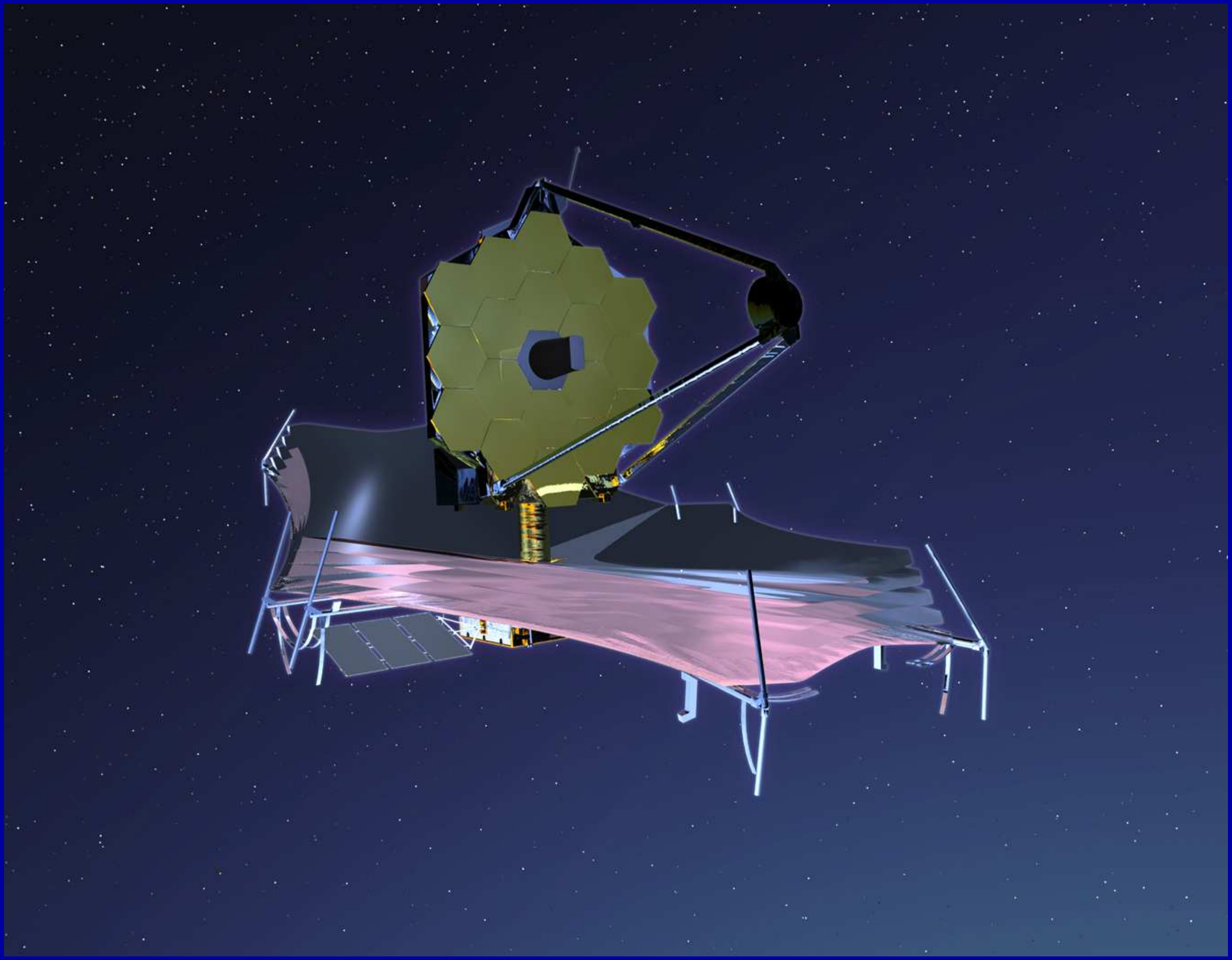
High-precision galaxy surveys & catalogs: JWST & beyond

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

Collaborators: S. Cohen, R. Jansen (ASU), N. Hathi (UC-R), R. Ryan (UC-D), & H. Yan (OSU)



Great Surveys workshop, Santa Fe, NM, Fr. Nov. 21, 2008

OUTLINE: FUTURE FACILITIES / Main Science Goals

(1) JWST 2013: First Light, Start of H-Reionization, Pop-III objects

- When and how did the First Light Pop-III dominated objects form?
- How, and how slow, did Pop-III star dominated objects start H-reionization?
- How, and how much, did Pop-III objects shape the onset of Pop-II formation and its IMF?

(2) HST/WFC3 2009: Galaxy Assembly & the End of H-Reionization

- How do DM halos at $z \gtrsim 6$ transform into spirals and ellipticals today?
- How and why did the (dwarf dominated!) galaxy luminosity function and mass function evolve with epoch?
- (How) did dwarf galaxy assembly finish H-reionization at $z \simeq 6$?

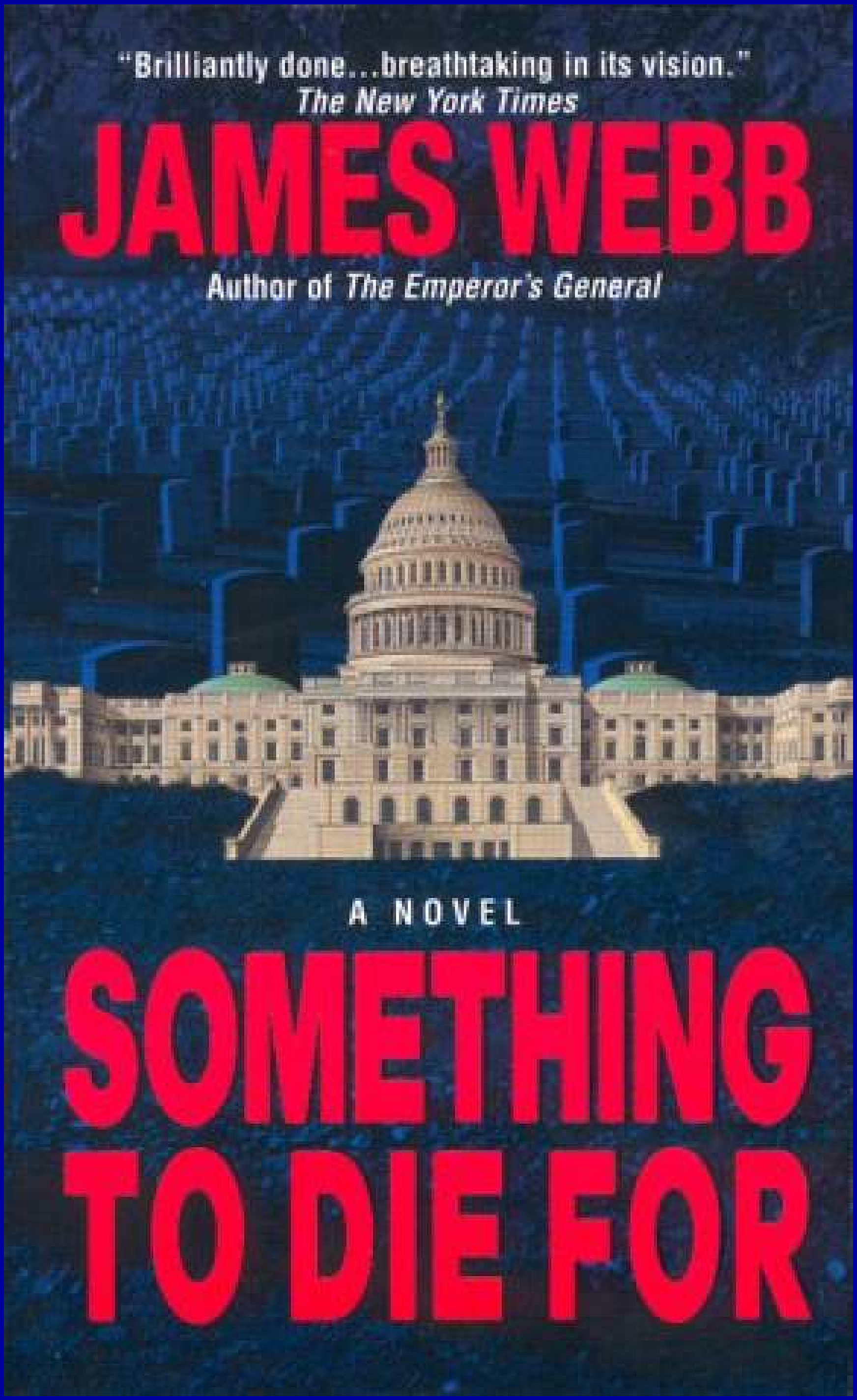
(3) THEIA/Star-Formation Camera $\gtrsim$2015: a 4m UV–optical HST sequel: Galaxy Assembly, AGN Growth, & He-Reionization

- How did AGN hole growth keep up with galaxy assembly, and how much was either controlled by the epoch dependent merger rate?

- (How) did AGN growth finish He-reionization at $z \simeq 3$?

- (How) did feedback from SNe shape the faint-end LF-slope evolution. How did AGN feedback control the bright-end LF-evolution?

	FWHM	λ-range (μm)	AB-mag (10-σ; 100 hrs)
JWST:	$\gtrsim$0.08"	0.7–28.5	31.5 (1.5 nJy)
HST/WFC3:	$\gtrsim$0.04"	0.19–1.7	29.5 (10 nJy)
Theia/SFC:	$\gtrsim$0.02"	0.19–1.1	32.5 (0.6 nJy)



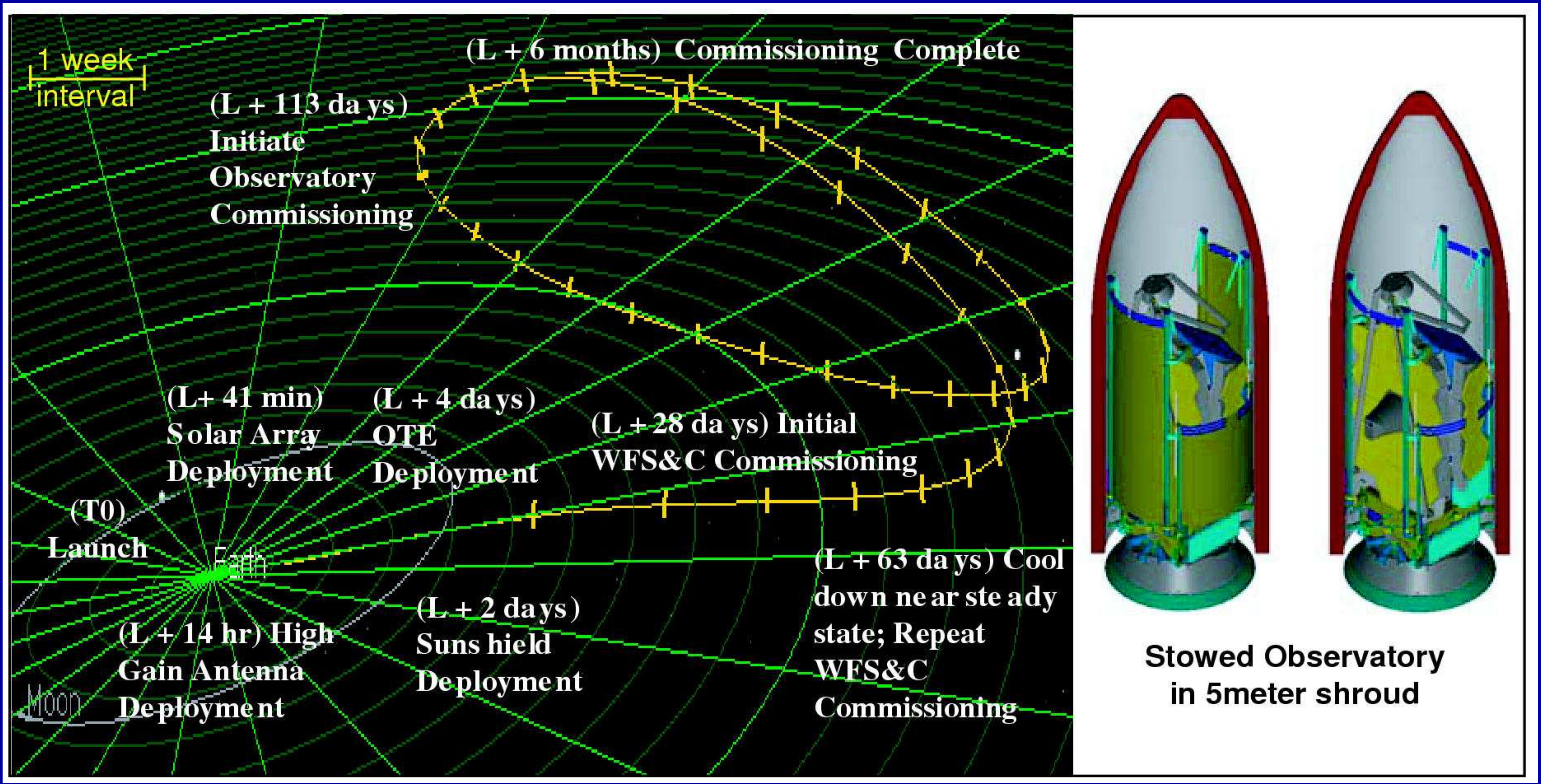
Need hard-working grad students & postdocs in $\gtrsim$2013 ... It'll be worth it!

(1) 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).

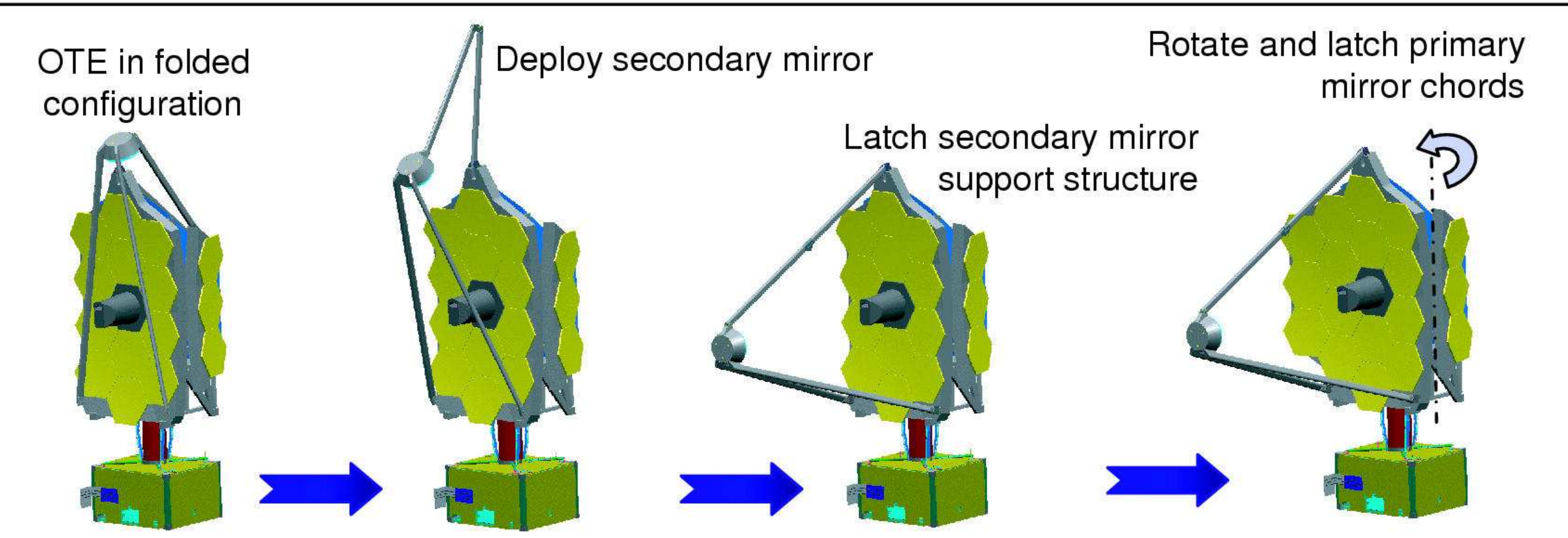
Life size model of JWST: displayed at the Jan. 2007 AAS mtg in Seattle.

(1) How will JWST travel to its L2 orbit?



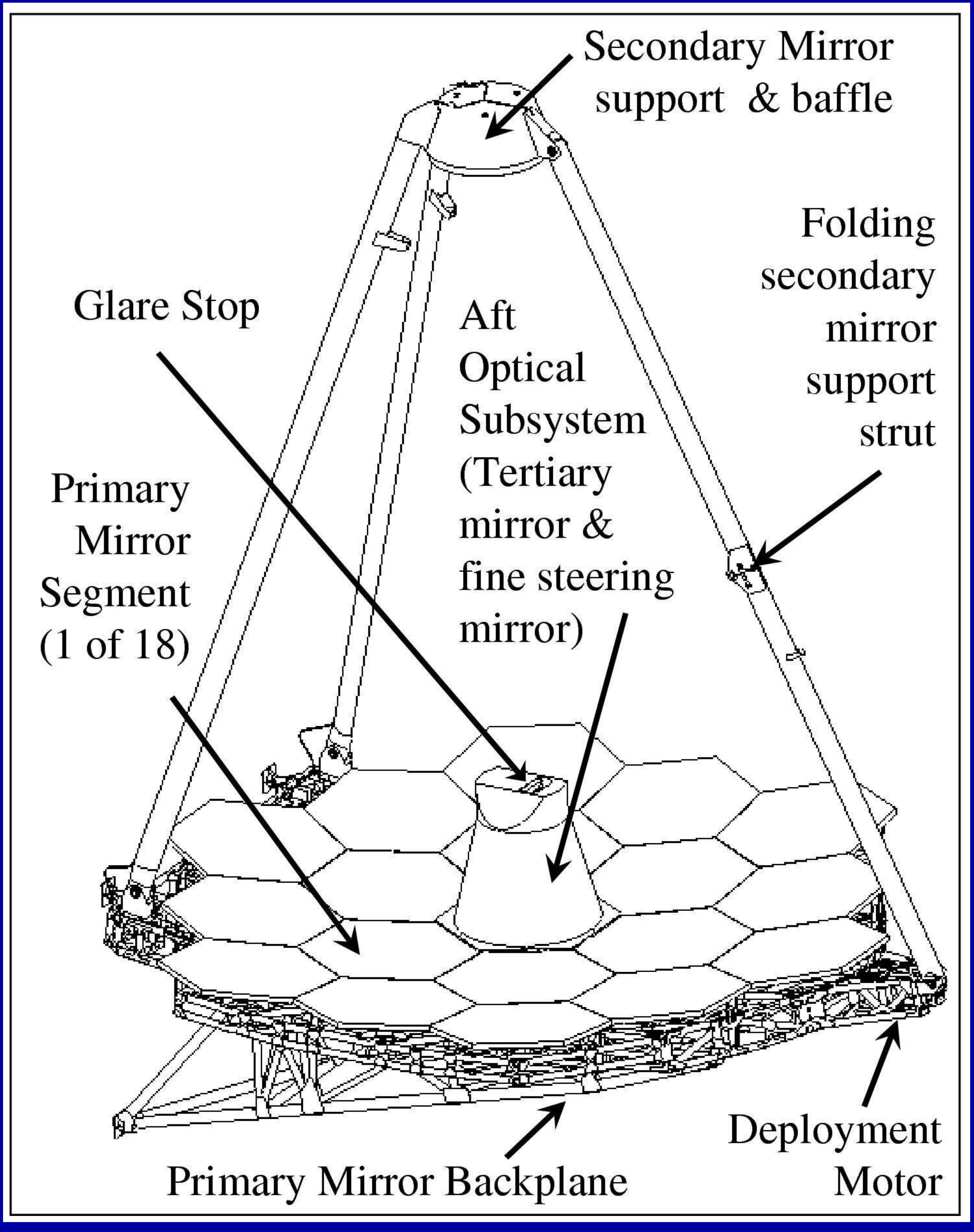
After launch in June 2013 with an Ariane-V vehicle, JWST will orbit around the the Earth–Sun Lagrange point L2. From there, JWST can cover the whole sky in segments that move along in RA with the Earth, have an observing efficiency $\gtrsim$70%, and send data back to Earth every day.

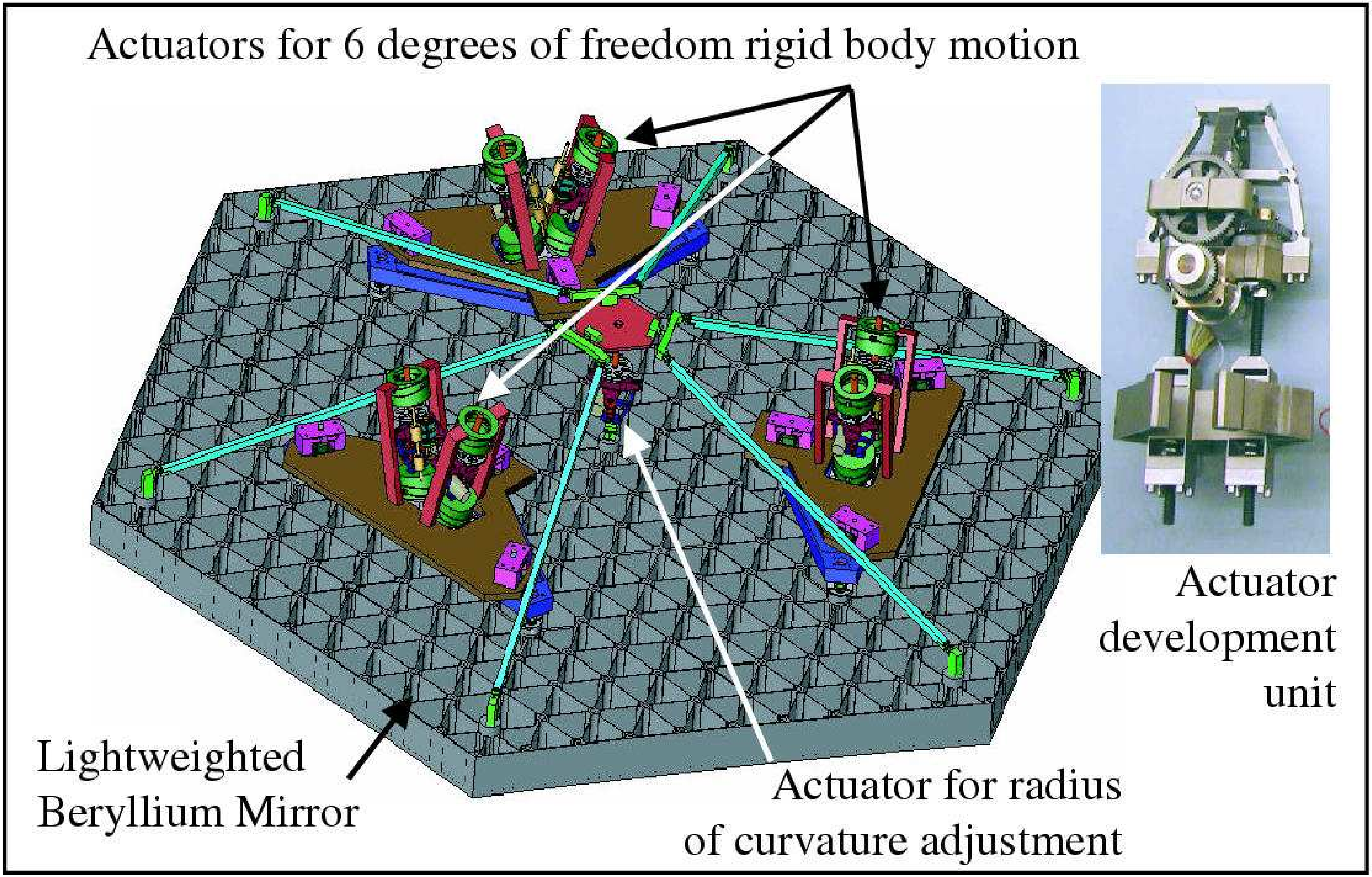
(1) How will JWST be automatically deployed?



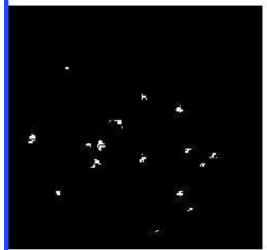
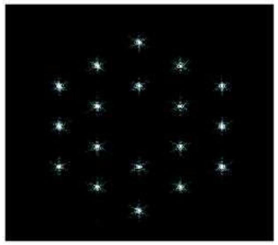
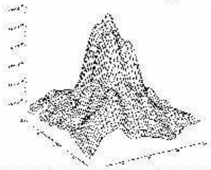
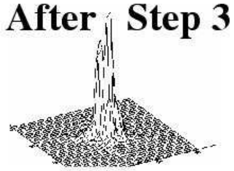
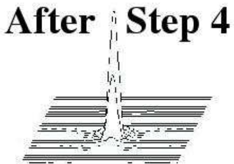
During its several month journey to L2, JWST will be automatically deployed in phases, its instruments will be tested and calibrated, and it will then be inserted into an L2 halo orbit.

The entire JWST deployment sequence can and will be tested several times on the ground — but in 1-G.


Secondary Mirror support & baffle
Folding secondary mirror support strut
Glare Stop
Aft Optical Subsystem (Tertiary mirror & fine steering mirror)
Primary Mirror Segment (1 of 18)
Deployment Motor
Primary Mirror Backplane



Active mirror segment support through hexapods (7 d.o.f.), similar to Keck.

		Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	After Step 1 	18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 µm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
2. Coarse Alignment Secondary mirror aligned Primary RoC adjusted	After Step 2 	Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	WFE < 200 µm (rms)
3. Coarse Phasing - Fine Guiding (PMSA piston)	After Step 3 	WFE: < 250 µm rms	WFE < 1 µm (rms)
4. Fine Phasing	After Step 4 	WFE: < 5 µm (rms)	WFE < 110 nm (rms)
5. Image-Based Wavefront Monitoring	After Step 5 	WFE: < 150 nm (rms)	WFE < 110 nm (rms)

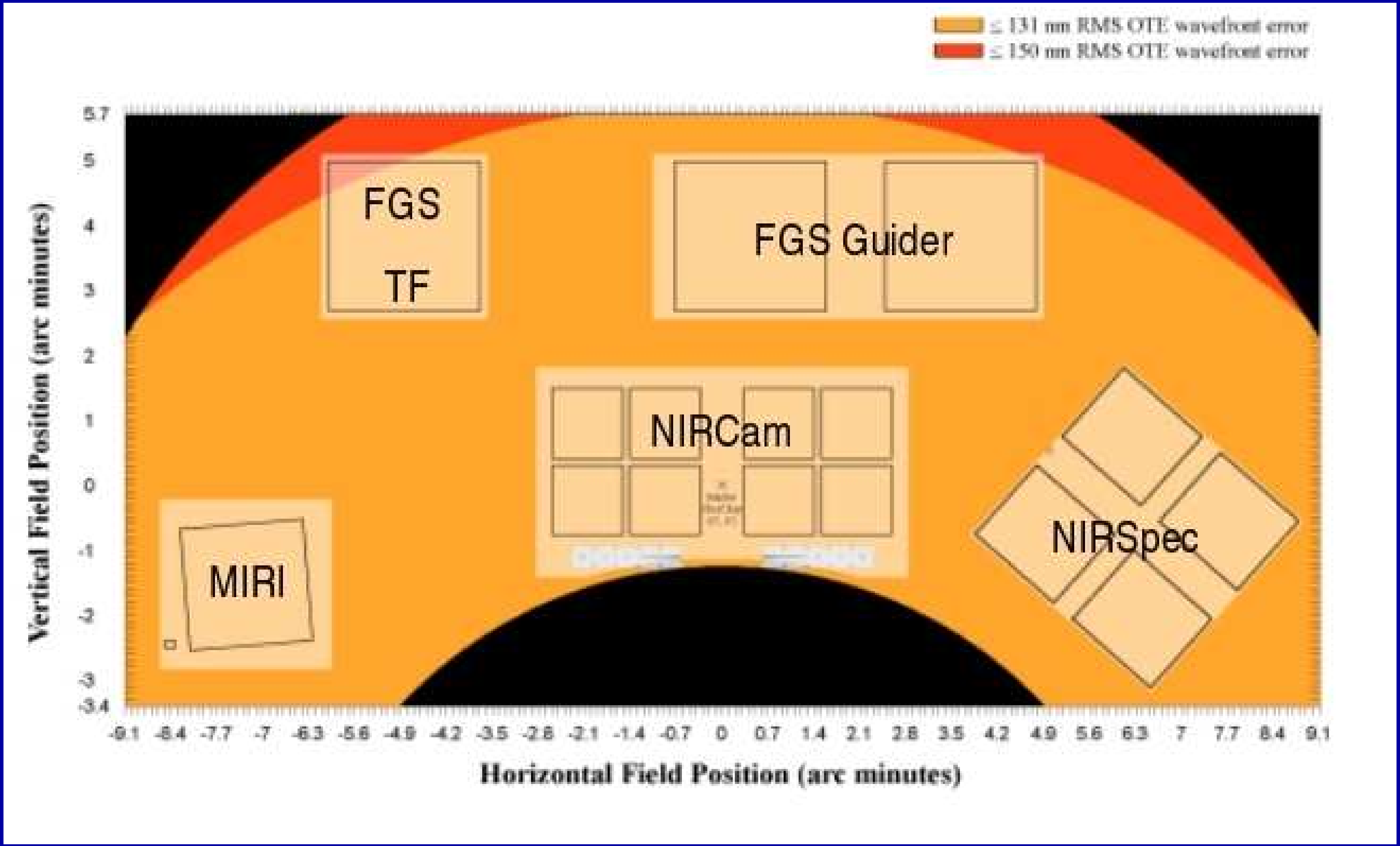
JWST's Wave Front Sensing and Control is similar to that at Keck and HET.

