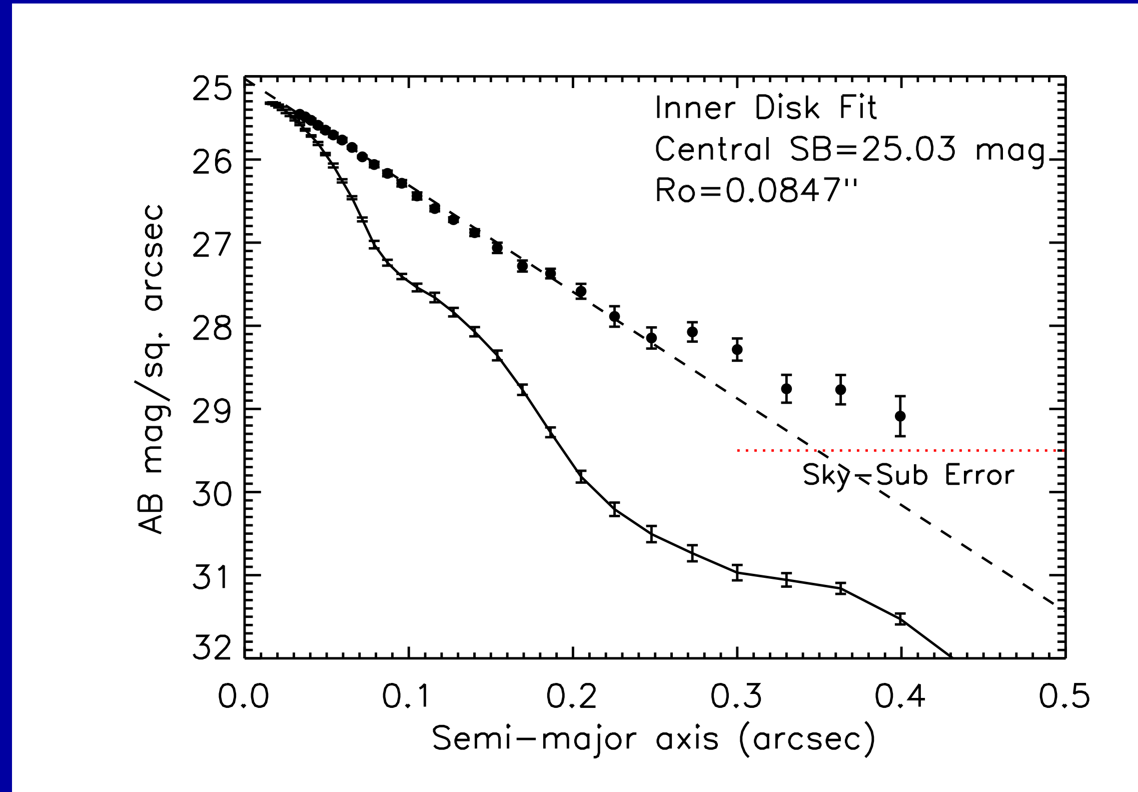
HUDF shows that luminosity function of z≃6 objects (Yan & Windhorst 2004, b) may be very steep: faint-end Schechter slope $|\alpha|\simeq$1.6–2.0.

⇒ Dwarf galaxies and not quasars likely completed the reionization epoch at z≃6. This is what JWST will observe in detail to z≳20.



- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.
- Objects at $z \gtrsim 9$ are rare, since volume element is small and JWST samples brighter part of LF. JWST needs the quoted sensitivity/aperture (A), field-of-view (FOV=Ω), and wavelength range (0.7-28 μm).





Sum of 49 isolated i-drops:
=5000 hrs HUDF z-band.
[$\simeq$ 330 hrs JWST 1 μm]

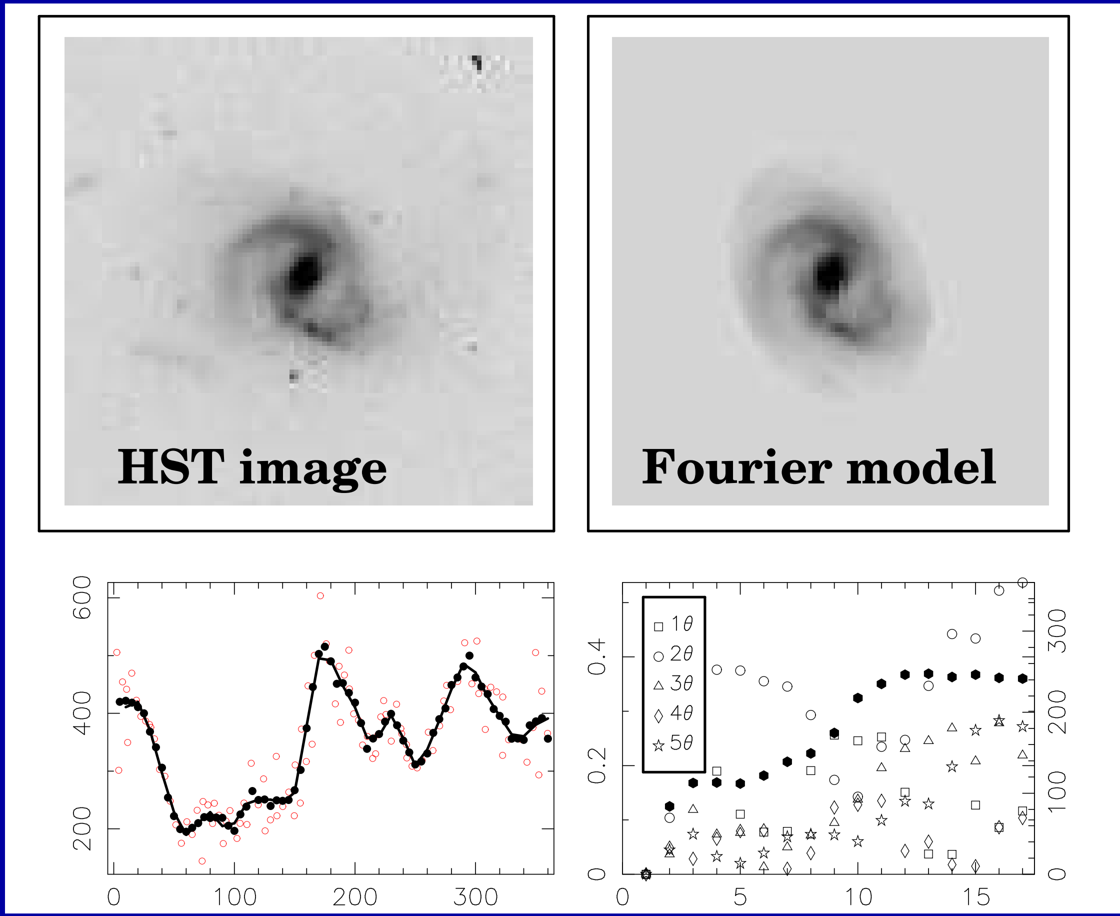
ACS light-profile, PSF and sky-error:
Deviates from exp. disk at $r_e \gtrsim 0\farcs25$
$\Rightarrow$ Dyn. age (z$\simeq$6) $\simeq$ 100-200 Myr
(*cf.* N. Hathi et al. 2006)

HST/ACS cannot accurately measure individual light-profiles at z$\simeq$6.

JWST can do this well for z$\gtrsim$6 in very long integrations.

Dynamical timescale $\simeq$ SED timescale $\Rightarrow$ Bulk of SF at $z_{form} \simeq 7.0 \pm 0.5$??

