Technical aspects of how *JWST* can measure First Light, Reionization, and Galaxy Assembly.

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Abstract

We review the technical aspects of how the 6.5 meter James Webb Space Telescope (JWST) can measure First Light, Reionization, Galaxy Assembly (see Stiavelli et al. and other posters), building on lessons learned from the Hubble Space Telescope (HST). We show what combination of area, depth, and wavelength coverage are needed for JWST to detect a sufficient number of First Light objects, and to measure their evolving luminosity function (LF). In detail, JWST will map the epoch of First light through Pop III star dominated objects at redshifts z=8–20, and its transition to the first Pop II stars in dwarf galaxies. The expected steep faint-end of the dwarf galaxy LF at redshifts z=6–7 likely provided the UV-flux needed to finish reionization.

We discuss: 1) what deep JWST images will look like compared to the Hubble UltraDeep Field (HUDF), given JWST's expected PSF performance; (2) simulations of what nearby galaxies observed in their restframe UV–optical light by HST would look like to JWST at very high redshifts; (3) quantitative methods to determine structural parameters of faint galaxies in deep JWST images as a function of cosmic epoch to delineate the progress of galaxy assembly; (4) to what extent JWST's short-wavelength performance — which needed to be relaxed in the 2005 redefinition of the telescope — will affect JWST's ability to accurately determine faint galaxy parameters; and (5) if ultradeep JWST images will run into the instrumental and natural confusion limits. A new generations of algorithms may be needed to automatically detect, measure and classify objects in very crowded, ultradeep JWST fields.

We demonstrate an interactive web-tool on a laptop that lets the user pan and zoom 3-D through the HUDF data-base from redshifts z=0 to z=6, with all galaxy images sorted versus spectro-photometric redshift, and visualize what JWST will add from AB=29.5–32.0 mag and between redshifts z=7–20. This work was funded by NASA JWST Interdisciplinary Scientist grant NAG5-12460 from GSFC, and grant HST/ED14-975 from STScI, operated by AURA for NASA under contract NAS 5-26555.

Outline

(1) What is JWST and how will it be deployed?
(see e.g., posters by Gardner, Doyon, Hutchings, Wright et al.)

(2) What instruments and sensitivity will JWST have?
(see e.g., posters by Gardner, M. Rieke, Stiavelli et al.)

(3) How can JWST measure First Light and Reionization?

(4) How can JWST measure Galaxy Assembly

(5) Predicted Galaxy Appearance for JWST at $z \simeq 1$–15

(6) How JWST's short-λ performance affects measurements of faint galaxy parameters

(7) Will deep JWST images run into the confusion limit?

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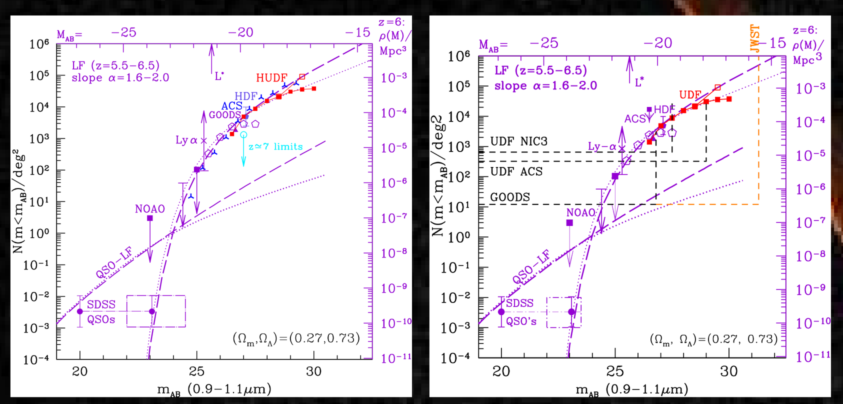
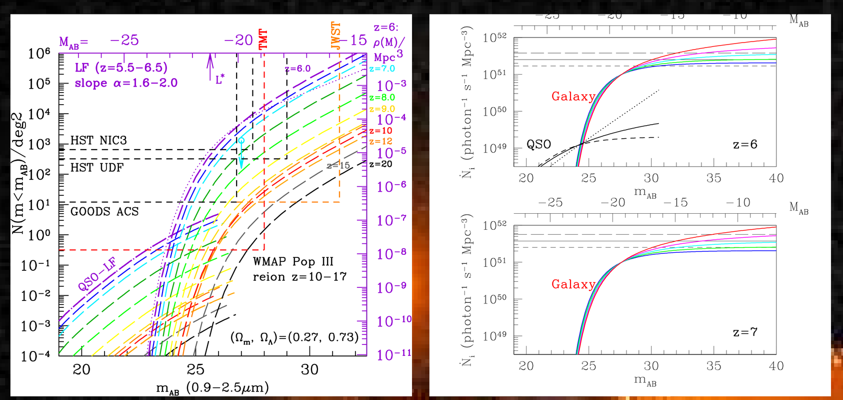
(3) How JWST will measure First Light and Reionization