Successful 2006 demo of H/W, S/W on 6/1 scale model (2 μm-Strehl$\gtrsim$0.85).

Need WFS-updates every $\sim$14 days, depending on scheduling/SC-illumination.

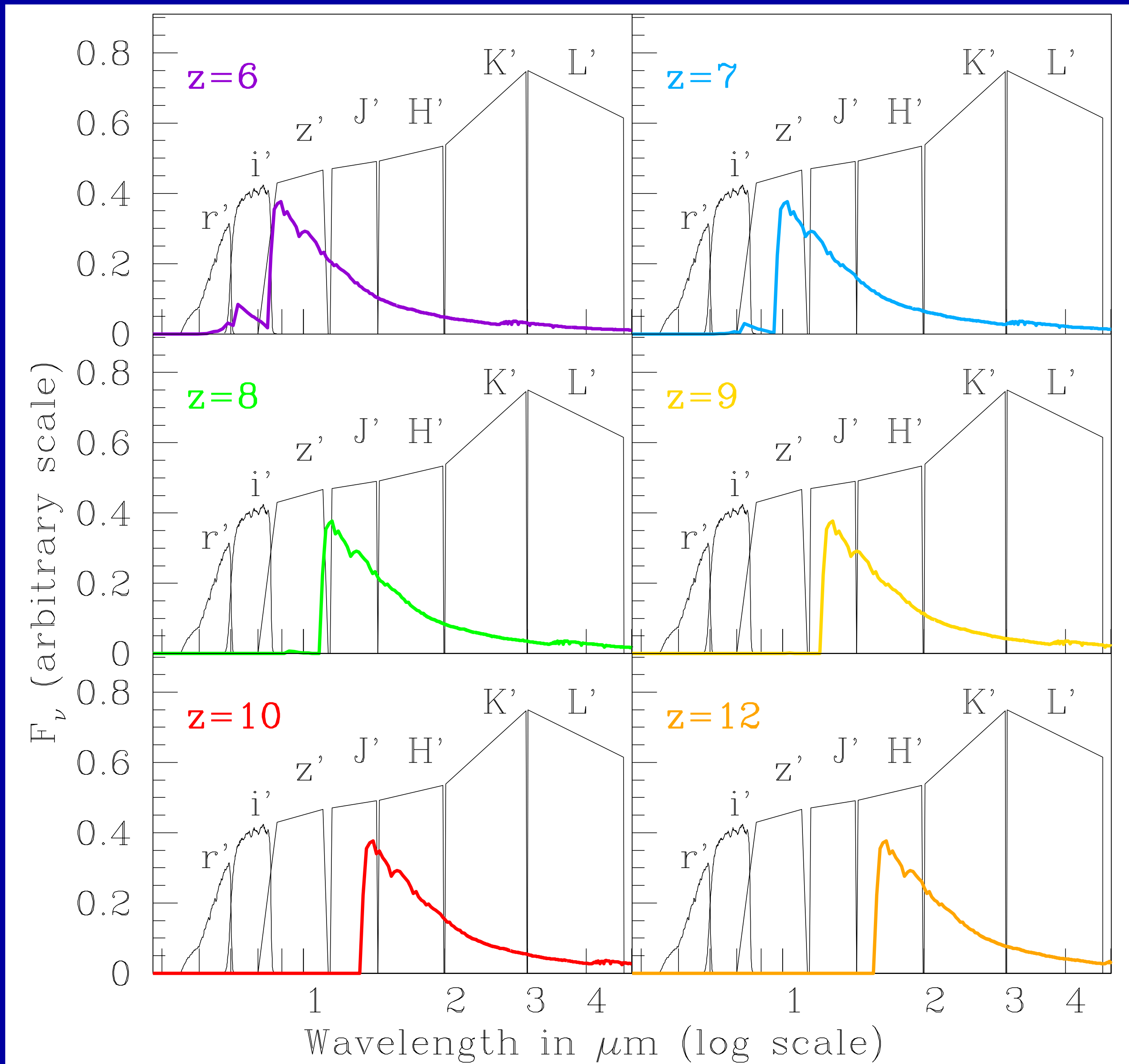
Ball 1/6-scale model: WFS produces diffraction-limited images at 2.0 μm.

(1) What instruments will JWST have?



All JWST instruments can in principle be used in parallel:

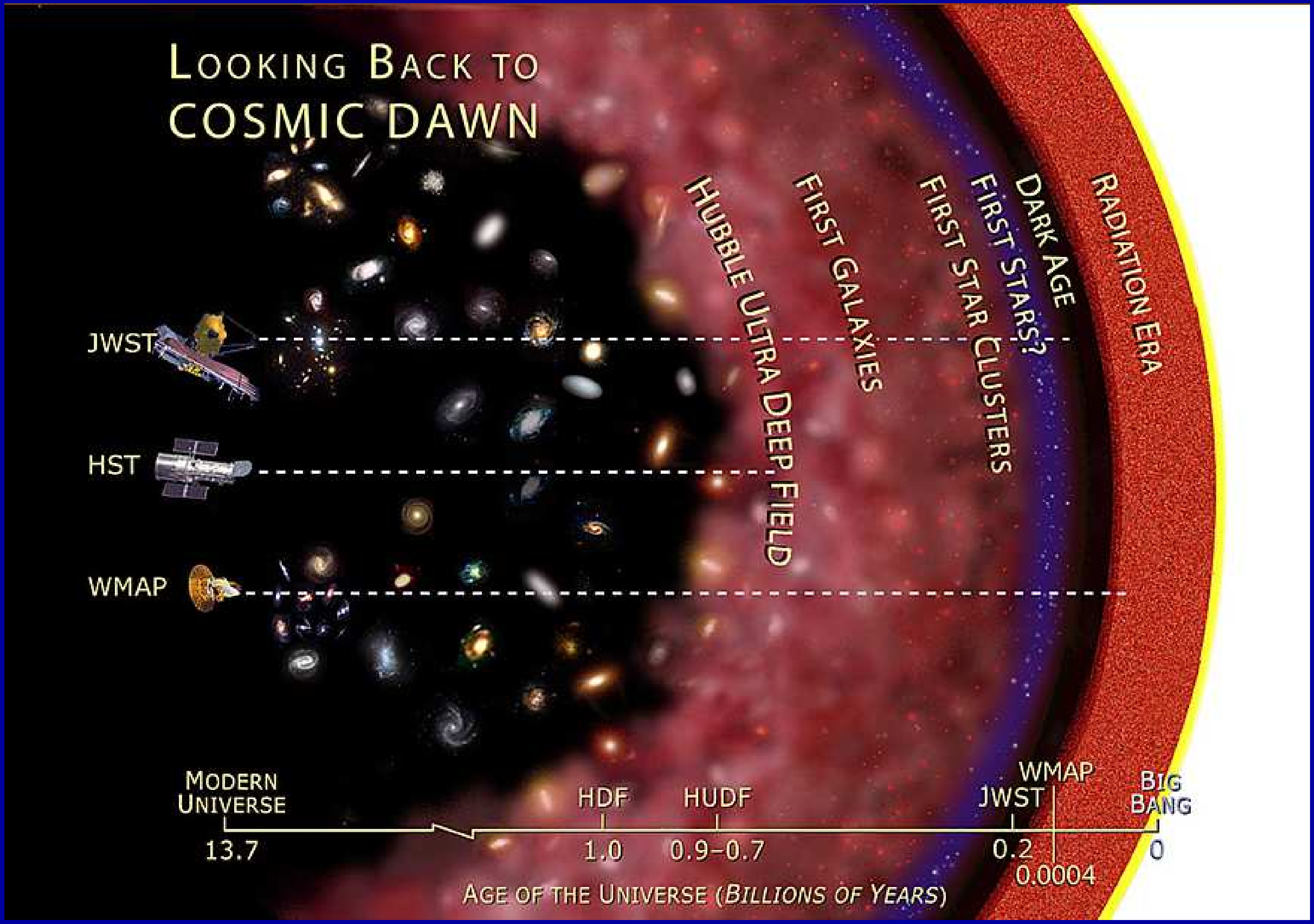
- Currently only being implemented for parallel *calibrations.*



- 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.

(1) JWST: First Light, H-Reionization, and Galaxy Assembly



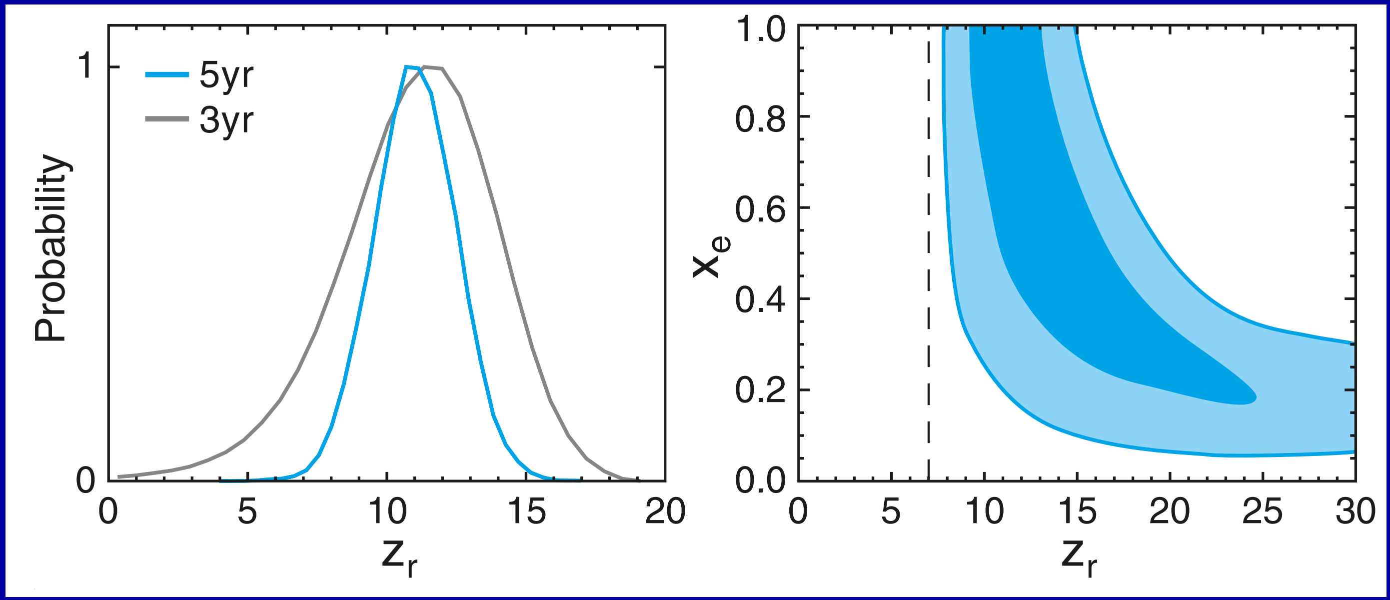
HST (+WFC3): Hubble sequence & galaxy evolution from z≃0 to z≃7–8.

JWST: First Light, Reionization, & (dwarf) Galaxy Assembly at z≃8–20.

WMAP: H-Recombination at z=1091±1. Imprints of all foregrounds.

Implications of the WMAP-year5 results on HST, JWST & SFC science:

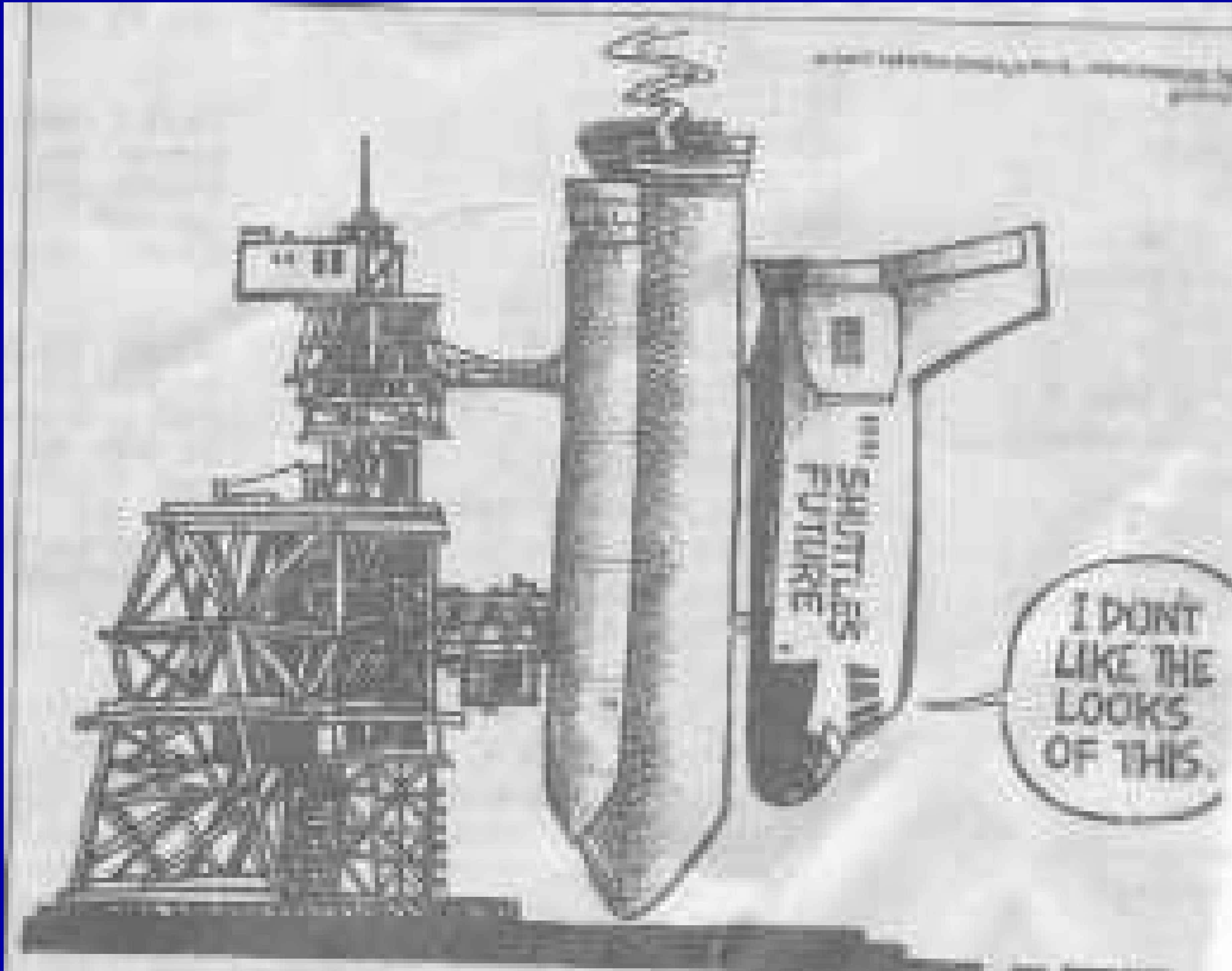
HST/WFC3, THEIA/SFC $z \lesssim 8 \longleftarrow$ $\longrightarrow$ JWST $z \simeq 8$–25



The WMAP year-5 data provided much better foreground removal (Dunkley ea. 2008; Komatsu ea. 2008). This implies that First Light & Reionization (see Lawrence, Furlanetto, this conf.) occurred between these extremes:

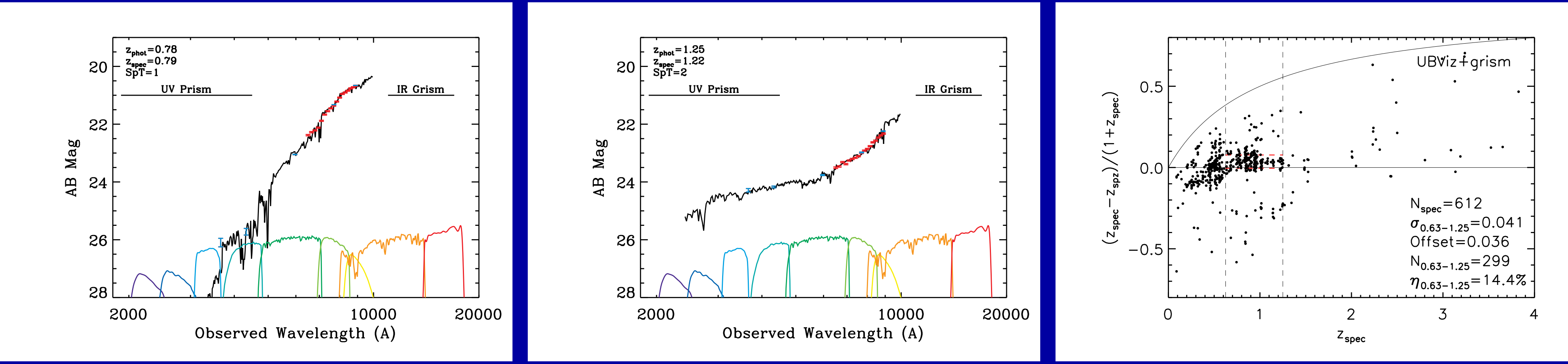
- (1) Universal & instantaneous at $z \simeq 10.8 \pm 1.4$, or, much more likely:
- (2) Inhomogeneous & drawn out: starting at $z \gtrsim 20$, peaking at $z \simeq 11$, ending at $z \simeq 7$. In both cases, the implications for HST, JWST, SFC are:
- HST has covered $z \lesssim 6$. HST/WFC3 & SFC will cover $z \lesssim 7$–8.
- For First Light & Reionization, JWST surveys cover $z \simeq 8$ to $z \simeq 15$–20.

(2) Hubble Wide Field Camera 3 — as of Spring 2008



If there are no further Shuttle issues, WFC3 will get launched May 12, 2009 ...

Power of combination of Grism and Broadband for WFC3



Lessons from the Hubble ACS grism surveys "GRAPES" and "PEARS" (Malhotra et al. 2005; Cohen et al. 2007; Ryan et al. 2007, ApJ, 668, 839):

- (a) Spectro-photo-z's from HST grism + BViz(JH) considerably more accurate than photo-z's alone, with much smaller catastrophic failure %.

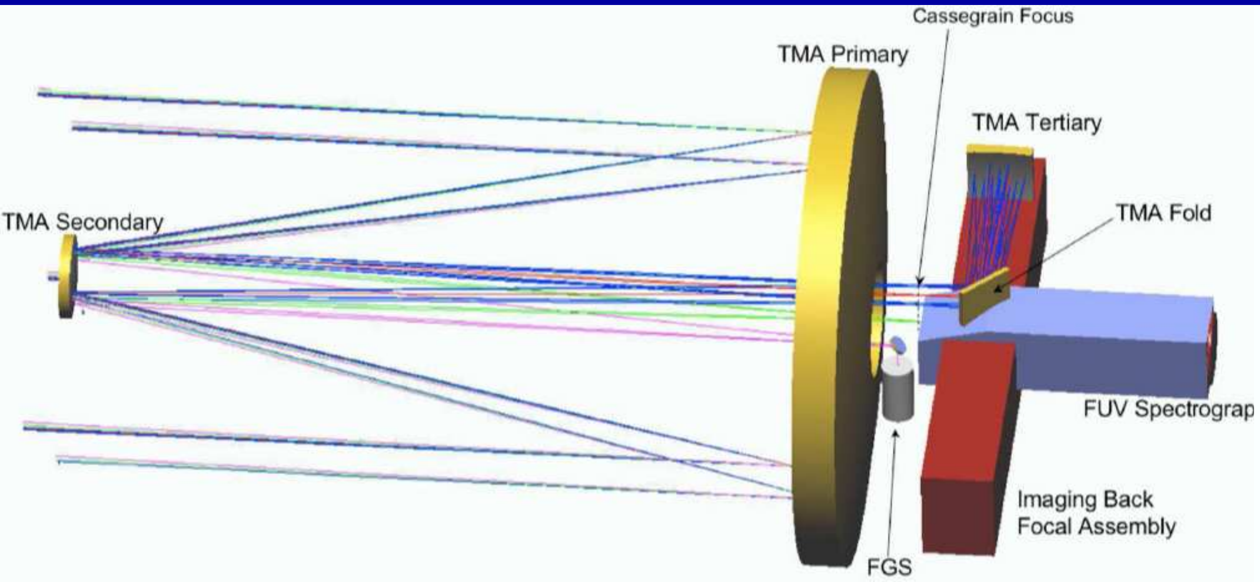
- (b) Redshifts for $\gtrsim$13,000 objects to AB$\gtrsim$27.0–27.5 mag; $\sigma_z/(1+z)\lesssim0.04$.

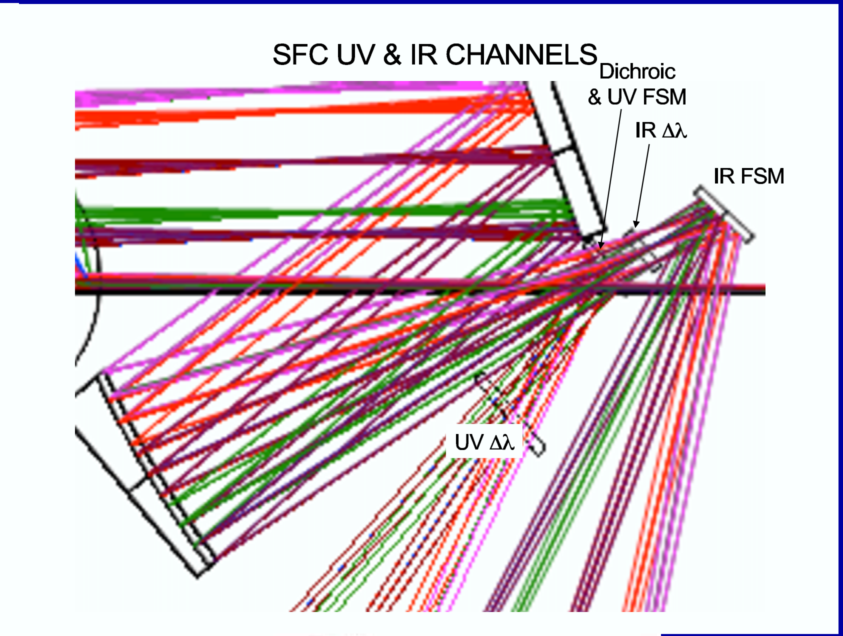
- (c) WFC3 will provide full panchromatic sampling from 0.2–1.7 μm: UV and near-IR broad-band imaging and R$\sim$100 grism spectroscopy.

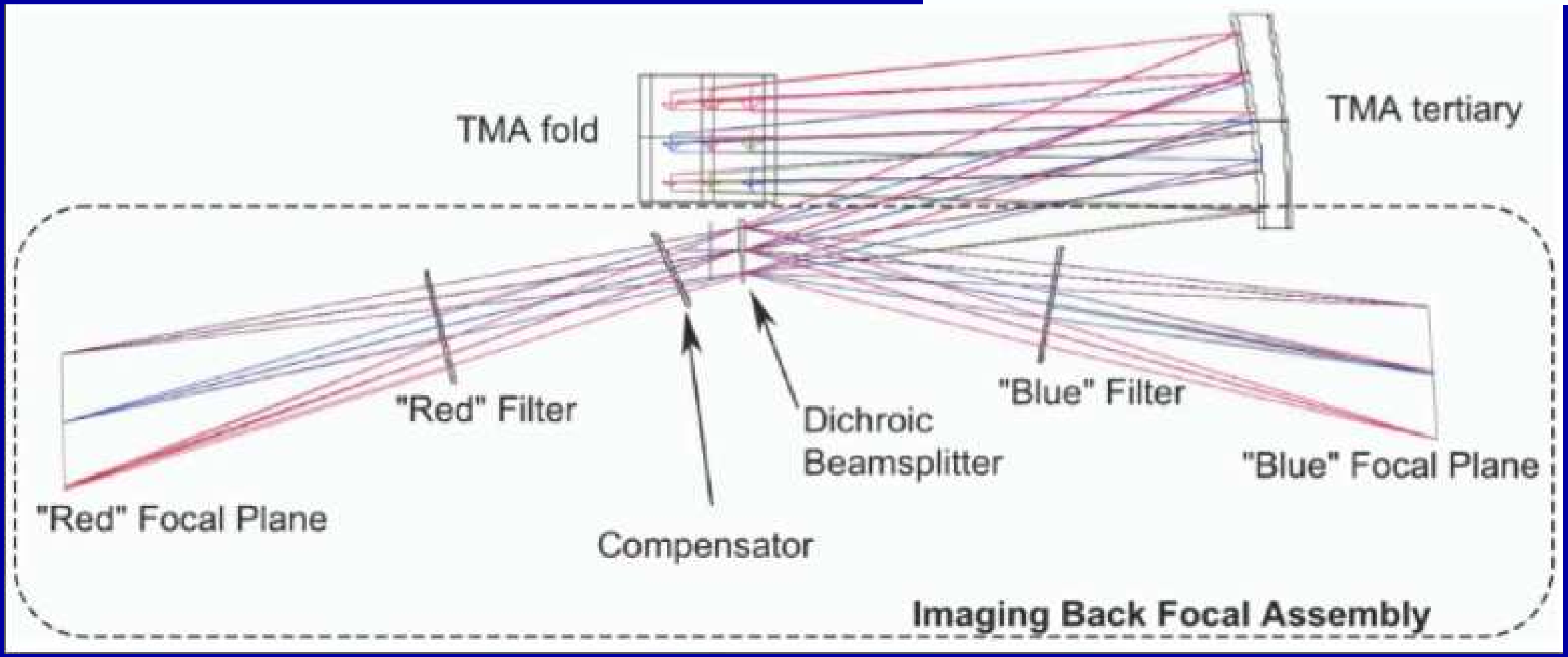
- This yields high accuracy spectro-photo-z's (spz's $\lesssim$2–3%) for faint galaxies of all types to AB$\simeq$27.0–29.0 mag (10σ in $\sim$2–80 orbits/filter).

See also talks by Gawiser, Padmanabhan (this conf.)