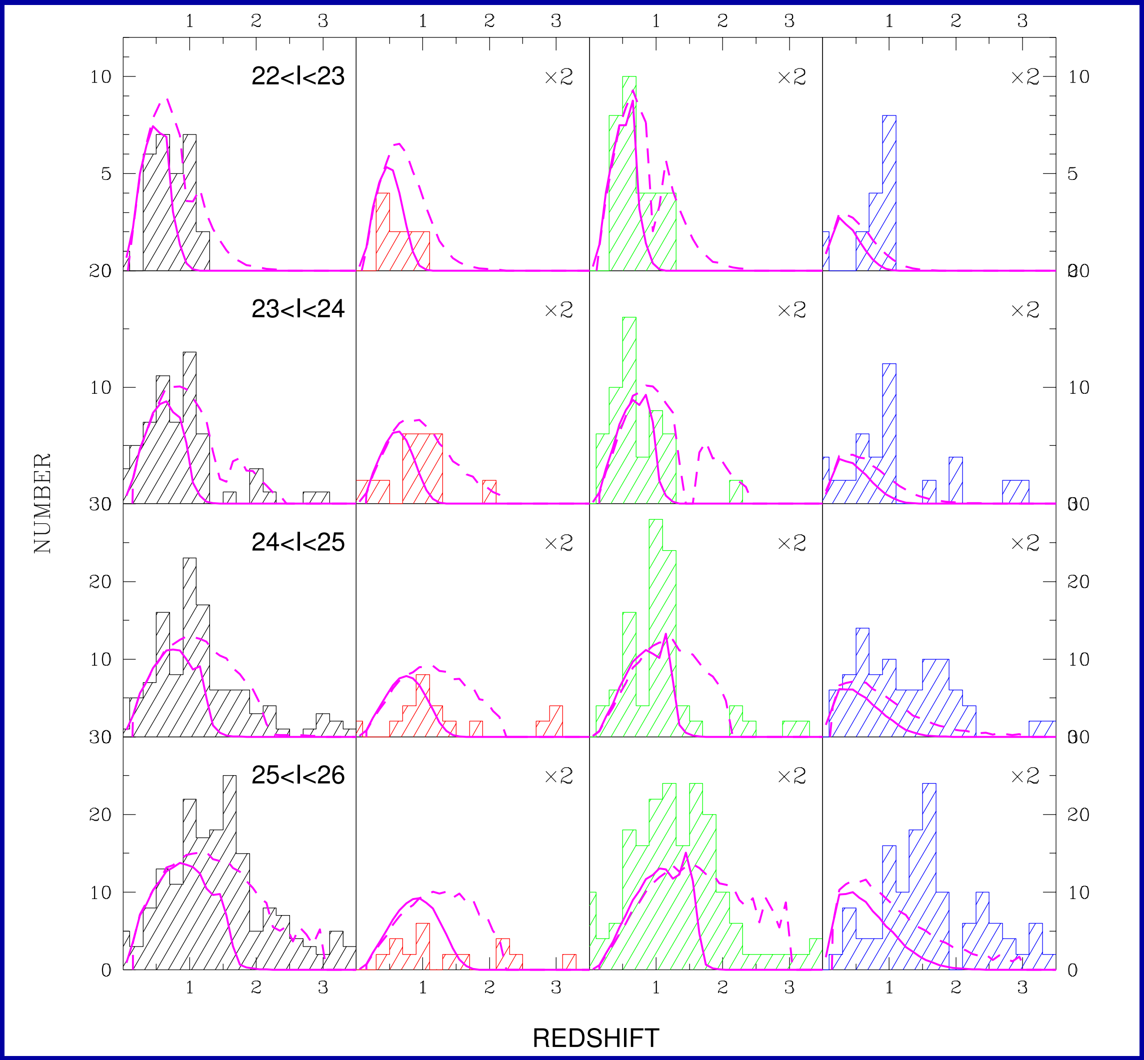
• (5) How JWST can measure Galaxy Assembly



Fourier Decomposition is a robust way to measure galaxy morphology and structure in a quantitative way (Odewahn et al. 2002):

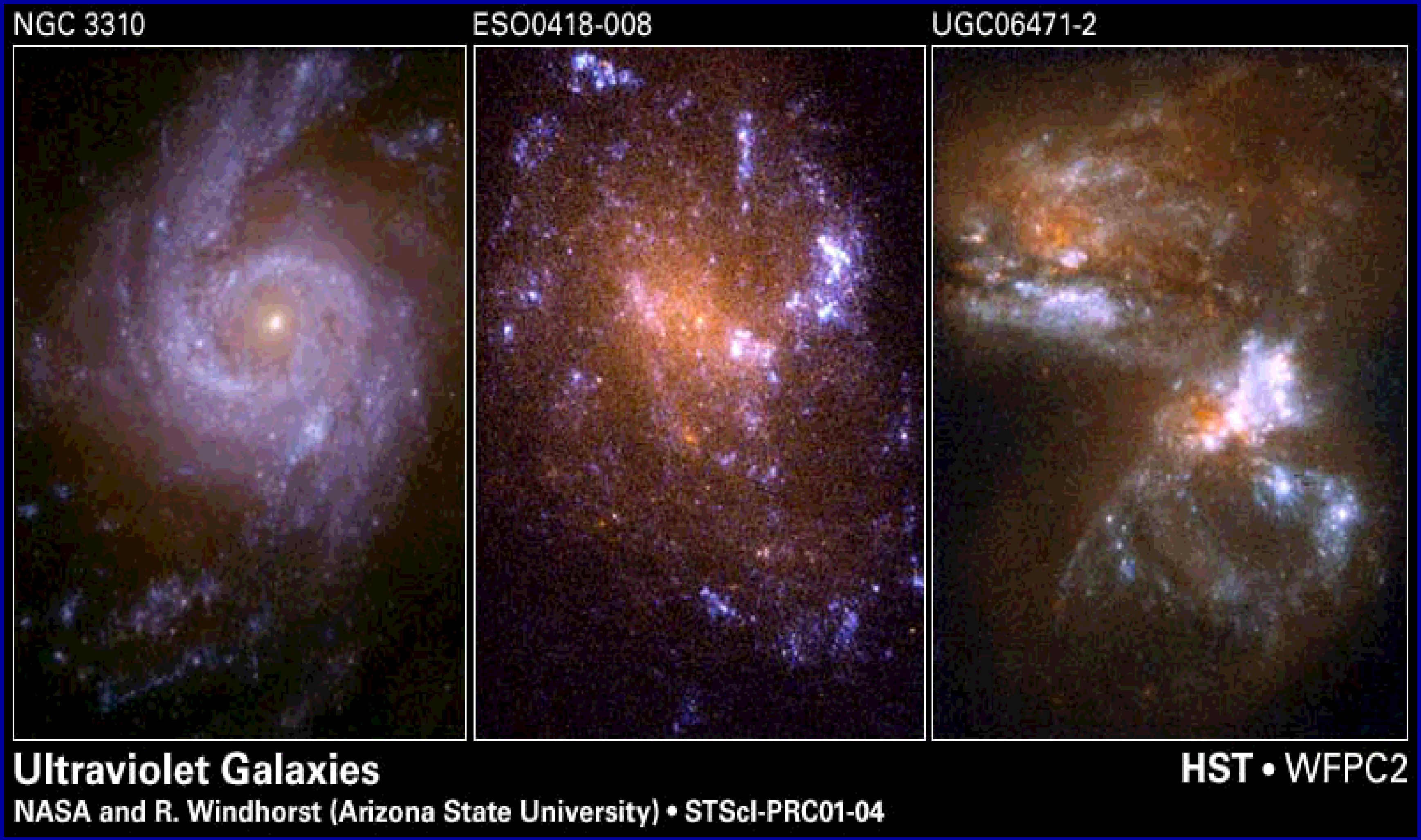
- (1) Fourier series are made in successive concentric annuli.
- (2) Even Fourier components indicate symmetric parts (arms, rings).
- (3) Odd Fourier components indicate asymmetric parts (bars etc).
- (4) JWST can measure the evolution of each feature directly.

Total Ell/S0 Sabc Irr/Mergers



- JWST can measure how galaxies of all Hubble types formed over a wide range of cosmic time, by measuring their redshift distribution as a function of rest-frame type.
- For this, the types must be well imaged for large samples from deep, uniform and high quality multi-wavelength images, which JWST can do.

