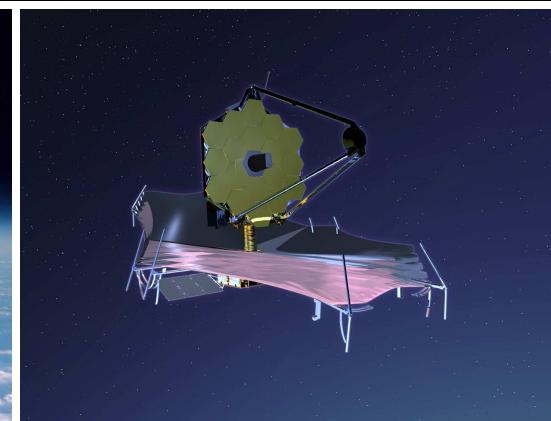


L.Z. Fang's astrophysics & China: Musings on First Light, Galaxy Assembly & Supermassive Blackhole Growth.

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

Collaborators: S. Cohen, R. Jansen (ASU), C. Conselice (UK), S. Driver (OZ), & H. Yan (U. MO)

(Ex) ASU Grads: N. Hathi, H. Kim, M. Mechtley, R. Ryan, M. Rutkowski, A. Straughn, & K. Tamura



Xing-Long Station

HST \gtrsim 2002–2009

JWST \gtrsim 2018

Exploring the Dark Universe: Frontier of Cosmology and Astrophysics in the 21st Century;

Workshop honoring Prof. Li Zhi Fang, Steward Observ., Univ. of Arizona, Tucson, Sunday Oct. 7, 2012.



Professor Fang Li Zhi had many scientific interests, each of which greatly inspired astrophysics and its development in China and world-wide:

- (1) Gravity, Structure Formation, Clusters of Galaxies;
- (2) Relativity and Cosmology;
- (3) Active Galactic Nuclei (AGN).

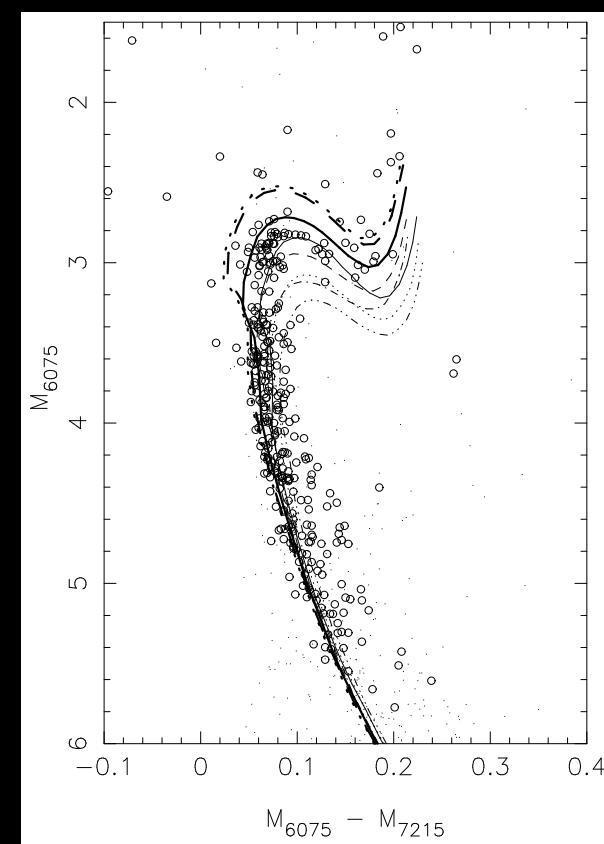
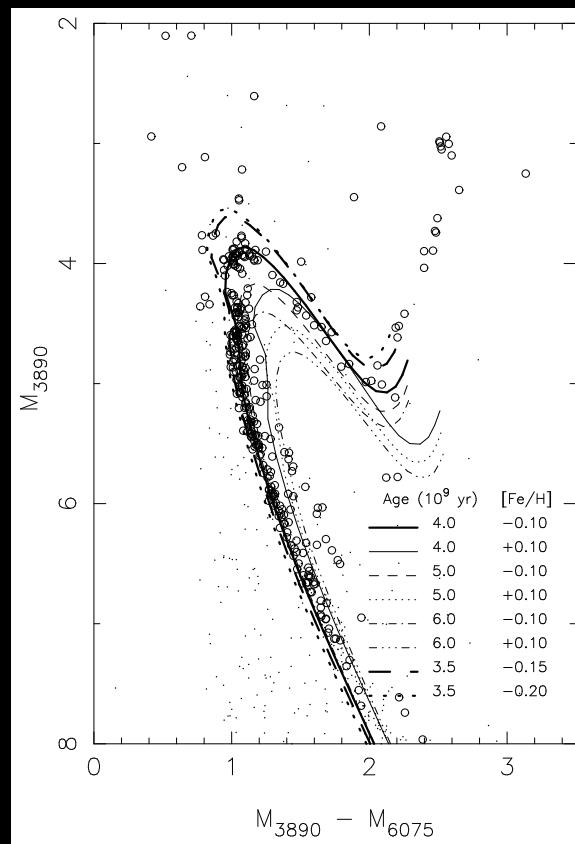
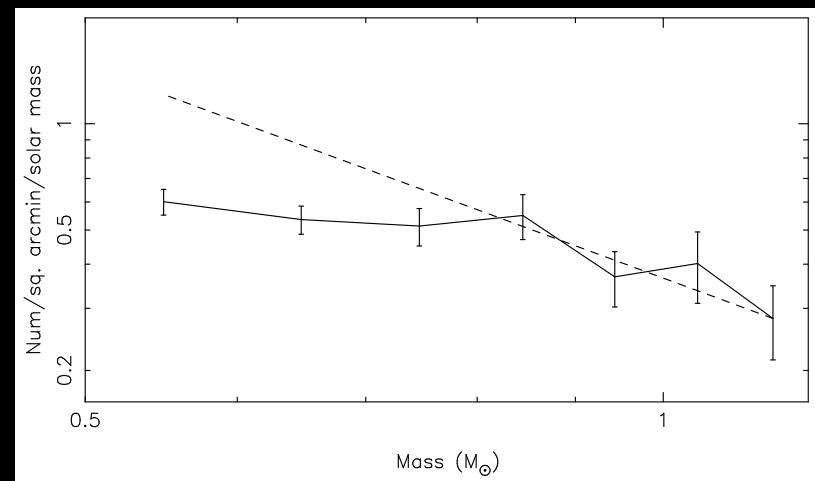
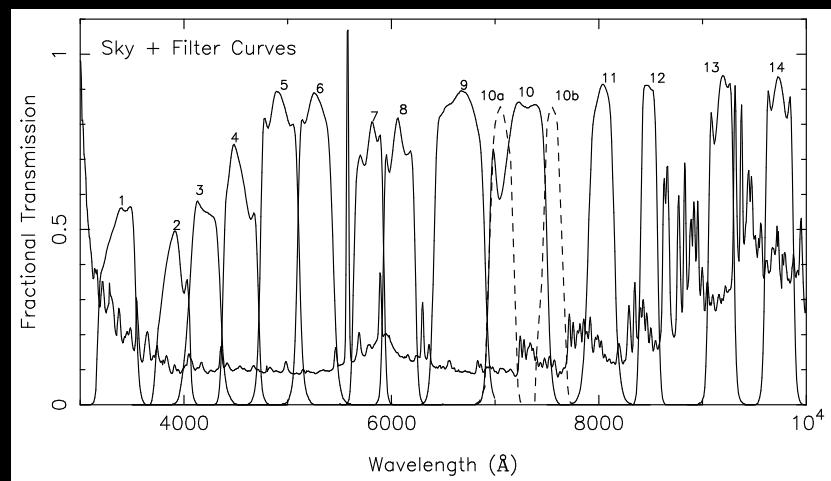
Today, I will speak about some of the work Prof. Fang inspired, and some of my own work in the context of his work.

Outline

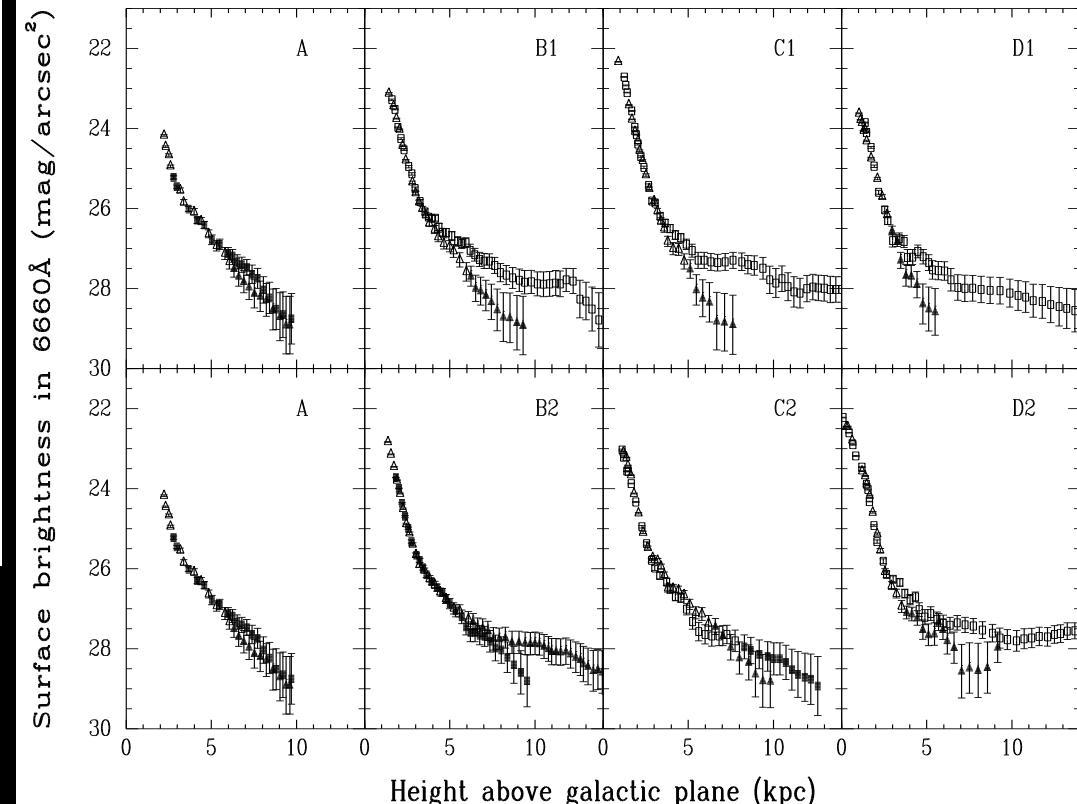
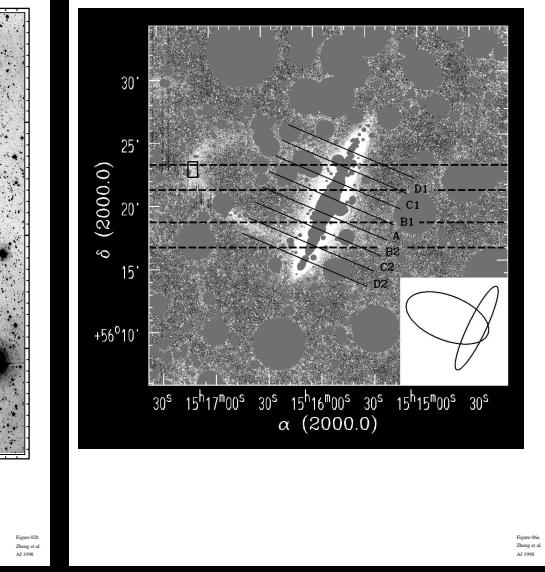
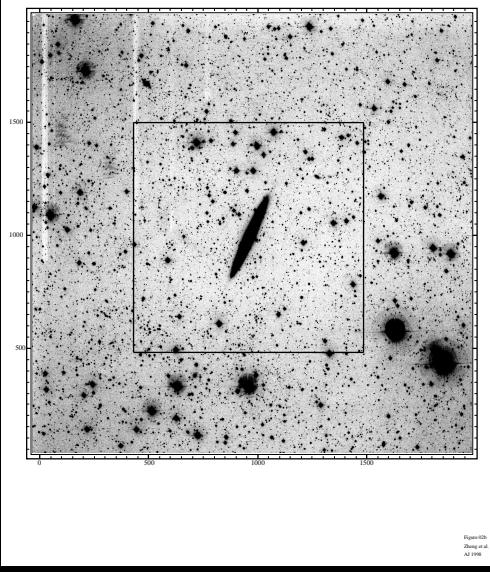
- (0) The Beijing-Arizona-Taiwan-CT BATC survey in 15 medium-bands.
- (1) Recent key aspects of the Hubble Wide Field Camera 3.
- (2) Measuring Galaxy Assembly and Supermassive Black-Hole Growth.
- (3) How will JWST measure the Epoch of Galaxy Assembly?
- (4) How will JWST measure the Epochs of First Light & Reionization?
- (5) Summary and Conclusions.