[TOP-LEFT] The HUDF showed that the LF of $z \simeq 6$ objects may be very steep, with faint-end Schechter slope $|\alpha| \simeq 1.6$–2.0 (Yan & Windhorst 2004a, b; Ryan et al. 2007).
$\Longrightarrow$ Dwarf galaxies and not quasars likely completed the reionization epoch at $z \simeq$6–7. This is what JWST will observe in detail to $z \simeq 20$.

[TOP-RIGHT] HST/ACS has made significant progress at $z \simeq 6$, 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 $A \cdot \Omega \cdot \Delta \log(\lambda)$ cannot map the entire reionization epoch. NICMOS similarly is limited to $z \lesssim 8$–10.
$\Longrightarrow$ Only JWST will allow us to trace the *entire* reionization epoch.

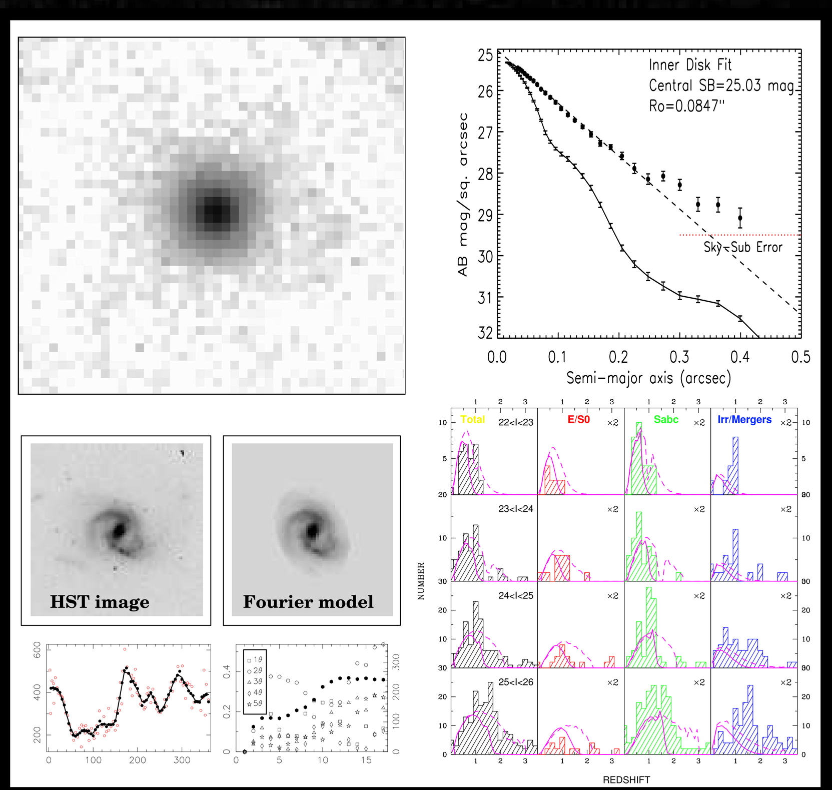
[BOTTOM-LEFT] For JWST to see First Light sources in realistic model scenarios, it needs to have the quoted sensitivity/aperture (A), field-of-view (Ω), and λ-range (0.7–28 μm) to see Ly-break galaxies and their UV-continuum to $z \simeq 20$. The JWST design assumes that objects at $z \simeq 20$ are rare, since the volume element is small and JWST samples the brighter part of the LF at $z \gtrsim 10$.