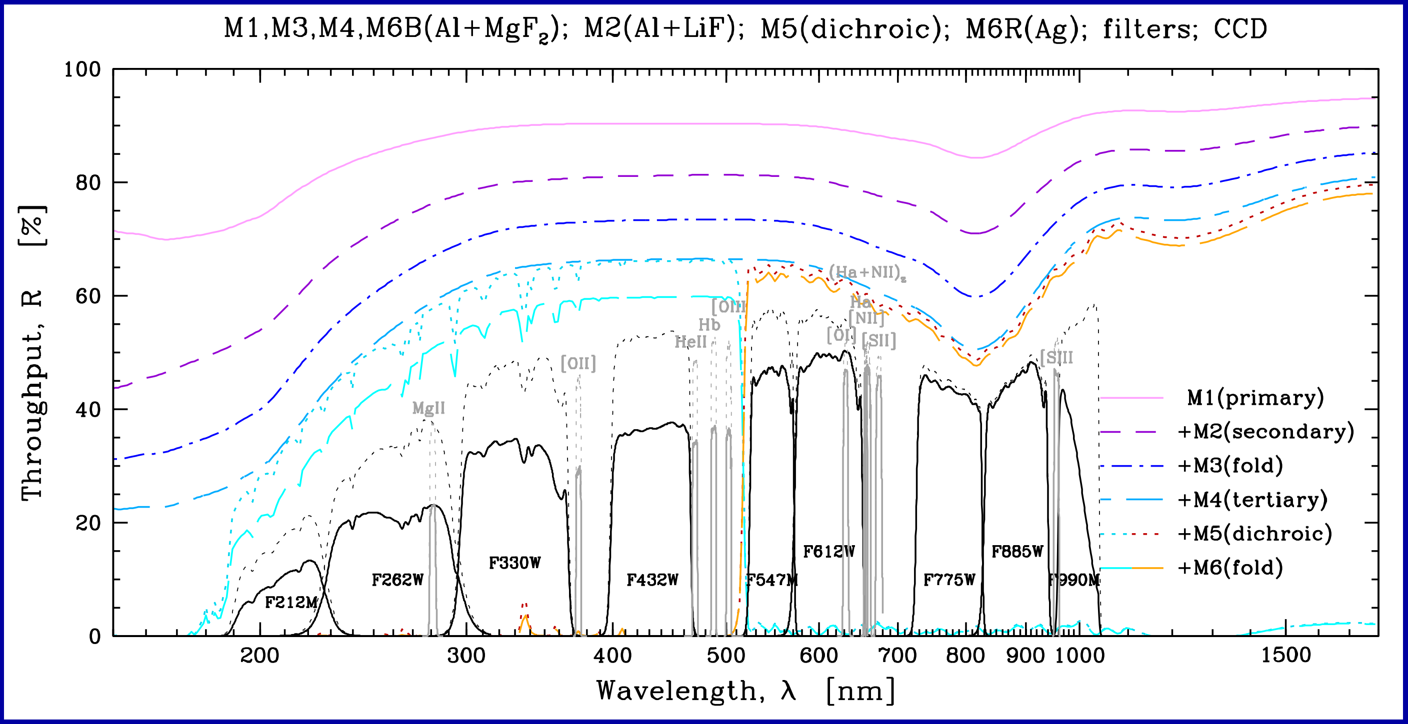
(3) Beyond 2015: 4m THEIA/Star-Formation Camera in L2

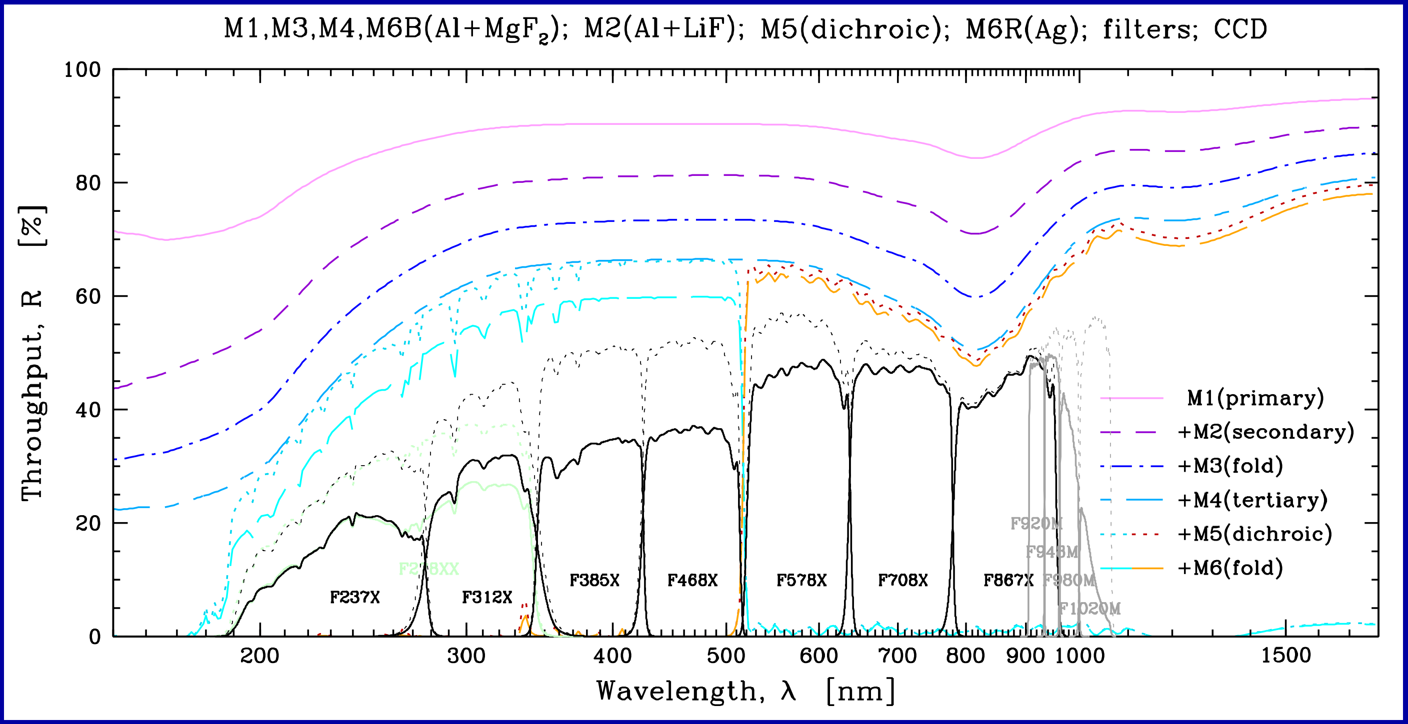




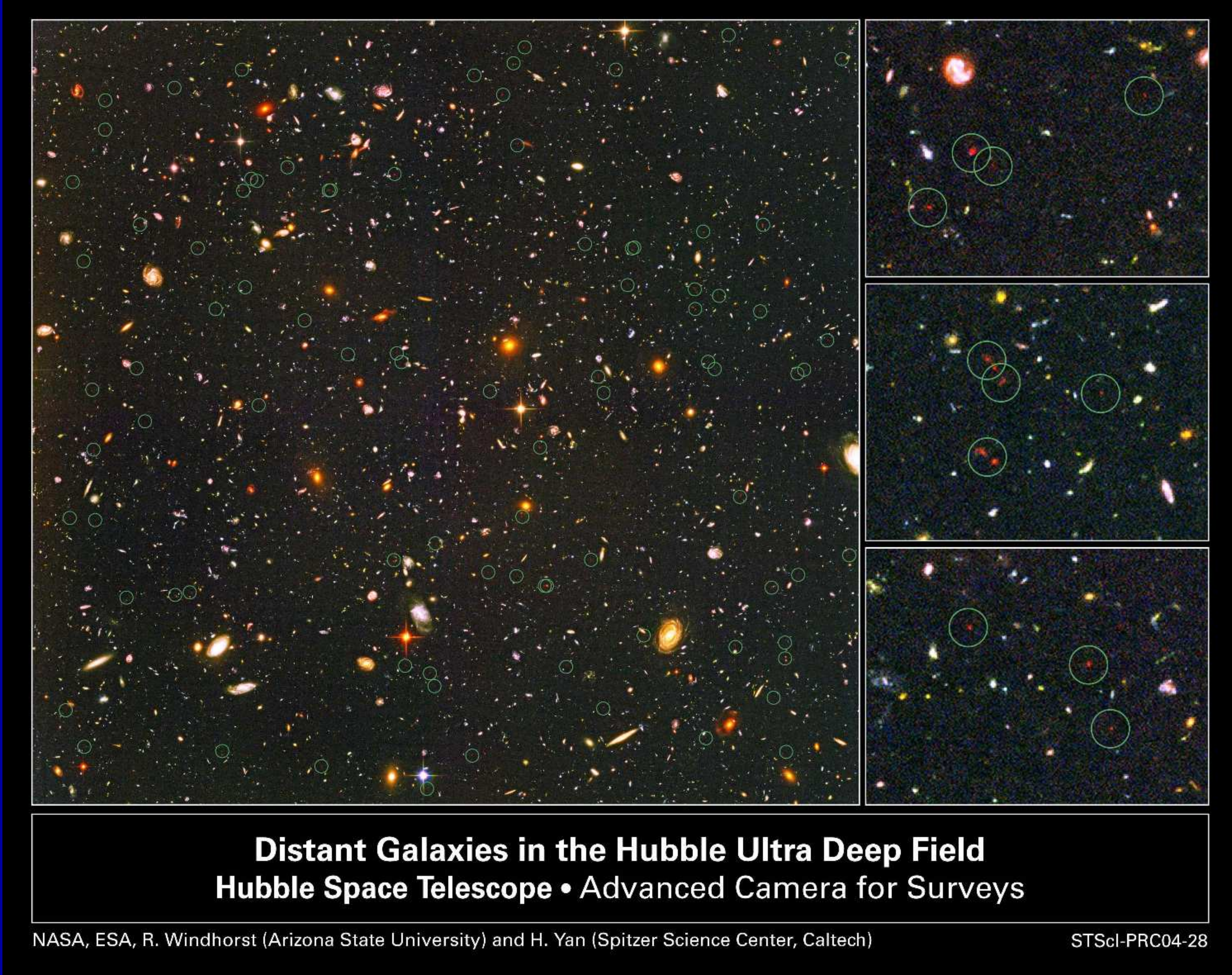


THEIA/Star-Formation Camera (SFC): 4 meter UV-Optical sequel to HST



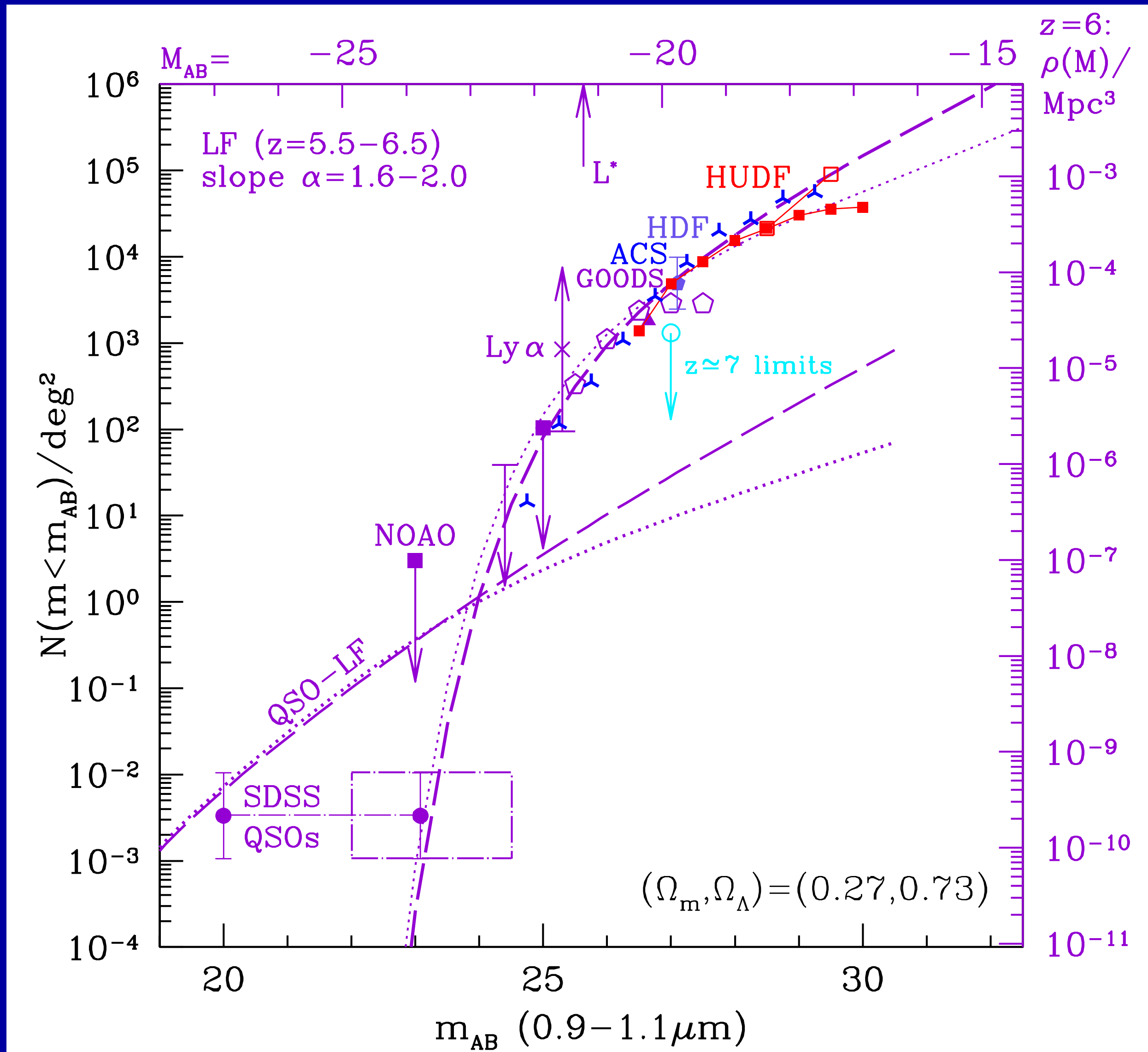


THEIA/SFC reaches AB≃31 mag for **λ**≃0.2–1.1 nm at 0.02-0.07" FWHM.



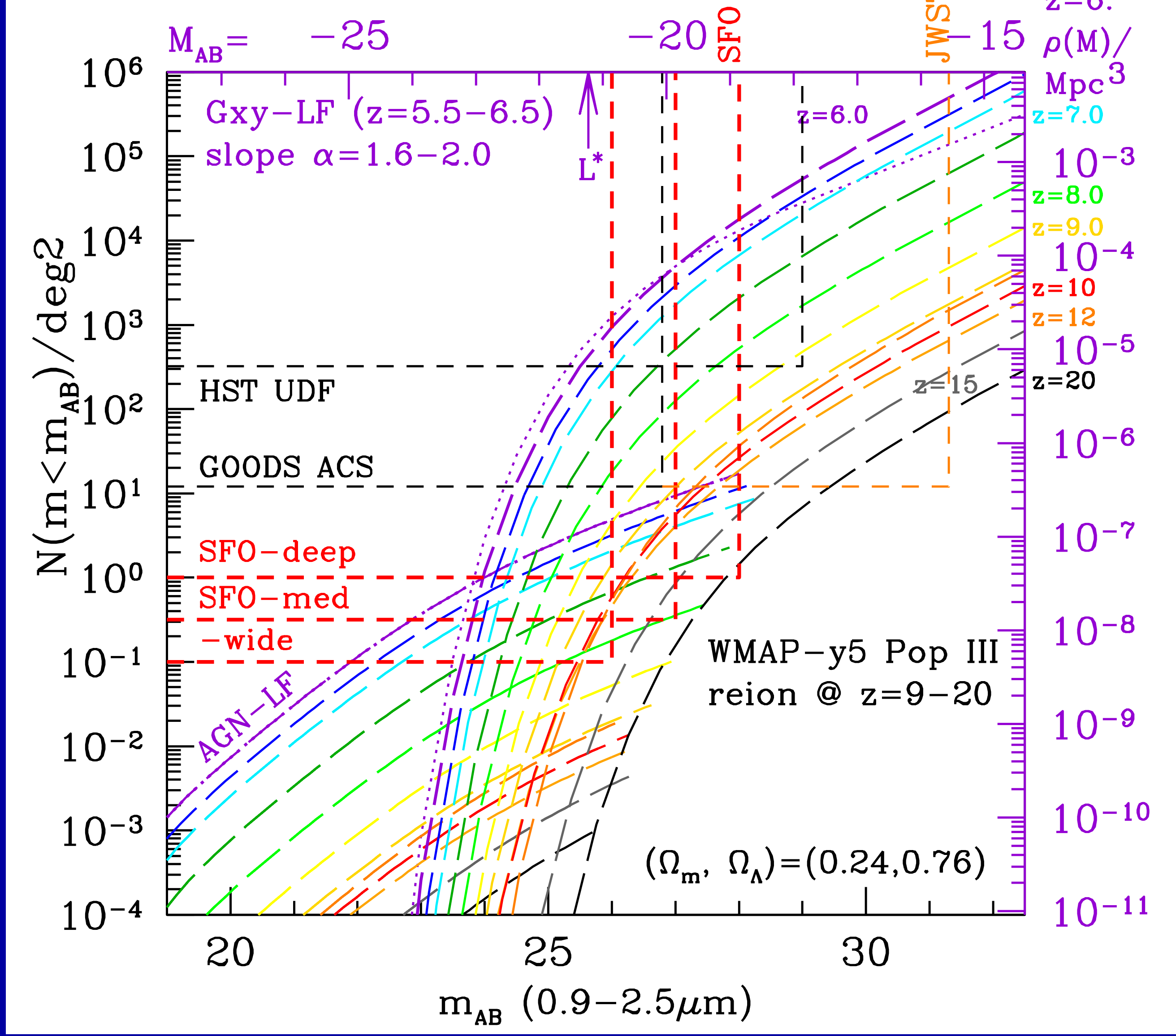
HUDF i-drops: faint galaxies at z$\simeq$6 (Yan & Windhorst 2004), most spectroscopically confirmed at z$\simeq$6 to AB$\lesssim$27.0 mag (Malhotra et al. 2005).

(1) How JWST can measure First Light and Reionization



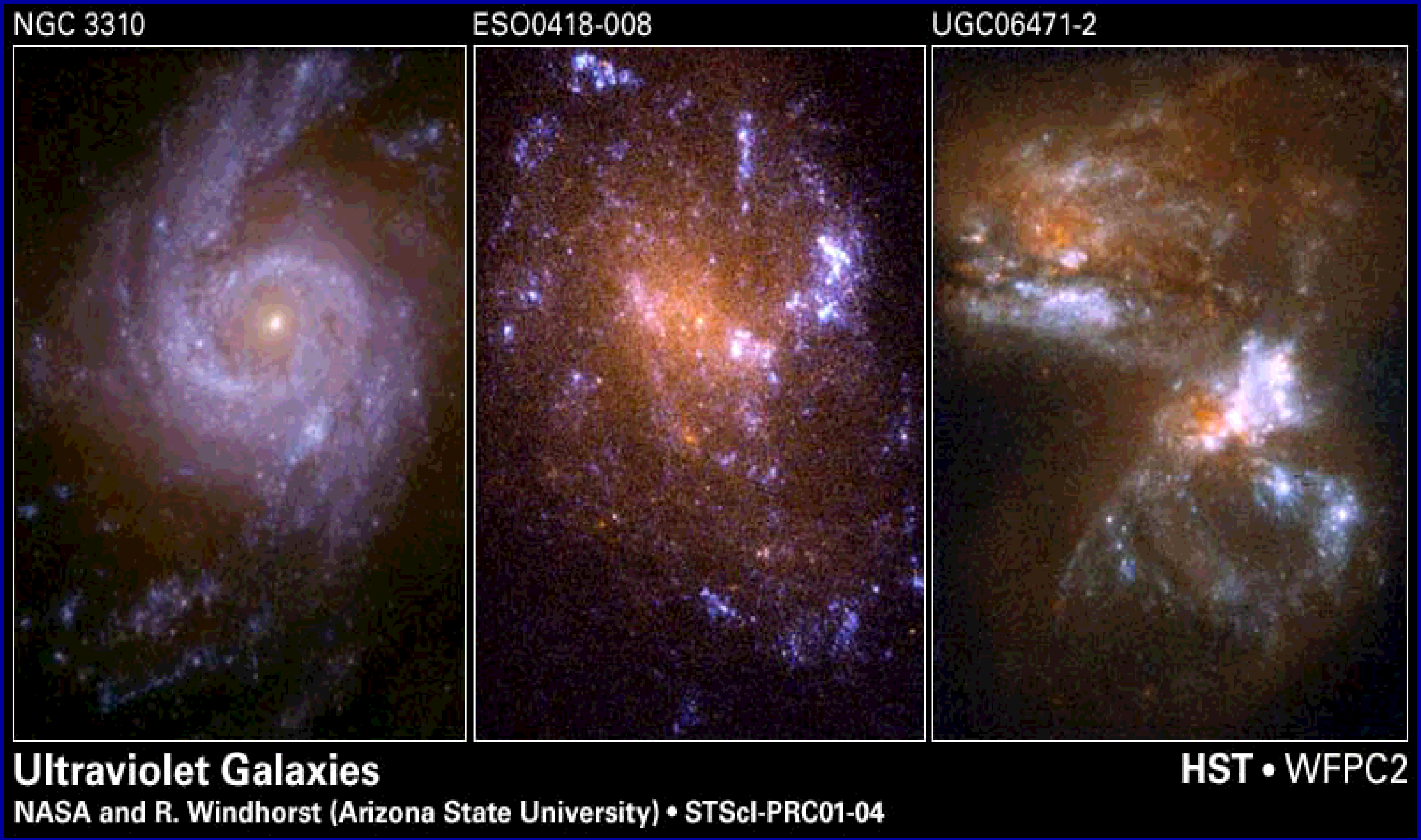
HUDF shows that luminosity function of z≃6 objects (Yan & Windhorst 2004a, b) may be very steep: faint-end Schechter slope $|\alpha|\simeq$1.6–2.0.

⇒ Dwarf galaxies and not quasars likely completed the reionization epoch at z≃6. This is what JWST will observe in detail for z$\gtrsim$7–20.



- 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), FOV ($=\Omega$), and λ-range (0.7-28 μm) to detect First Light objects.

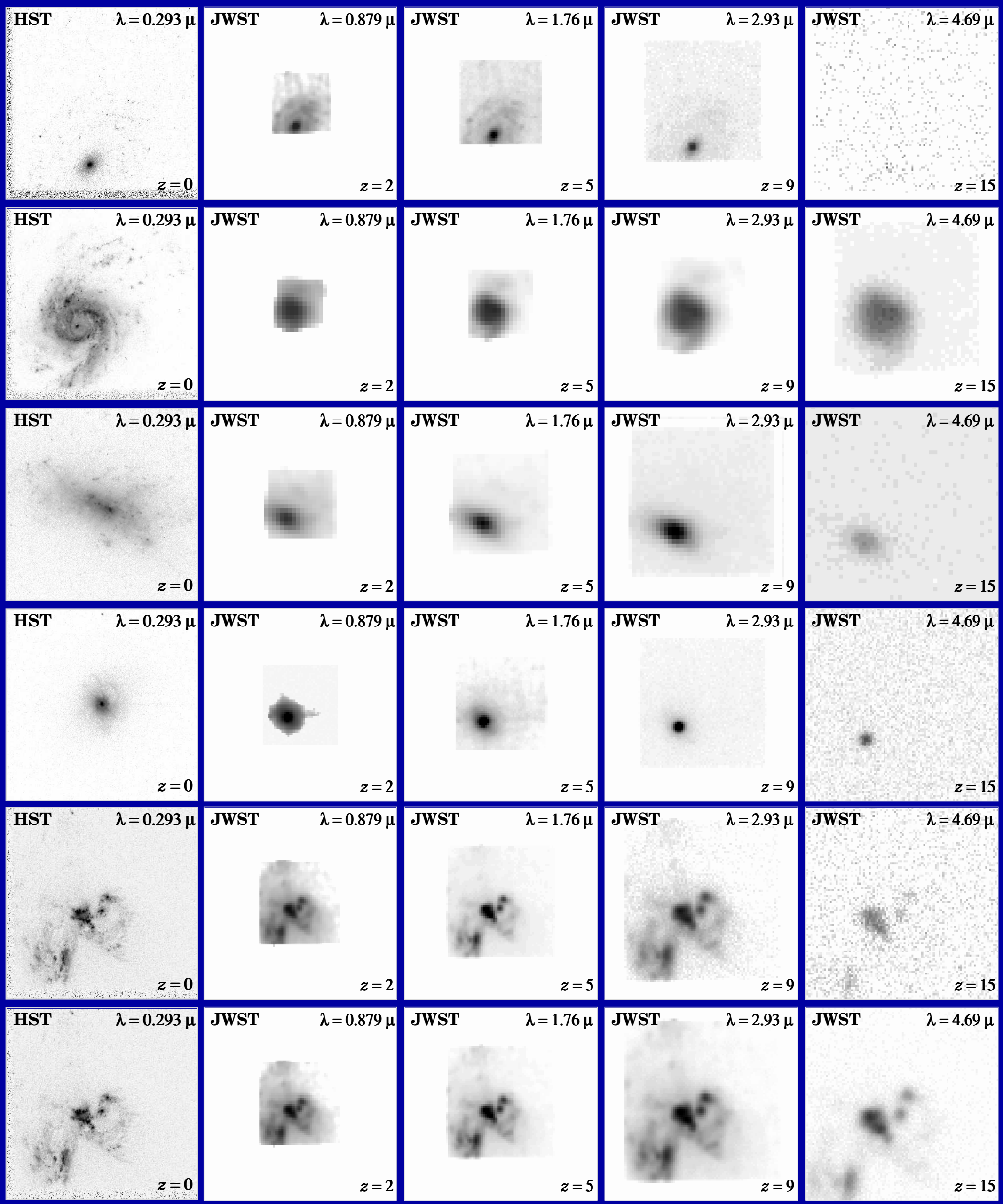
(1) Predicted Galaxy Appearance for JWST at z≃1–15



- 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.

(1) 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:

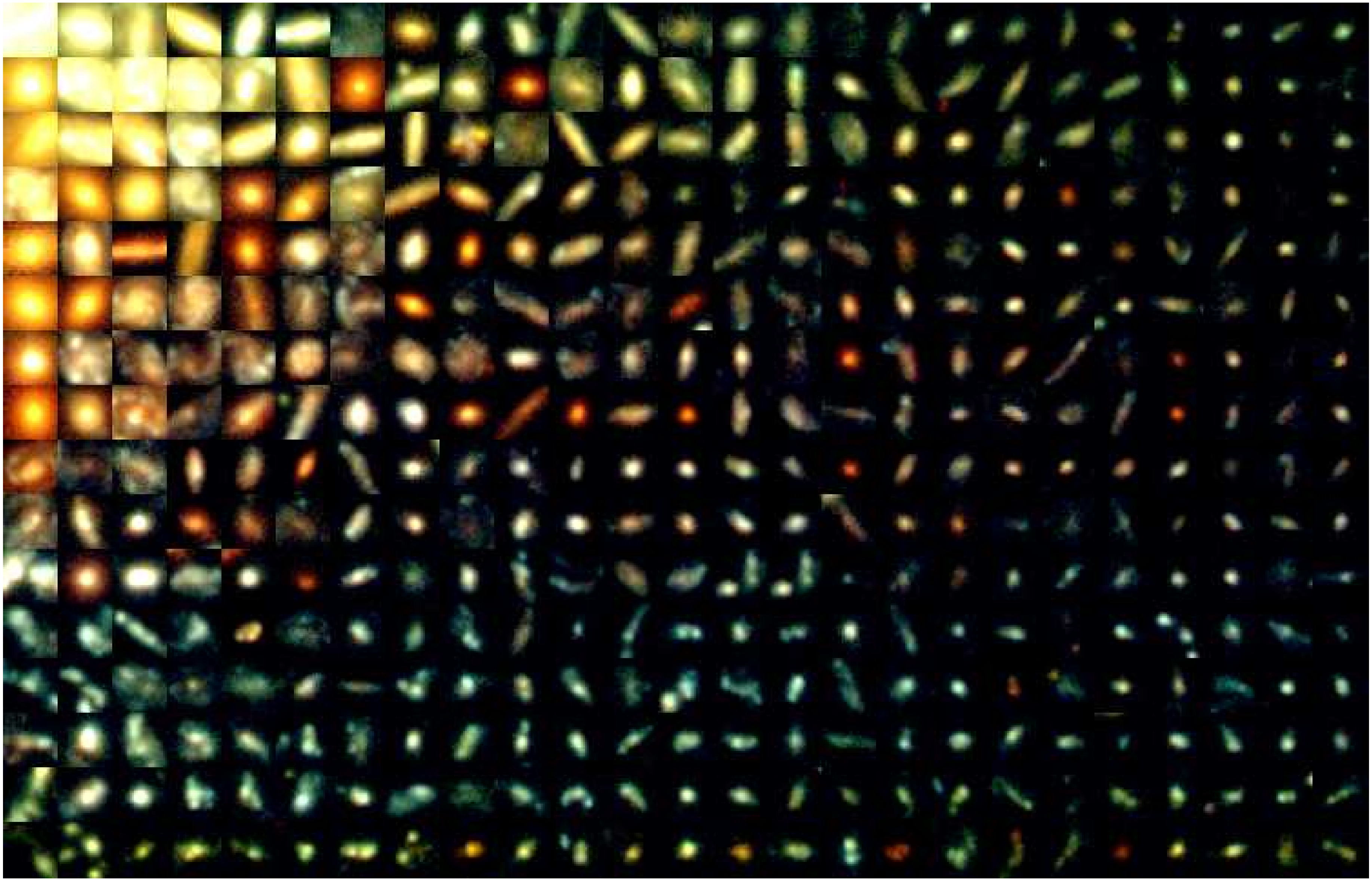
- (1) Most disks will SB-dim away at high z, but most formed at z$\lesssim$1–2.
- (2) High SB structures are visible to very high z.
- (3) Point sources (AGN) are visible to very high z.
- (4) High SB-parts of mergers/train-wrecks, etc., are visible to very high z.

(2) How HST/WFC3 and JWST will measure Galaxy Assembly

R. Windhorst (Arizona State University) and NASA

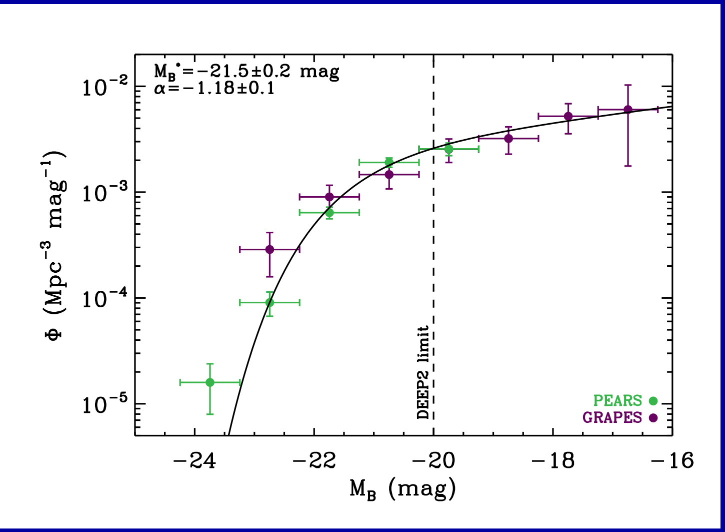
One of the remarkable discoveries of HST was how numerous and small faint galaxies are — the building blocks of the giant galaxies seen today.