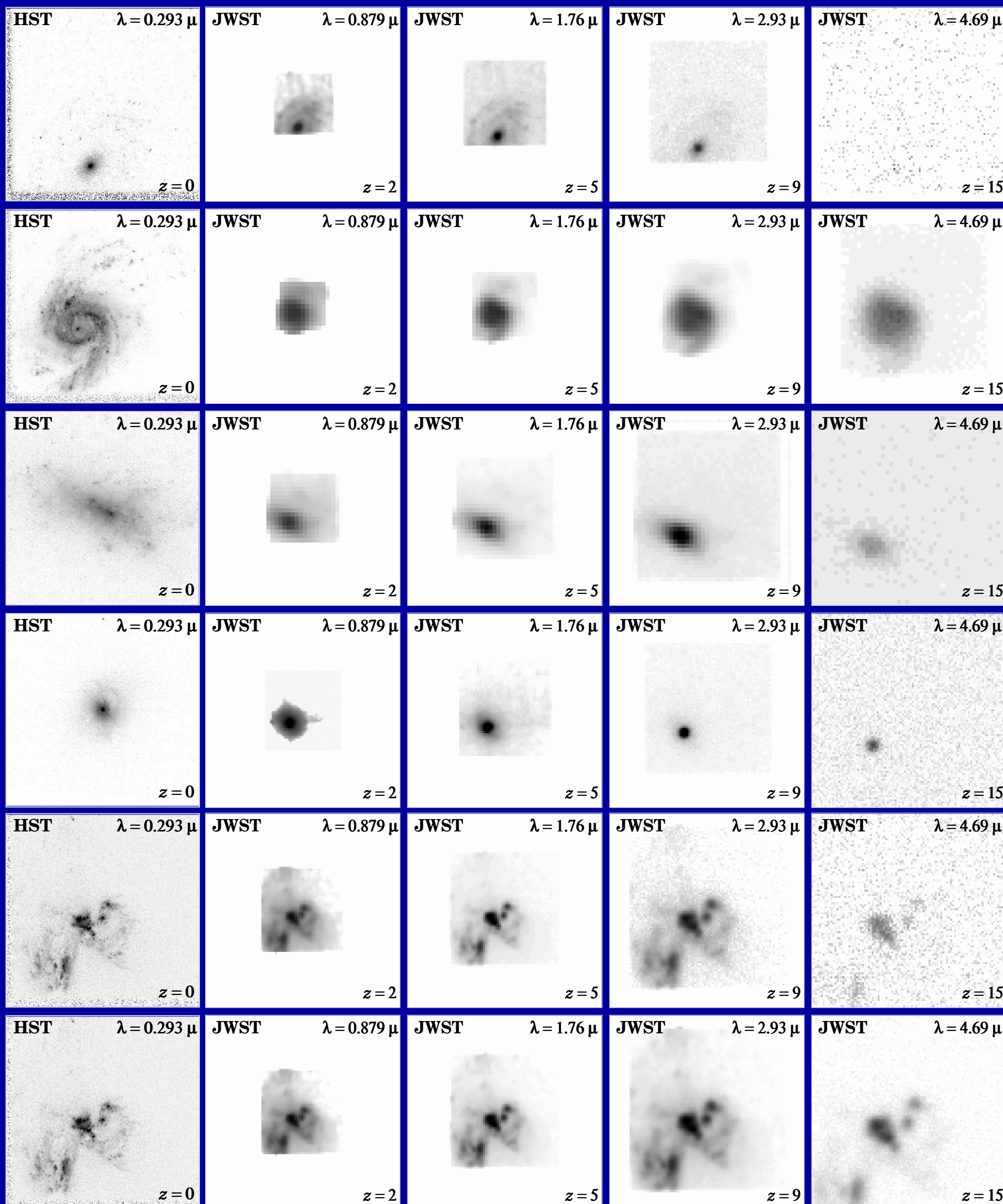
Driver et al. 1998, Astrophys. J. Letters, 496, L93



- The uncertain rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often copious amounts of dust superimposed.
- This makes comparison with very high redshift galaxies seen by JWST complicated, although with good images a quantitative analysis of the restframe-wavelength dependent morphology and structure can be made.

(6) Predicted Galaxy Appearance for JWST at z≃1–15

HST z=0 JWST z=2 z=5 z=9 z=15



With proper restframe-UV training, JWST can quantitatively measure the evolution of galaxy morphology and structure over a wide range of cosmic time:

- (1) Most disks will SB-dim away at high z, but most formed at z$\lesssim z_{form}\simeq$1–2.
- (2) High SB structures are visible to very high z.
- (3) Point sources (AGN) are visible to very high z.
- (4) High SB-parts of mergers/train-wrecks are visible to very high z.

Summary and Conclusions

(1) High resolution imaging of (faint) high redshift galaxies needs to be done from space, because:

- (a) Faint high redshift ($z \gtrsim 2$–3) galaxies are small with $r_{hl} \lesssim 0\farcs15$.
- (b) Ground-based sky not dark enough and PSF not stable enough to do the very long integrations needed to go faint ($AB \gtrsim 27$ mag).

(2) HST has led the study of faint galaxy evolution, showing that galaxies form hierarchically over time through repeated mergers with:

- (a) sizes growing steadily over time as $r_{hl}(z) \propto r_{hl}(0).(1+z)^{-s}$, $s \simeq 1$.
- (b) the Hubble sequence gradually coming into place for $z \lesssim 1$–2.
- (c) the onset of dwarf galaxies (at $z \lesssim 8$) ending reionization at $z \simeq 6$.

(3) JWST will allow to do these studies into the epoch of First Light at $z \simeq 8$–20, and trace galaxy SED's in the restframe-optical at $z \lesssim 12$.

SPARE CHARTS

- References and other sources of material shown:

http://www.jwst.nasa.gov/

http://www.stsci.edu/jwst/

http://www.jwst.nasa.gov/ISIM/index.html

http://ircamera.as.arizona.edu/nircam/

http://ircamera.as.arizona.edu/MIRI/

http://www.stsci.edu/jwst/instruments/nirspec/

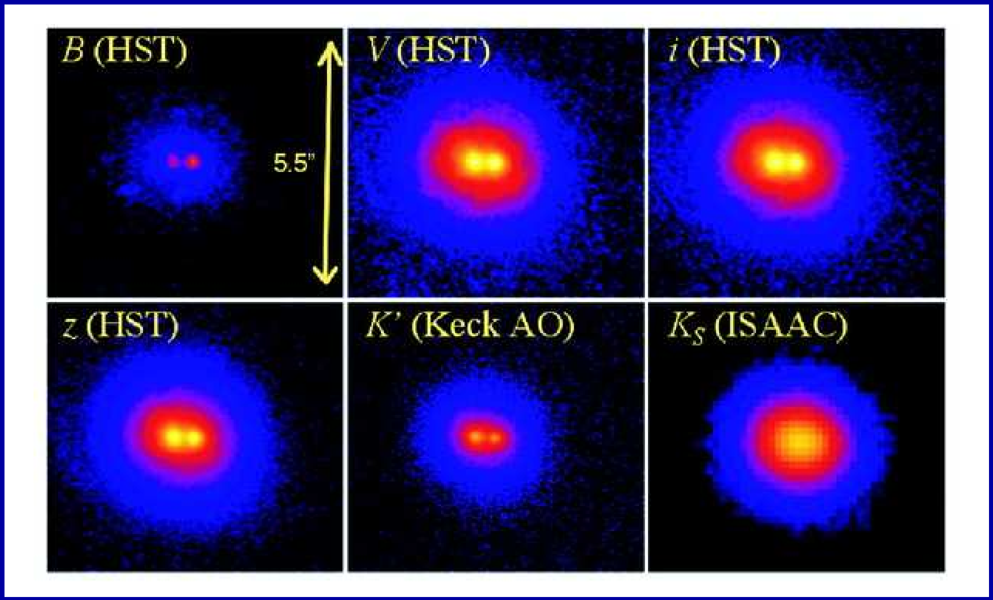
http://www.stsci.edu/jwst/instruments/nirspec/mems.html

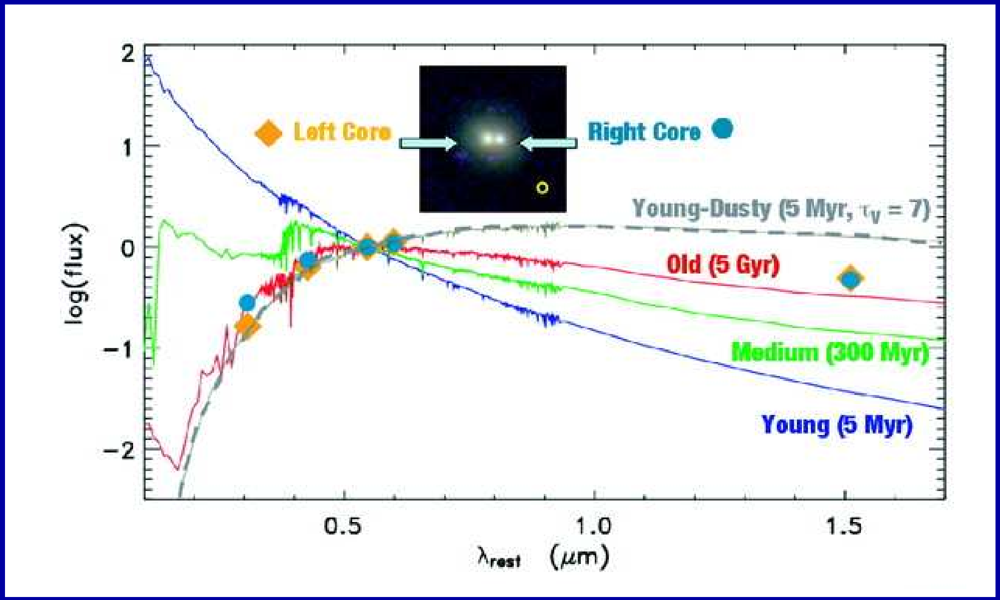
http://www.stsci.edu/jwst/instruments/guider/

Gardner, J., Mather, J., Clampin, M., Greenhouse, M., Hammel, H., Hutchings, J., Jakobsen, P., Lilly, S., Lunine, J., McCaughrean, M., Mountain, M., Rieke, G., Rieke, M., Smith, E., Stiavelli, M., Stockman, H., Windhorst, R., & Wright, G. ("the JWST Flight Science Working Group") 2004, Proc. SPIE, Vol. 4014, p. 001–012, in press "The Science Requirements of the James Webb Space Telescope" (and references therein).