[BOTTOM-RIGHT] • A steep LF of $z \simeq 6$ objects (Yan & Windhorst 2004a, b) could provide enough UV-photons to complete the reionization epoch at $z \simeq 6$.
• Pop II dwarf galaxies may not have started shining *pervasively* much before $z \simeq$ 7–8, or no H I would be seen in the foreground of $z \simeq 6$ quasars.
• JWST will measure this numerous population of dwarf galaxies from the end of the reionization epoch at $z \simeq 6$ into the epoch of First Light (Pop III stars) at $z \simeq 10$–20.

(4) How JWST will measure Galaxy Assembly

• Galaxies of all types formed over a wide range of cosmic time, but with a notable transition around $z \simeq 0.5$–1.0:
(a) Sub-galactic units rapidly merge from $z \simeq 7 \rightarrow 1$, growing into bigger units.
(b) Merger products start to settle as galaxies with giant bulges and/or large disks around $z \simeq 1$. These evolved mostly passively since then, 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. This needs to take the morphological K-correction into account, which is anchored in the UV structure of nearby galaxies (Taylor-Mager et al. 2007; Windhorst et al. 2002).



(See also posters by N. Hathi et al. , R. Ryan et al. , A. Straughn et al.)

[FAR LEFT-TOP] Sum of 49 isolated i-drops: $\simeq$5000 hrs HUDF in z-band, which is equivalent to $\simeq$330 hrs with JWST at 1 μm. [LEFT-TOP] The composite ACS surface brightness profile, PSF and sky-error deviates from that of an exponential disk at $r_e \gtrsim 0.25''$ $\Longrightarrow$ Dynamical age ($z \simeq 6$) $\simeq$ 100–200 Myr (Hathi et al. 2007).

• HST/ACS cannot accurately measure surface brightness profiles of individual $z \simeq 6$ objects, but JWST can do this in detail for $z \gtrsim 6$ in very long integrations.

Dynamical time scales $\simeq$SED time scale $\Longrightarrow$ Bulk of Pop II SF at $z_f \simeq 7.0 \pm 0.5$?

[FAR LEFT-BOTTOM] Fourier Decomposition is a robust technique of measuring galaxy morphology and structure in a quantitative way (Odewahn et al. 2002):

• Fourier series are fit to the signal in successive concentric annuli

• Even Fourier components describe symmetric parts (arms, rings, bars)

• Odd Fourier components describe asymmetric parts (spurs, lopsided arms, bars, etc.)

JWST can measure the evolution of such features directly.

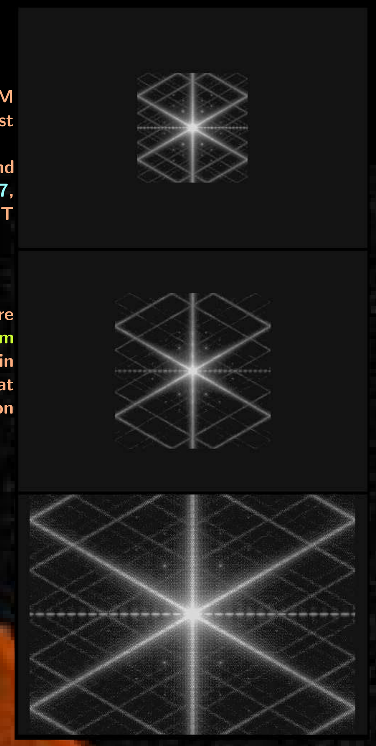
[LEFT-BOTTOM] JWST can measure how galaxies of all types formed over a wide range of cosmic time, by measuring their redshift distribution as a function of rest-frame type, or as function of a particular Fourier component. (Figure from Driver et al. 1998)
• For this, the types must be well imaged for large samples from deep uniform, and high-quality multi-wavelength images — which JWST can do.