Sponsored by NASA/HST & JWST

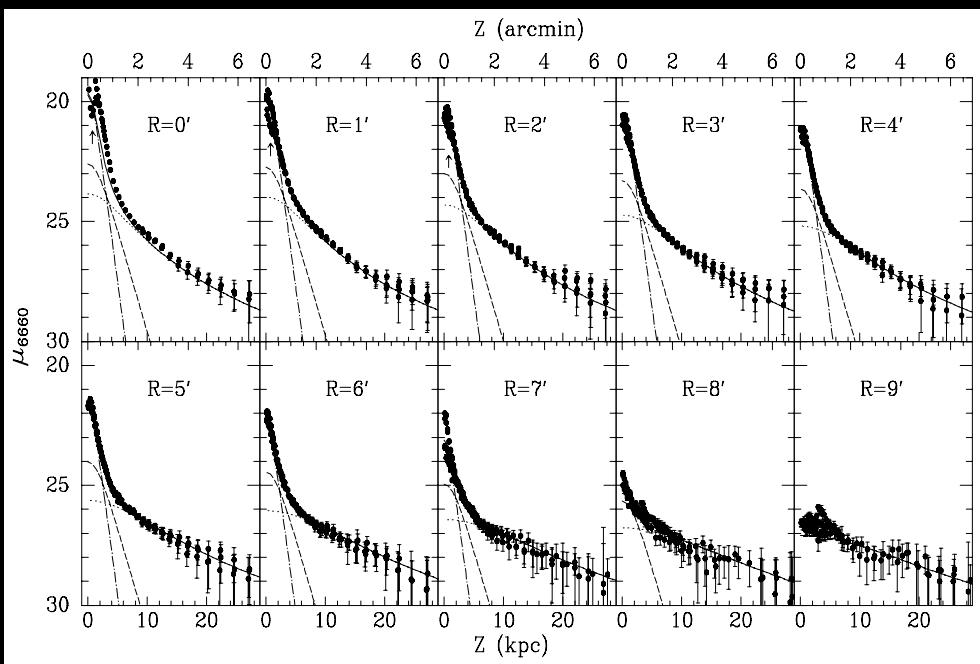
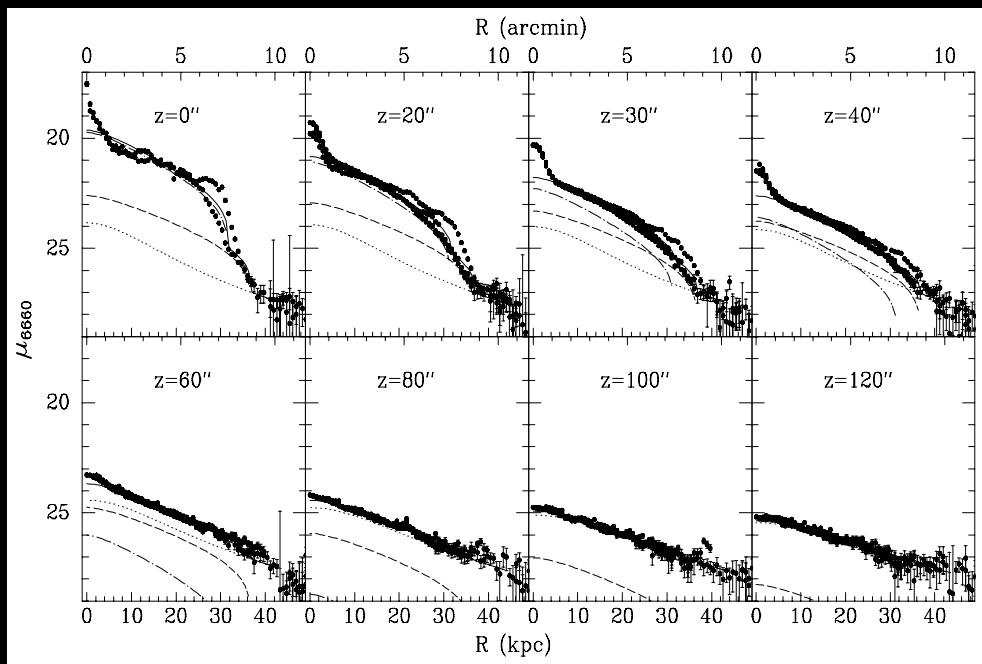
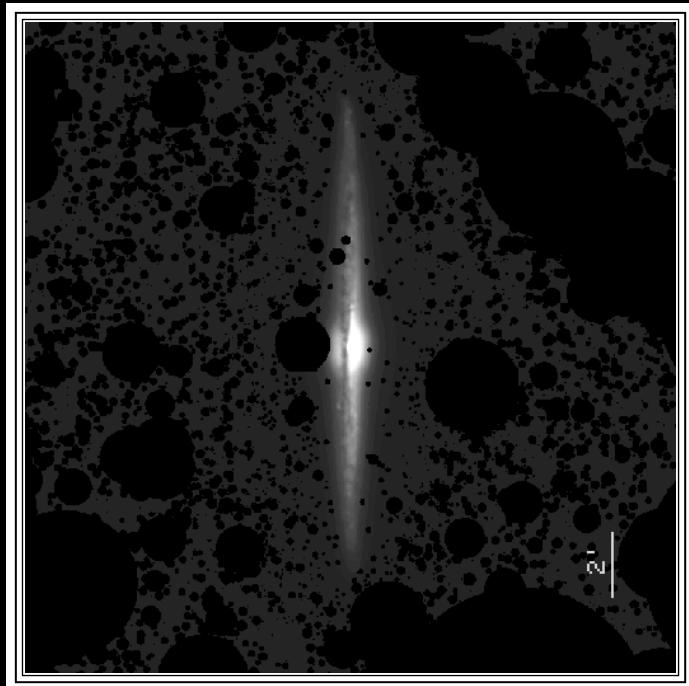
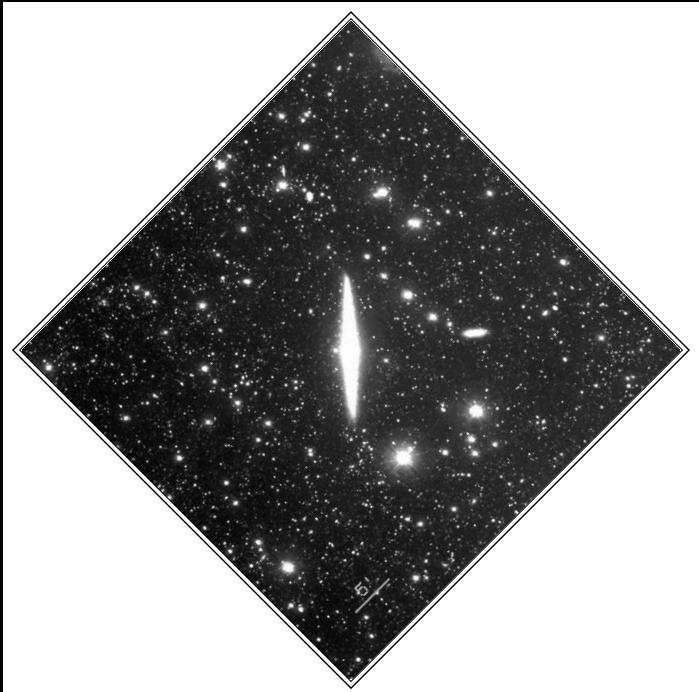


15 medium-band BATC 2% photometry of M67: Binary main sequence & Hertzsprung gap! (Fan, X., et al. 1996, AJ, 112, 628; astro-ph/9604178).

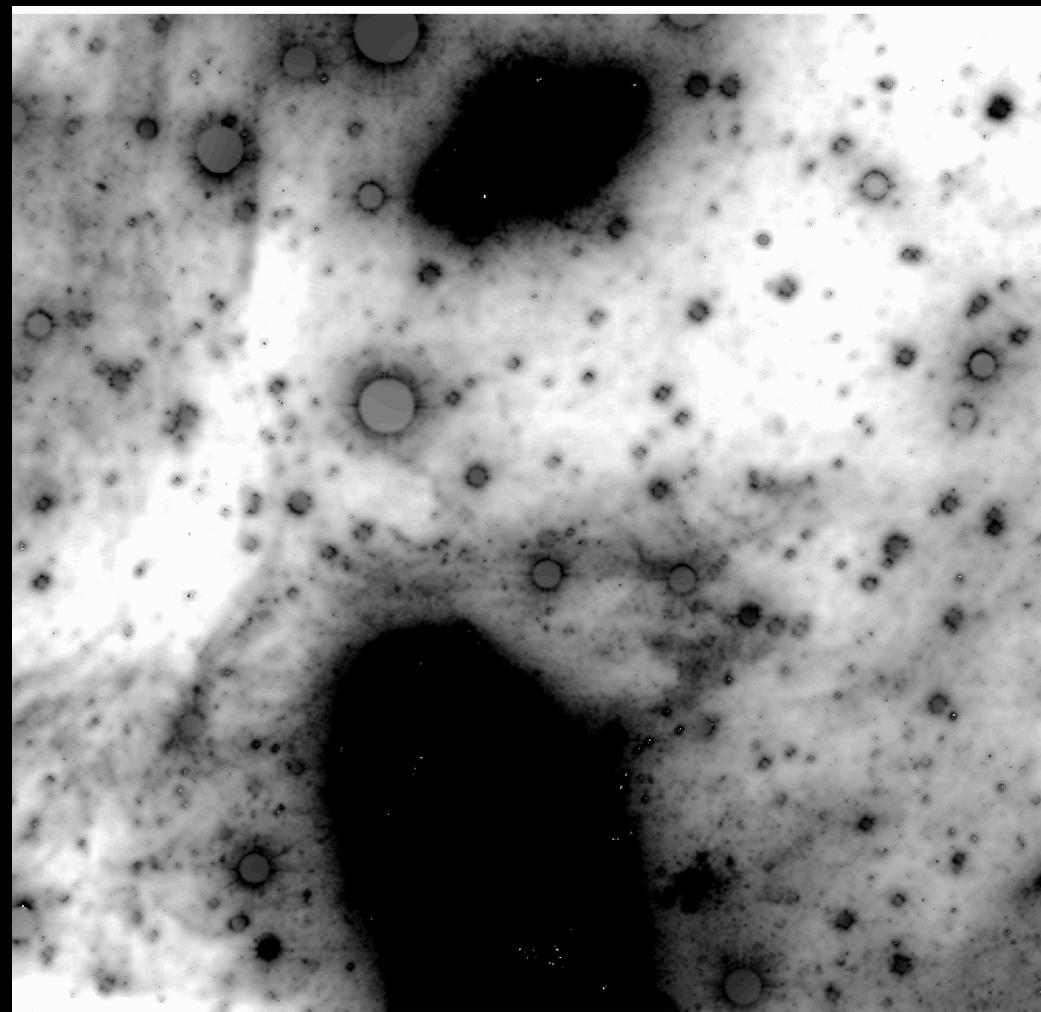
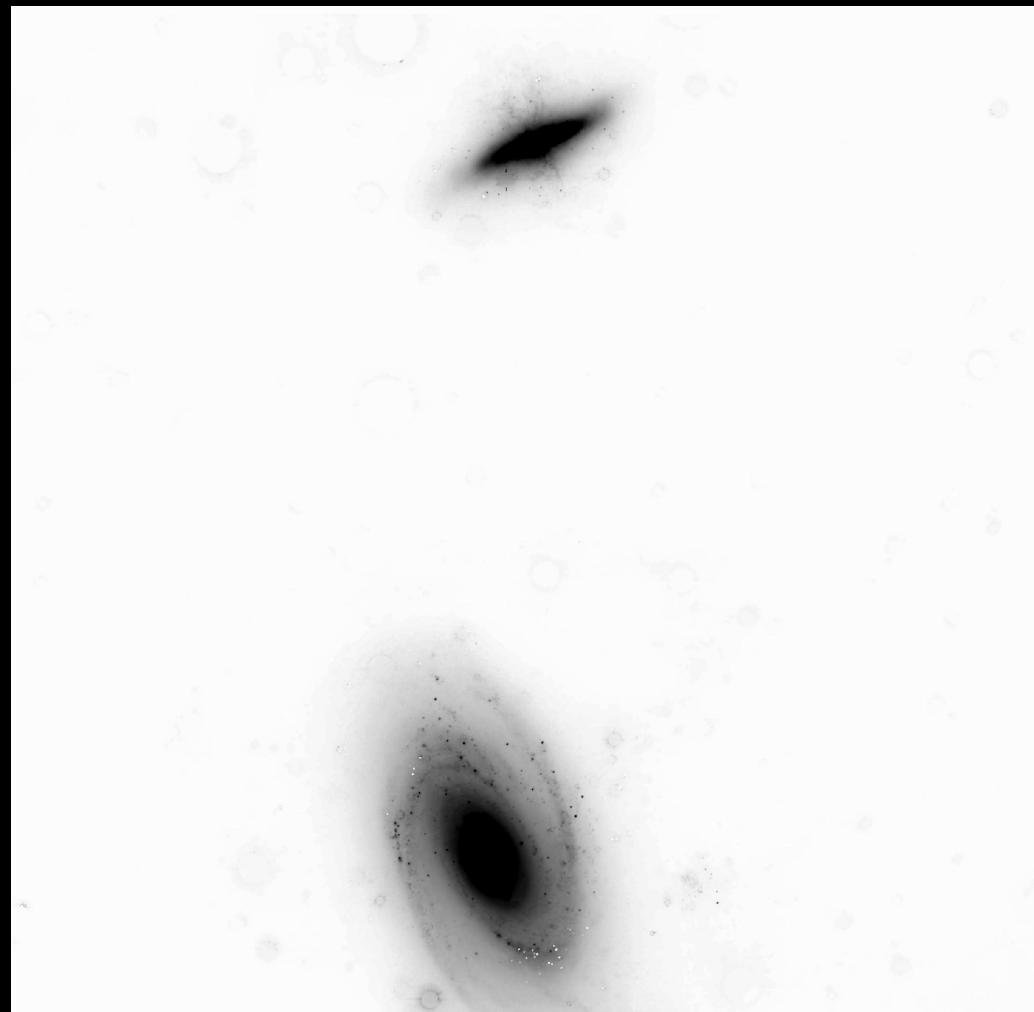