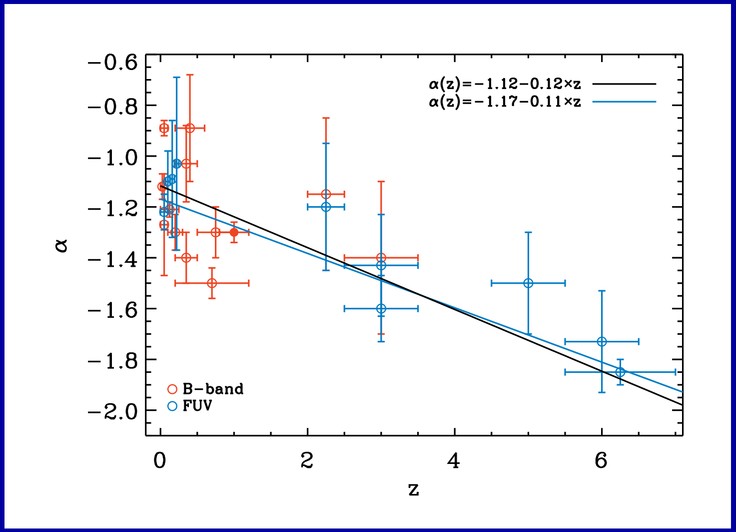
THE HUBBLE DEEP FIELD CORE SAMPLE ($I < 26.0$)

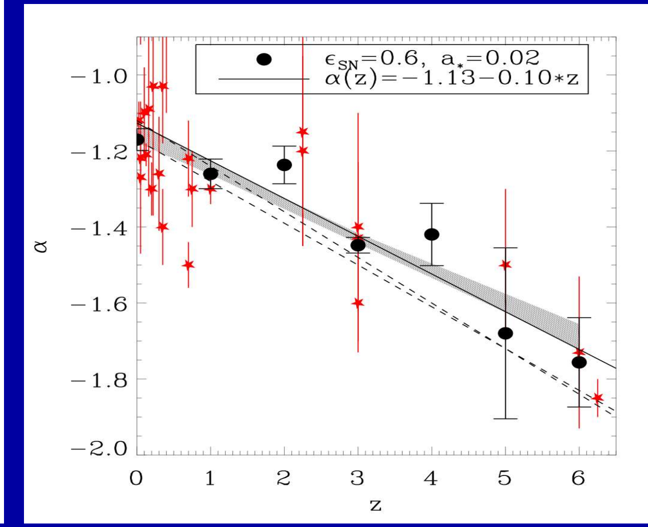


z	Age ($q_o = 0.5$)
0.19	77%
0.44	58%
0.54	52%
0.64	48%
0.74	44%
0.87	39%
0.97	36%
1.03	35%
1.14	32%
1.24	30%
1.41	27%
1.61	24%
1.76	22%
2.05	19%
2.57	15%
3.59	10%

(2) Faint-end LF-slope evolution (fundamental, like local IMF)



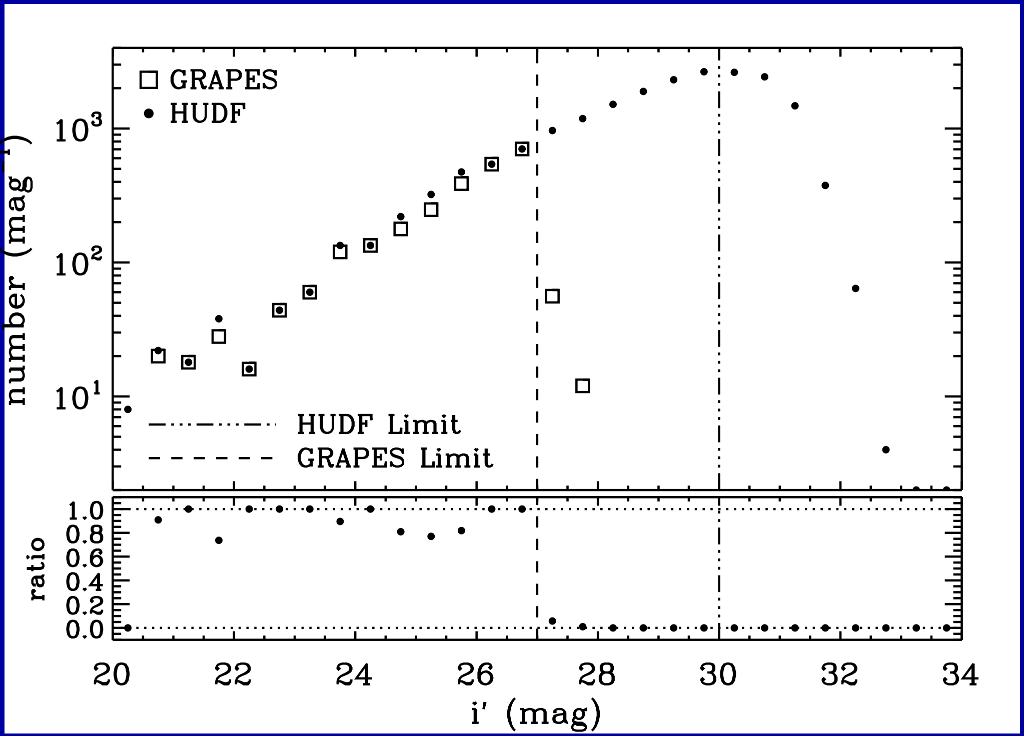


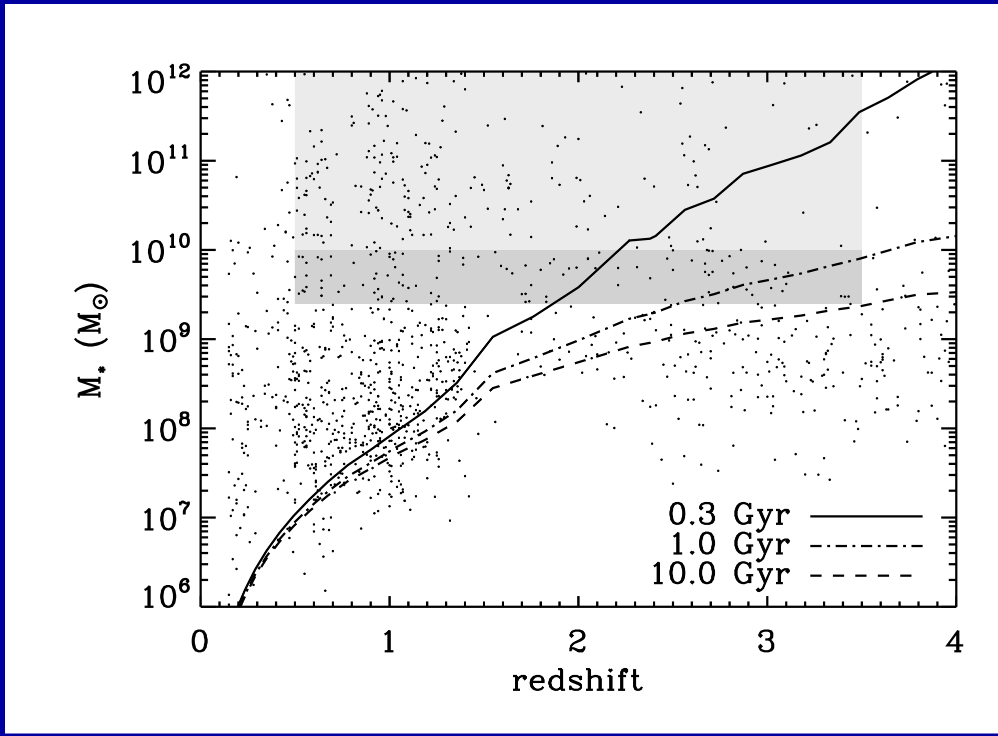


Faint-end LF-slope at z$\gtrsim$1 with accurate ACS grism z's to AB$\lesssim$27 (Cohen et al.; Ryan et al. 2007, ApJ, 668, 839) constrains hierarchical formation:

- Star-formation and SN feedback produce different faint-end slope-evolution: new physical constraints (Khochfar ea. 2007, ApJL, 668, L115).
- JWST will provide fainter spectra (AB$\lesssim$29) and spectro-photometric redshifts to much higher z ($\lesssim$20). JWST will trace α-evolution for z$\lesssim$12.
- Can measure environmental impact on faint-end LF-slope α directly.
- Expect convergence to slope $|\alpha|\equiv$2 at z$>$6 before feedback starts.
- Constrain onset of Pop III SNe epoch, Type II & Type Ia SN-epochs.

(2) Epoch dependent major merger rate to AB$\lesssim$27–29 mag, z$\lesssim$6.





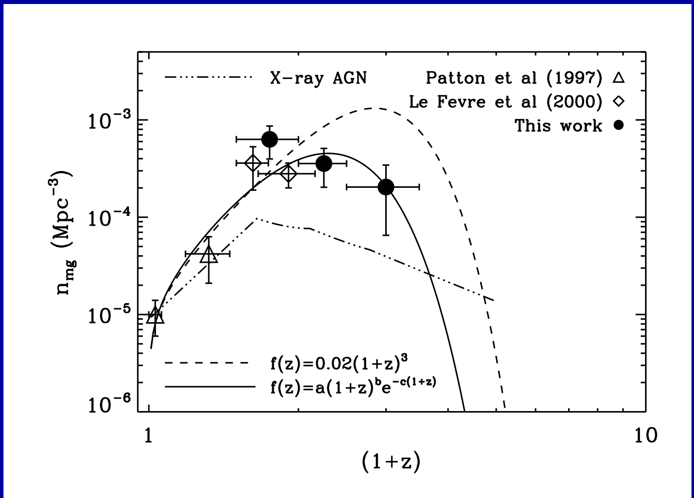
Ryan et al. (2007): HST/ACS grism pair-fraction(z) — sample selection:

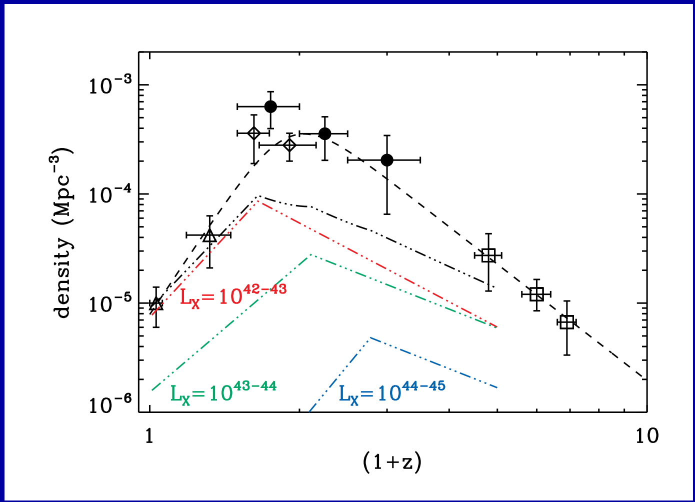
- HUDF broad-band point source completeness at $i_{AB} \lesssim$30.0 mag.
- HUDF ACS grism point source completeness at $i_{AB} \lesssim$27.0 mag.

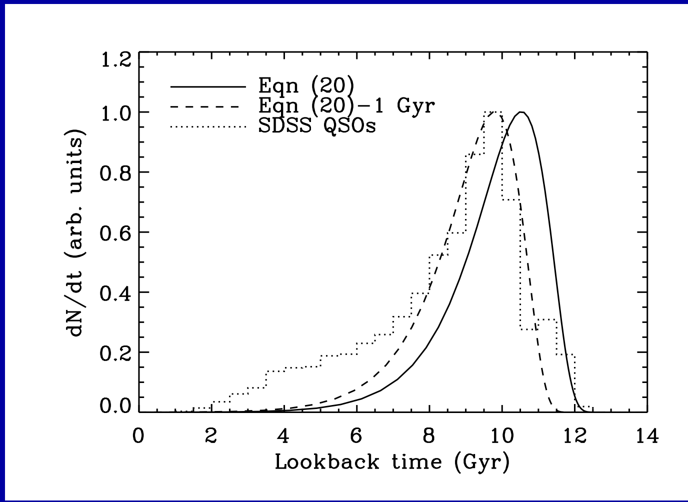
Mass completeness limit for z$\lesssim$2 from flux limits/SED fitting:

- M$\gtrsim$$10^{10.0}$ $M_\odot$ for primary galaxy mass in pair.
- M$\gtrsim$$10^{9.4}$ $M_\odot$ for secondary galaxy mass in pair (0.25$\leq$$M_2/M_1$$\leq$1).

(2) Epoch dependent major merger rate to AB$\lesssim$27–29, X-ray n(z)







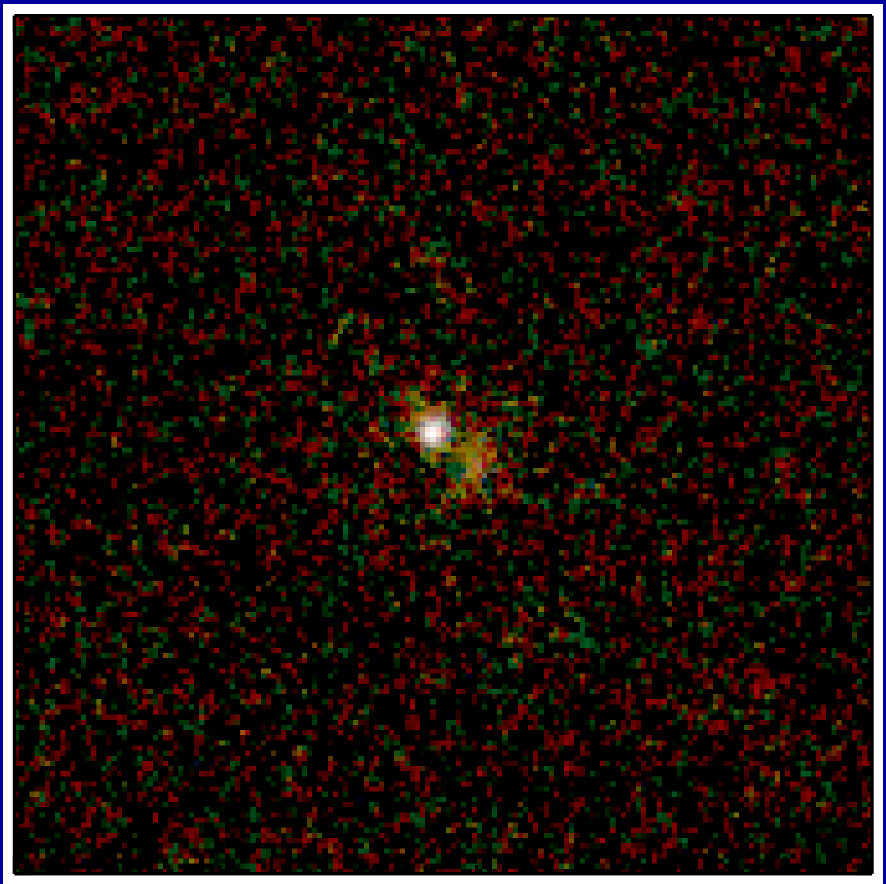
Ryan et al. (2007, 2008): HST/ACS grism epoch-dependent galaxy pairs fraction for AB$\lesssim$27 mag, z$\lesssim$6: spectro-photo-z's for both objects in pair.

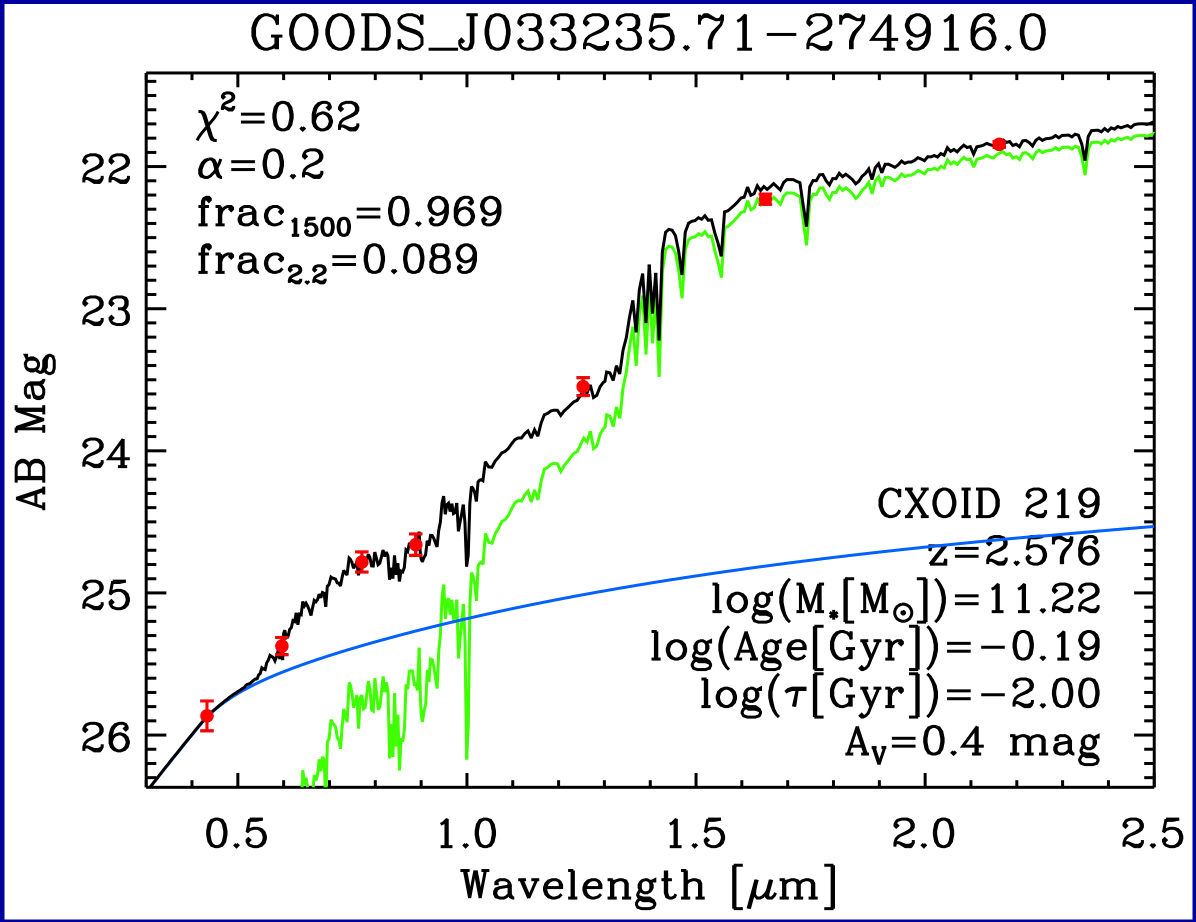
Galaxy major ($0.25 \leq M_2/M_1 \leq 1$) merger density compared to Chandra SDSS QSO density vs. epoch: similar curves except for $\sim$1 Gyr offset?

$\Rightarrow$ Qualitatively supports the hydro models: there may be a $\sim$1 Gyr delay between major mergers and visible SMBH feeding — AGN.

The *panchromatic* SFC filters will map entire epoch dependent merger & AGN-growth history, and the AGN–merger time delay $\Delta t(M, M_2/M_1, L)$ for 10^6 galaxy pairs at $AB_1 \lesssim 29$ mag, z$\lesssim$7.

(3) Ages of Radio and X-ray hosting galaxies vs. epoch





Cohen et al. (2008):

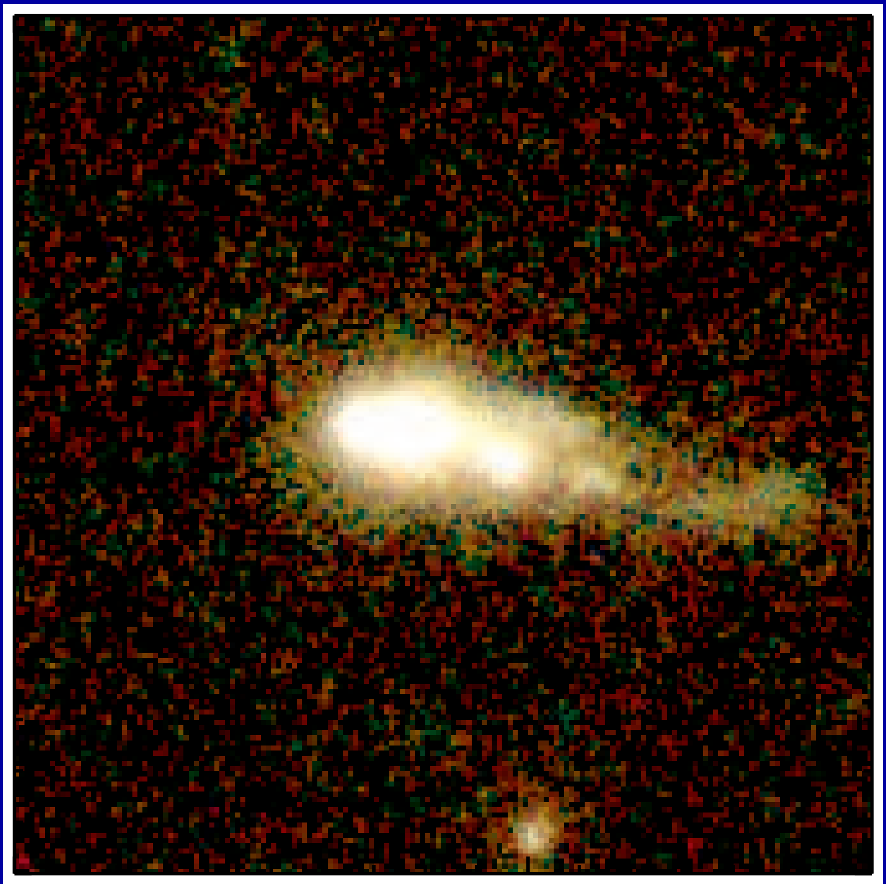
GOODS/VLT BVizJHK images + VLT redshifts

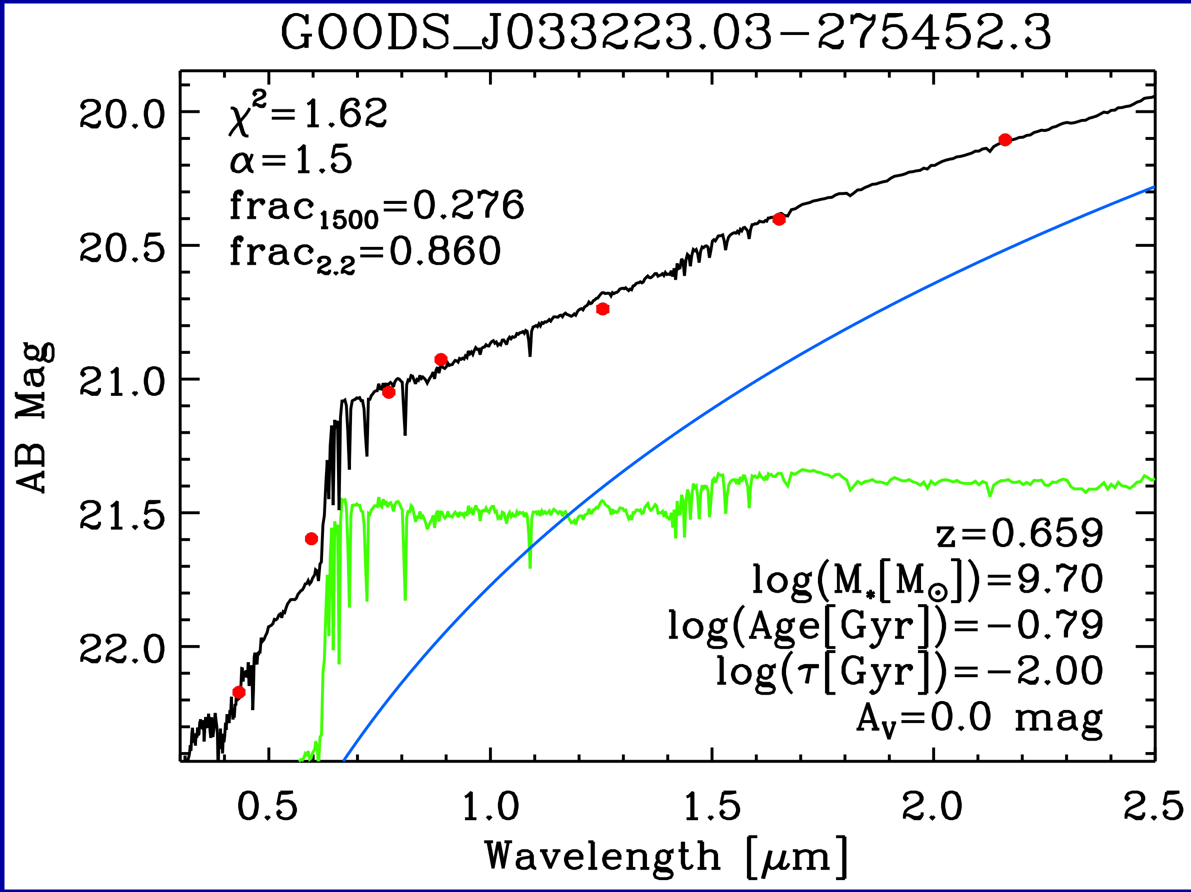
+ Best fit Bruzual-Charlot (2003) stellar SED

+ power law AGN.

A significant blue power-law needs to be added.

(3) Ages of Radio and X-ray hosting galaxies vs. epoch





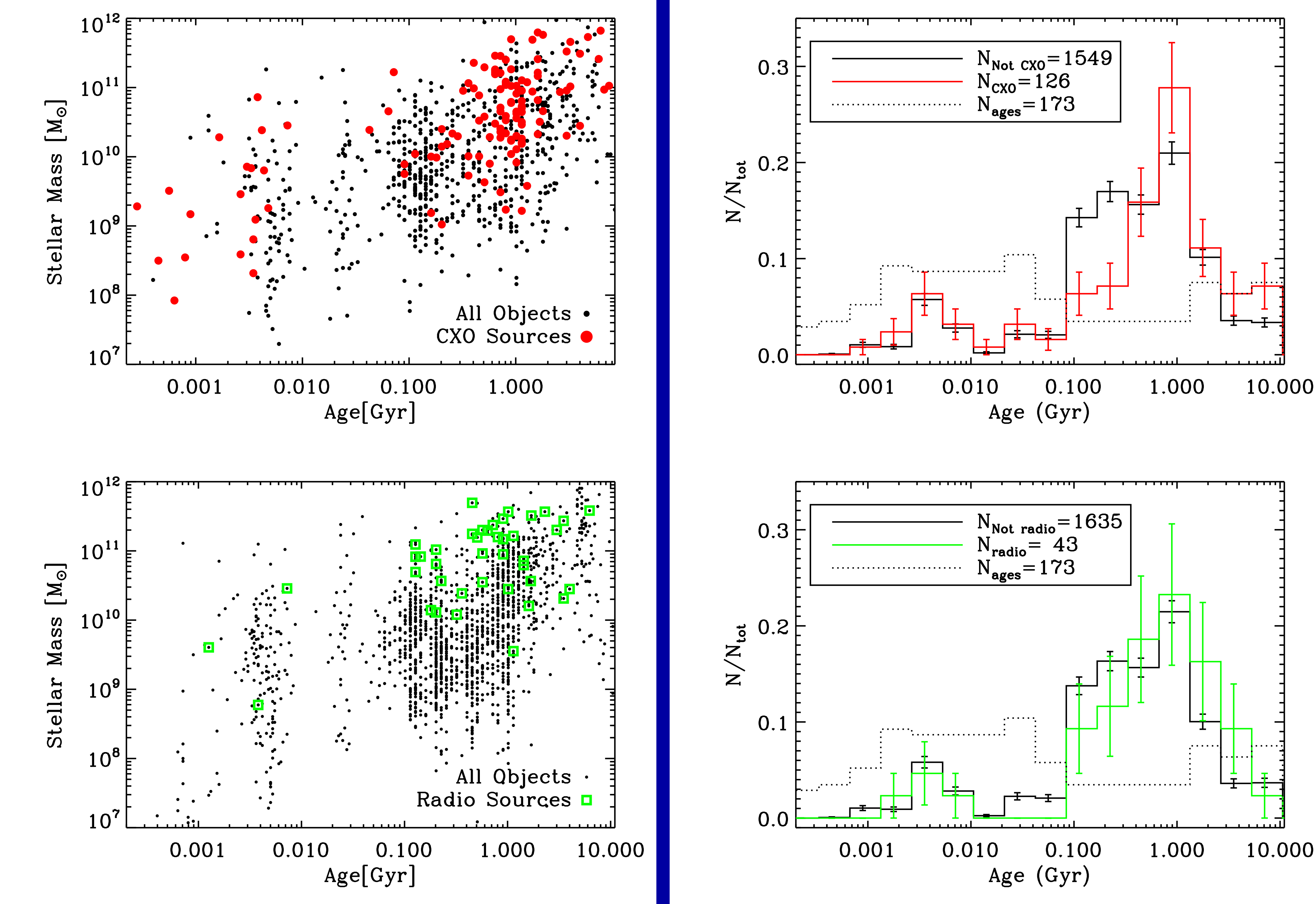
Cohen et al. (2008):

GOODS/VLT BVizJHK images + VLT redshifts

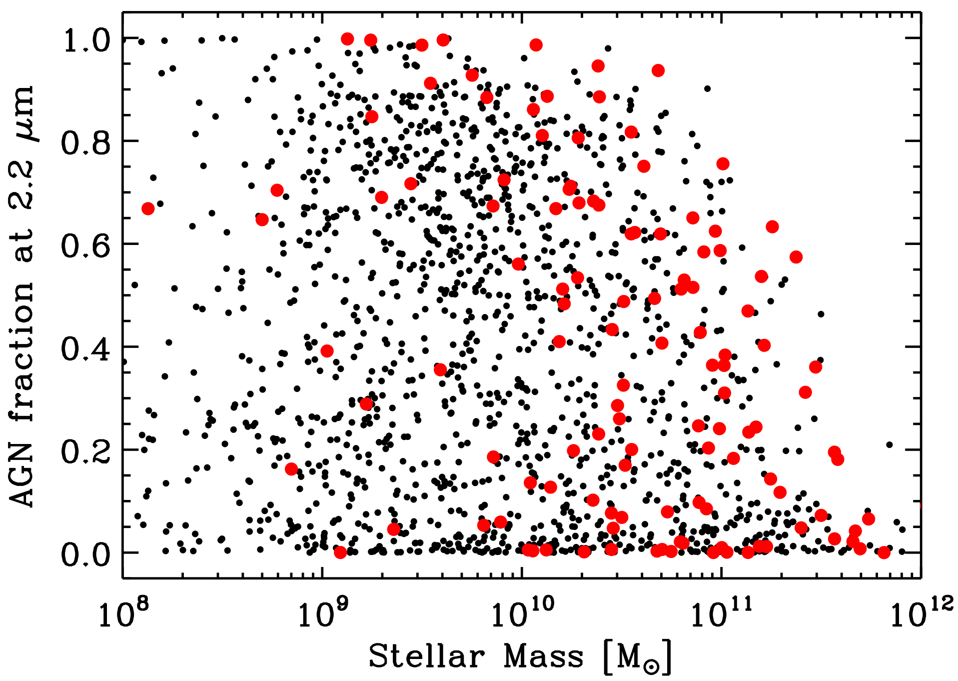
+ Best fit Bruzual-Charlot (2003) stellar SED

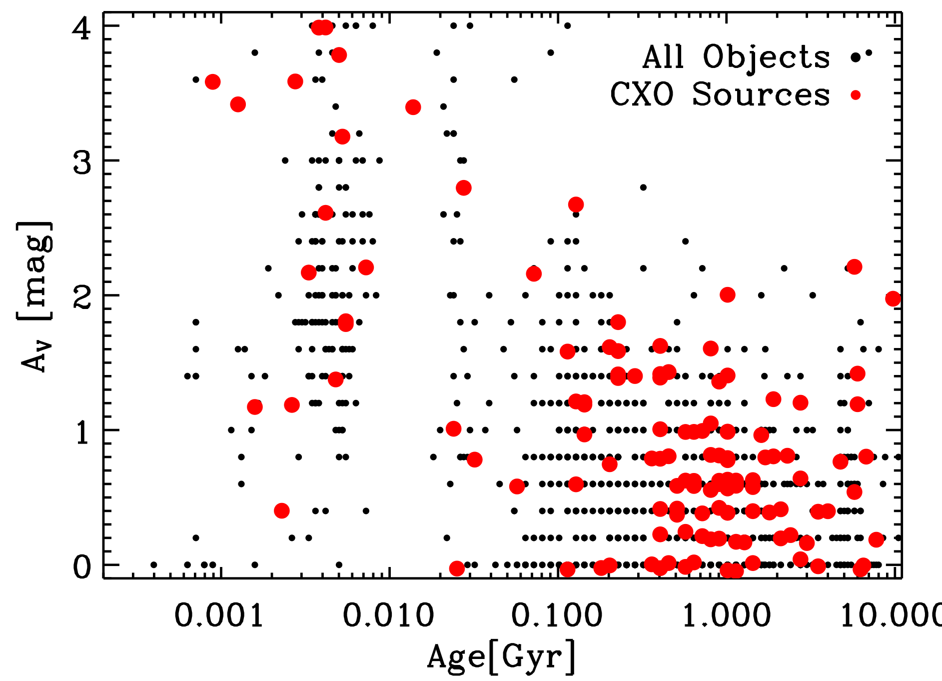
+ power law AGN.