Mather, J., Stockman, H. 2000, Proc. SPIE Vol. 4013, p. 2-16, in "UV, Optical, and IR Space Telescopes and Instruments", Eds. J. B. Breckinridge & P. Jakobsen (Berlin: Springer)

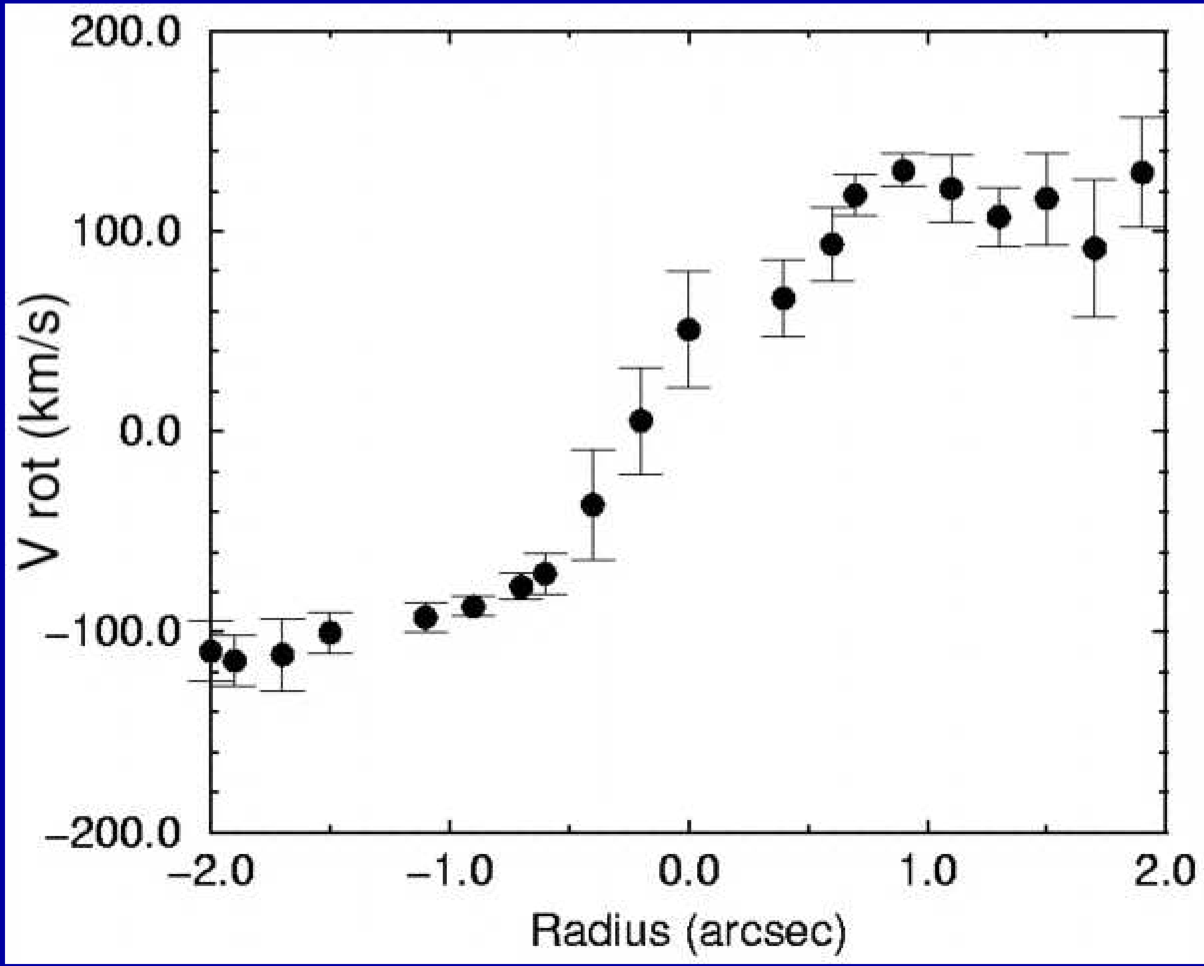
• (1) What can and has been done from the ground?





Ground-based AO in K-band with Keck (Melbourne et al. 2005 ApJL, 625, L27):

- Match or supersede HST resolution if have nearby AO guide star.
- But dynamic range, PSF stability, and sky-brightness no match to space.
- $\Rightarrow$ Do brighter objects, but can get very high resolution from ground.
- Can decompose stellar populations and dust.



Ground-based AO in K-band with Keck (Steinbring 2004 ApJ, 155, 15):

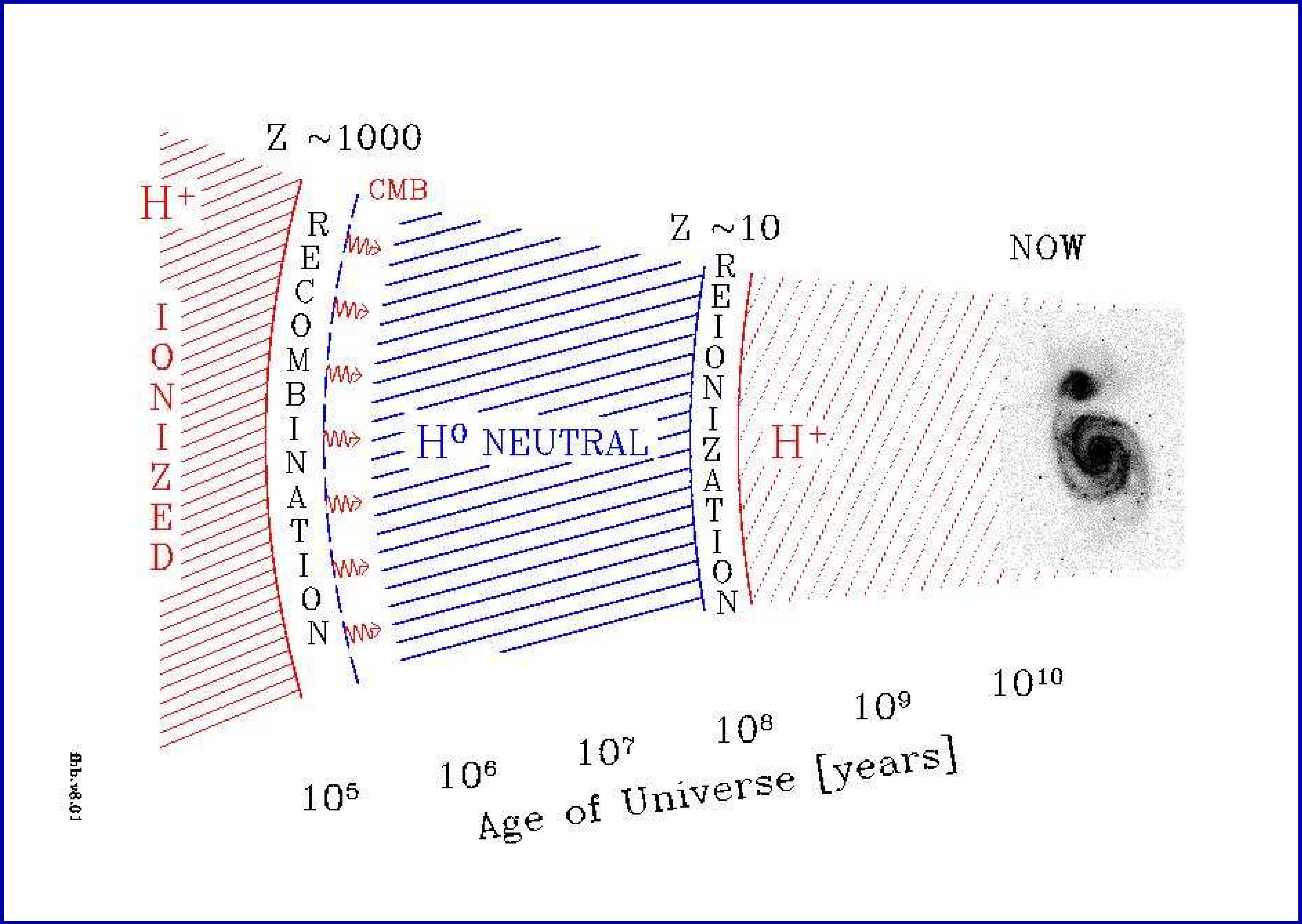
- Can do rotation curves of faint galaxies → masses etc. Match or exceed HST resolution if have nearby AO guide star.

- Low dynamic range & bright sky → ground cannot go as faint and obtain as wide a field-of-view as HST.

• (4) What is the James Webb Space Telescope (JWST)?

• A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy from 0.6 to 28 μm, to be launched by NASA $\gtrsim$2013. It has a nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging (AB$\lesssim$31.5) and spectroscopy (AB$\lesssim$29 mag).