15 medium-band imaging of NGC 5907: SB profile to AB \simeq 29 mag arcsec $^{-2}$
 (Zheng, Z. Y., et al. 1999, AJ, 117, 2757; astro-ph/9902276):

- A clear polar ring is visible as a result from a recent interaction with a nearby dwarf galaxy!
- The 60 cm Schmidt at Xinglong station capable of very low-SB imaging, despite its sky brightness!



15 medium-band imaging of N4565: Radial & Vertical SB-profile to AB \simeq 29 mag arcsec $^{-2}$ (Wu, H. et al. 2002, AJ, 123, 1364; astro-ph/0111433)

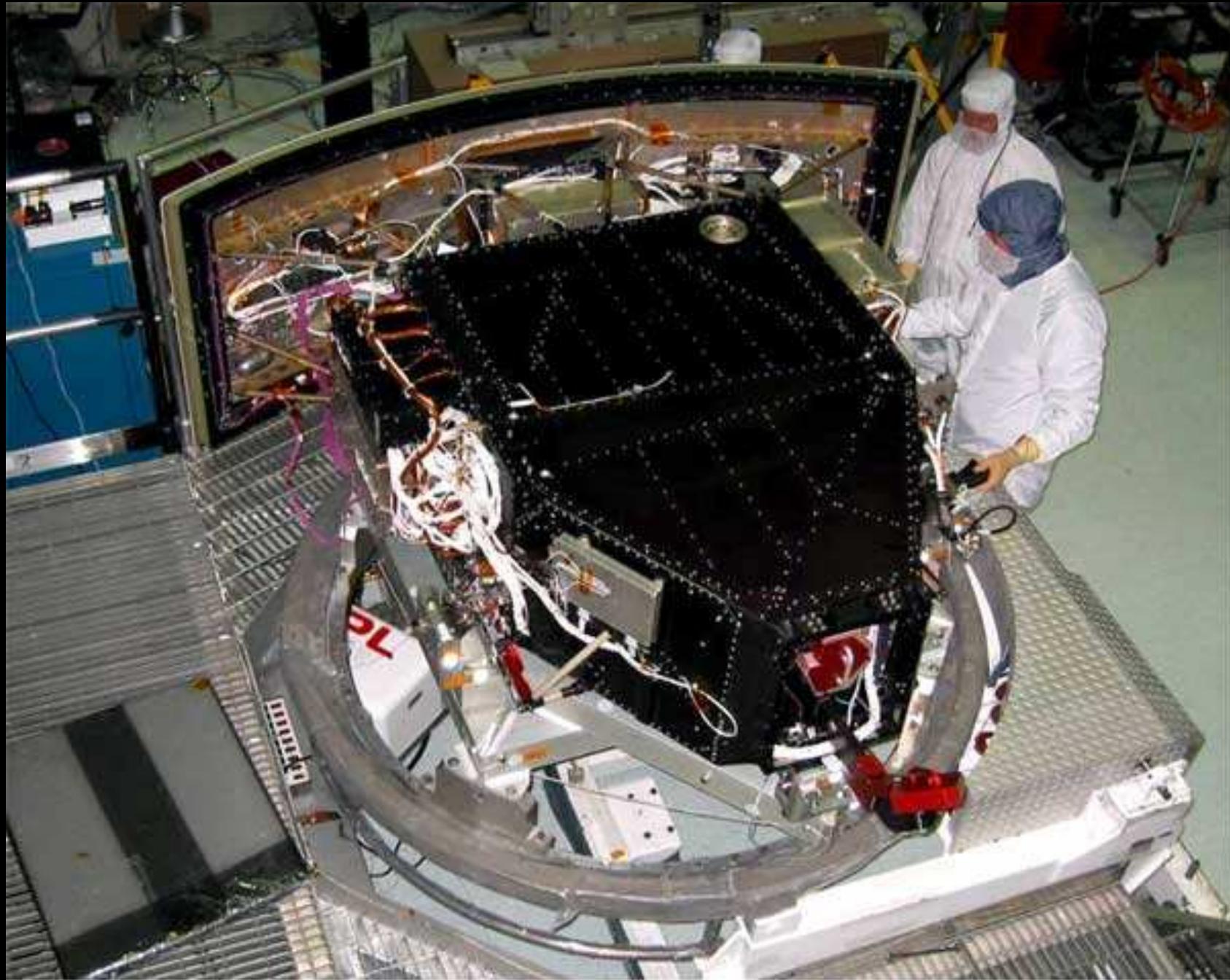


15 medium-band BATC imaging of M81+M82: low-SB ($AB \simeq 29$ mag arcsec $^{-2}$) structures seen where the HI is found!

- Very faint tidal trails of stars and gas.

Zhou, X., et al. (2003, A&A, 397, 361; astro-ph/0209459)

(1) WFC3: Hubble's new Panchromatic High-Throughput Camera



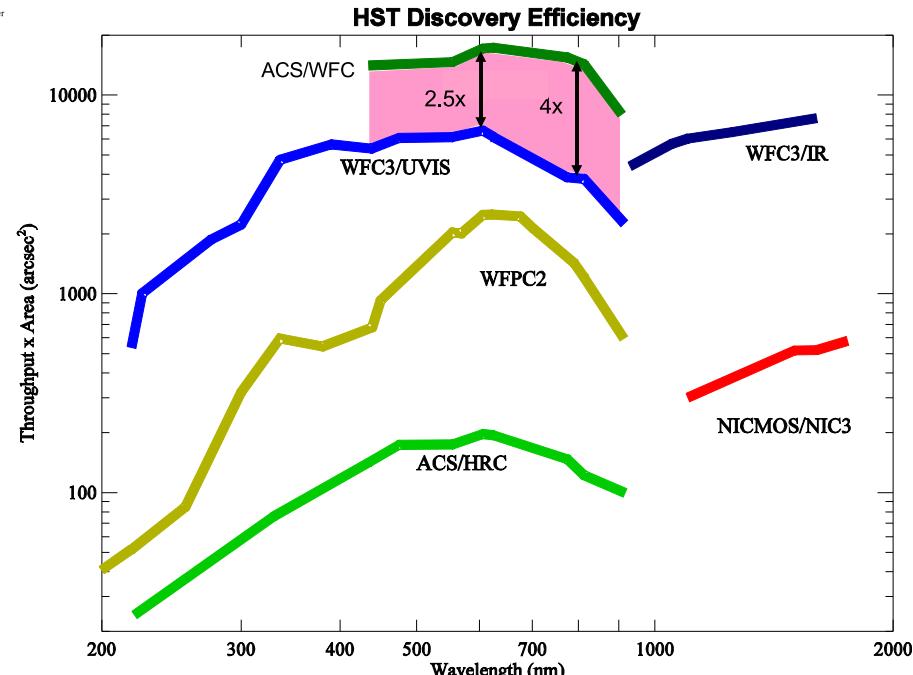
HST WFC3 and its IR channel: a critical pathfinder for JWST science.



Goddard Space Flight Center

Hubble Space Telescope Program

Role of ACS in HST Post-SM4 Imaging Capability



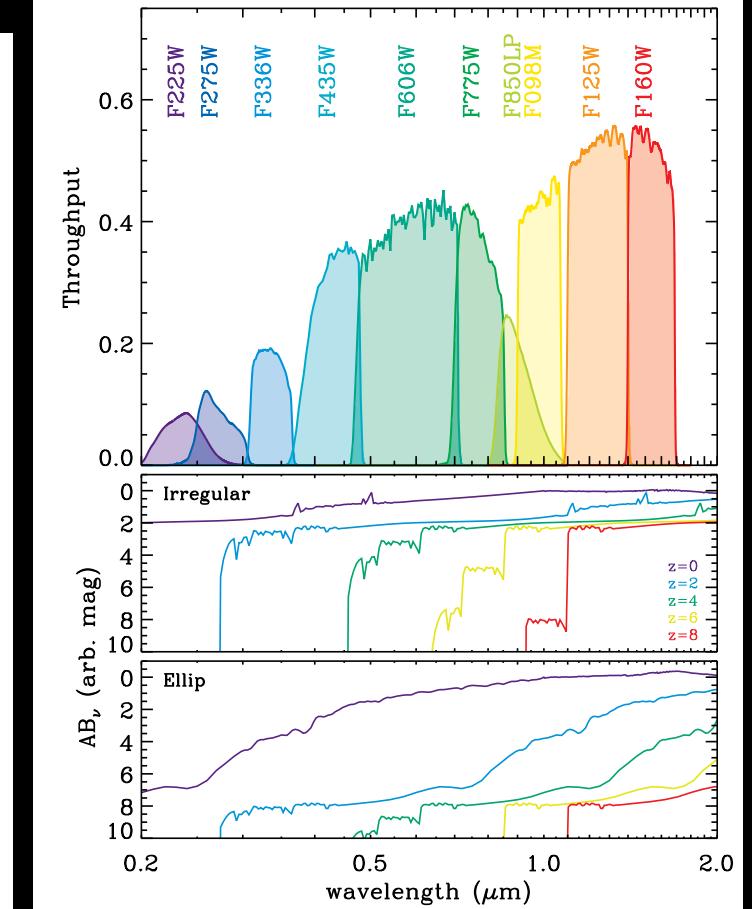
ACS/WFC superior to WFC3 survey efficiency at visible-red wavelengths

030507_PMB_ACSS_Status.ppt

- QE $\gtrsim 70\%$, $4k \times 4k$ array of $0\farcs04$ pixel, FOV $\simeq 2\farcs67 \times 2\farcs67$.