A significant red power-law needs to be added.



• X-ray and Radio galaxies are a bit older than the general field population at the same redshift, but by no more than $\lesssim$0.5–1 Gyr on average.





Cohen et al. (2008): Best fit 2μm AGN-fraction & A_V vs. Stellar Mass for X-ray hosting and field gxys.

- In hydrodynamical models (Hopkins et al. 2006), dust and gas are expelled *after* the starburst peaks and *before* before the AGN becomes visible.

- Older galaxies appear to have less dust. But age-Fe/H relation.

- SFC will map weak AGN-fraction of $\lesssim 10^6$ objects inside $\gtrsim 10^7$ faint galaxies at AB$\lesssim$31 mag, z$\lesssim$7.

(6) Summary of Future Science Capabilities

What questions will JWST be able to address after 2013?

(1) Find First Light sources — Pop III dominated objects — at $z \gtrsim 8$–10, and how they started H-reionization.

(2) Map the faint-end of the dwarf galaxy LF from $z \simeq 12$ to $z \lesssim 6$ and its faint-end slope evolution.

(3) How did Pop III objects seed the first Pop-II dominated objects: dwarf galaxies? How did their UV output finish H-reionization at $z \simeq 6$–7?

(4) The onset of AGN during galaxy assembly at $z \gtrsim 6$, and the origin of the Hubble sequence since $z \simeq 1$–2.

JWST will have a major impact on astrophysics after 2013:

- Current generation of graduate students and postdocs will be using JWST during their professional career.
- JWST will define the next frontier to explore: the Dark Ages at $z \gtrsim 20$.

What questions will HST/WFC3 be able to address after May 2009?

(1) How much earlier did the epoch-dependent major merger density peak, compared to the peak X-ray or radio selected AGN ρ(z)?

(2) How much older are Radio and X-ray selected galaxies (0.5–1 Gyr?) than the typical faint field galaxy age at the same z (0.1–0.3 Gyr)?

(3) How does AGN growth stay in pace with gxy assembly & bulge growth? How did the M_{SMBH} vs. M_{bulge} mass relation come into place?

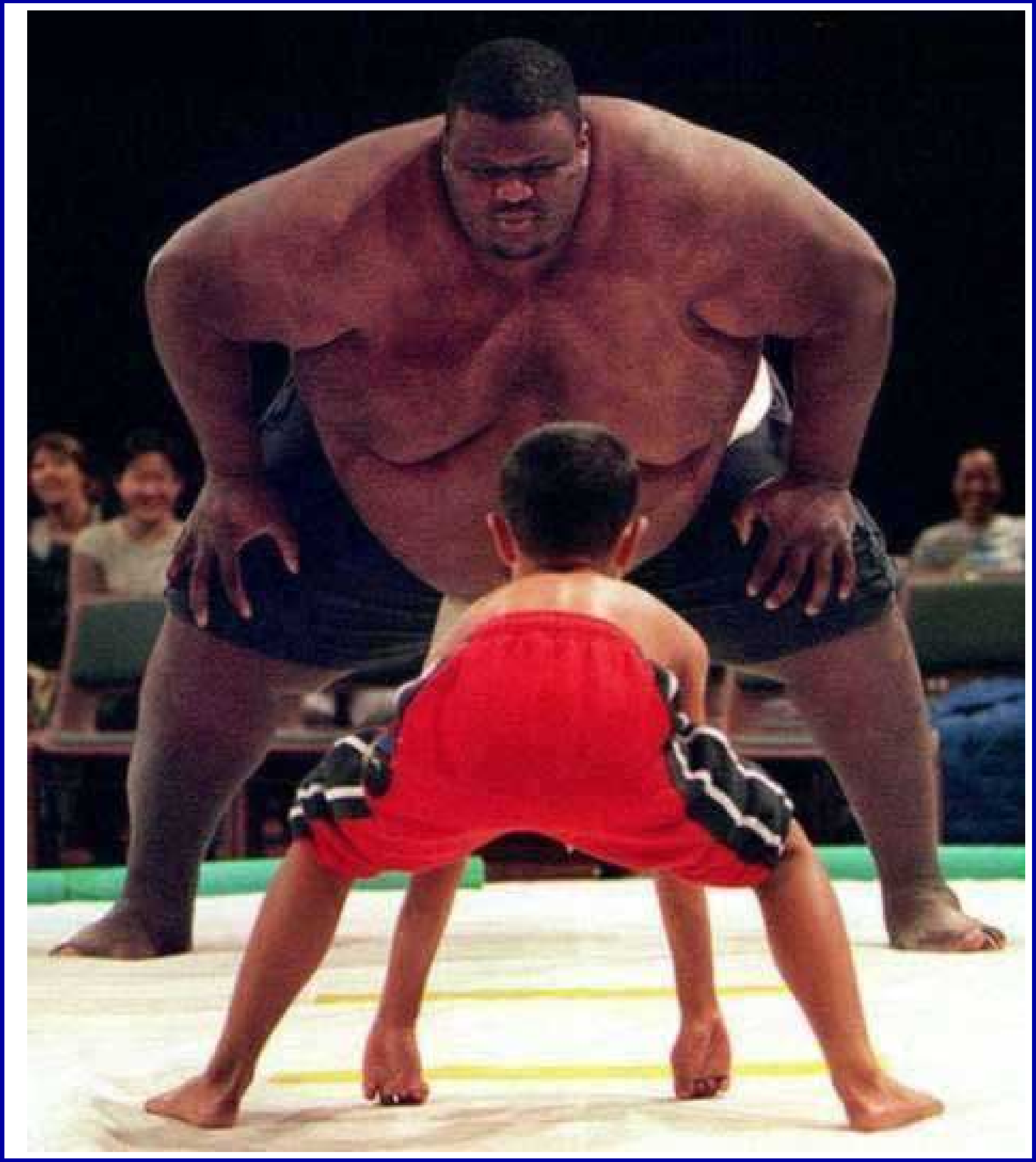
What questions can a 4 meter THEIA/SFC address after 2015?

(1) Provide unprecedented panchromatic (λ0.2–1.1μm), wide (0.1 deg^2), deep (AB$\lesssim$32 mag) imaging & accurate spz's ($\lesssim$2%) for z$\lesssim$7.

(2) SFC's proper sampling and stable PSF's will study & subtract weak AGN variability, and the spatial distribution of physical SED parameters.

- Map the entire epoch dependent merger & AGN-growth history, from $\lesssim 10^6$ weak AGN in 10^7 faint galaxies to AB$\lesssim$31, z$\lesssim$7.
- Measure the environmental impact on faint-end LF-slope α(z) directly, and constrain feedback(z) — from Type II, Pop I/Type Ia SN, & AGN.
- Measure Ly-cont escape fraction for each pop from 10^6 objects.

SPARE CHARTS



At the end of H-reionization, dwarfs had beaten the Giants by $z \simeq 6$, but ...

"You've done it now, David - Here comes his mother."

What comes around, goes around ... He-reionization by AGN at $z \simeq 3$?

- References and other sources of material shown:

http://www.asu.edu/clas/hst/www/jwst/ [Talk, Movie, Java-tool]

http://wwwgrapes.dyndns.org/udf_map/index.html [Clickable HUDF map]

http://www.jwst.nasa.gov/ and http://www.stsci.edu/jwst/

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/guider/

Gardner, J. P., Mather, J. C., Clampin, M., Doyon, R., Greenhouse, M. A., Hammel, H. B., Hutchings, J. B., Jakobsen, P., Lilly,S. J., Long, K. S., Lunine, J. I., McCaughrean, M. J., Mountain, M., Nella, J., Rieke, G. H., Rieke, M. J., Rix, H.-W., Smith, E. P., Sonneborn, G., Stiavelli, M., Stockman, H. S., Windhorst, R. A., & Wright, G. S. 2006, Space Science Reviews, 123, 485–606 (astro-ph/0606175)

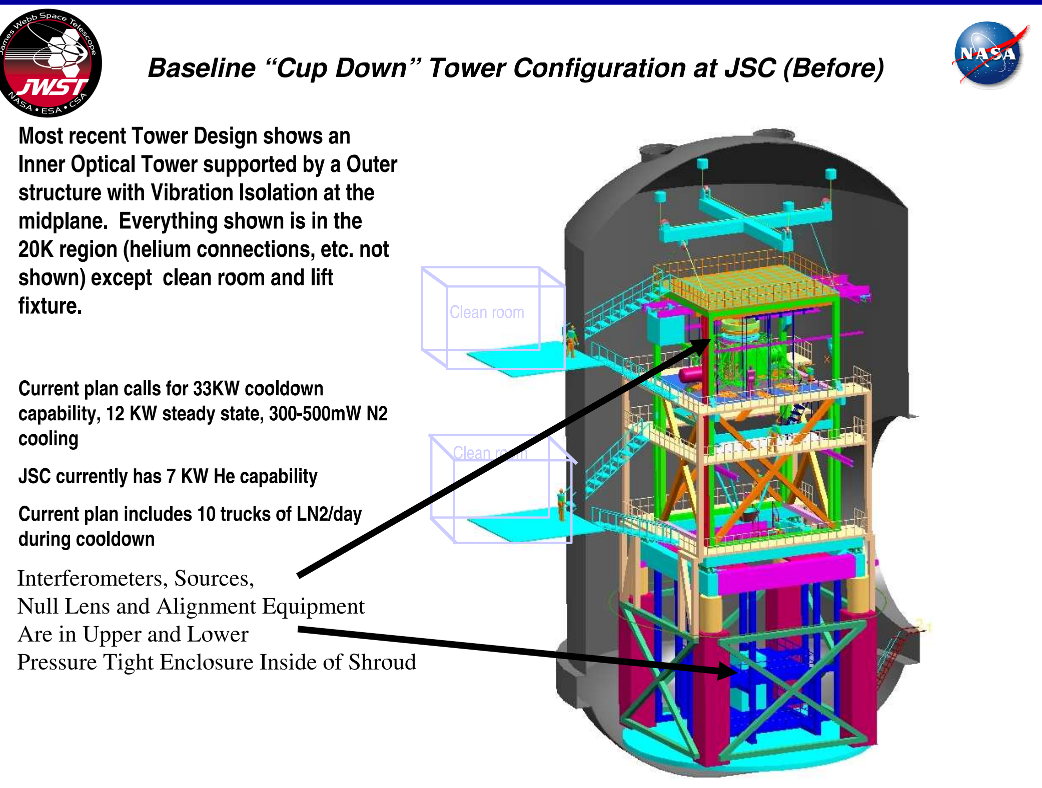
Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

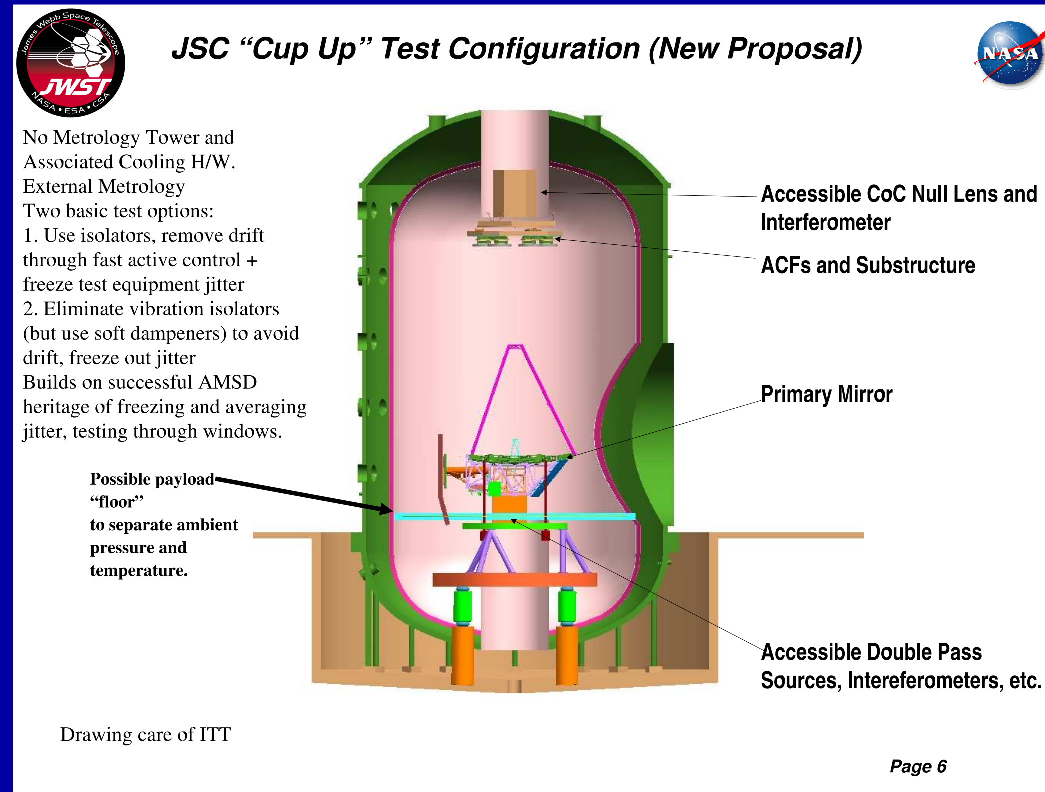
Windhorst, R. A., et al. 2007, Advances in Space Research, Vol. 42, p. 1–10, in press (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"

Northrop Grumman Expertise in Space Deployable Systems

- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements



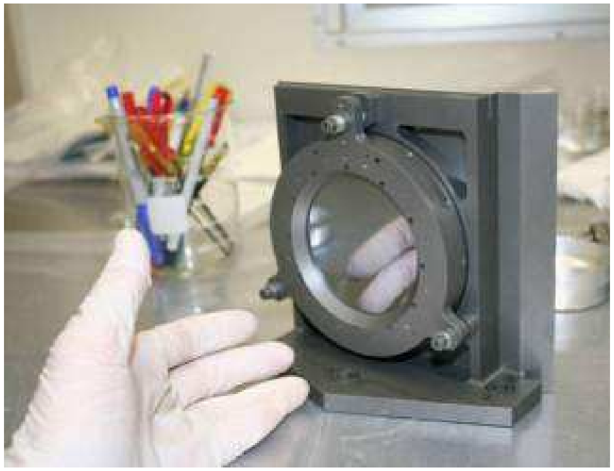




JWST underwent several significant replans and risk-reduction schemes:

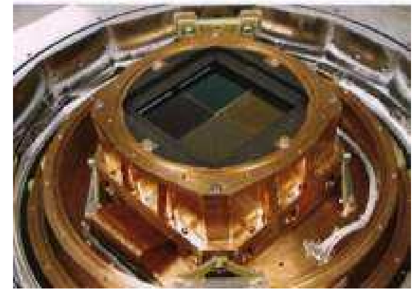
- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6), $i.e.$, demonstration in a relevant environment — ground or space.
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes system wide Mission PDR and Non-Advocate Review.

Instrument Qual and ETU Model Hardware

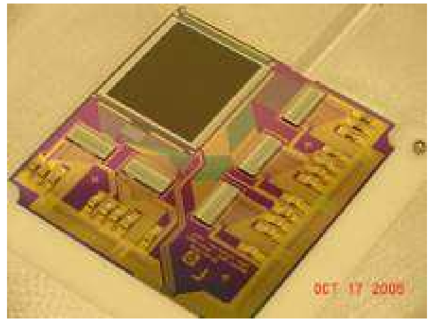


NIRCam Dichroic Beamsplitter

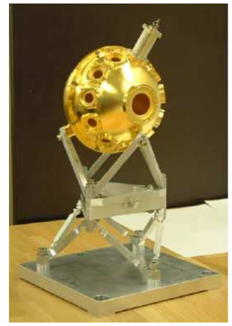
NIRCam Pupil Imaging Lens Set



NIRCam Detectors



NIRSpec Microshutter



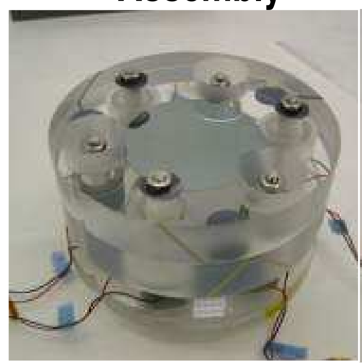
NIRSpec Calibration Assembly

NIRSpec Mirror

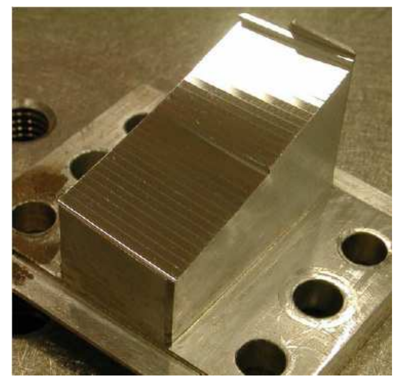
SiAs MIR Detector

MIRI Electronics

NIRSpec Fore Optics Mirror Assembly



FGS/TF Etalon Filter



NIRSpec Image Slicer Mirror

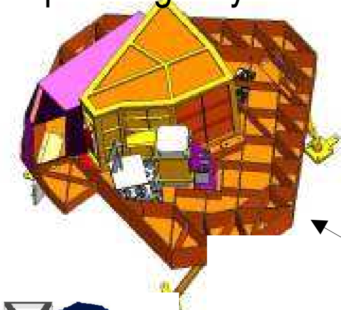
JWST flight hardware is being constructed in 2007–2008

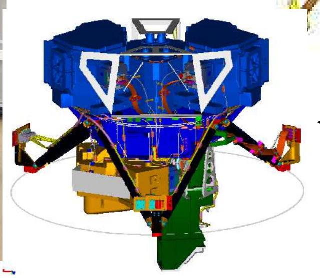
(1) What instruments will JWST have? US (UofA, JPL), ESA, and CSA.

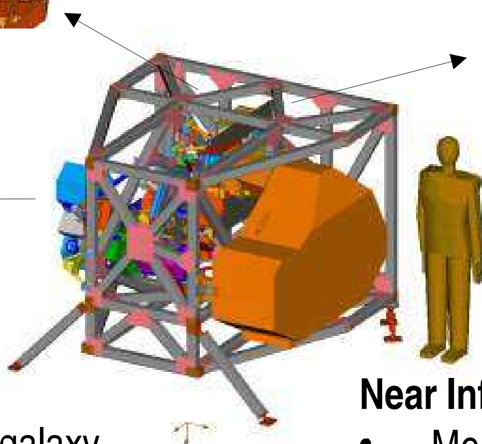
Instrument Overview

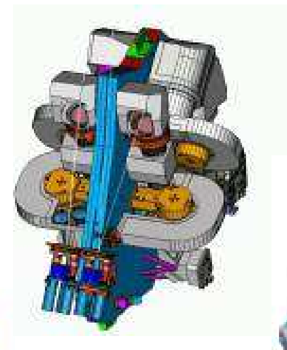
Fine Guidance Sensor (FGS)
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

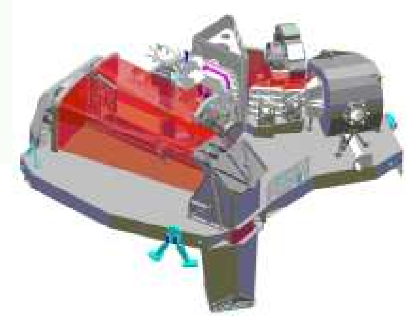
Near Infra-Red Camera (NIRCam)
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC







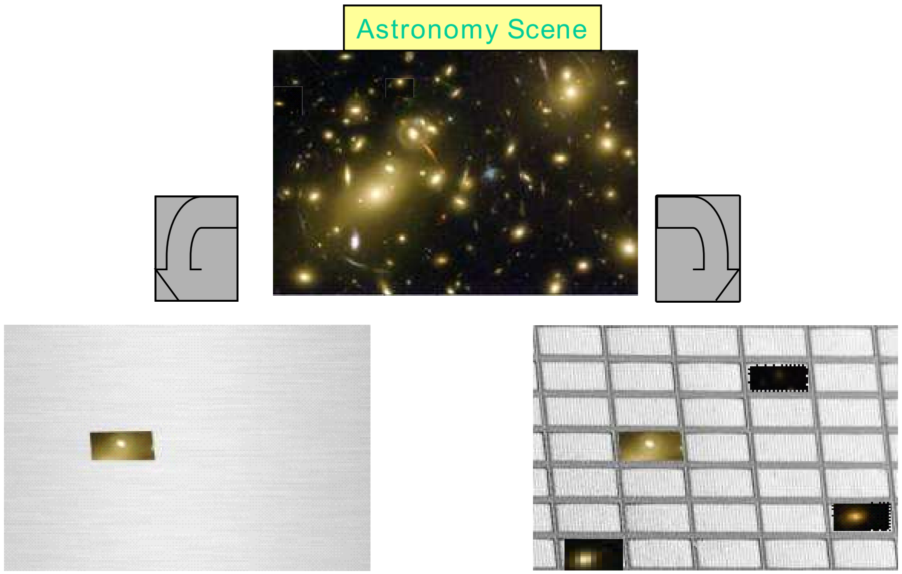




Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

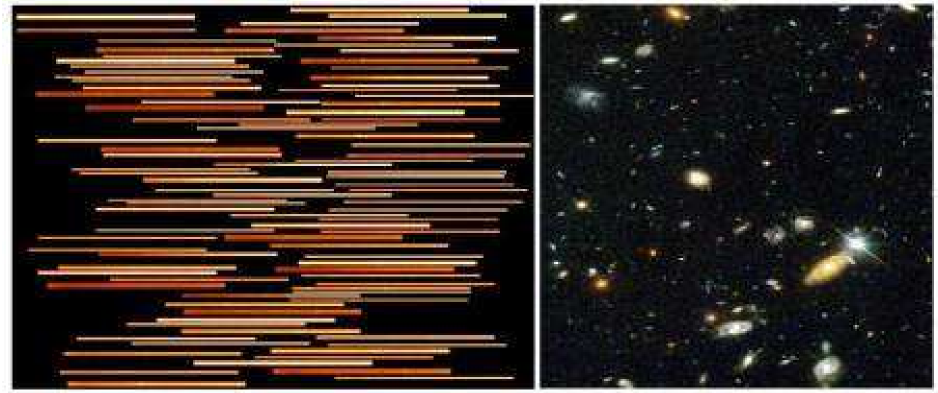
Near Infra-Red Spectrograph (NIRSpec)
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

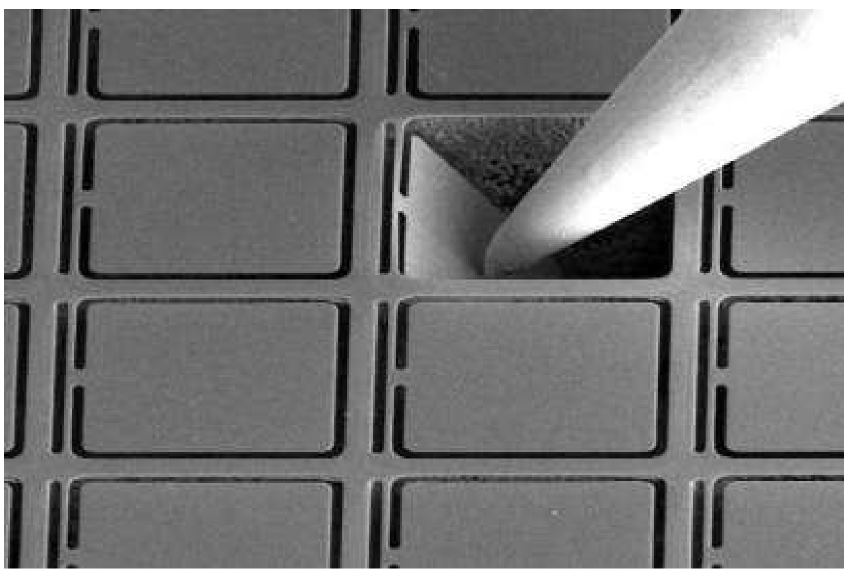
Micro Shutters



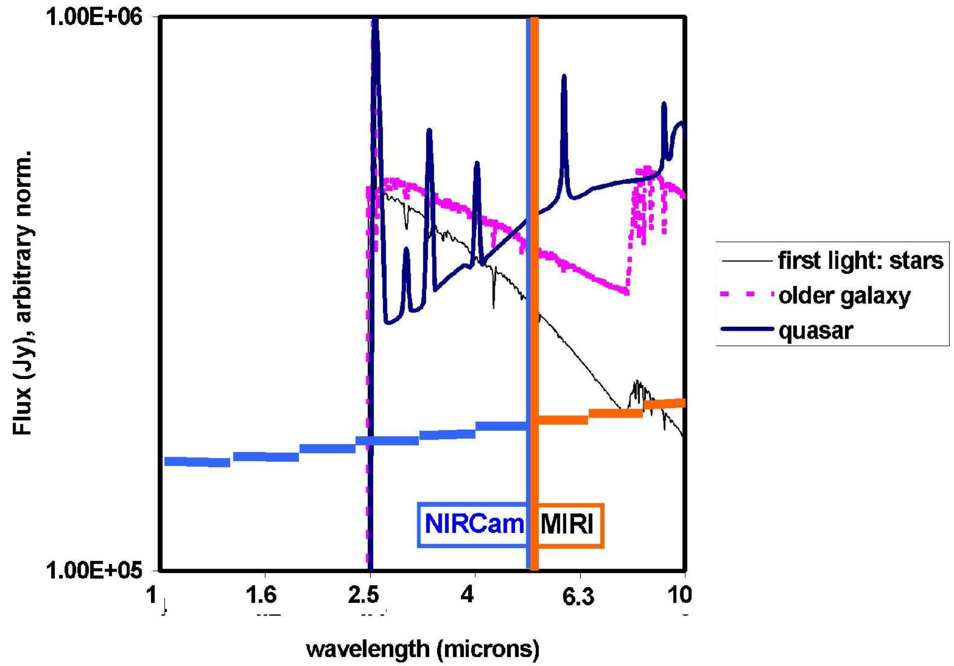
Metal Mask/Fixed Slit

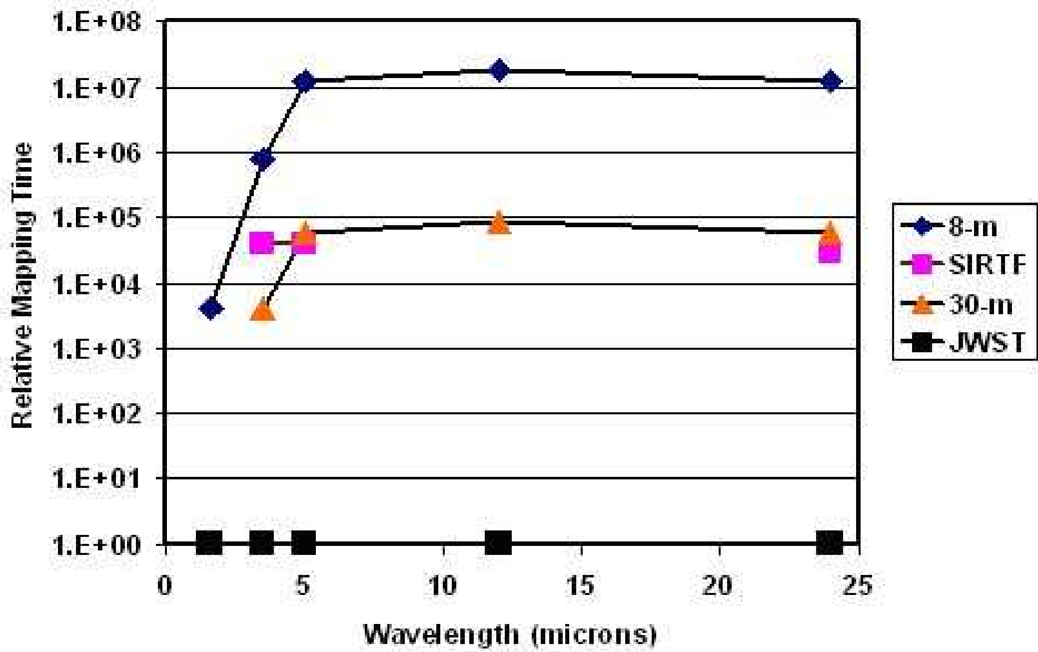
Shutter Mask





(1) What sensitivity will JWST have?