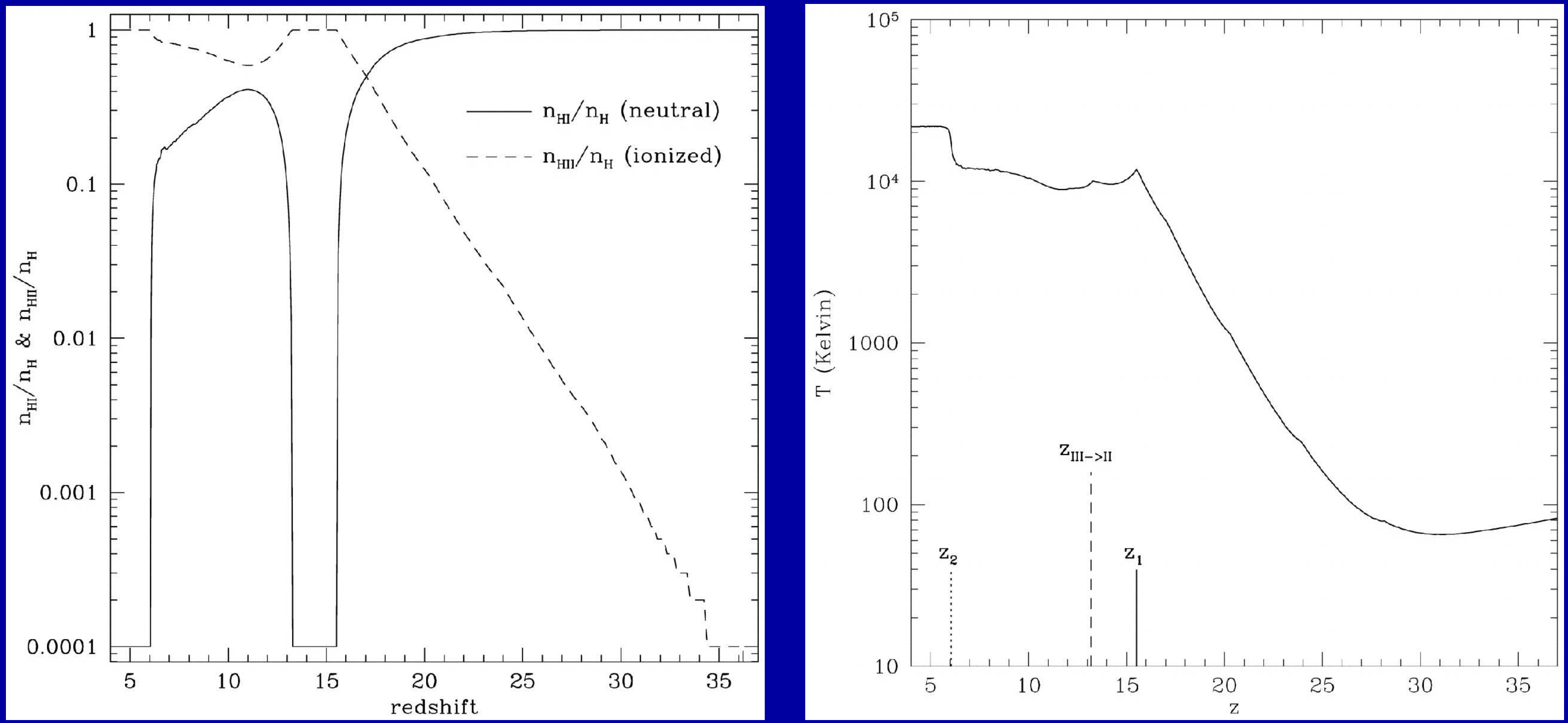
• (4a) What is First Light and Reionization?



WMAP: First light may have happened in two epochs (Cen 2003):

- (1) Population III stars with 200-1000 $M_\odot$ at z$\simeq$11–20 (First Light).
- (2) First Population II stars (halo stars) form in dwarf galaxies of mass=10^6 to 10^9 $M_\odot$ at z$\simeq$6–9, which complete reionization (*cf.* F. Briggs 2002).

$\Rightarrow$ JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.



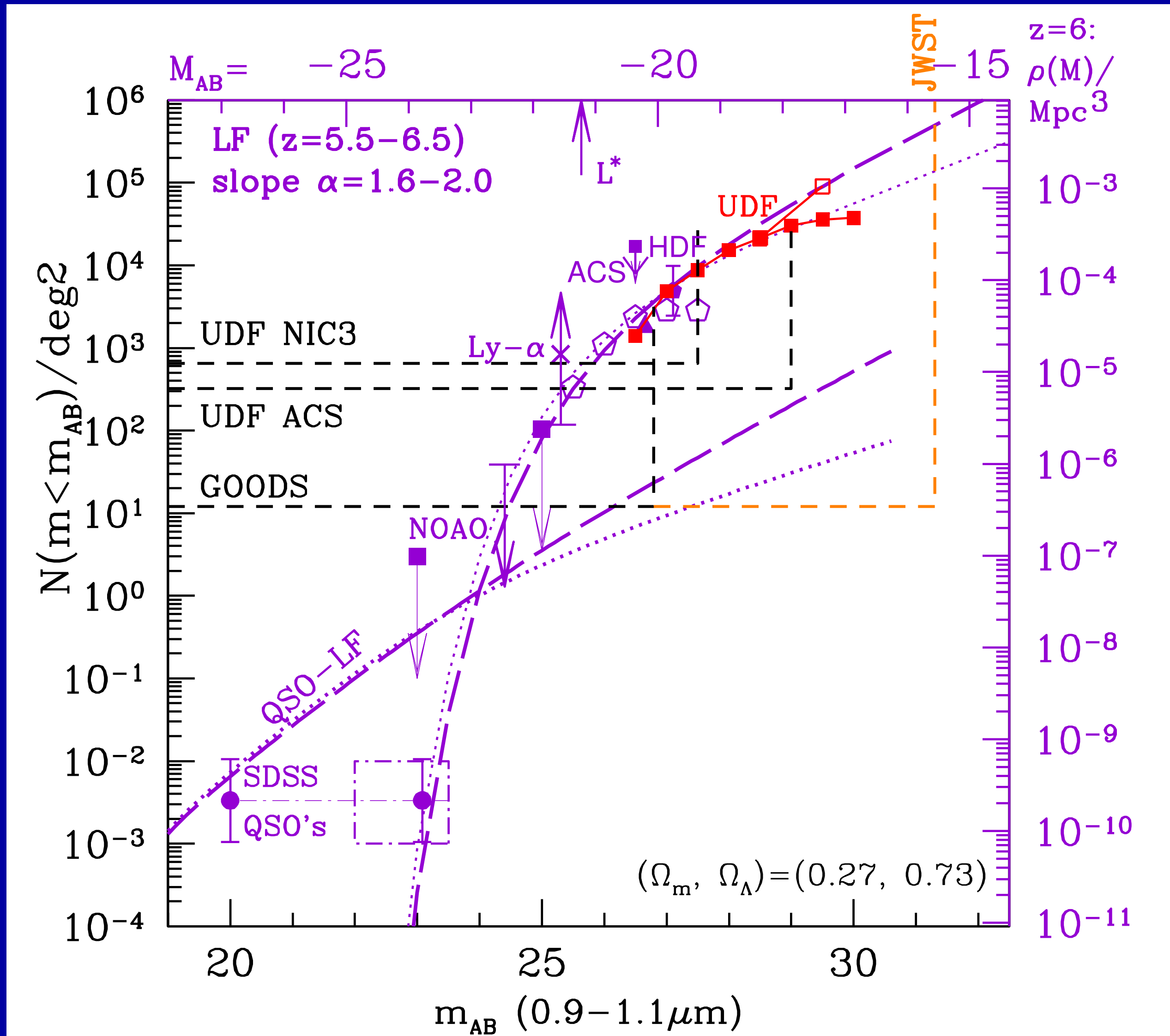
WMAP and detailed Hydrodynamical models (Cen 2003) suggest that:

- (1) Population III stars caused epoch of First Light at z$\simeq$11–20.