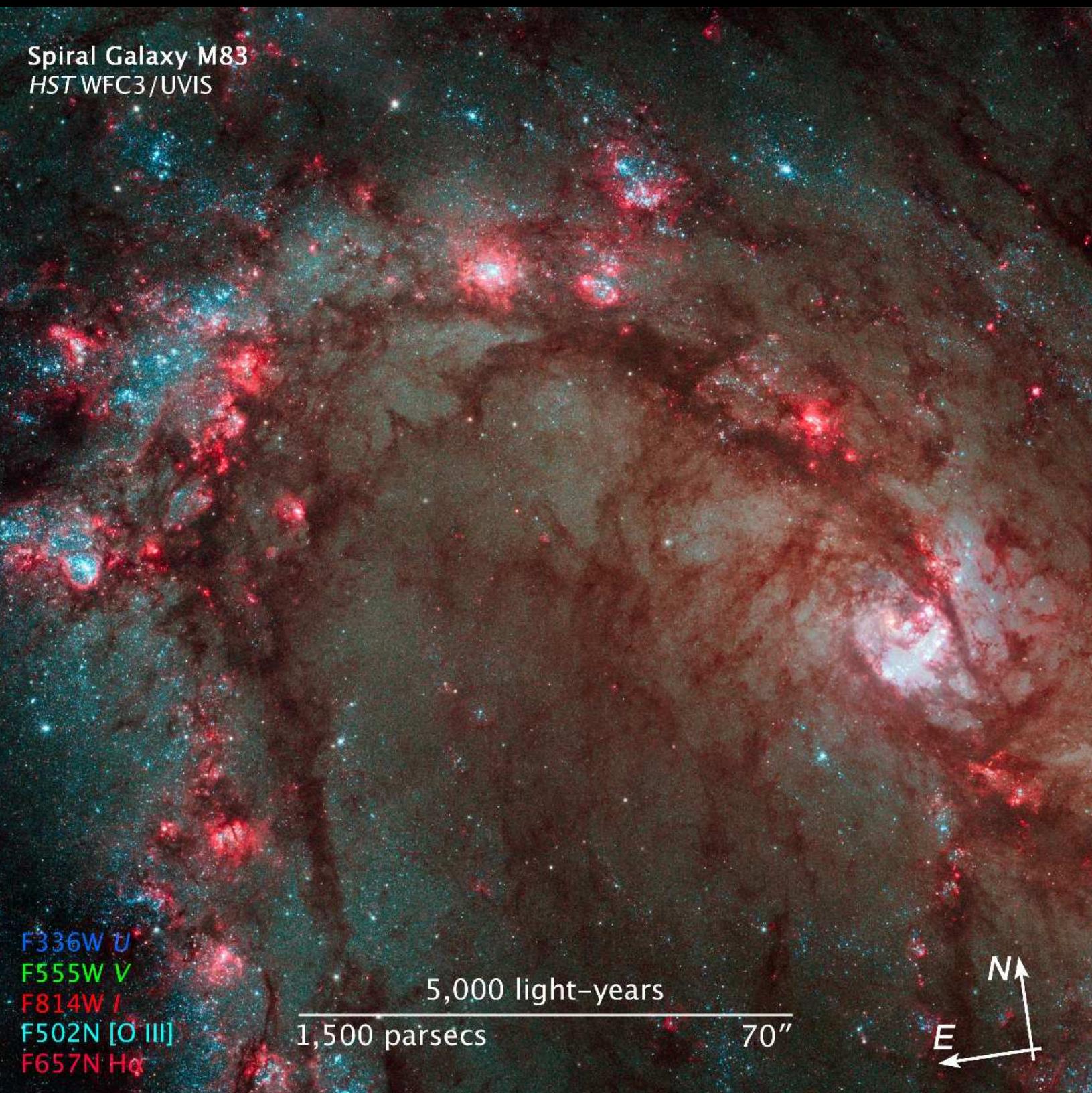
- QE $\gtrsim 70\%$, $1k \times 1k$ array of $0\farcs13$ pixel, FOV $\simeq 2\farcs25 \times 2\farcs25$.

- HST WFC3 and its IR channel a critical pathfinder for JWST science.



9

Spiral Galaxy M83
HST WFC3/UVIS

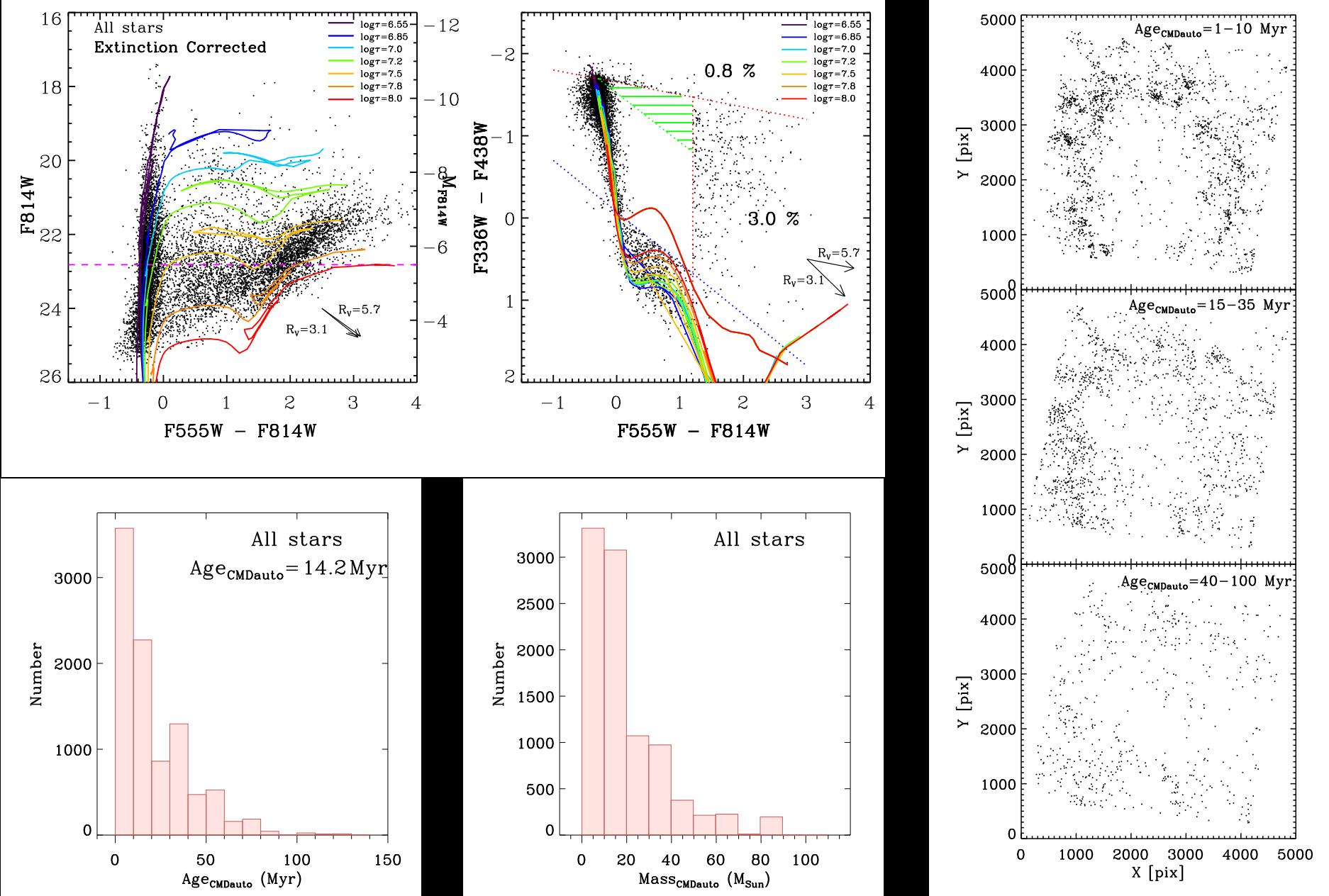


F336W U
F555W V
F814W I
F502N [O III]
F657N H α

5,000 light-years
1,500 parsecs

70"

N
E



Well determined dust-corrected ages for stars in M83, with formation and dissipation along/across spiral arms (Hwihyun Kim et al. 2012, ApJS).

JWST can do this in much dustier environments and for older stellar populations. But must do all we can with HST in UV-blue before JWST flies!

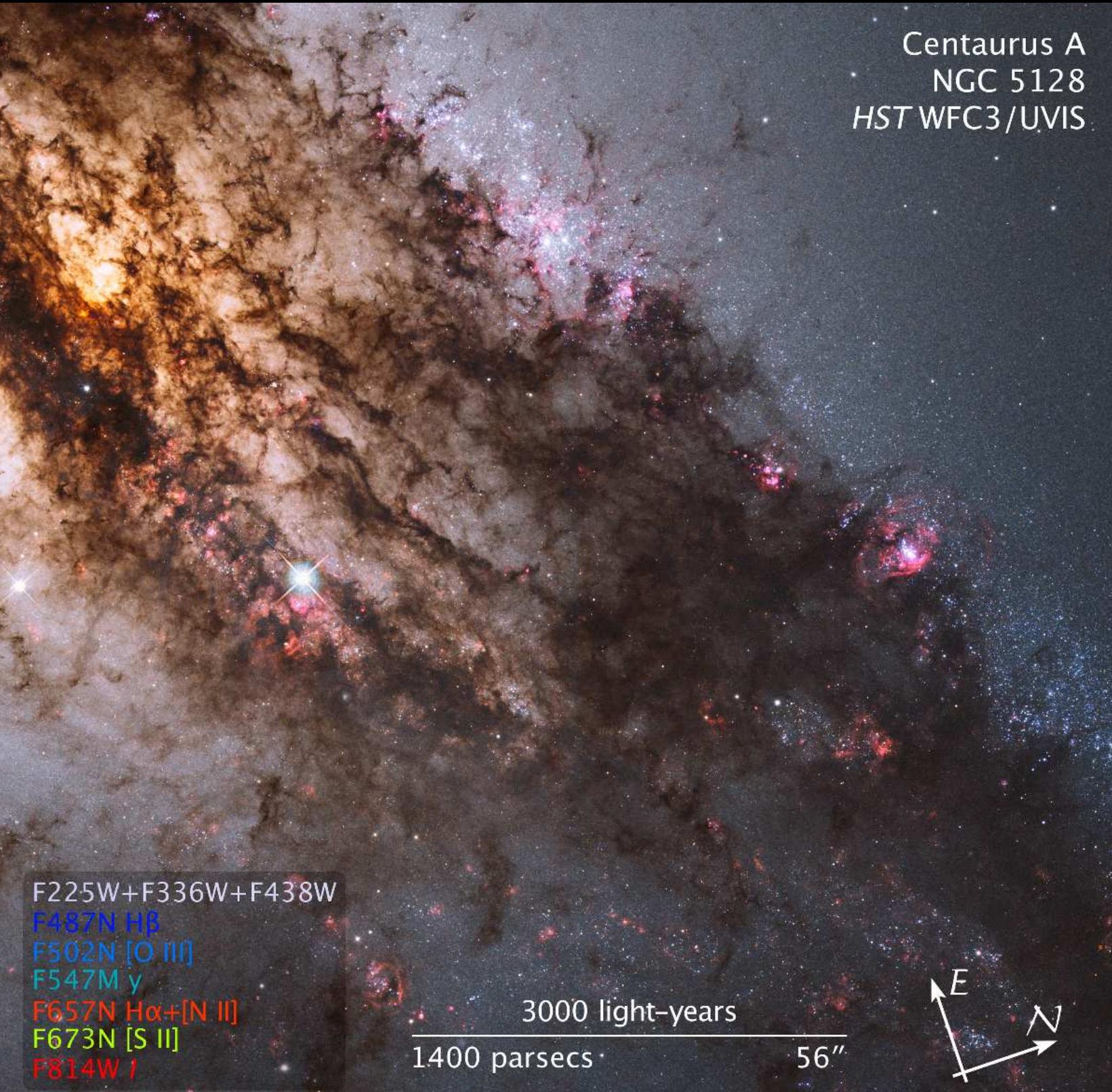
- (2) Measuring Galaxy Assembly and Supermassive Black-Hole Growth.