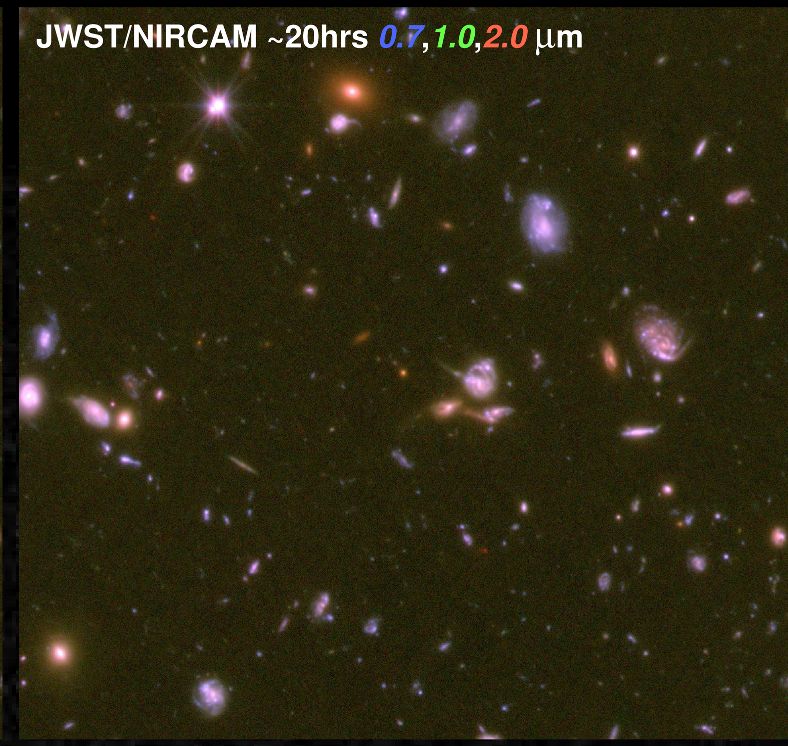
(6) How JWST's short-λ performance affects faint galaxy parameters

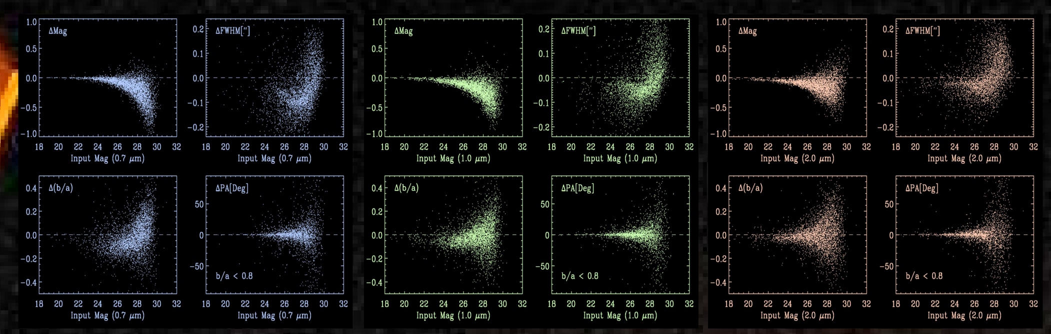
[TOP LEFT] PSF models for the 6.5 m JWST (from Ball Aerospace and GSFC) and NIRCAM 0.7 μm, 1.0 μm (<150 nm WFE), and 2.0 μm (diffraction limit). Note that stretch and contrast were chosen to highlight the faint structure in the wings of the PSFs.
[TOP MIDDLE] Portion of the Hubble Ultra-Deep Field: 240 hrs HST/ACS in V, i' and z', and
[TOP RIGHT] a simulated $\lesssim$20 hrs JWST integration of that same field with NIRCAM at 0.7, 1.0 and 2.0 μm, obtained by convolving the observed HST/ACS HUDF with the model JWST PSFs.