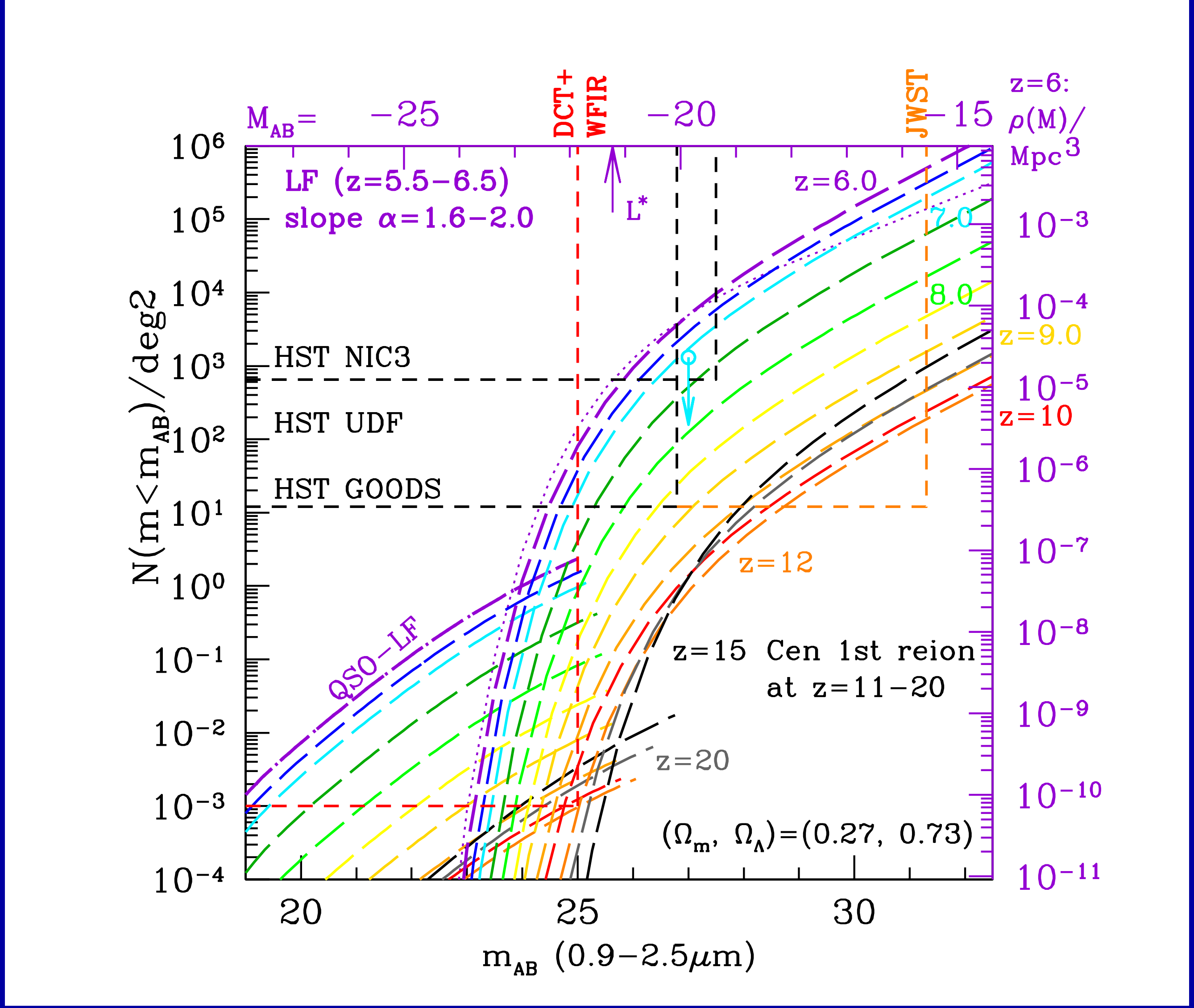
- (2) Pop III supernovae may have caused the Second Dark Ages at z=9–11, since they heated the IGM, which could not cool until:

- (3) The first Pop II stars started forming in dwarf galaxies with 10^7–10^9 $M_\odot$ at z$\simeq$6–9.

$\Rightarrow$ This will be visible to JWST in the luminosity function (LF) of the first star-forming objects at z$\simeq$20$\rightarrow$6.



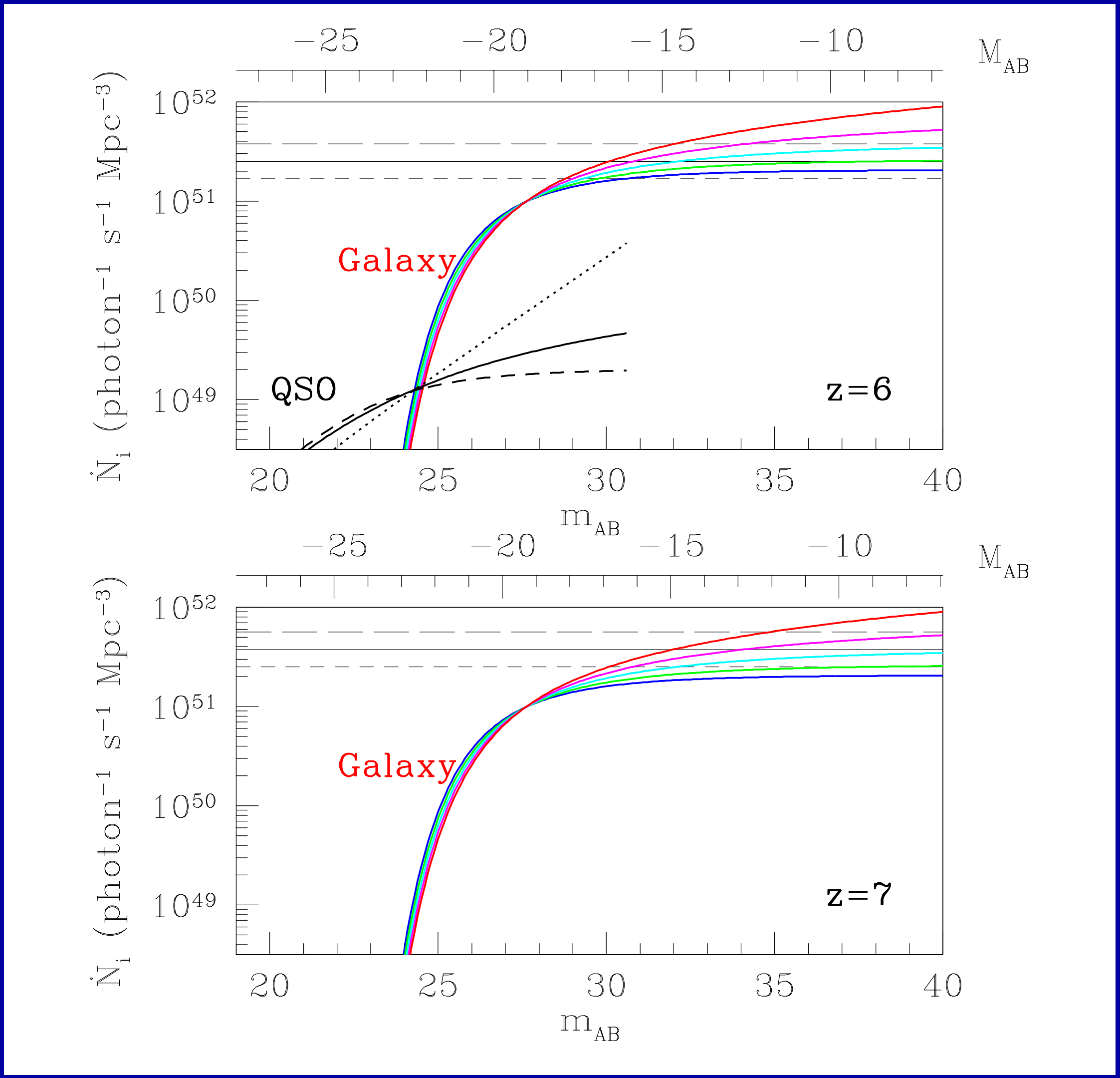
• HST/ACS has made significant progress at z≃6, surveying very large areas (GOODS, GEMS, COSMOS), or using very long integrations (HUDF). ACS can detect objects at z$\lesssim$6.5, but its discovery space A.**Ω**.**Δ**log(**λ**) cannot map the entire reionization epoch. NICMOS similarly is limited to z$\lesssim$8–10. JWST will be able to trace the entire reionization epoch.



• Red boundaries indicate part of the galaxy and QSO LF that a 4–8m class telescope with WF IRCam can explore to z=10 and AB$\lesssim$25 mag.