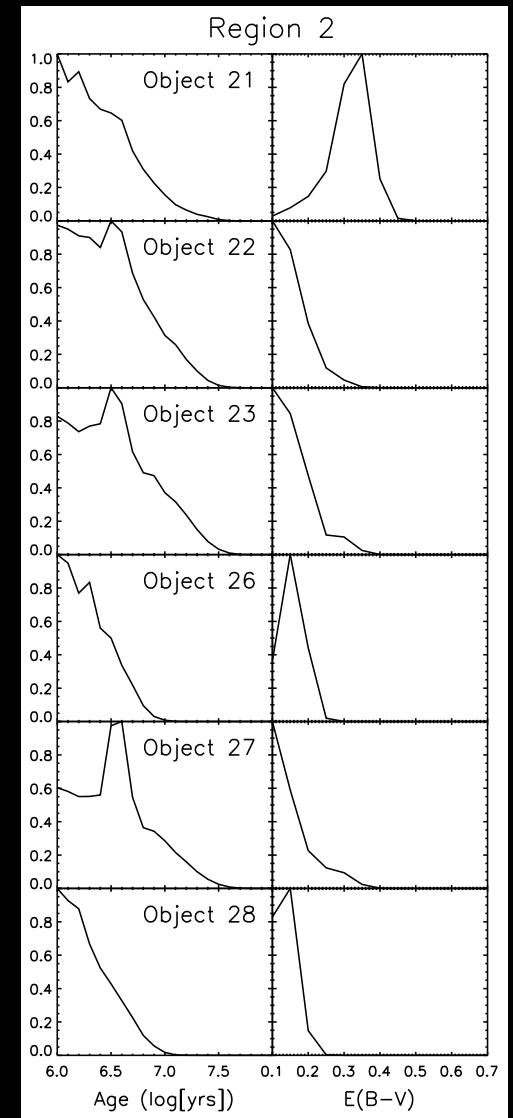
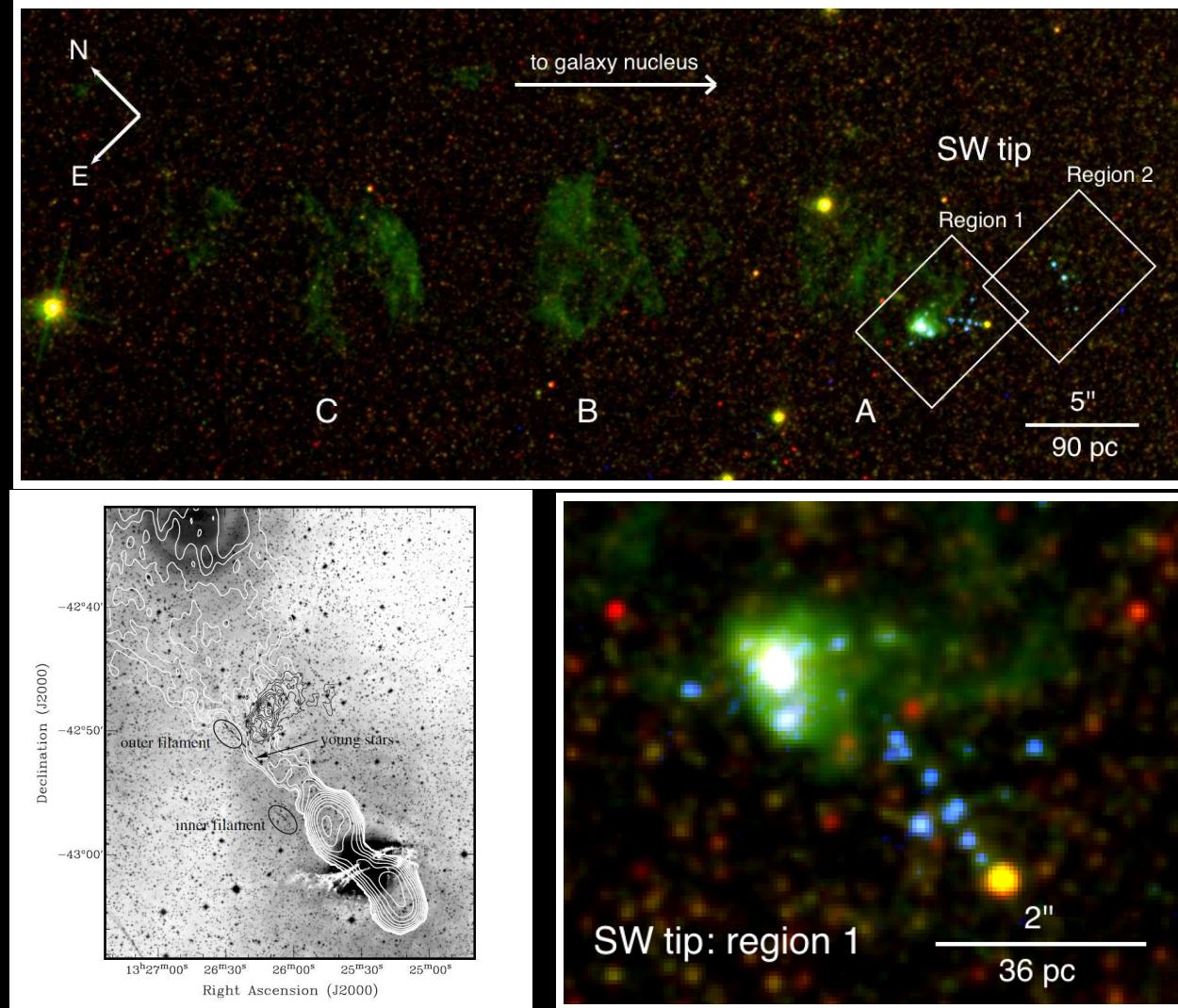


"For God's sake, Edwards. Put the laser pointer away."

The danger of having Quasar-like devices too close to home ...

Centaurus A
NGC 5128
HST WFC3/UVIS



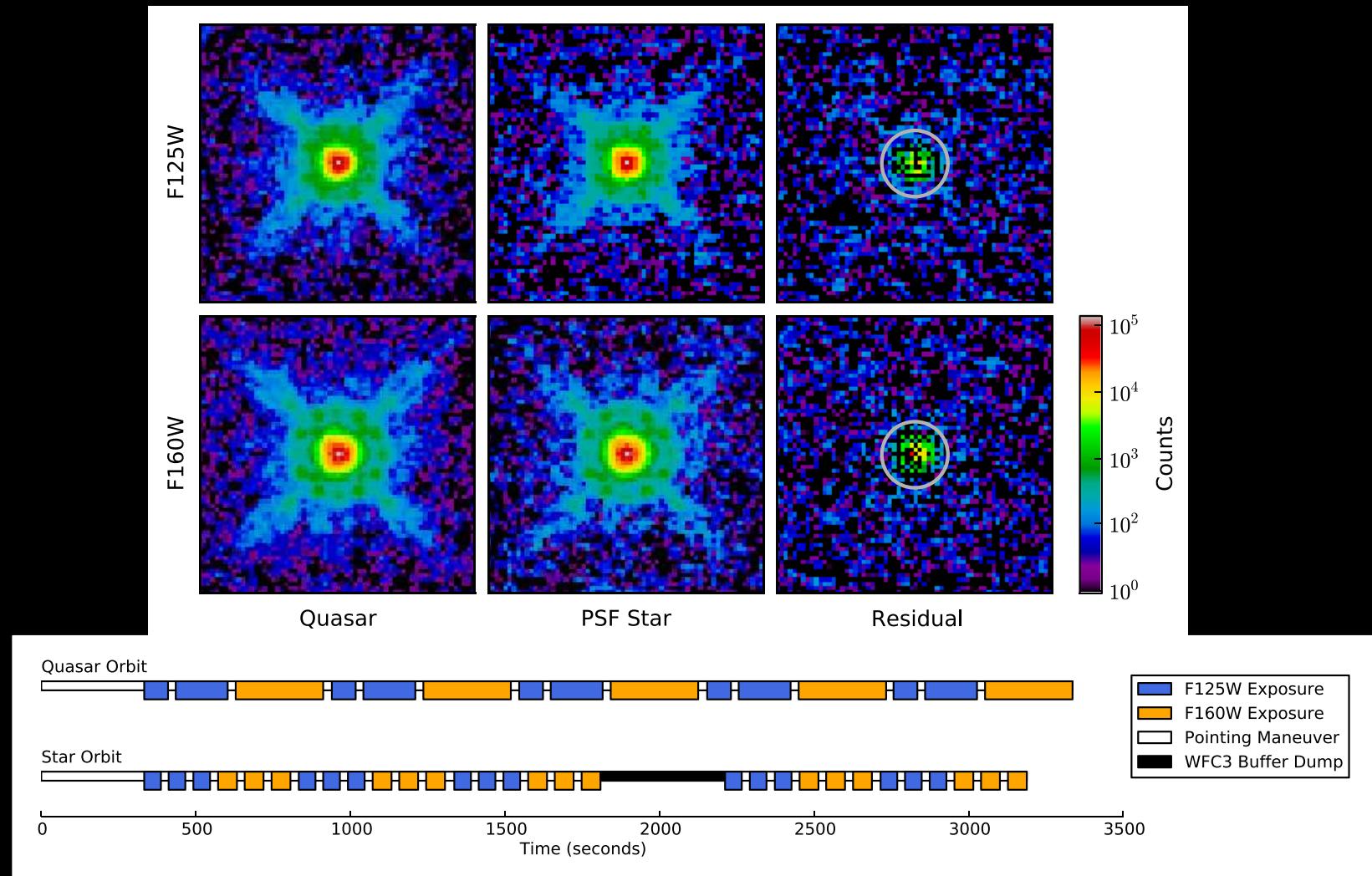


Well determined ages for young (~ 2 Myr) stars in Centaurus A jet with star-formation in jet's wake (Crockett et al. 2012, MNRAS, 421, 1602).

JWST will trace older stellar pops and SF in much dustier environments.

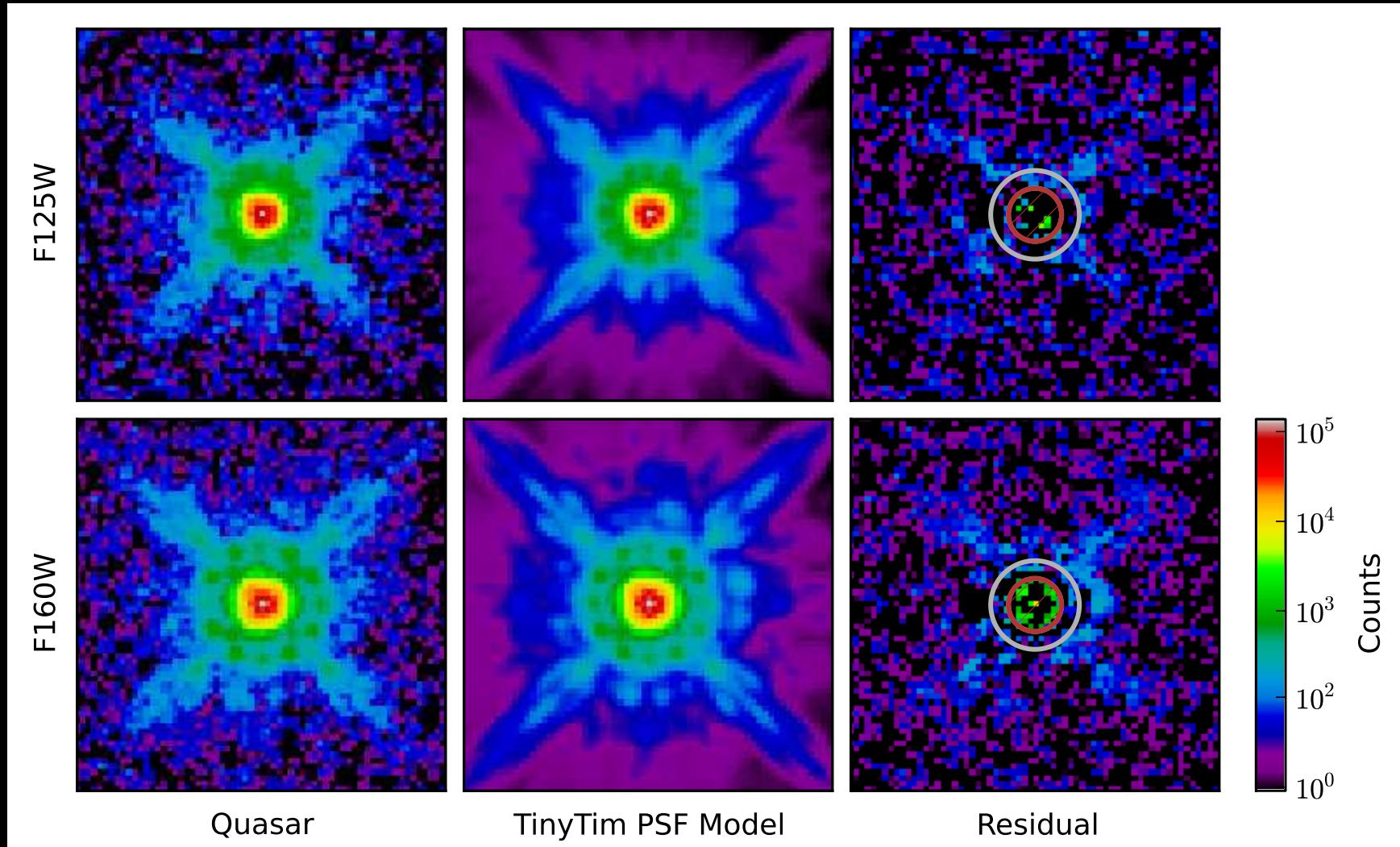
- We must do all we can with HST in UV–blue before JWST flies.