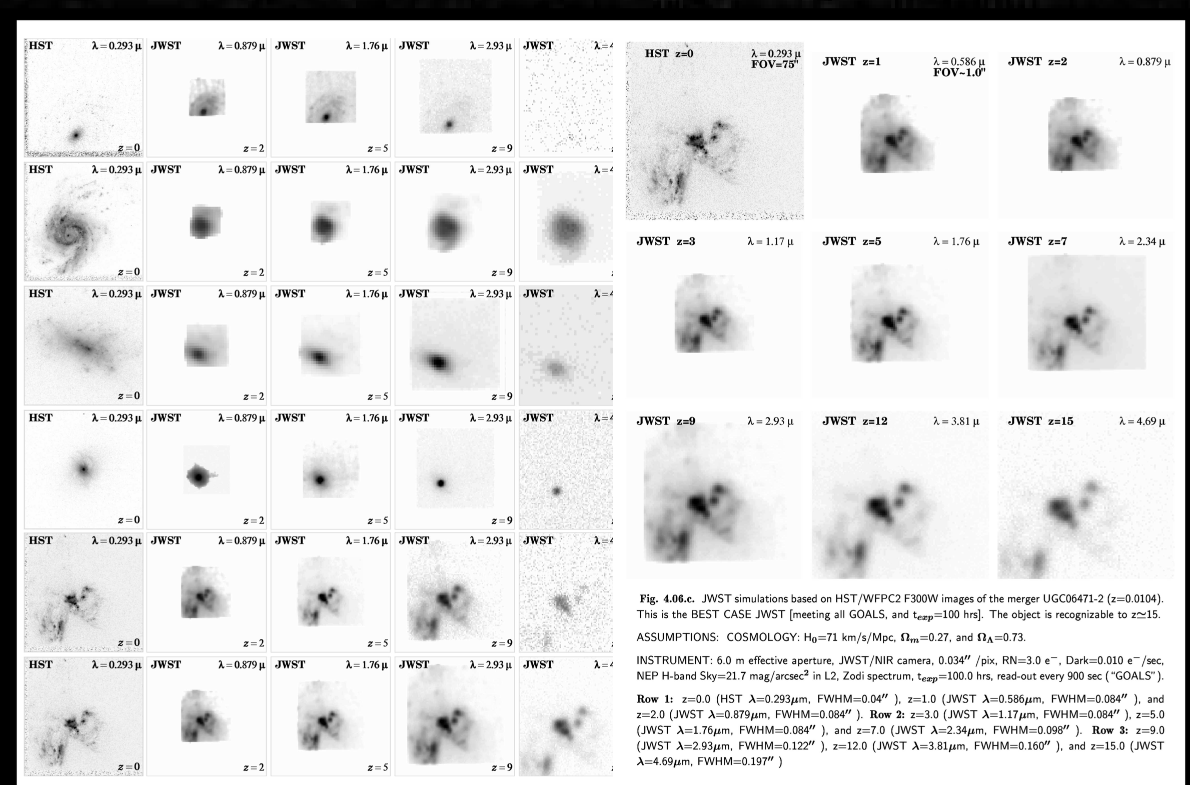
[BOTTOM RIGHT] Comparison of a detail within the ACS and NIRCAM images.