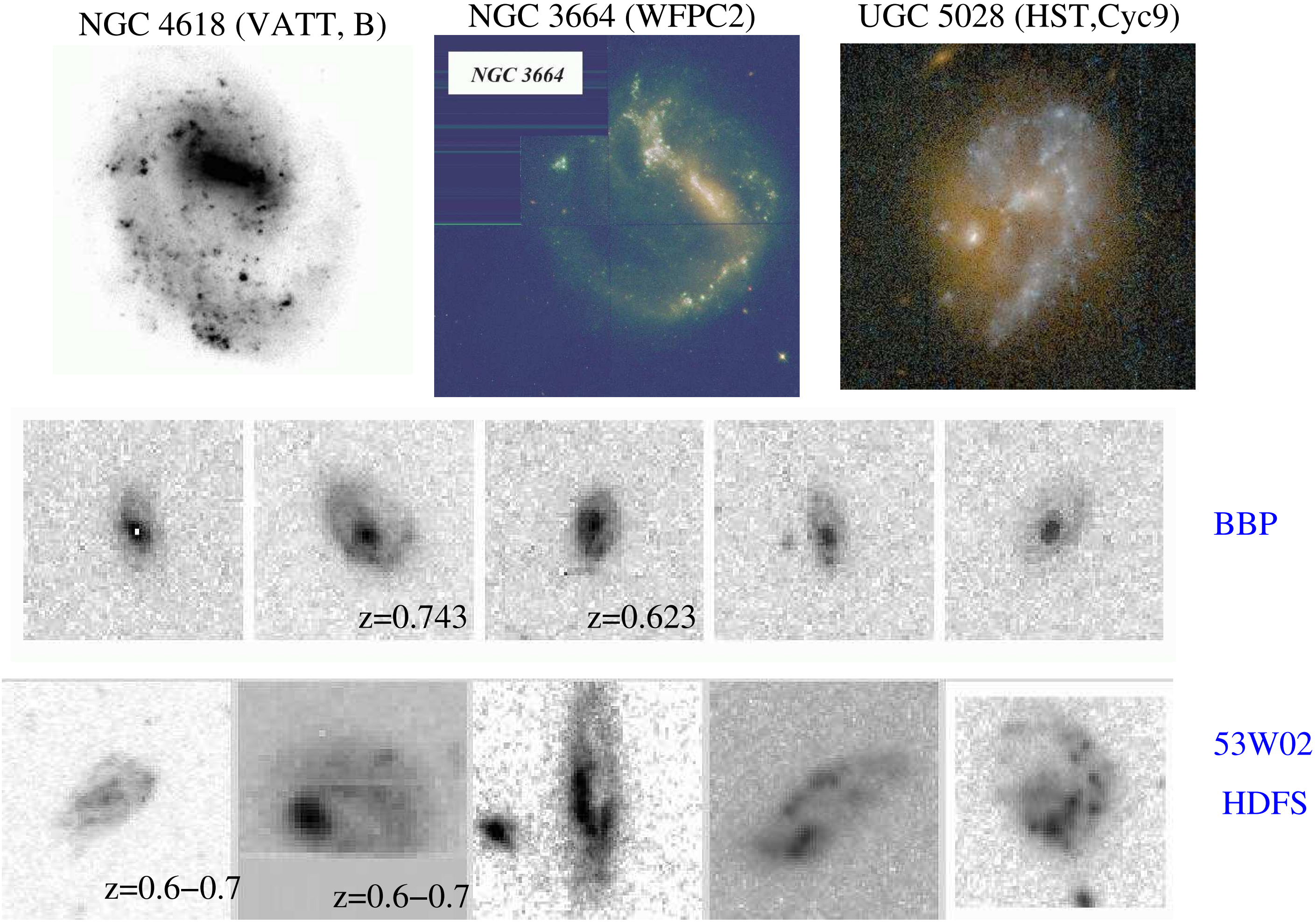
• A ground-based wide-field near-IR survey to AB$\lesssim$25 mag z$\lesssim$10 is an essential complement to the JWST First Light studies:

Co-evolution of supermassive black-holes and proto-bulges for z$\lesssim$10.



- A steep LF of z≃6 objects (Yan & Windhorst 2004) could provide enough UV-photons to complete the reionization epoch at z≃6.
- Pop II dwarf galaxies may not have started shining *pervasively* much before z≃7–8, or no H-I would be seen in the foreground of z≳6 quasars.
- JWST will measure this numerous population of dwarf galaxies from the end of the reionization epoch at z≃6 into the epoch of First Light (Pop III stars) at z≳10.

Massive Star Formation: Near and Far



Fourier Decomposition of nearby and distant galaxies in JWST images will directly trace the evolution of bars, rings, spiral arms, and other structural features. This measures the detailed history of galaxy assembly in the epoch z≃1–3 when most of today's giant galaxies were made.

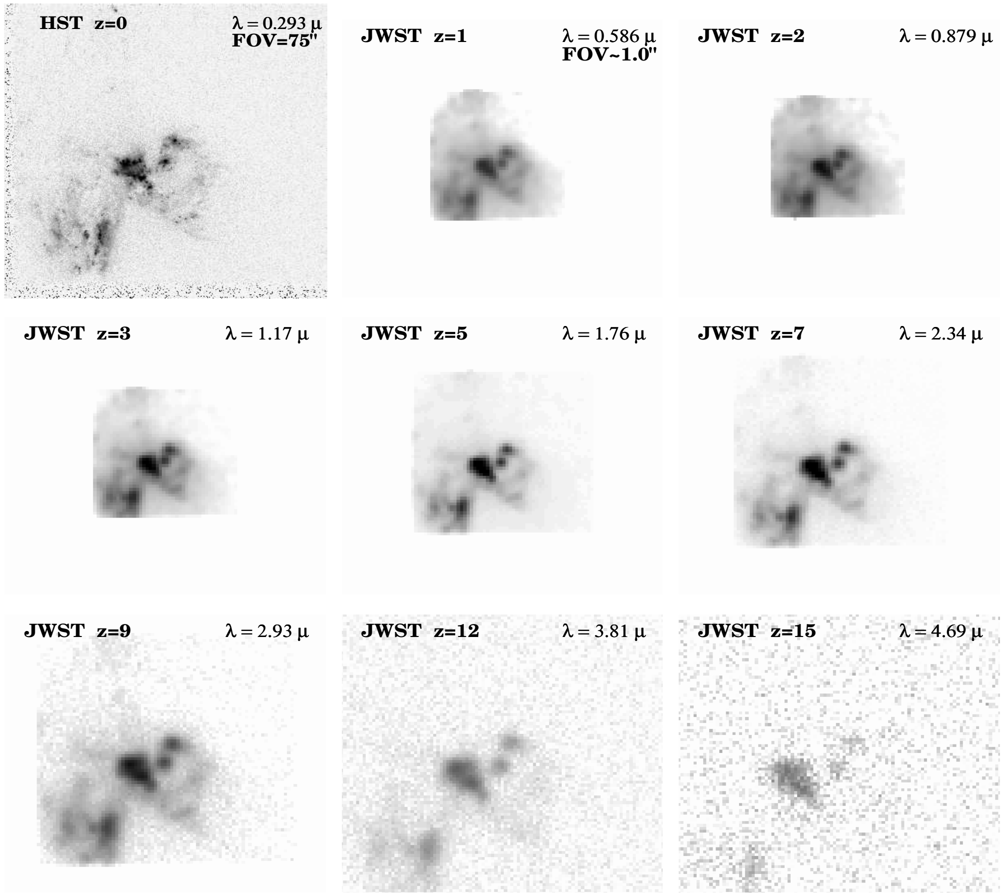


Fig. 4.06.a. JWST simulations based on HST/WFPC2 F300W images of the merger UGC06471-2 (z=0.0104). Note that the two unresolved star-bursting knots in the center remain visible until z∼12, beyond which the SB-dimming also kills their flux. This is the NOMINAL JWST [= (GOALS+REQUIREMENTS)/2].

ASSUMPTIONS: COSMOLOGY: H_0=71 km/s/Mpc, Ω_m=0.27, and Ω_Λ=0.73.

INSTRUMENT: 6.0 m effective aperture, JWST/NIRCam, 0.034″ /pix, RN=5.0 e^-, Dark=0.020 e^-/sec, NEP H-band Sky=21.7 mag/arcsec^2 in L2, Zodiacal spectrum, t_{exp}=1.0 hrs, read-out every 900 sec ("NOMINAL").

Row 1: z=0.0 (HST λ=0.293μm, FWHM=0.04″), z=1.0 (JWST λ=0.586μm, FWHM=0.084″), and z=2.0 (JWST λ=0.879μm, FWHM=0.084″). **Row 2:** z=3.0 (JWST λ=1.17μm, FWHM=0.084″), z=5.0 (JWST λ=1.76μm, FWHM=0.084″), and z=7.0 (JWST λ=2.34μm, FWHM=0.098″). **Row 3:** z=9.0 (JWST λ=2.93μm, FWHM=0.122″), z=12.0 (JWST λ=3.81μm, FWHM=0.160″), and z=15.0 (JWST λ=4.69μm, FWHM=0.197″)

The galaxy merger UGC06471-2 (z=0.0104) is a major and very dusty collision of two massive disk galaxies.

It shows two bright unresolved star-bursting knots to the upper-right of the center, which remain visible until z≃12, beyond which the cosmic SB-dimming kills their flux. These are more typical for the small star-forming objects expected at z≃10–15.

This is the NOMINAL JWST = (GOALS+REQUIREMENTS)/2.