(2) HST WFC3 observations of Quasar Host Galaxies at $z \approx 6$ (age $\lesssim 1$ Gyr)



- Careful contemporaneous orbital PSF-star subtraction: Removes most of “OTA spacecraft breathing” effects (Mechtley ea 2012, ApJL, 756, L38)
- PSF-star (AB=15 mag) subtracts $z=6.42$ QSO (AB=19) nearly to the noise limit: NO host galaxy detected $100\times$ fainter (AB $\gtrsim 23.5$ mag at $r\gtrsim 0\farcs3$).

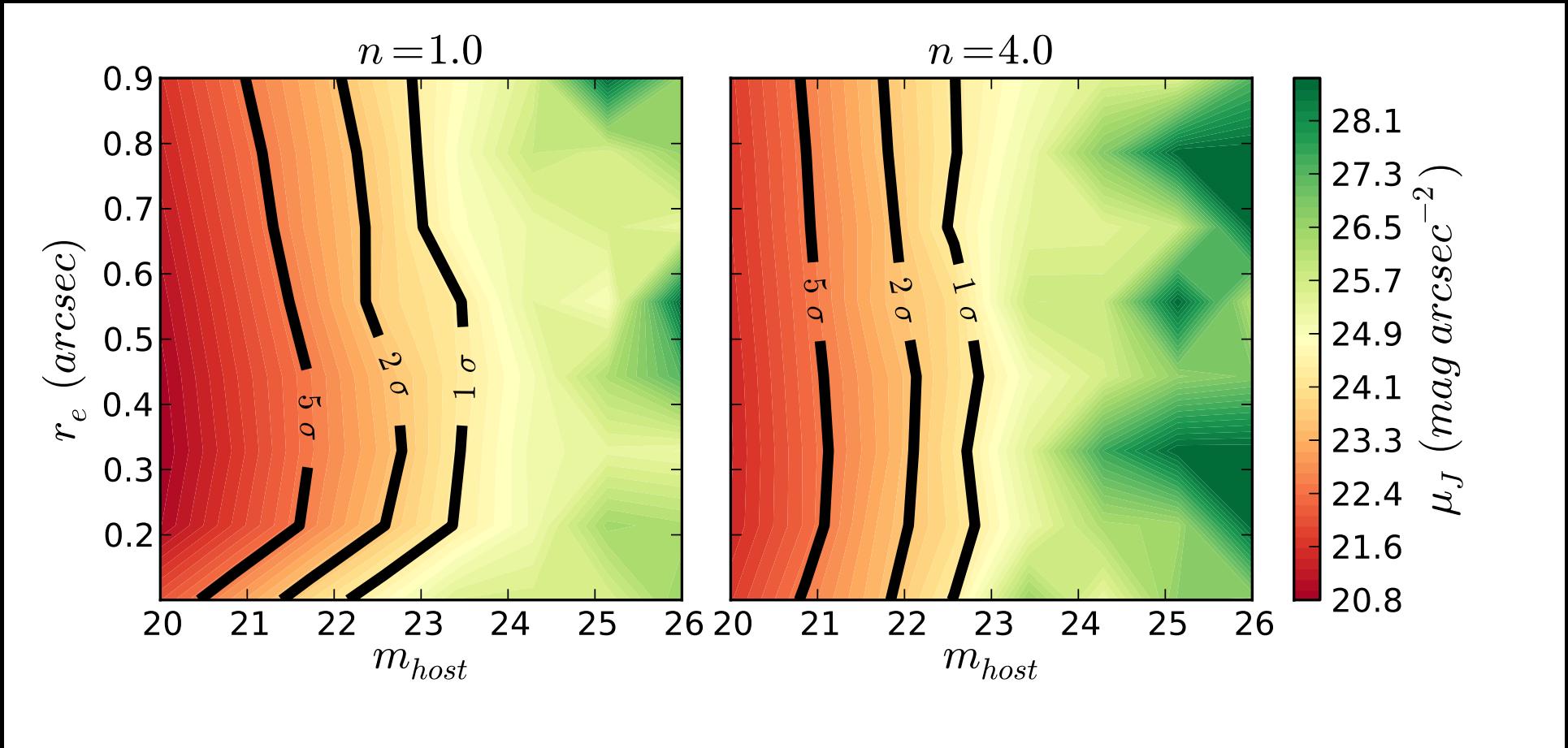
(2) HST WFC3 observations of Quasar Host Galaxies at $z \approx 6$ (age $\lesssim 1$ Gyr)



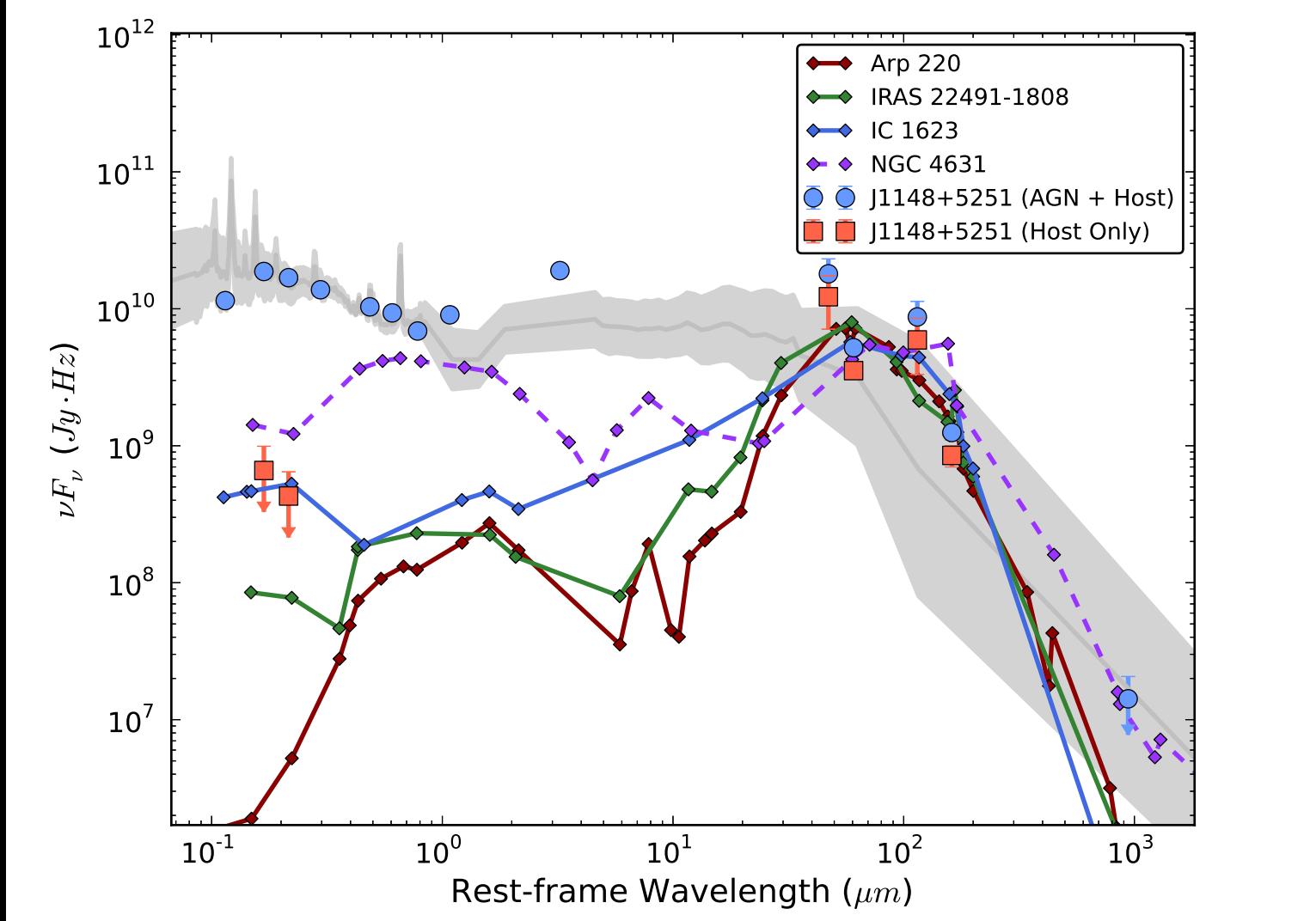
- TinyTim fit of PSF-star + GalFit models QSO nearly to the noise limit: NO $z=6.42$ host galaxy at $AB \gtrsim 23.5$ mag at radius $r \simeq 0\farcs3$ – $0\farcs5$.

THE most luminous Quasars in the Universe: Are all their host galaxies faint (dusty)? \Rightarrow Major implications for Galaxy Assembly–SMBH Growth.

(2) HST WFC3 observations of Quasar Host Galaxies at $z \approx 6$ (age $\lesssim 1$ Gyr)

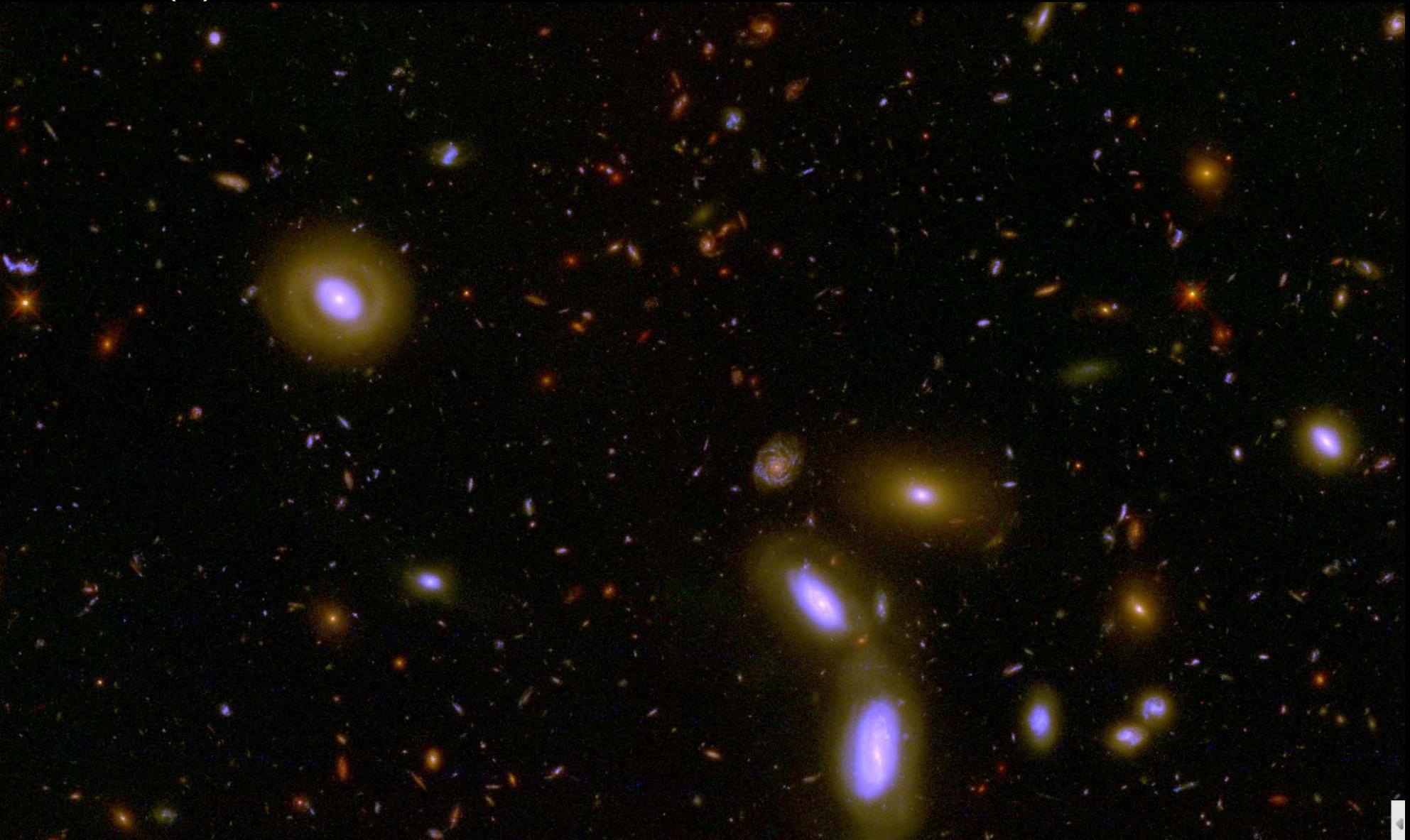


- TinyTim fit of PSF-star + GalFit models of galaxy light-profile, nearly to the noise limit: NO host galaxy at $\text{AB} \gtrsim 23.0$ mag with $r_e \simeq 0\farcs5$ (Mechtley et al. 2012, ApJL, 756, L23; astro-ph/1207.3283).
- JWST Coronagraphs can do this $10\text{--}100\times$ fainter (and for $z \lesssim 20$, $\lambda \lesssim 28\mu\text{m}$) — but need JWST diffraction limit at $2.0\mu\text{m}$ and clean PSF to do this.