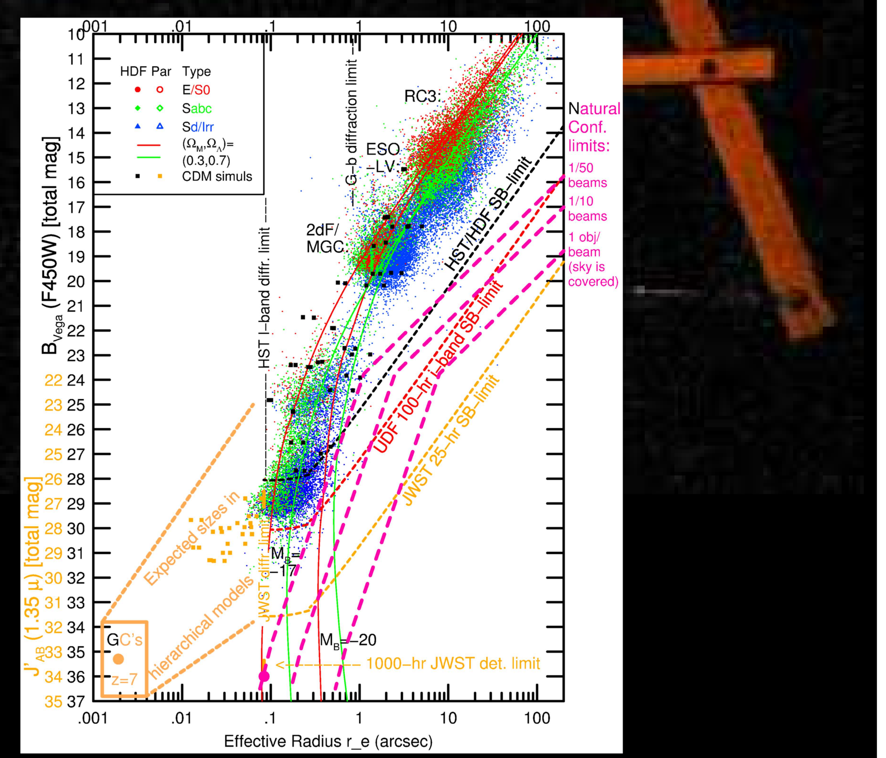
[BOTTOM LEFT] Differences between theoretical and measured values (Airy−JWST, where $EE_{jwst}(1\,\mu m) = 0.60$), of m_{tot}, FWHM, PA and b/a for faint galaxies, for 0.7 μm, 1.0 μm and 2.0 μm. For EE=0.60, the bias in position angle is modest and random. The biases in m_{tot}, FWHM, and b/a are significant at 0.7 and 1.0 μm for the redesigned JWST, but at 2.0 micron the diffraction limit produces correctable biases. Further details can be found on URL: http://www.asu.edu/clas/hst/www/jwst/











(7) Do deep JWST images run into the confusion limit?

Effective galaxy radii vs. B- or J-band mag (Windhorst et al. 2007). Various ground-based and HST surveys are plotted, as are predictions for JWST (in orange). Slanted black, red, and orange lines indicate the point-source and surface-brightness (SB) sensitivity limits for HST/HDF, HUDF, and JWST, respectively. Red and green curved lines indicate non-evolving galaxy sizes anchored in the RC3 using WMAP cosmology. Orange points with $r_e \lesssim 0\farcs085$ show hierarchical simulations below the HST and JWST diffraction limits (Kawata et al. 2004). The pink dot at J=34 AB-mag shows that even ultradeep JWST images will not run into the instrumental confusion limit. Dashed pink lines indicate the natural confusion limit for 50, 10 and 1 object per galaxy $\pi\, r_e^2$ (see Windhorst et al. 2007). Hence, even surveys shallower than the HST/HDF will run into some natural confusion, where outer parts of objects start to overlap. Object deblending algorithms that take the galaxy profile/structure and PSF into account are needed to address these issues for JWST.

(5) Prediced appearance to JWST of $z \sim 1$–15 galaxies

[FAR-LEFT] With proper rest-frame UV training, JWST can quantitatively measure the evolution of galaxy morphology and structure over a wide range of cosmic time:
• Disks tend to SB-dim away at high z, but most formed only at $z \lesssim z_f \simeq 1$–2
• High-SB structures remain visible to very high redshifts
• Point sources (e.g., AGN) remain visible to very high z
• High-SB parts of mergers and train-wrecks are visible to very high redshifts.

[LEFT] The galaxy merger UGC 06471–2 (z=0.0104; Windhorst et al. 2002). This is for 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 in the upper right) is recognizable to $z \simeq 15$ (Windhorst et al. 2006).
This does not imply that observing galaxies at $z \simeq 15$ with JWST will be easy. On the contrary, since galaxies formed through hierarchical merging, many SF-knots at $z \simeq 10$–15 will be 10^1–$10^4\times$ less luminous than shown here, requiring to push JWST to its limits.

References and other sources of material:

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