The NIRCam and MIRI sensitivity complement each other, straddling 5 μm in wavelength, and together allow objects to be found to redshifts z=15–20 in $\sim 10^5$ sec (28 hrs) integration times.

LEFT: NIRCam and MIRI broadband sensitivity to a Quasar, a "First Light" galaxy dominated by massive stars, and a 50 Myr "old" galaxy at z=20.

RIGHT: Relative survey time vs. λ that Spitzer, a ground-based IR-optimized 8-m (Gemini) and 30-m telescope would need to match JWST.

(1) How JWST can measure Galaxy Assembly

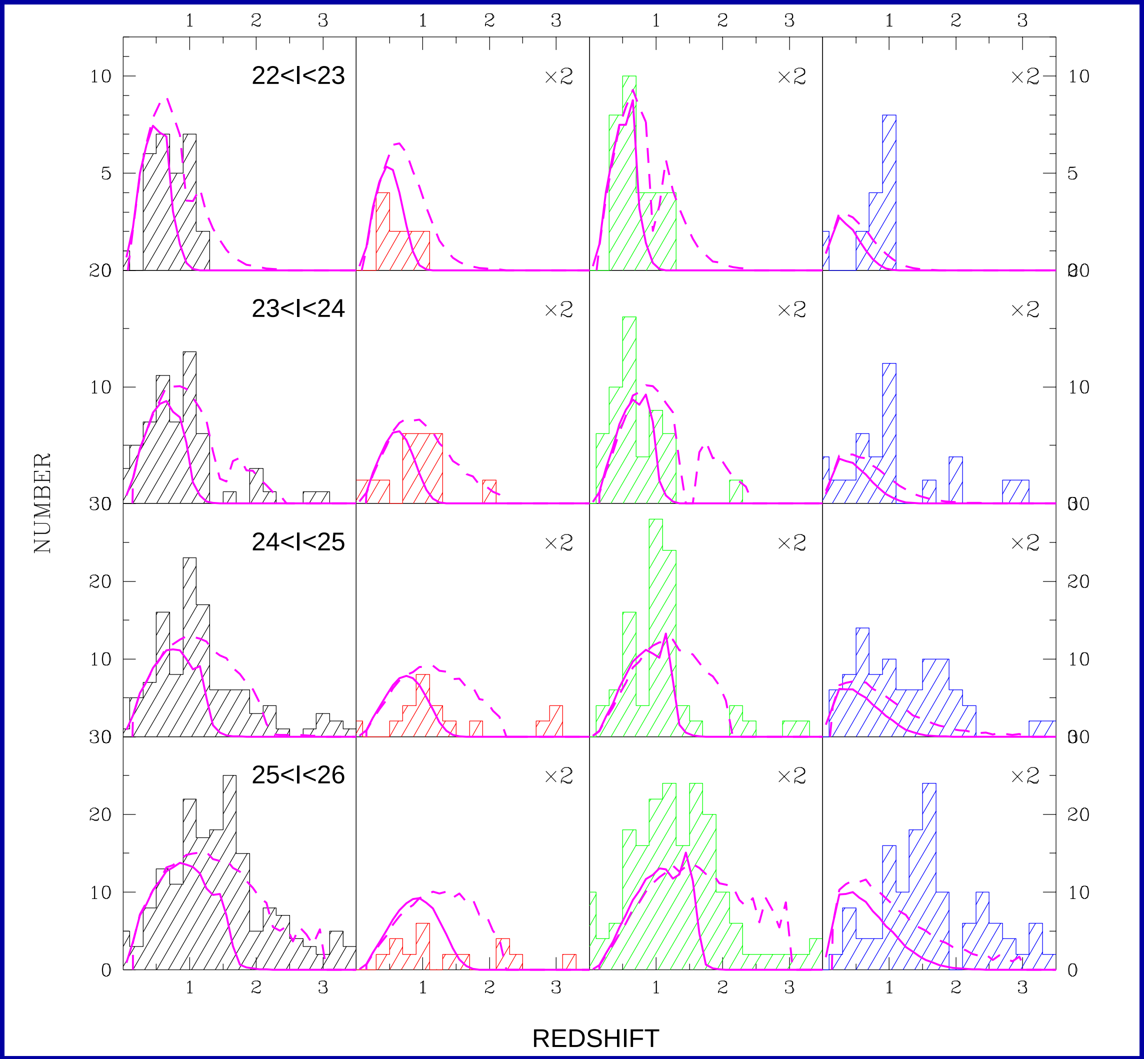
- Galaxies of all Hubble types formed over a wide range of cosmic time, but with a notable phase transition around $z \simeq 0.5$–1.0:

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

(2) Merger products start to settle as galaxies with giant bulges 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.

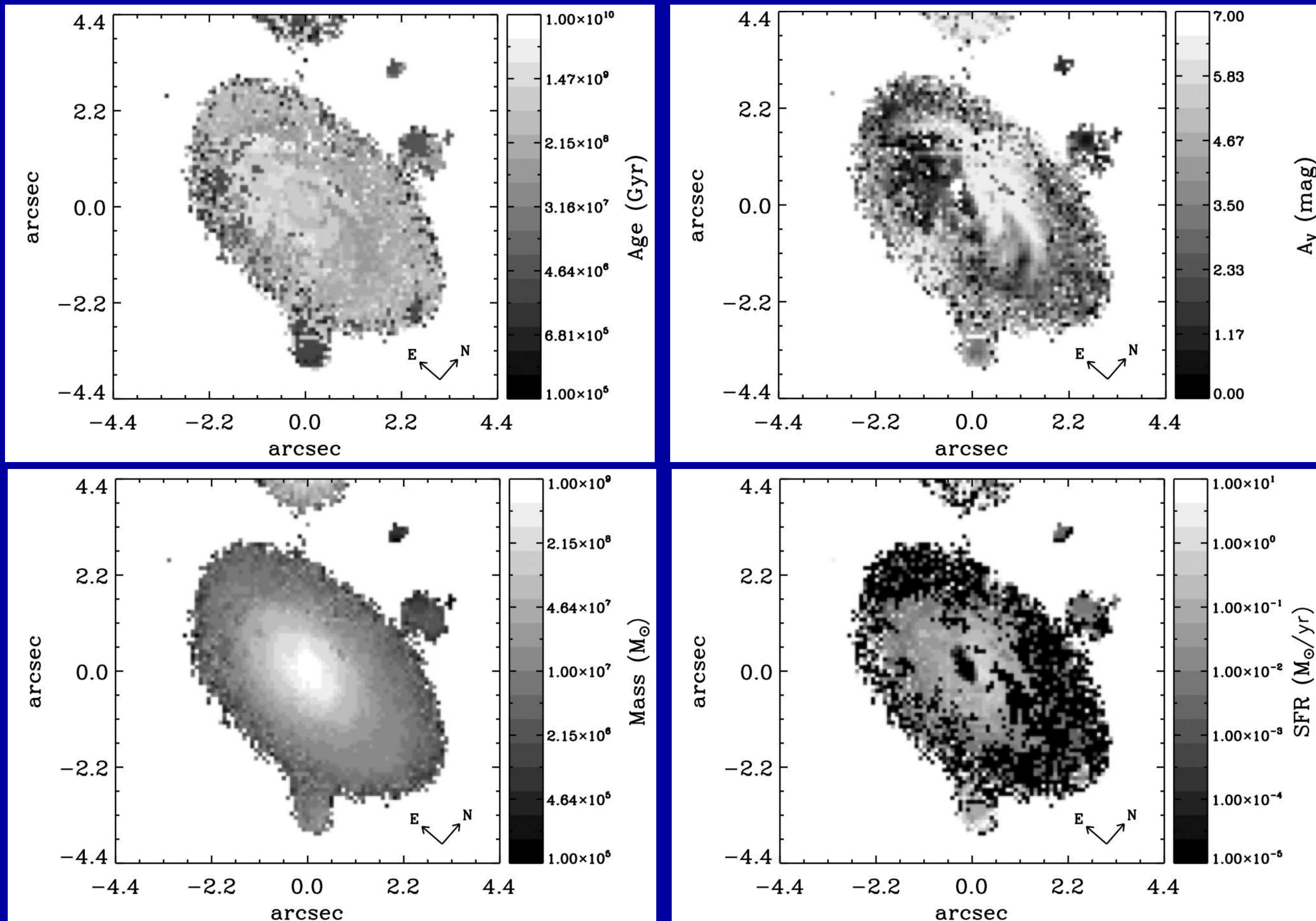
Total Ell/S0 Sabc Irr/Mergers



- 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

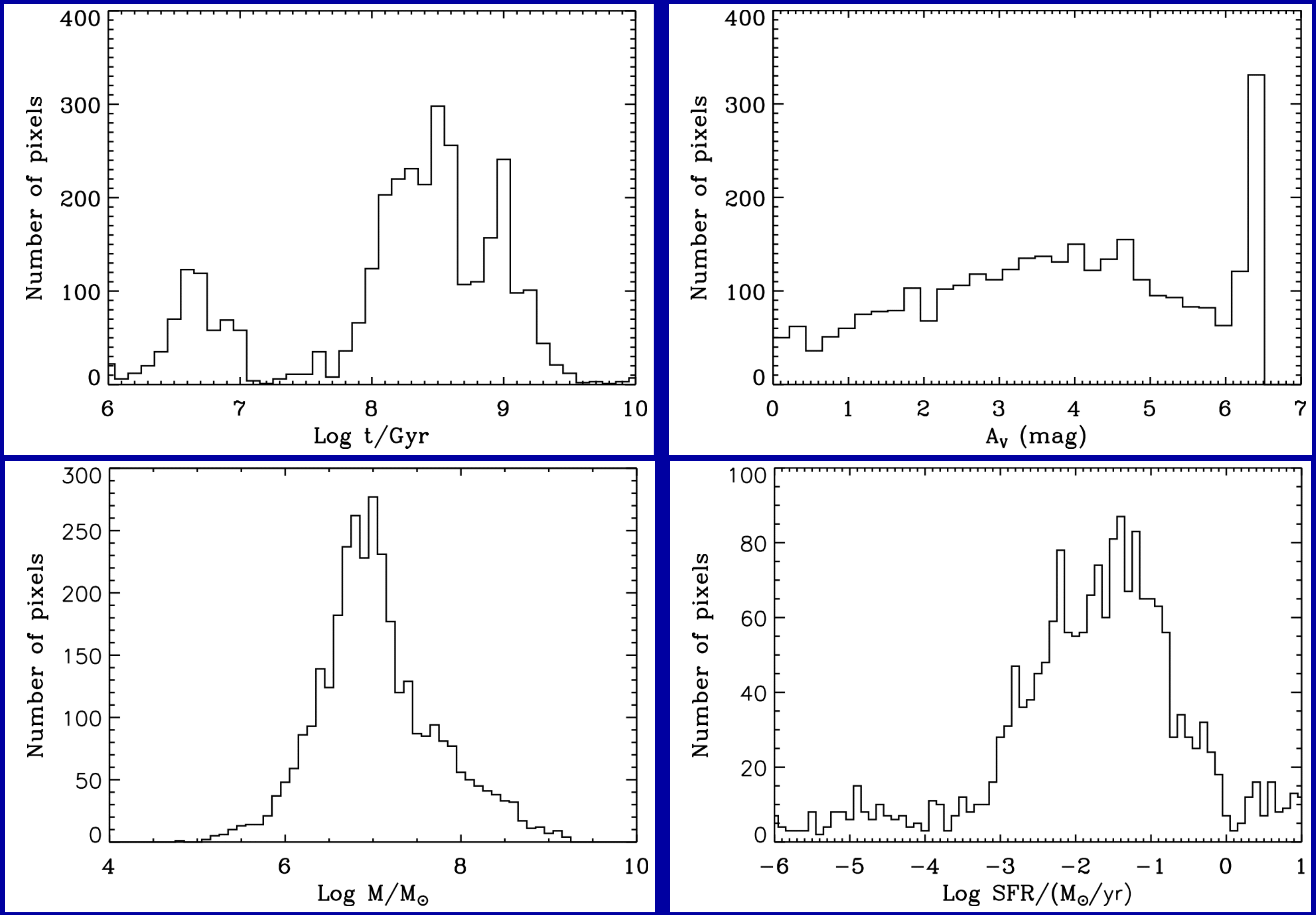
(2) Power of WFC3 UV–near-IR pix-pix SED decomposition



WFC3 UV–near-IR images can rather uniquely decompose galaxies into age-, dust-, mass-, and SFR-distributions ⟶ physical assembly models.

SFC will measure spatial distribution of physical parameters for $\gtrsim 10^6$ gxys.

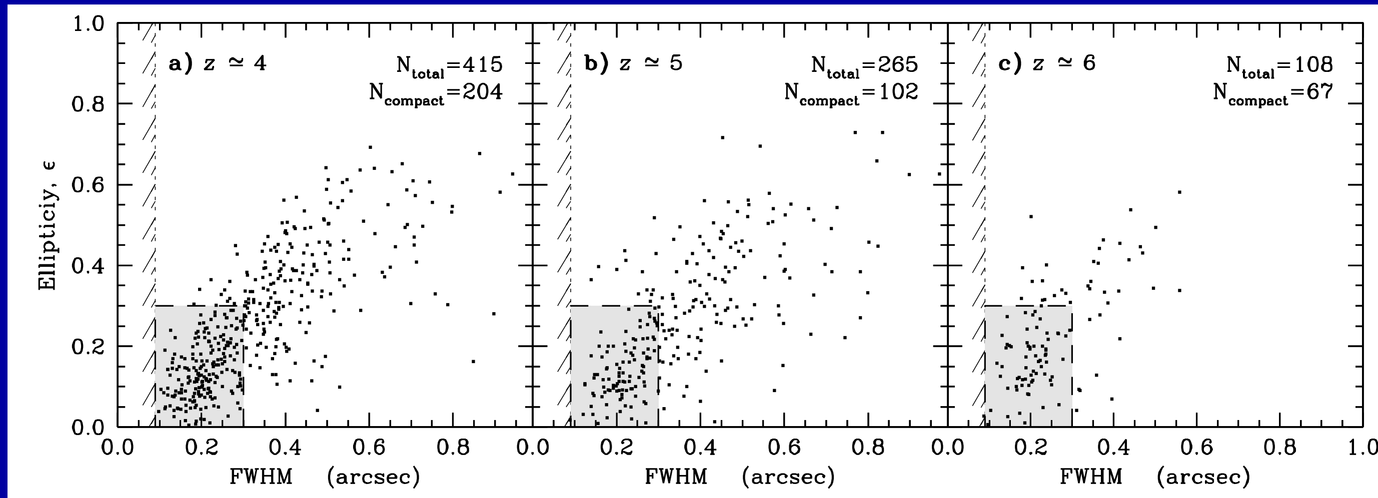
(2) Power of WFC3 UV–near-IR pix-pix SED decomposition

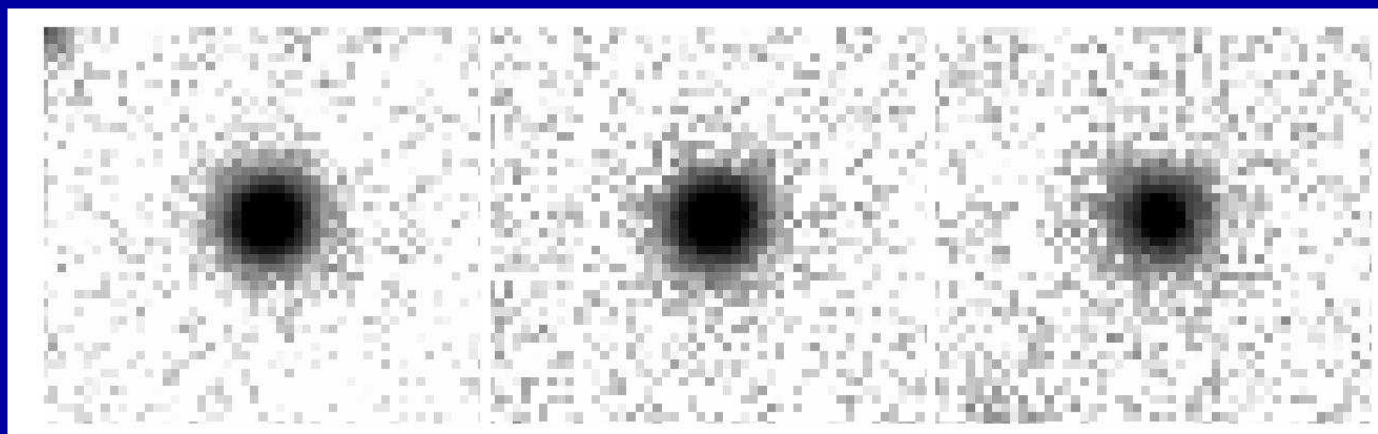


WFC3 UV–near-IR images can rather uniquely decompose galaxies into age-, dust-, mass-, and SFR-distributions ⟶ physical assembly models.

SFC will measure physical parameters of $\gtrsim 10^7$ gxys vs. mass & epoch.

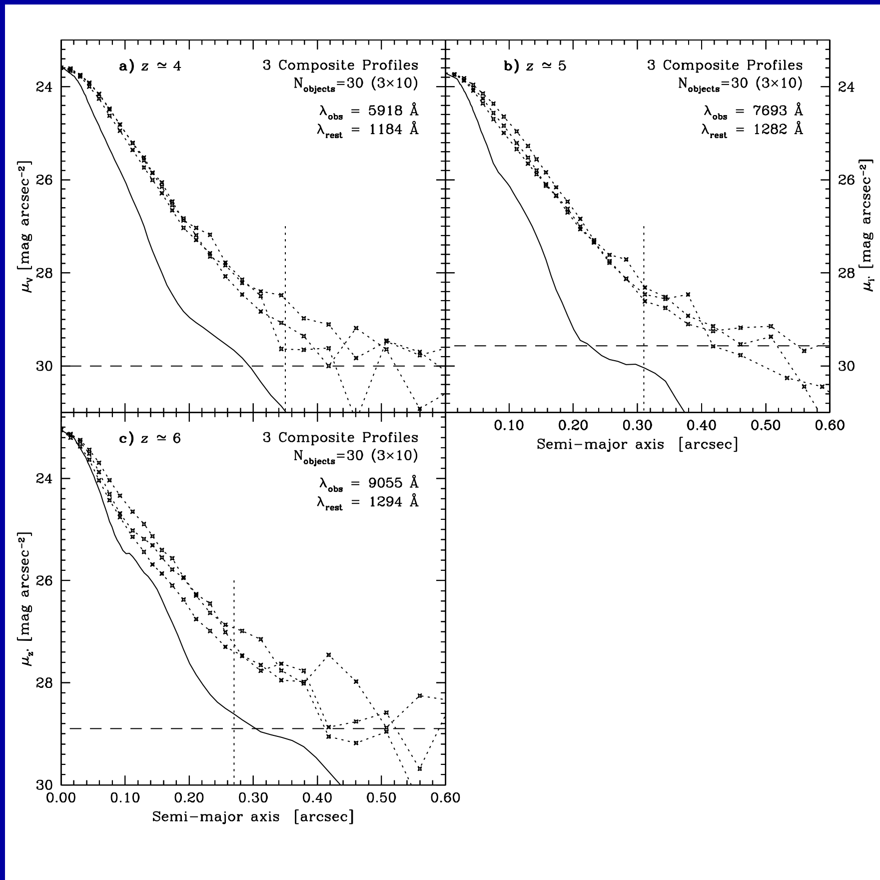
Dynamical ages of Dwarf Galaxies at z≃4–6?

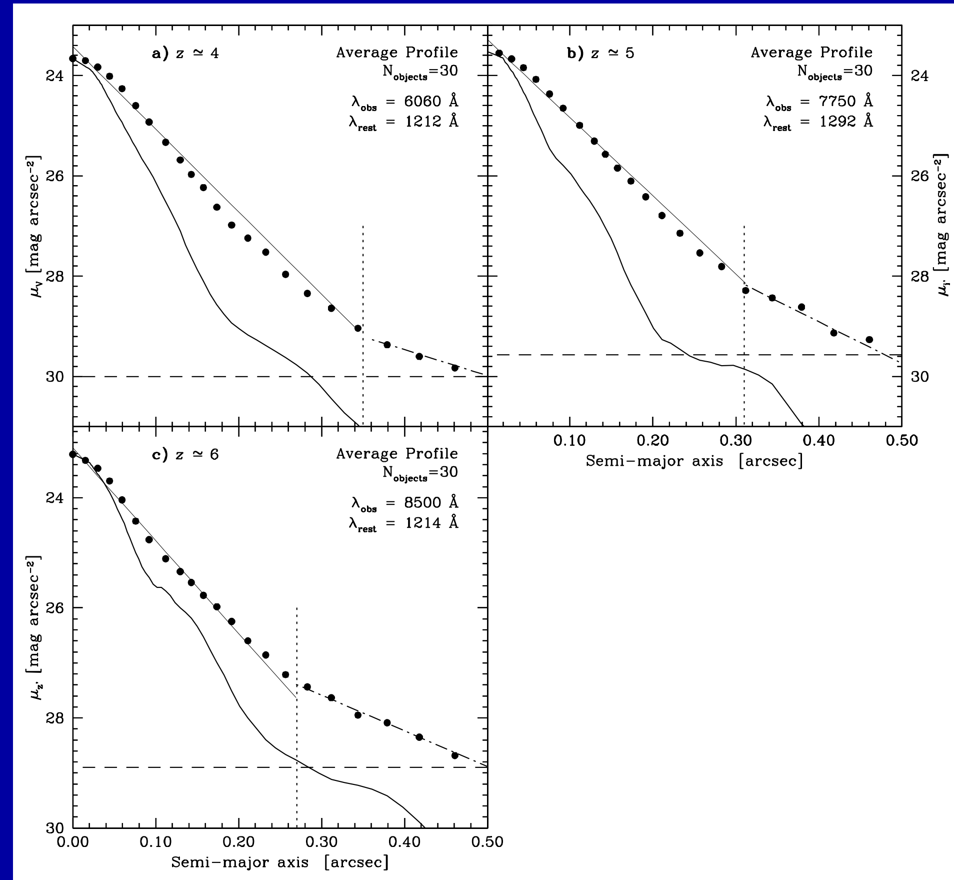




- Select all isolated, nearly unresolved ($2r_e \lesssim 0''.3$), round ($1-b/a \lesssim 0.3$) HUDF B-drops, V-drops, and i-drops. to AB=29.0 mag
- Construct average image stack and light-profiles of these dwarf galaxies at z≃4, z≃5, and z≃6.
- If these compact, round objects are intrinsically comparable, each stack has the S/N of ∼5000 HST orbits (≃300 JWST hrs; Hathi ea. 2008 AJ).

Dynamical ages of Dwarf Galaxies at z≃4–6?





- HUDF sky-subtraction error is 2–3.10^{-3} or AB≃29.0–30.0 mag/arcsec^2

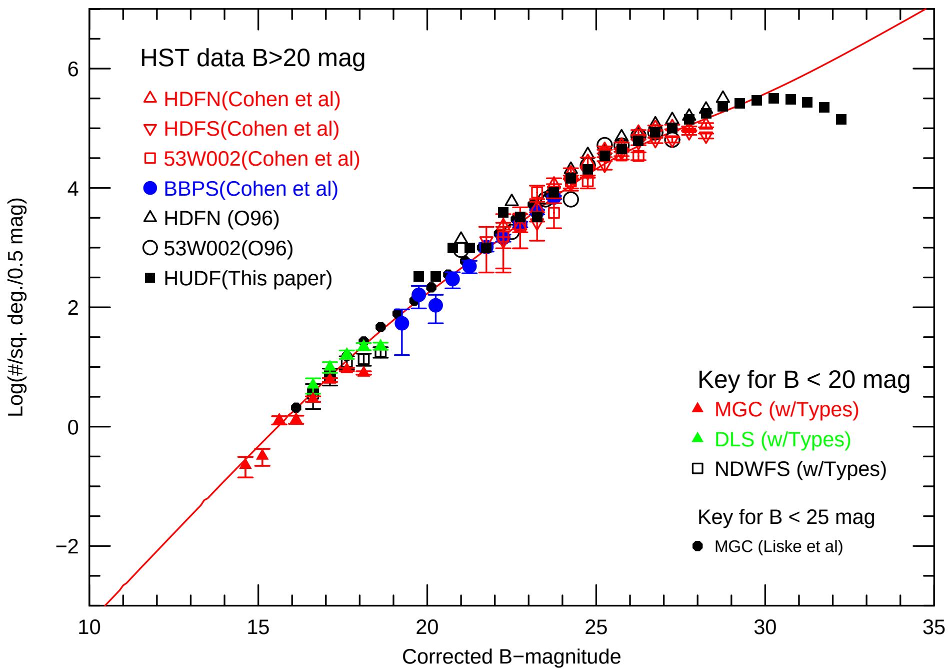
- Average 5000-orbit compact, round dwarf galaxy light-profile at z≃6–4 deviates from best fit Sersic n≃1.0 law (incl. PSF) at r$\gtrsim$0″.27–0″.35.

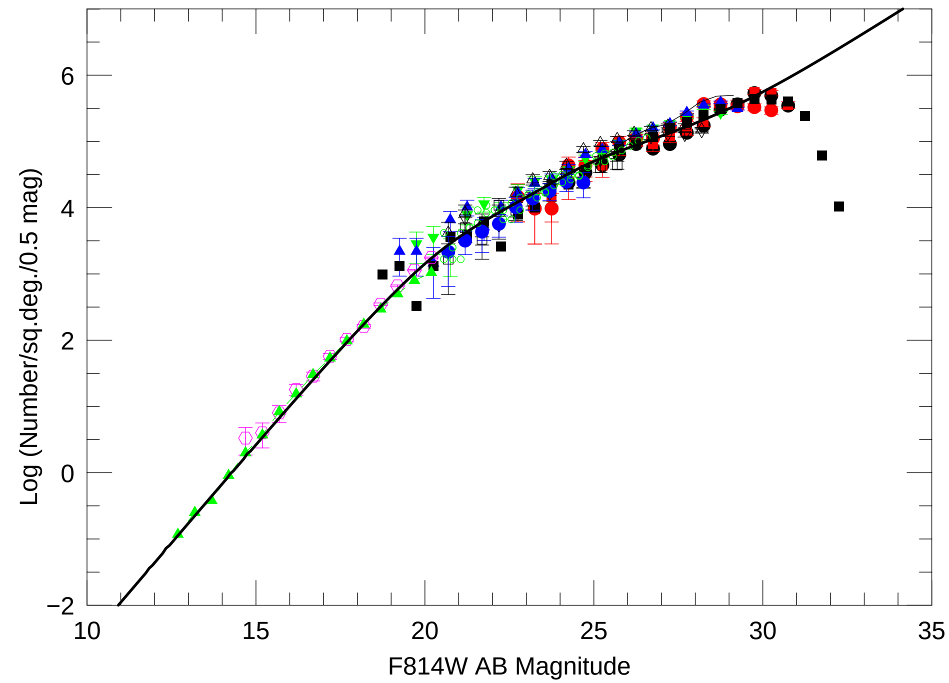
- If interpreted as virial radii in hierarchical growth, these imply dynamical ages of τ_{dyn}≃0.1-0.2 Gyr at z≃6–4 for the enclosed masses.

⇔ Comparable to their SED ages (Hathi et al.2007, AJ; astro-ph/0710.0007).