- Blue dots: $z=6.42$ QSO SED, Grey: Average radio-quiet QSO spectrum at $z \lesssim 1$ (normalized at 0.5μ). Red: $z=6.42$ host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages $\lesssim 1$ Gyr) normalized at $100\mu\text{m}$: Rules out $z=6.42$ spiral or bluer host galaxy SEDs. (U)LIRGs permitted.
- JWST Coronagraphs can do this $10\text{--}100\times$ fainter (and for $z \lesssim 20$, $\lambda \lesssim 28\mu\text{m}$).

- (3) How will JWST measure the Epoch of Galaxy Assembly?



10 filters with HST/WFC3 & ACS reaching AB=26.5–27.0 mag (10- σ) over 40 arcmin² at 0.07–0.15" FWHM from 0.2–1.7 μ m (UVUBVizYJH). JWST adds 0.05–0.2" FWHM imaging to AB \simeq 31.5 mag (1 nJy) at 1–5 μ m, and 0.2–1.2" FWHM at 5–29 μ m, tracing young+old SEDs & dust.

Some science results of the Wide Field Camera Early Release Science data:



Galaxy structure at the peak of the merging epoch ($z \approx 1-2$) is very rich: some resemble the cosmological parameters H_0 , Ω , ρ_O , w , and Λ , resp.

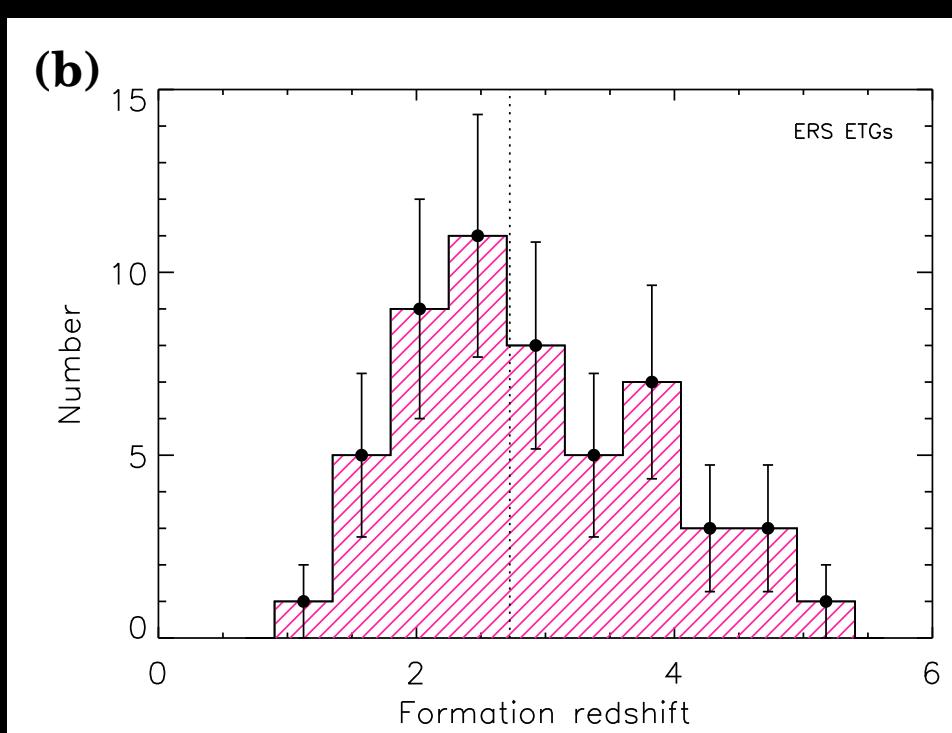
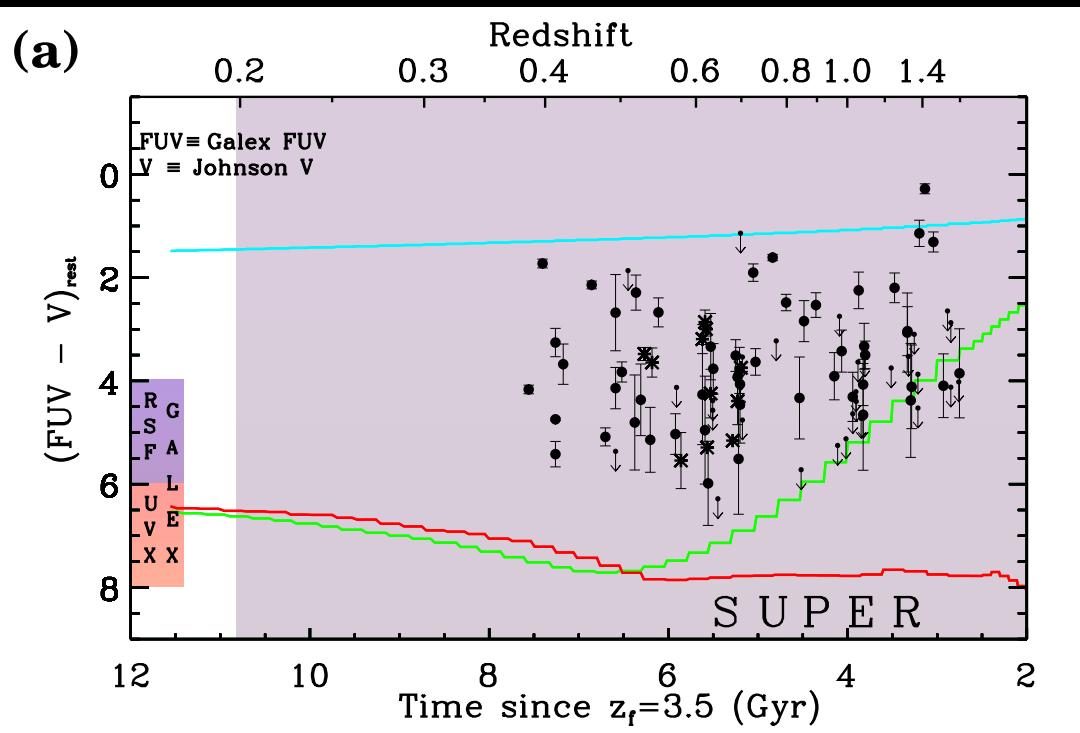


Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

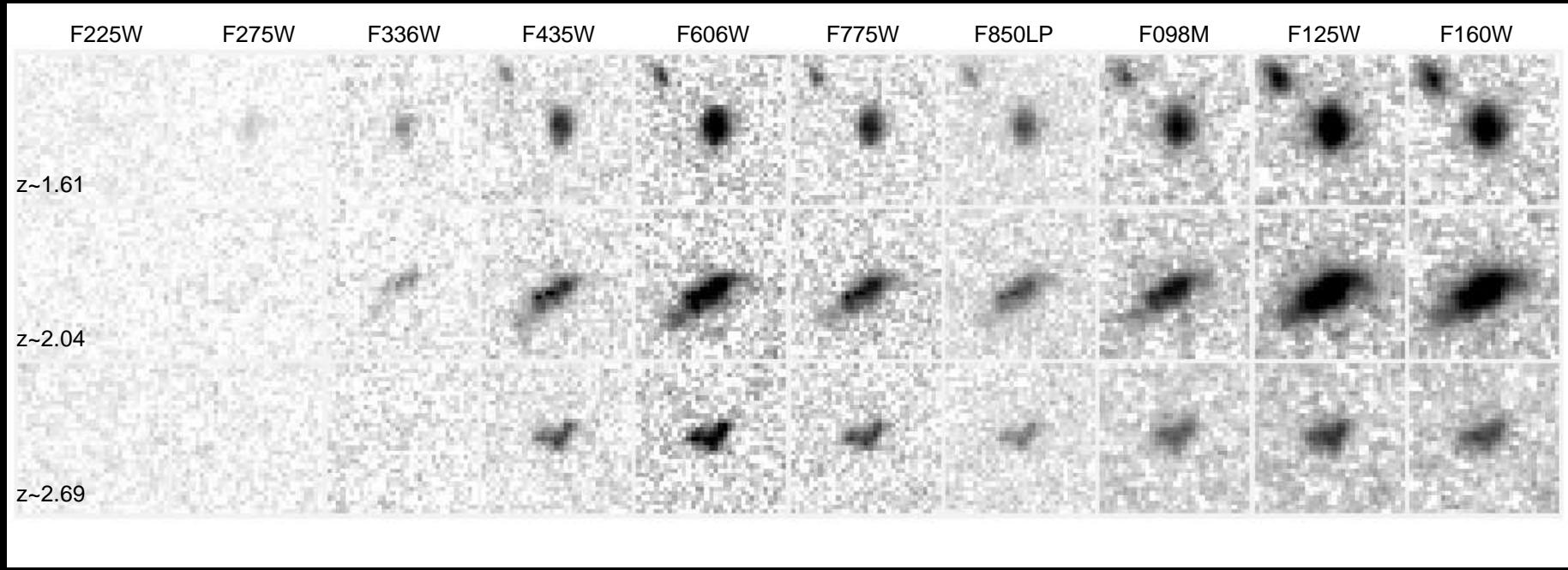
(Rutkowski ea. 2012 ApJS 199, 4) \Longrightarrow “Red & dead” galaxies aren’t dead!

- JWST will observe any such objects from 0.7–29 μm wavelength.

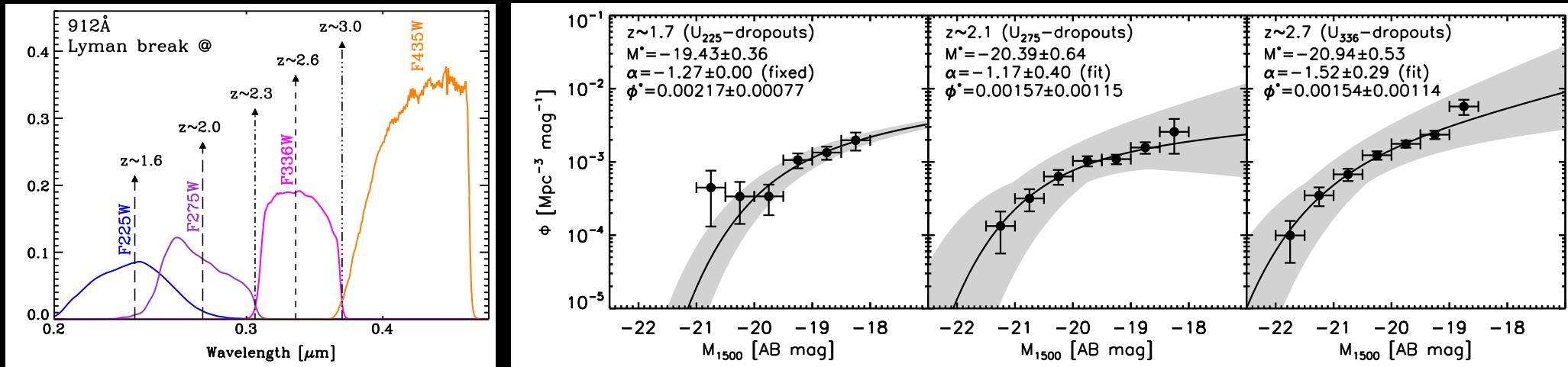
HST WFC3: Rest-frame UV-evolution of Early Type Galaxies since $z \lesssim 1.5$.