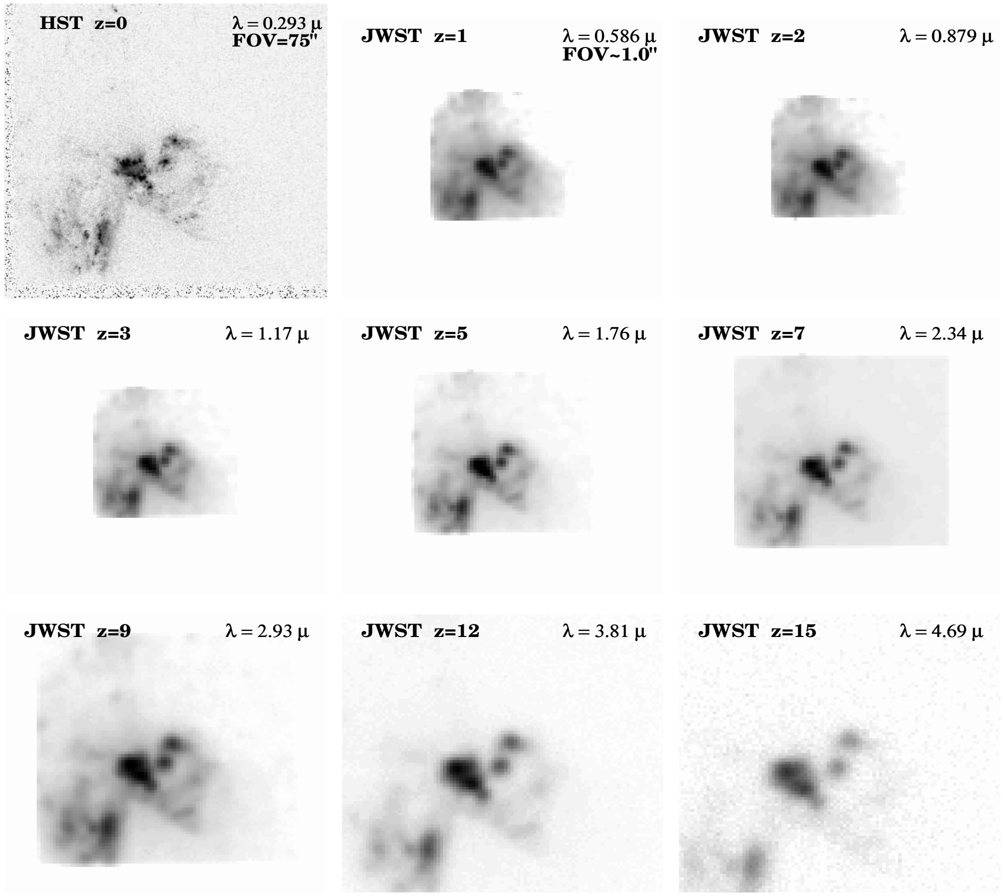


Fig. 4.06.c. JWST simulations based on HST/WFPC2 F300W images of the merger UGC06471-2 (z=0.0104). This is the BEST CASE JWST [meeting all GOALS, and t_{exp}=100 hrs]. The object is recognizable to z≃15.

ASSUMPTIONS: COSMOLOGY: H_0=71 km/s/Mpc, Ω_m=0.27, and Ω_Λ=0.73.

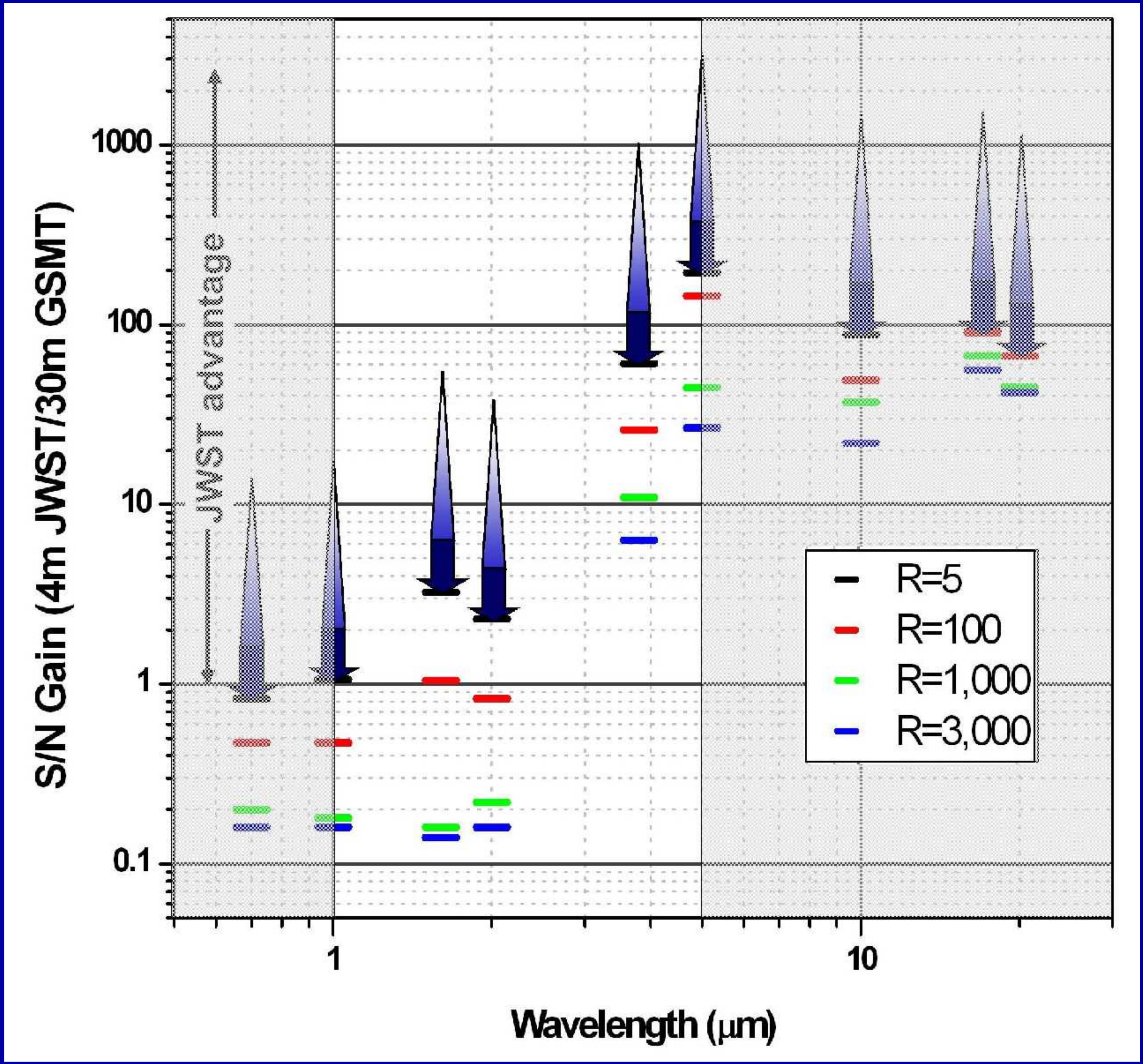
INSTRUMENT: 6.0 m effective aperture, JWST/NIR camera, 0.034″ /pix, RN=3.0 e^-, Dark=0.010 e^-/sec, NEP H-band Sky=21.7 mag/arcsec^2 in L2, Zodi spectrum, t_{exp}=100.0 hrs, read-out every 900 sec ("GOALS").

Row 1: z=0.0 (HST λ=0.293μm, FWHM=0.04″), z=1.0 (JWST λ=0.586μm, FWHM=0.084″), and z=2.0 (JWST λ=0.879μm, FWHM=0.084″). **Row 2:** z=3.0 (JWST λ=1.17μm, FWHM=0.084″), z=5.0 (JWST λ=1.76μm, FWHM=0.084″), and z=7.0 (JWST λ=2.34μm, FWHM=0.098″). **Row 3:** z=9.0 (JWST λ=2.93μm, FWHM=0.122″), z=12.0 (JWST λ=3.81μm, FWHM=0.160″), and z=15.0 (JWST λ=4.69μm, FWHM=0.197″)

The galaxy merger UGC06471-2 (z=0.0104).

This is the BEST CASE JWST. It assumes that all GOALS are met, and that t_{exp}=100 hrs. The whole object (including the two star-forming knots) is recognizable to z≃15.

This does not imply that observing galaxies at z=15 with JWST will be easy. On the contrary, since galaxies formed through hierarchical merging, many objects at z≃10–15 will be 10^1–$10^4\times$ less luminous, requiring to push JWST to its limits.



Conclusion: JWST must not be descoped to a 4 meter Arrows indicate:

Top: 6m JWST/Keck; Middle: 6m JWST/30m gb; Bottom: 4m JWST/30m gb