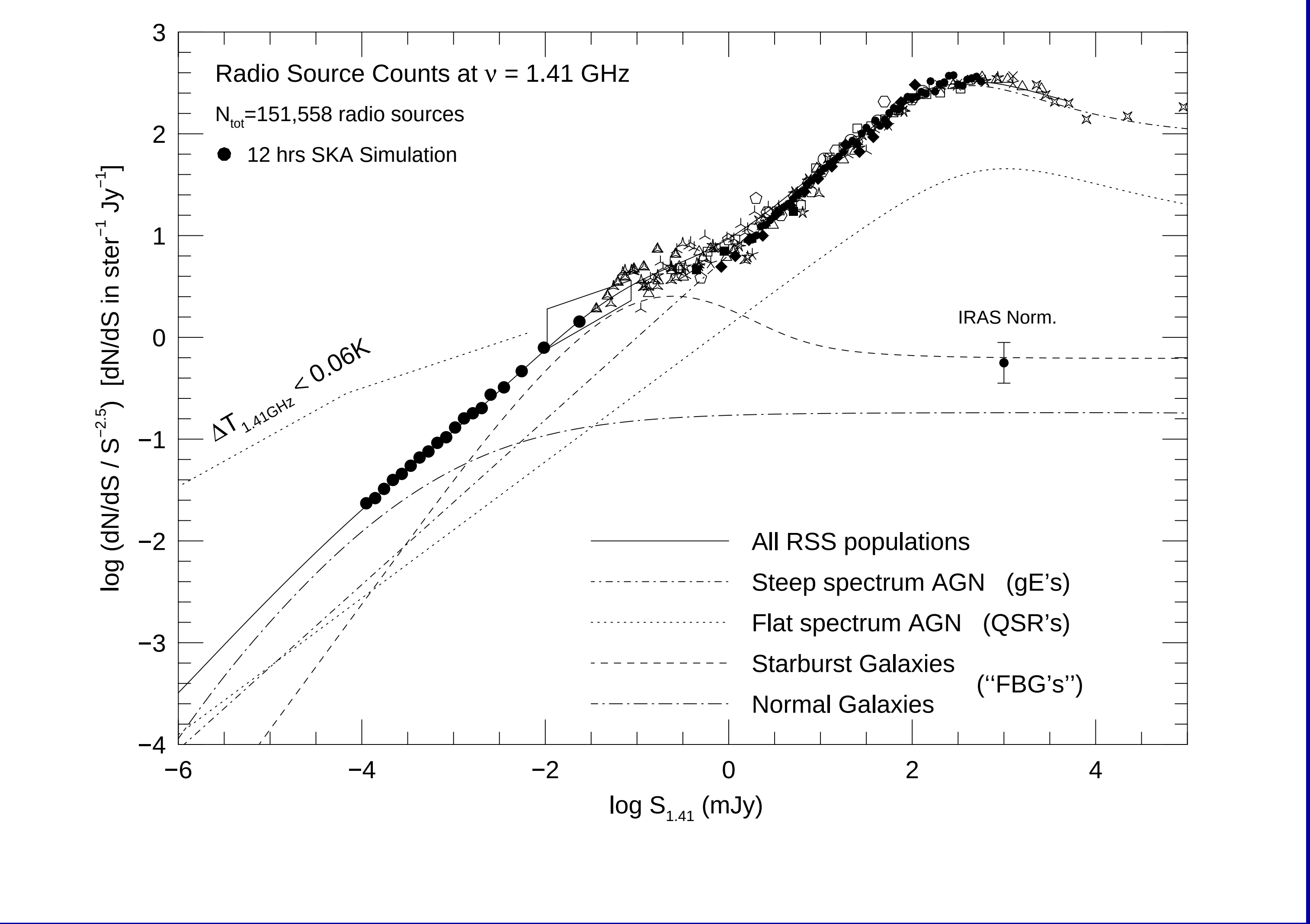
⇒ Global starburst that finished reionization at z≃6 started at z≃6.6?

Appendix 1: will JWST (& SKA) reach the Natural Confusion Limit?





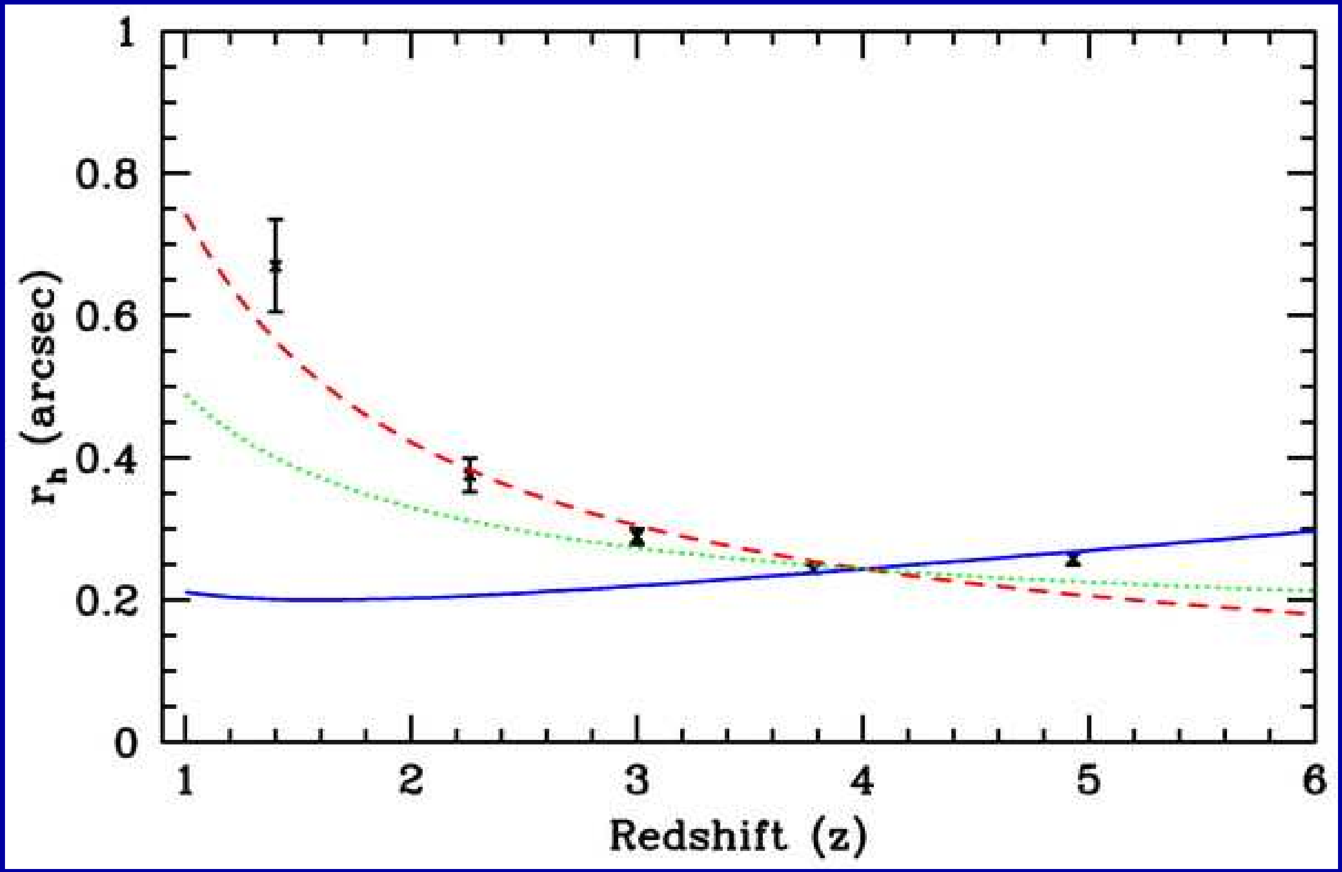
- HUDF galaxy counts (Cohen et al. 2006): expect an integral of $\gtrsim 2\times10^6$ galaxies/deg^2 to AB=31.5 mag ($\simeq$ 1 nJy at optical wavelengths). JWST and SKA will see similar surface densities to $\simeq$1 and 10 nJy, resp.
- $\Rightarrow$ Must carry out JWST and SKA nJy-surveys with sufficient spatial resolution to avoid object confusion (from HST: this means FWHM$\lesssim$0$''$.08).
- $\Rightarrow$ Observe with JWST/NIRSpec/MSA and SKA HI line channels, to disentangle overlapping continuum sources in redshifts space.



1.41 GHz source counts (Windhorst et al. 1993, 2003) from 100 Jy to 10 μJy + 12-hr SKA simulation of Hopkins et al. (2000) to 100 nJy.

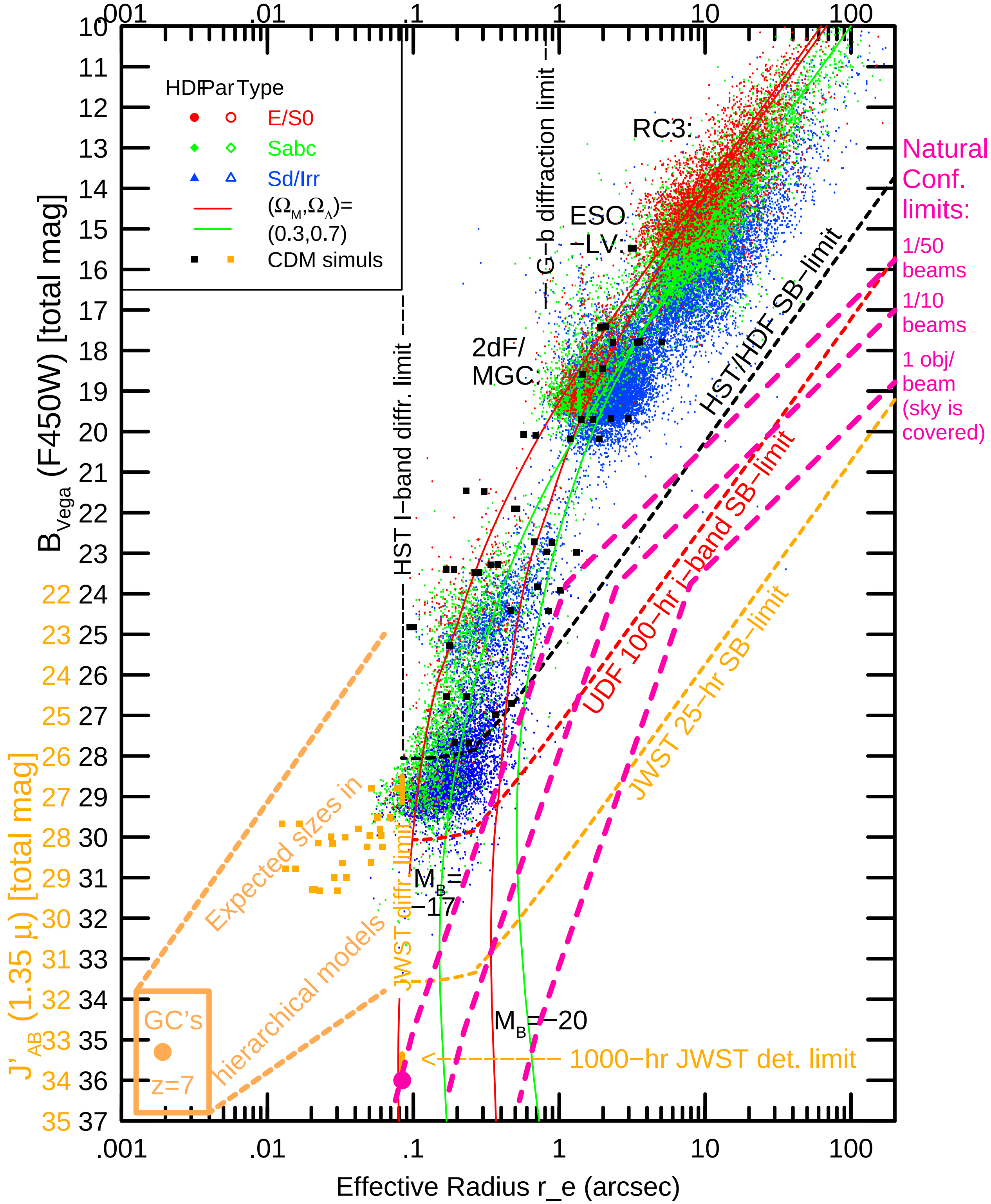
Models: AGN: ellipticals (dot-dash) + quasars dominate at $\gtrsim$1 mJy, starbursts (dashed) below 1 mJy, spirals (dot-long dash) dominate below 100 nJy. Radio surveys trace complete history of AGN activity and cosmic SFH.

See talks by Bower, Carilli, Ekers (this conf.)

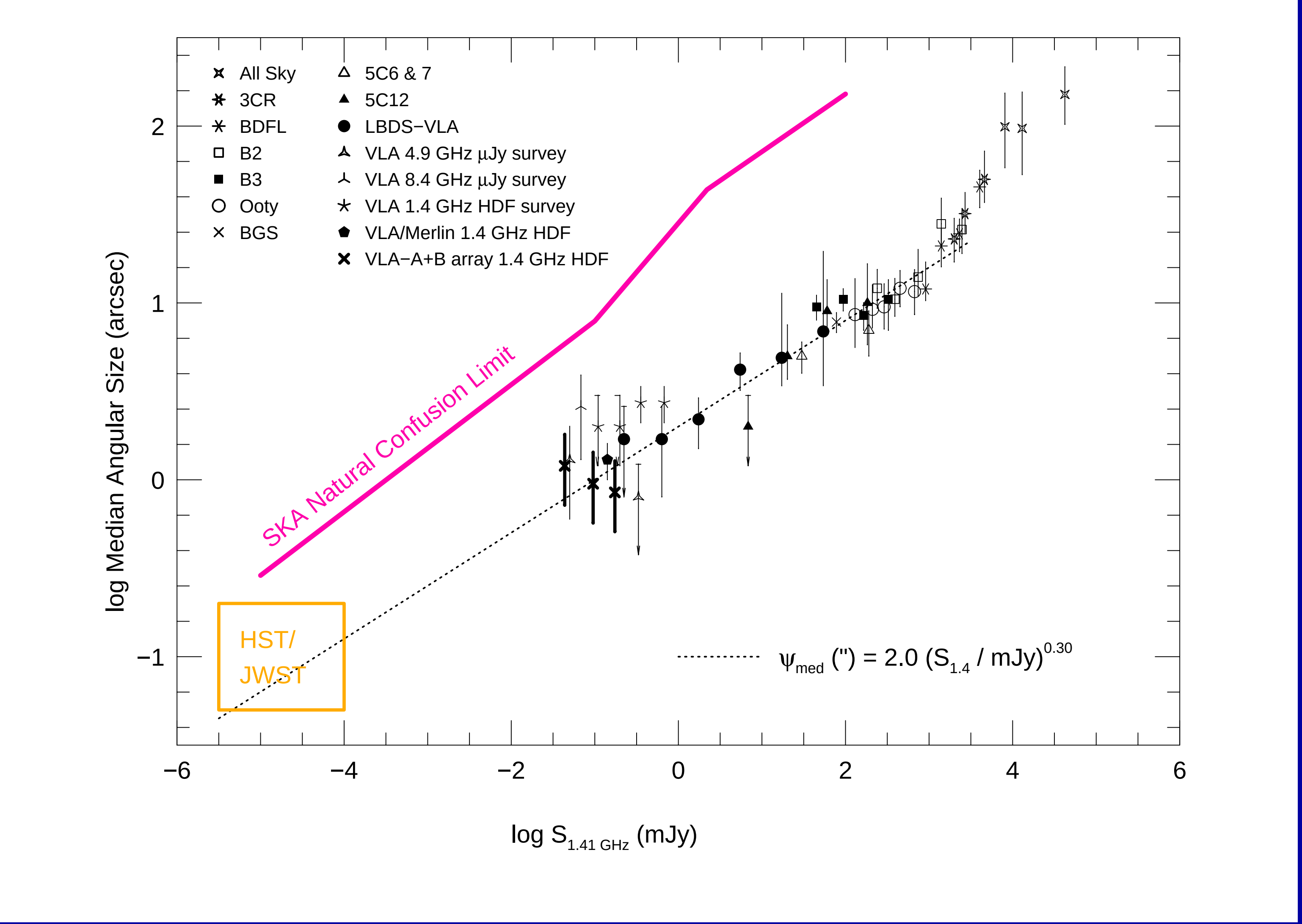


HST GOODS measured galaxy size evolution (Ferguson et al. 2004 ApJL):

- 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: $r_{hl}(z) \propto r_{hl}(0) \, . \, (1+z)^{-s}$, $s \simeq 1$.
- Caused by hierarchical formation of galaxies, leading to intrinsically smaller galaxies at higher redshifts, where fewer mergers have occurred.
- JWST & SKA must anticipate the small $\lesssim 0\farcs15$ sizes of faint galaxies.



HDF Par Type
E/S0
Sabc
Sd/Irr
(Ω_M,Ω_Λ)=
(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
JWST diffr. limit
Natural
Conf.
limits:
1/50
beams
1/10
beams
1 obj/
beam
(sky is
covered)
Expected sizes in
hierarchical models
GC's
z=7
M_B=
−17
M_B=−20
<−−−−−−−−− 1000−hr JWST det. limit
B_Vega (F450W) [total mag]
J'_AB (1.35 μ) [total mag]
Effective Radius r_e (arcsec)
.001
.01
.1
1
10
100



Median angular size vs. 1.41 GHz flux from 100 Jy down to 30 μJy (Windhorst et al. 2003). SKA sizes at 10–100 nJy are estimated from the HST N(r_{hl}) to AB=30 mag (3 nJy), where both detect $\gtrsim 10^6$ objects/deg^2.

Purple line is the natural confusion limit due to the intrinsic source sizes, above which sources unavoidably overlap. SKA needs $\sim 0''.10$ FWHM resolution to best match the expected HI and radio continuum sizes.

Combination of ground-based and space-based HST surveys show:

- (1) Apparent galaxy sizes decline from the RC3 to the HUDF limits:

- (2) At the HDF/HUDF limits, this is *not* only due to SB-selection effects (cosmological $(1+z)^4$-dimming), but also due to:

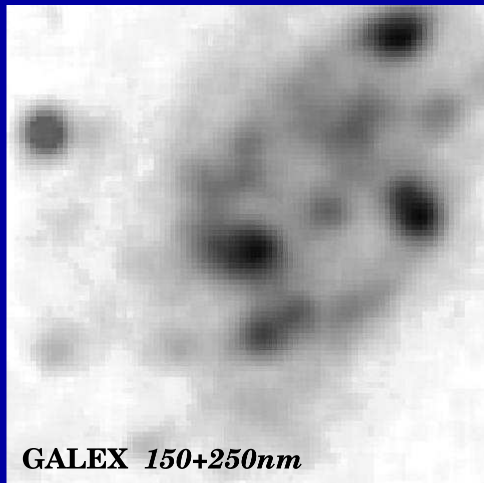
- (2a) hierarchical formation causes size evolution: $r_{hl}(z) \propto r_{hl}(0)\,(1+z)^{-1}$

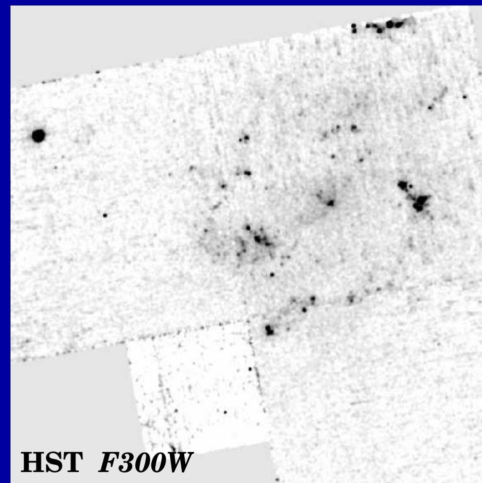
- (2b) increasing inability of object detection algorithms to deblend galaxies at faint mags ("natural" confusion $\neq$ "instrumental" confusion).

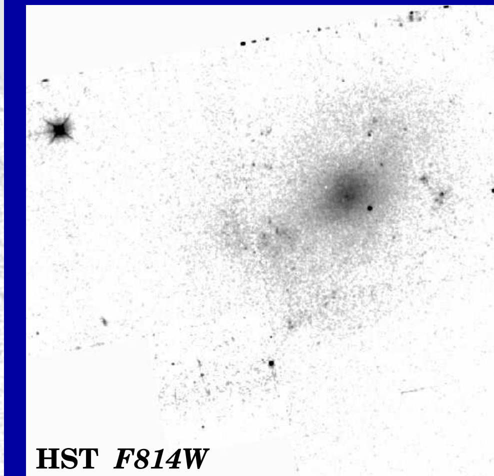
- (3) At AB$\gtrsim$30 mag, JWST and at $\gtrsim$10 nJy, SKA will see more than 2×10^6 galaxies/deg^2. Most of these will be unresolved ($r_{hl} \lesssim 0\farcs1$ FWHM (Kawata et al. 2006). Since $z_{med}\simeq$1.5, this influences the balance of how $(1+z)^4$-dimming & object overlap affects the catalog completeness.

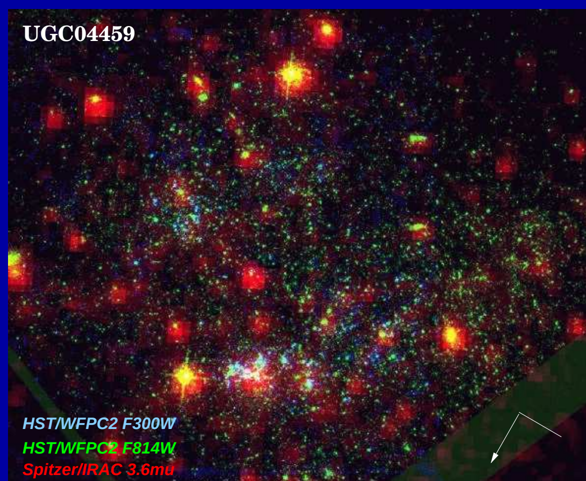
- For details, see Windhorst, R. A., et al. 2007, Advances in Space Research, Vol. 42, p. 1–10, in press (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"

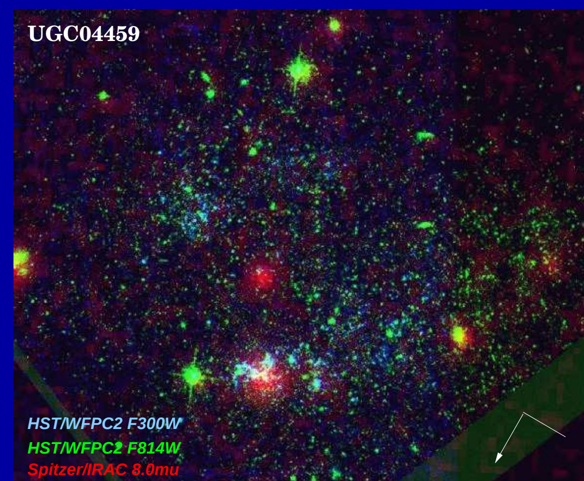
App. 2: The Lyman continuum escape fraction $f_{esc}(z)$ of dwarf galaxies



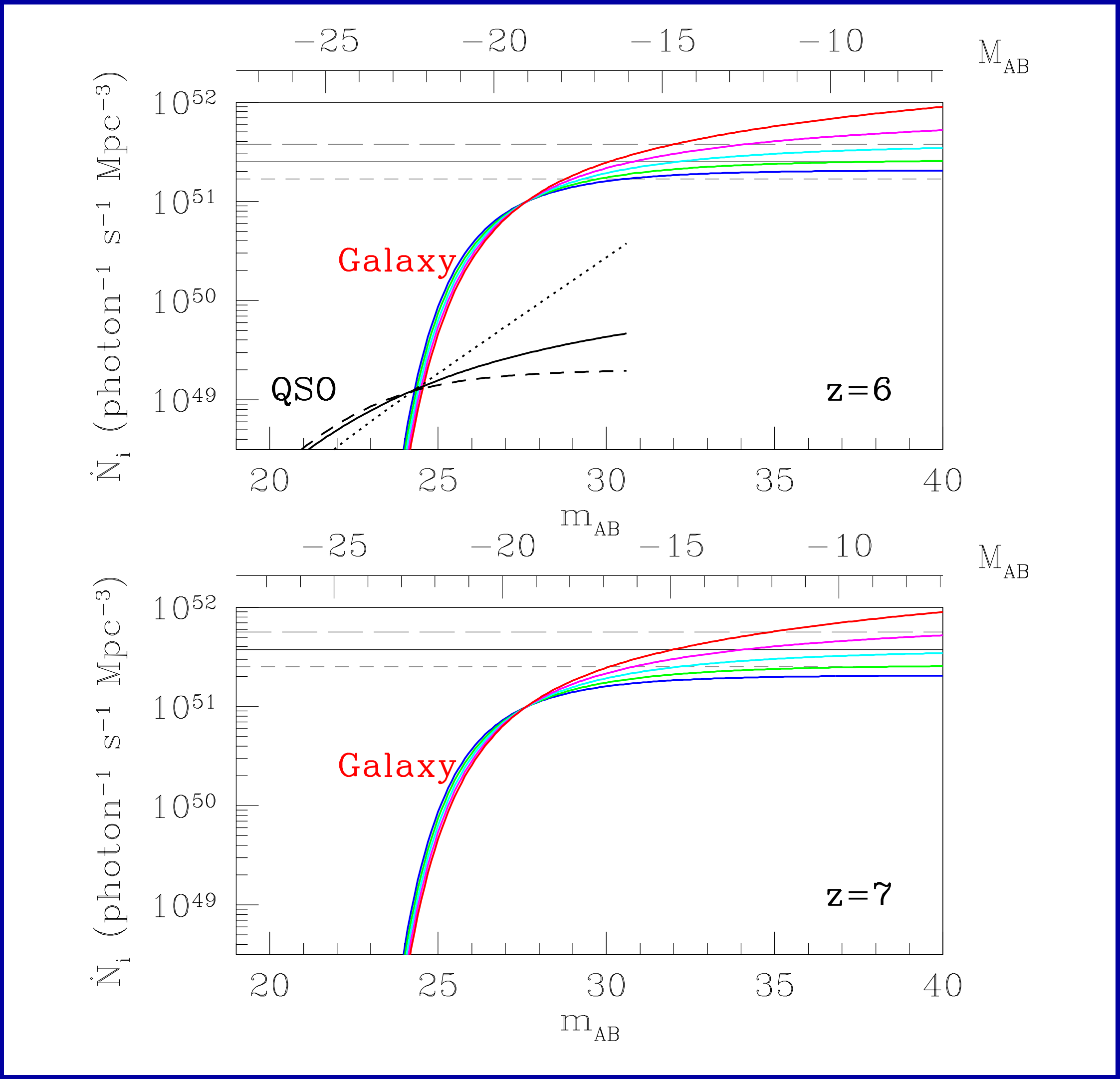






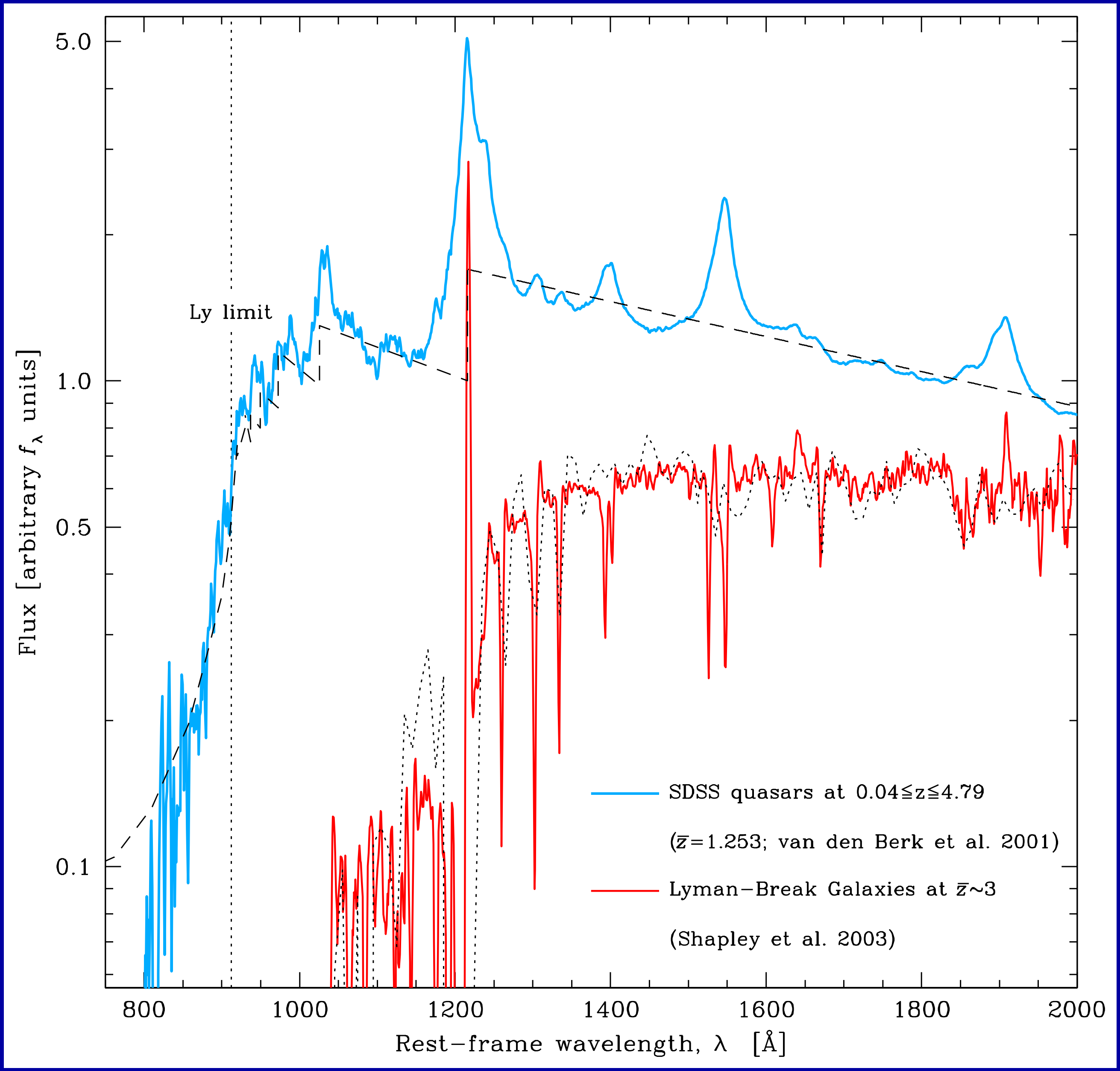


- GALEX, HST/UV and Spitzer IRAC images of nearby late-type dwarf galaxies suggests enough (SN-driven?) holes between their dust that UV-photons can escape: covering factors $\gtrsim$20% ($\propto f_{esc}$? $\leftrightarrow$ HI).
- Steidel et al. (2001): z$\simeq$3 LBG's have UV-escape fraction f_{esc} $\simeq$10%.
- Yan & Windhorst (2004) assume that f_{esc} at z$\simeq$6 is at least as high.



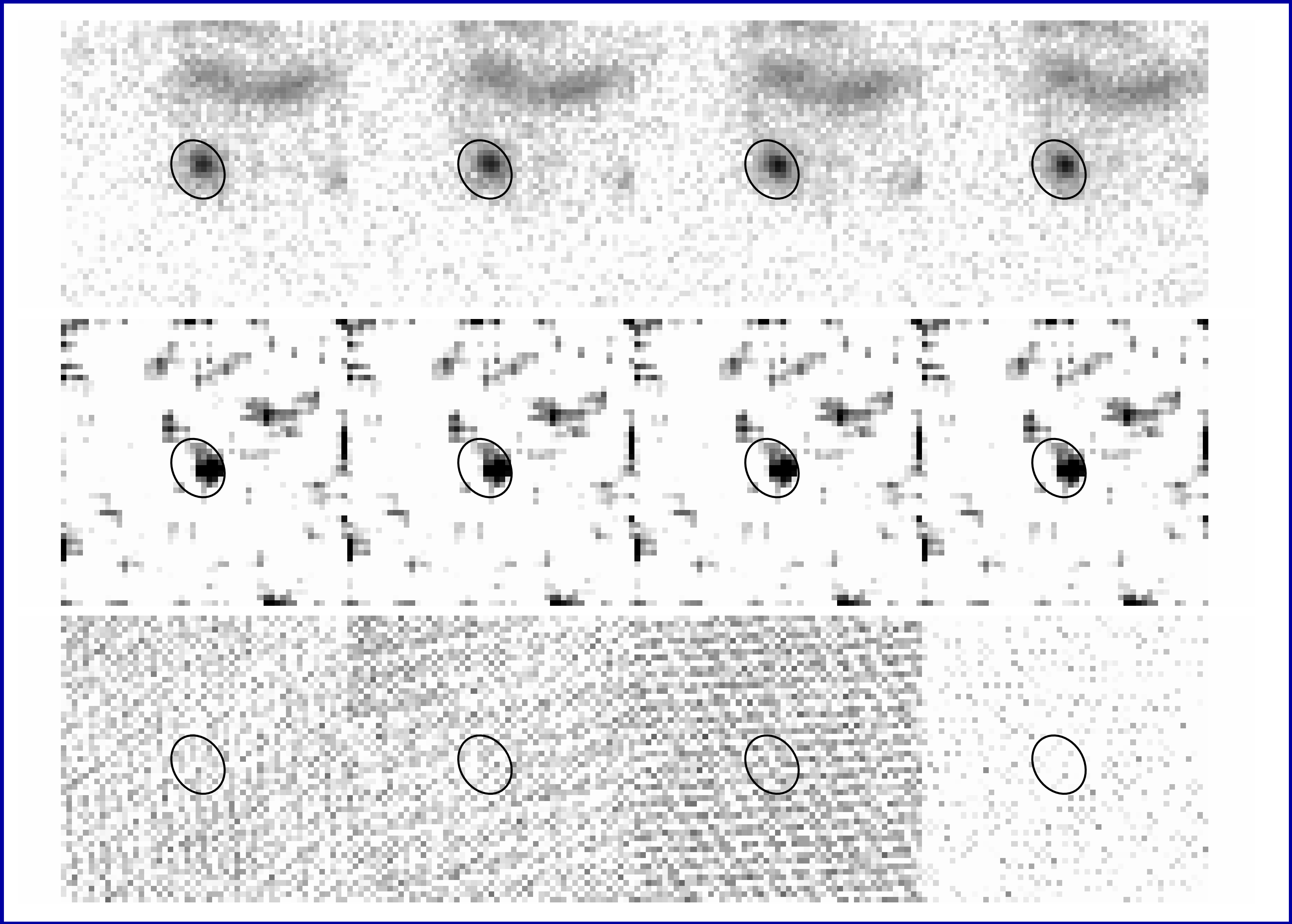
- A steep LF of z≃6 objects (Yan & Windhorst 2004a, ApJL, 600, L1) could provide enough UV-photons to complete the reionization epoch at z≃6 (if $f_{esc} \gtrsim 10\%$).
- Pop II dwarf galaxies may not have started shining *pervasively* much before z≃7–8, or no H-I would be seen in the foreground of 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.

Caveat: Can the Hard-UV of weak AGN outshine Dwarf Galaxies?



• In principle, the hard-UV of QSO's and weak AGN can outdo the young SED's of LBG's or dwarf galaxies, but likely by no more than $\gtrsim$1 dex.

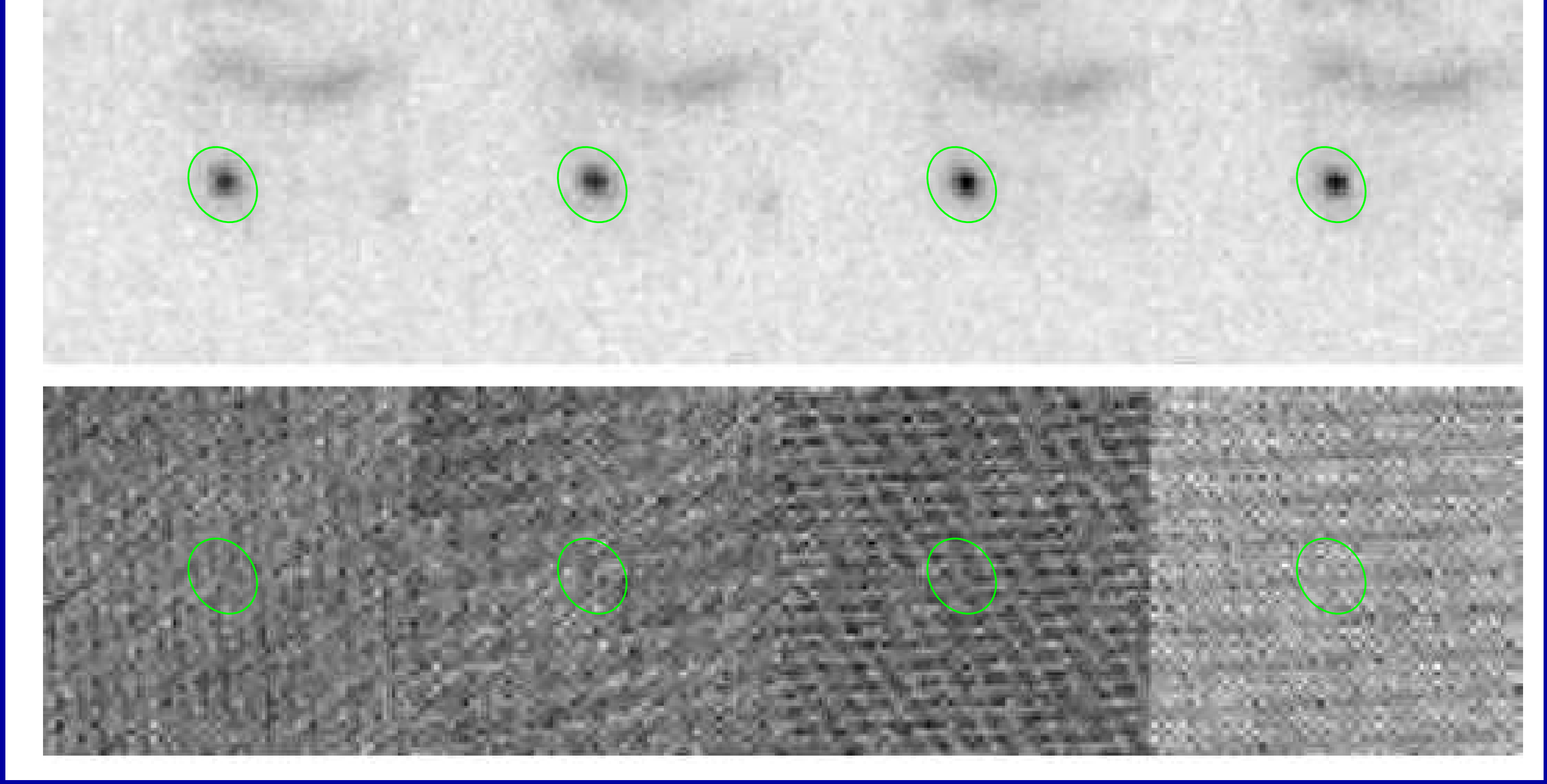
App. 3: Faint Variable Objects in the Hubble UltraDeep Field

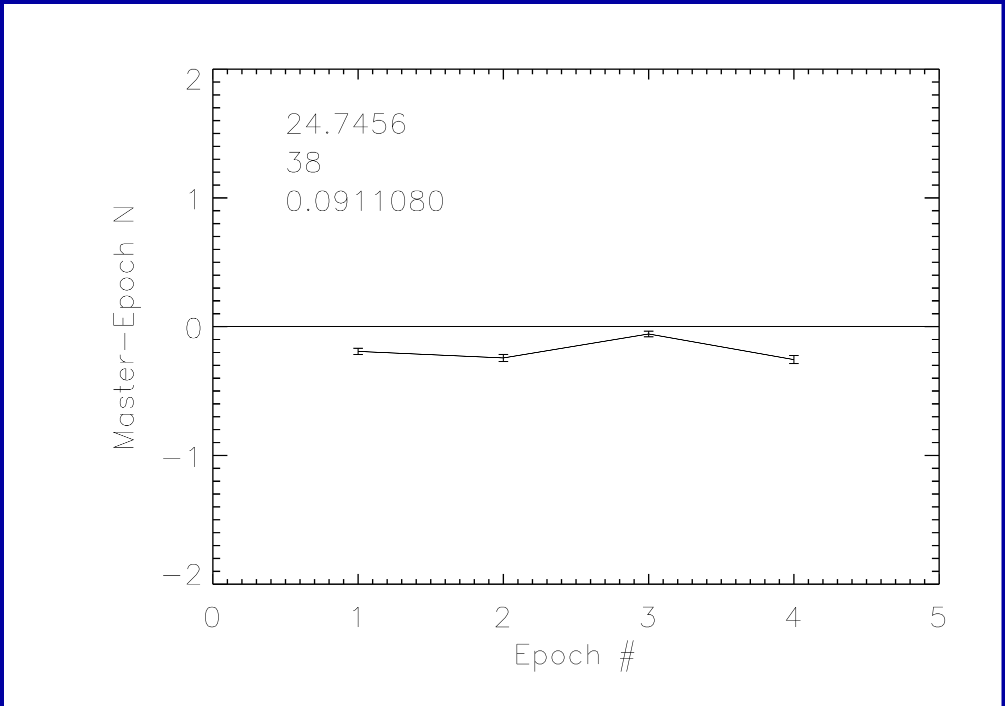


Top: 4 HUDF Epochs; Middle: 1 Variance map; Bottom: 4 Weight-maps.

Details in Cohen, S. H., et al. 2006, ApJ, 639, 731 (astro-ph/0511414).

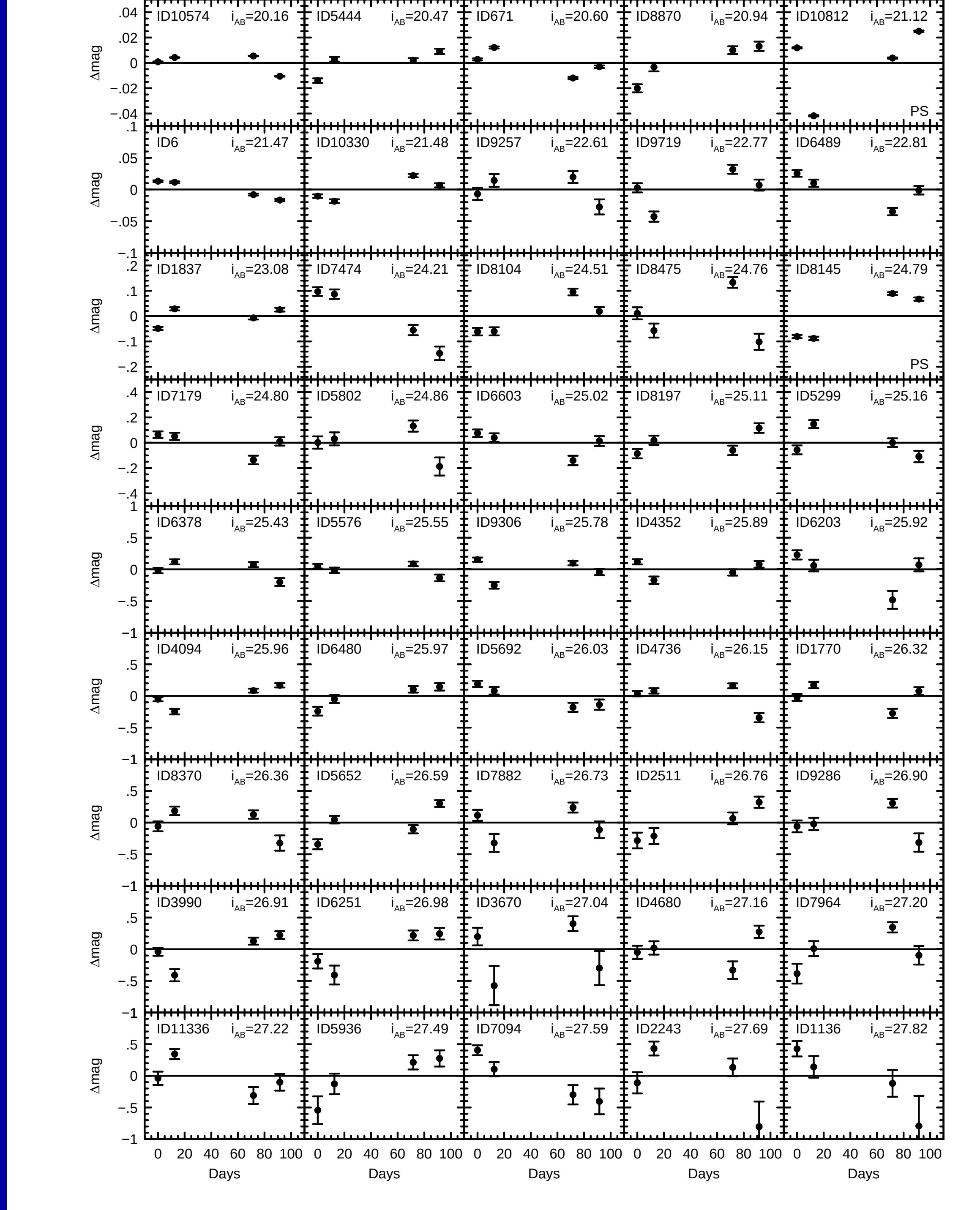
See also talks by Djorgovski, York (this conf.)



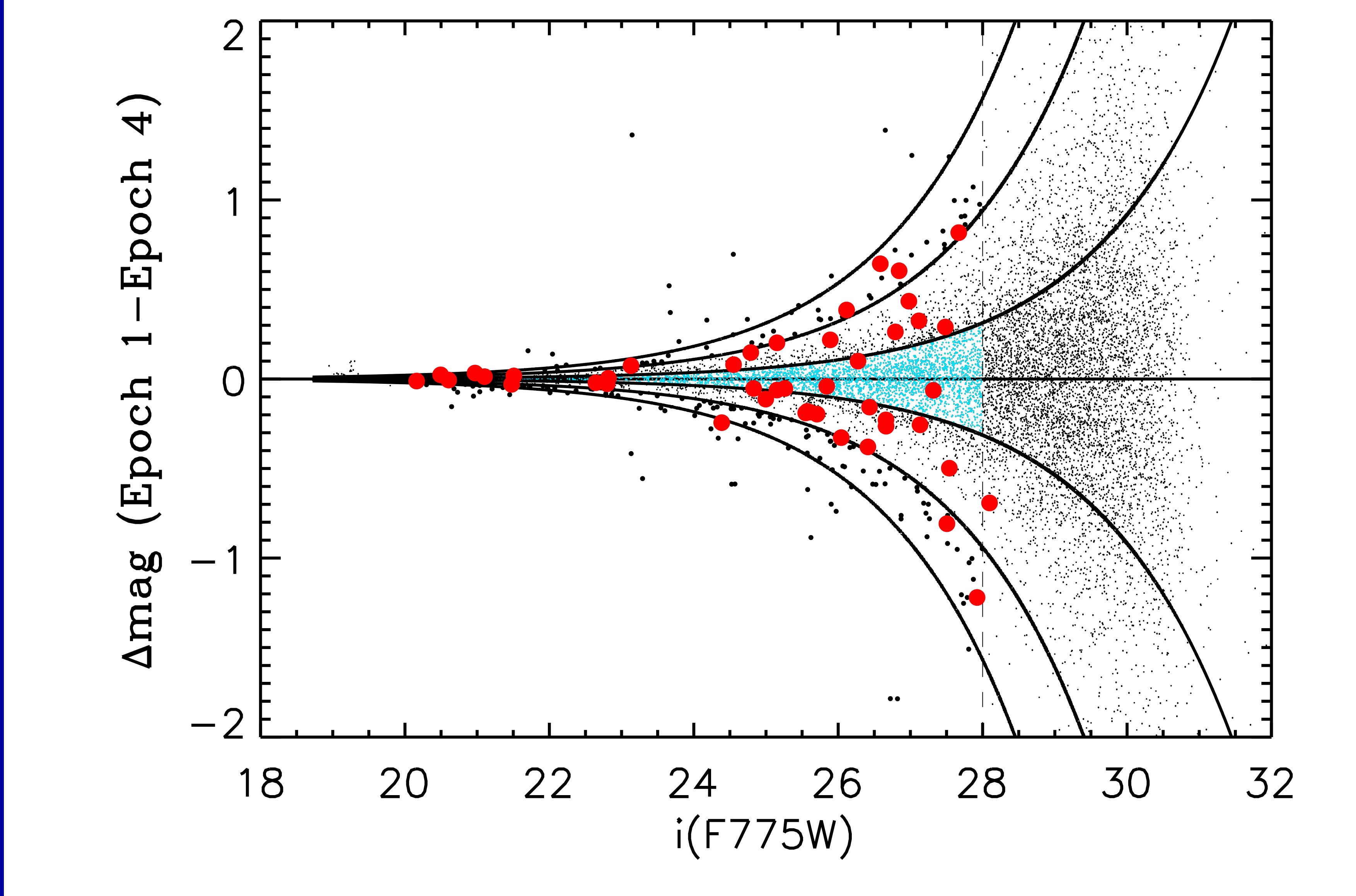


i'-Var Cand # 38 (z=1.122):

9% variability, AGN

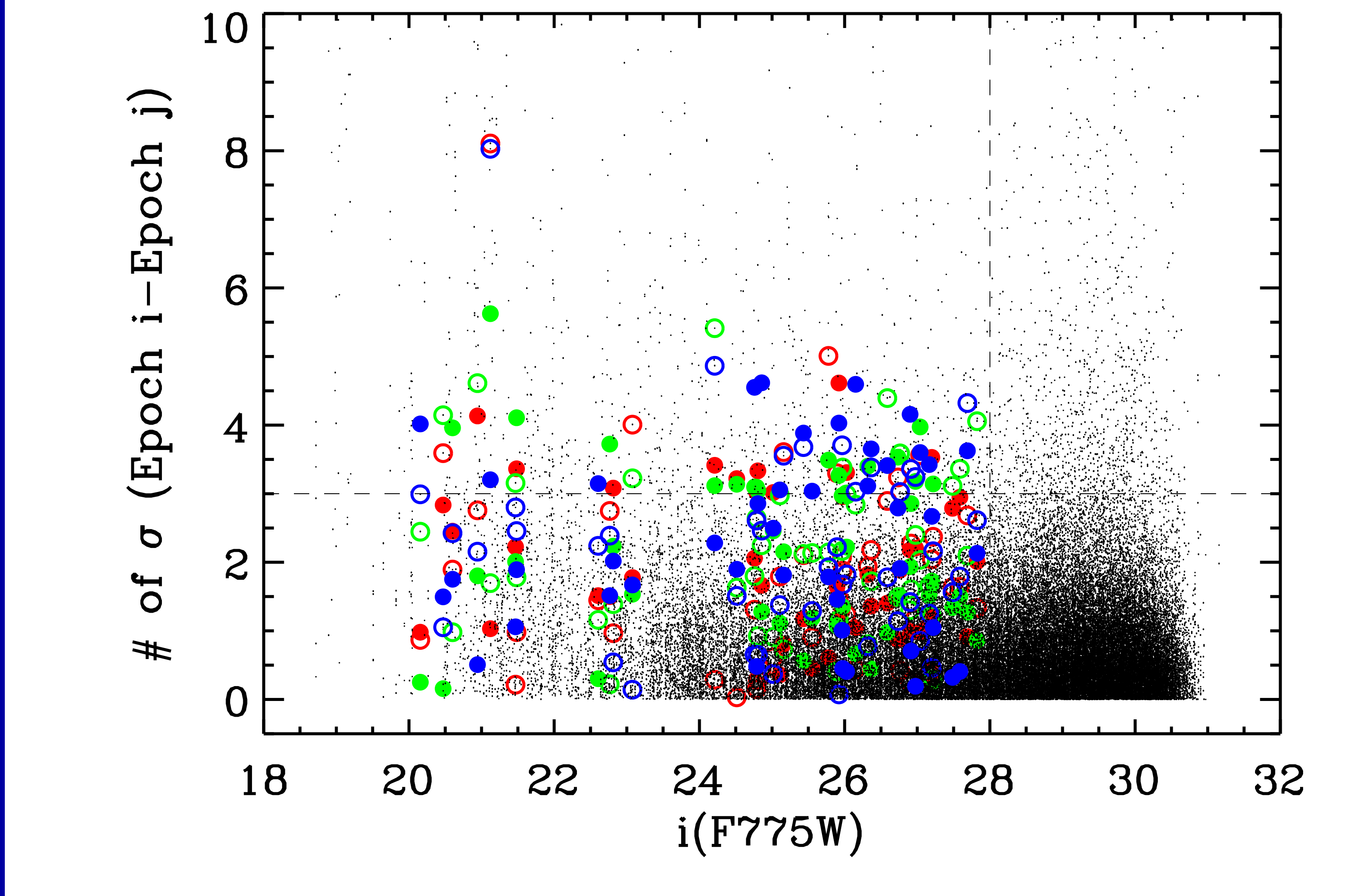


- Light curves: Can detect bright HUDF variables if |Δmag| $\lesssim$1–2% !



Flux ratio of all objects between two HUDF epochs (Δt$\simeq$few weeks–months) vs. total i-band flux. Lines are at $\pm 1.0\sigma$ (blue), $\pm 3.0\sigma$, $\pm 5.0\sigma$.

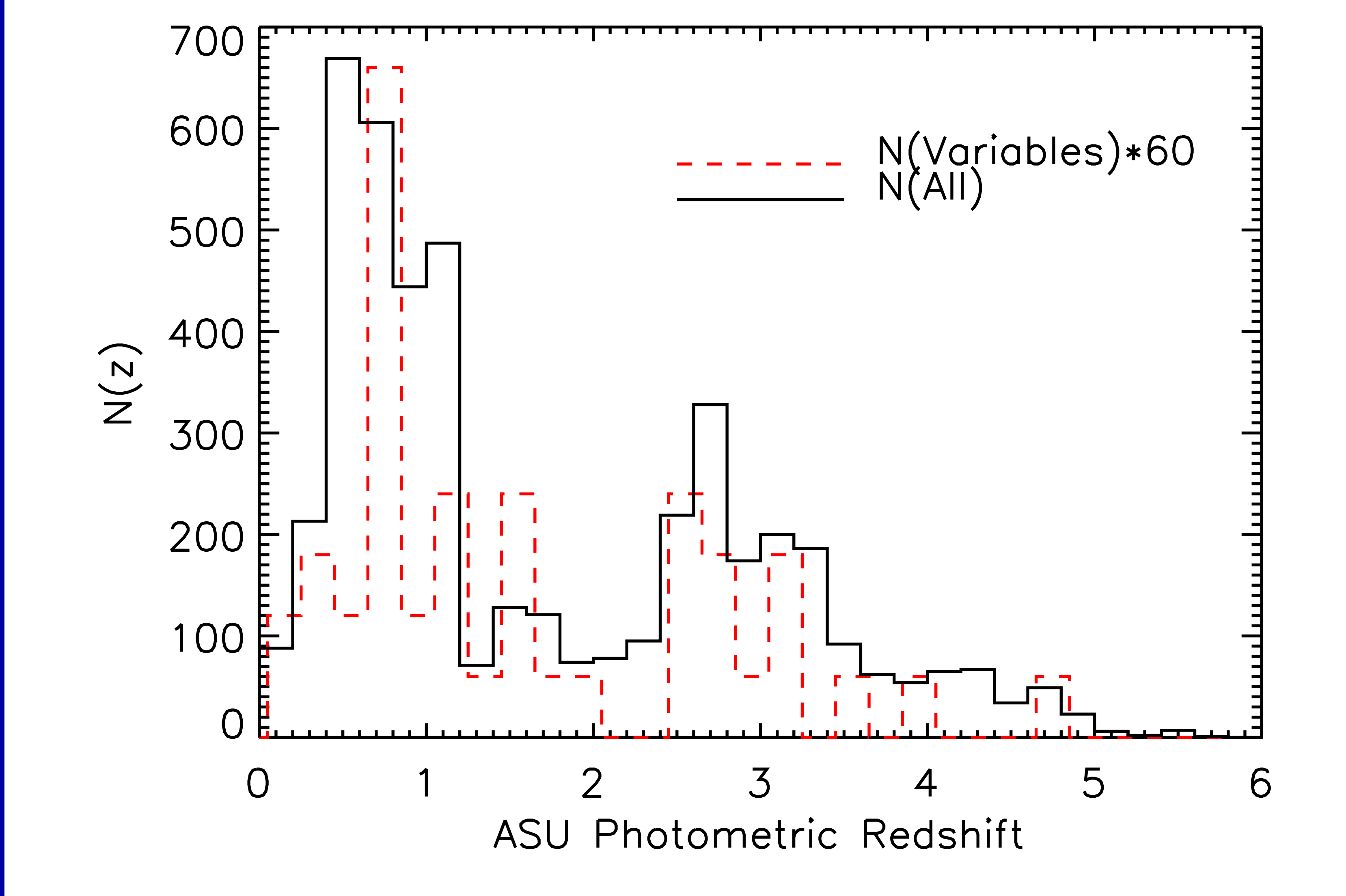
- All objects with |Delta mag|$\geq 3.0\sigma$ were inspected for plausible variability. This will yield $\lesssim$13 bogus detections if the noise were purely Gaussian.



• 3 out of 16 Chandra sources are faint point-like variable objects at $\gtrsim 3.0\sigma$.

• Other 13 Chandra sources are mostly brighter (early-type) galaxies, one is $\gtrsim 3.0\sigma$ variable $\Rightarrow$ Variable point sources are valid AGN candidates.

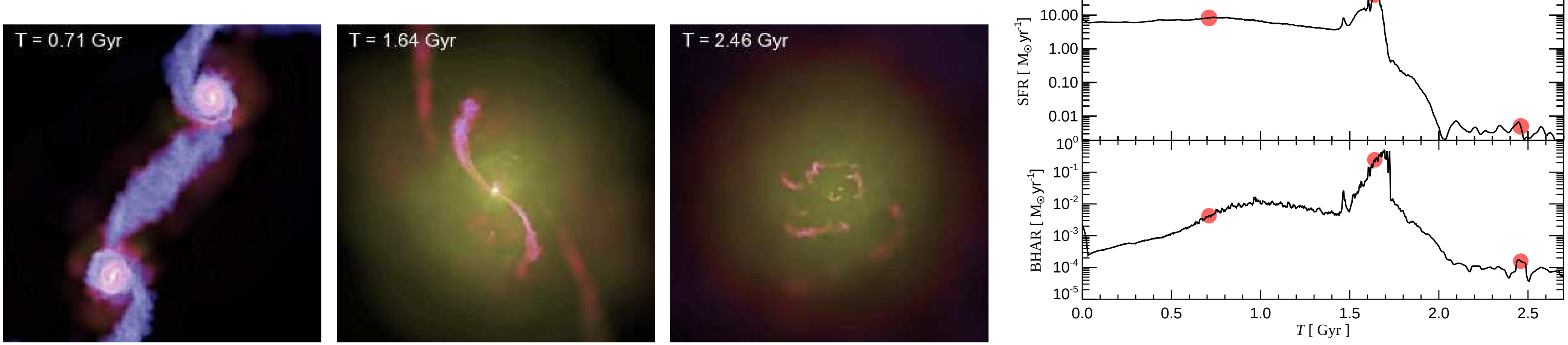
• We only sample ΔFlux $\gtrsim$10%—30% on timescales of months. The AGN sample is not complete — we miss all non-variable and obscured AGN.



- Variable objects show similar N(z) from BViz(JH) photo-z's as field galaxies. About 1% of all galaxies have variable weak AGN at all z's.

$\Rightarrow$ If variable objects are representative of all weak AGN, SMBH growth kept pace with the cosmic SFR (which peaks at $z \simeq 1$–2).

- SFC will find variable, weak AGN in $\gtrsim 10^6$ objects at $AB \lesssim 28$, $z \lesssim 8$.



- [LEFT] Simulated merger of two disk galaxies at three different times, including the effects of SMBH growth and AGN feedback by Springel, di Matteo, Hernquist (2005, ApJ, 620, 79). Shown is the gas distribution with color indicating temperature, and brightness indicating gas density.

- [RIGHT] Evolution of the accretion rate onto the SMBH (top) and the SF-rate (bottom). Red dots mark the times of the three images.

- Overlap between Tadpoles and Variables is very small — 1 object!

$\Leftrightarrow$ In hydrodynamical simulations, the object resembles a tadpole galaxy $\sim$0.7 Gyr after the merger starts, the AGN is triggered and expels the dust $\gtrsim$1.6 Gyr after the merger starts, *i.e.*, $\gtrsim$1 Gyr after the tadpole stage.

- SFC will study this for $\gtrsim 10^5$ mergers and $\gtrsim 10^4$ weak AGN at $z \lesssim 8$.