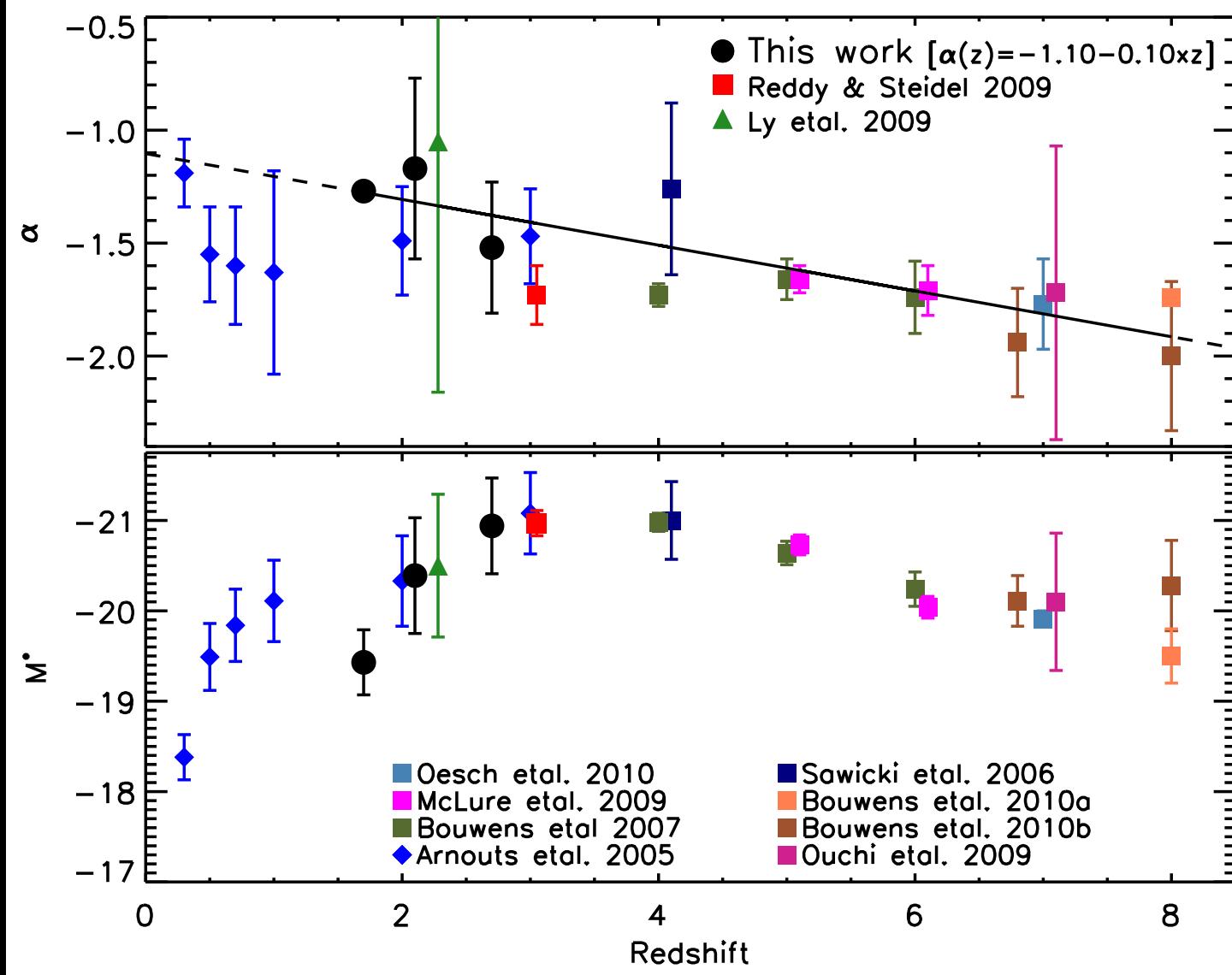
- 10-band WFC3 ERS data measured rest-frame UV-light in nearly all early-type galaxies at $0.3 \lesssim z \lesssim 1.5$ (Rutkowski et al. 2012, ApJS, 199, 4).
- ⇒ Most ETGs have continued residual star-formation after they form.
- Can determine their $N(z_{\text{form}})$, which resembles the cosmic SFH diagram (e.g., Madau et al. 1996). This can directly constrain the process of galaxy assembly and down-sizing (Kaviraj, Rutkowski et al. 2012, MNRAS).
- JWST can measure with Balmer+4000Å-break ages to $z \lesssim 11$.



Lyman break galaxies at the peak of cosmic SF ($z \simeq 1-3$; Hathi et al. 2010)

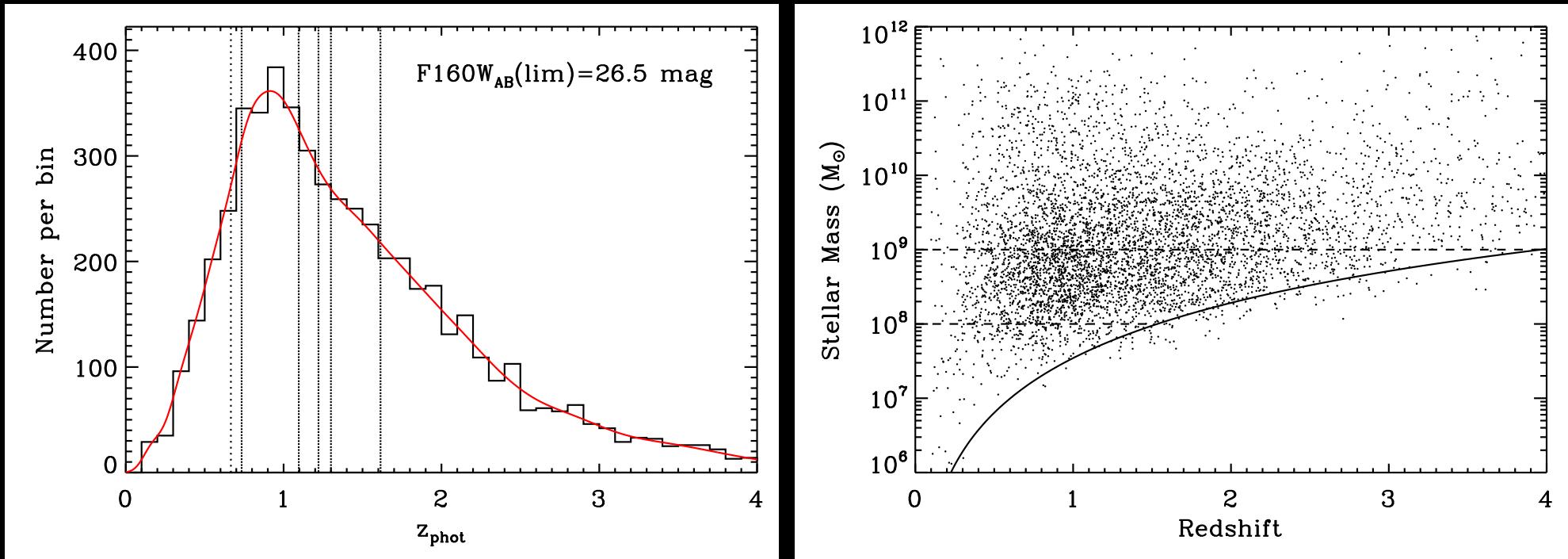


- JWST will similarly measure faint-end LF-slope evolution for $1 \lesssim z \lesssim 12$.
(e.g., Bouwens et al. 2010; Hathi et al. 2012, 2012; Oesch et al. 2010).



Measured faint-end LF slope evolution (top) and characteristic luminosity evolution (bottom) from Hathi et al. 2010 (ApJ, 720, 1708).

- In the JWST regime at $z \gtrsim 8$, expect faint-end LF slope $\alpha \simeq 2.0$.
 - In the JWST regime at $z \gtrsim 8$, expect characteristic luminosity $M^* \gtrsim -19$.
- ⇒ Could have critical consequences for gravitational lensing bias at $z \gtrsim 10$.



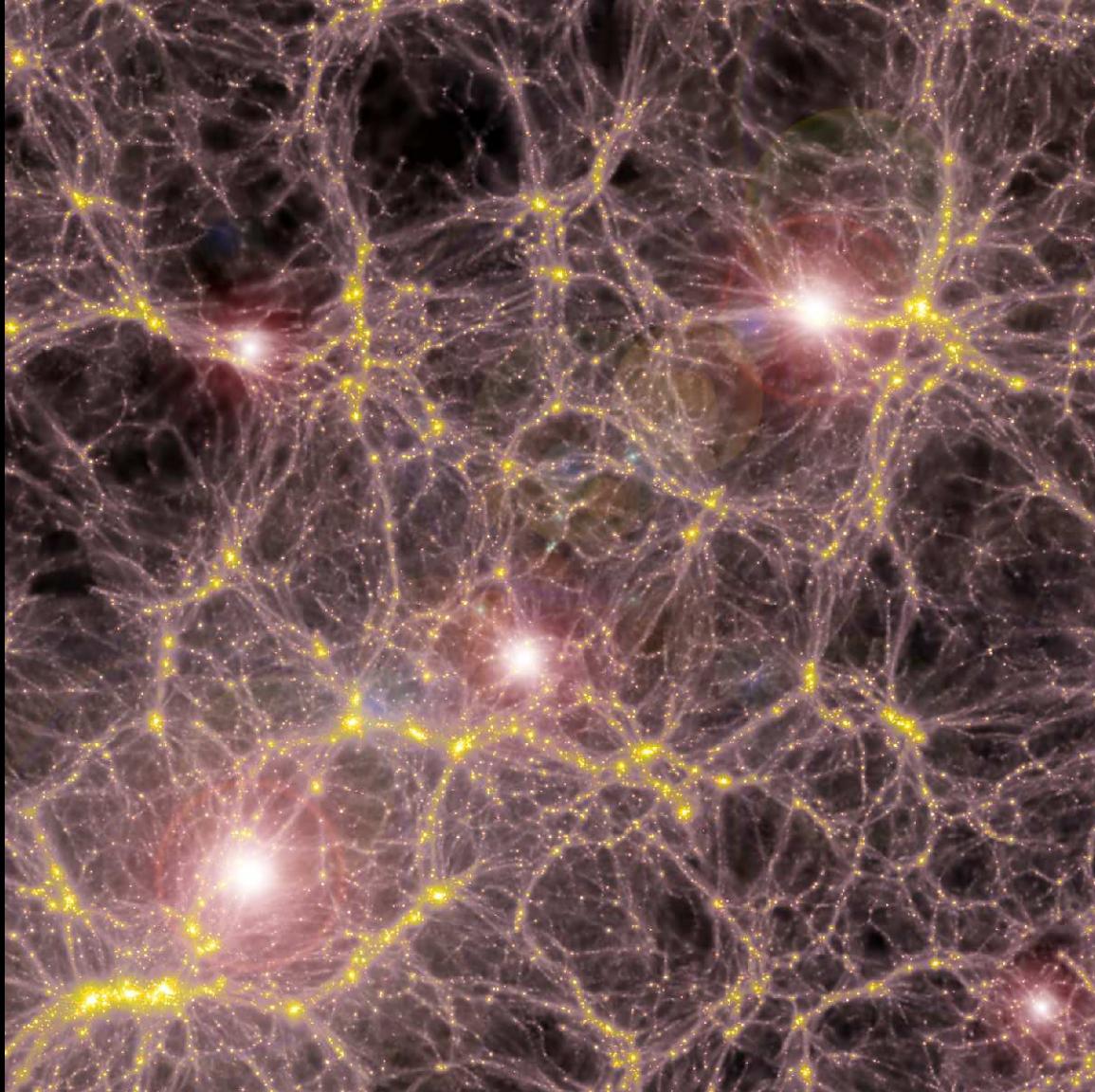
WFC3 ERS 10-band redshift estimates accurate to $\lesssim 4\%$ with small systematic errors (Hathi et al. 2010, 2012), resulting in a reliable $N(z)$.

- Measure masses of faint galaxies to AB=26.5 mag, tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?).

ERS shows WFC3's new panchromatic capabilities on galaxies at $z \simeq 0-7$.

- HUDF shows WFC3 $z \simeq 7-9$ capabilities (Bouwens⁺ 2010; Yan⁺ 2010).
- WFC3 is an essential pathfinder at $z \lesssim 8$ for JWST (0.7–29 μm) at $z \gtrsim 9$.
- JWST will trace mass assembly and dust content 3–4 mags deeper from $z \simeq 1-12$, with nanoJy sensitivity from 0.7–5 μm .

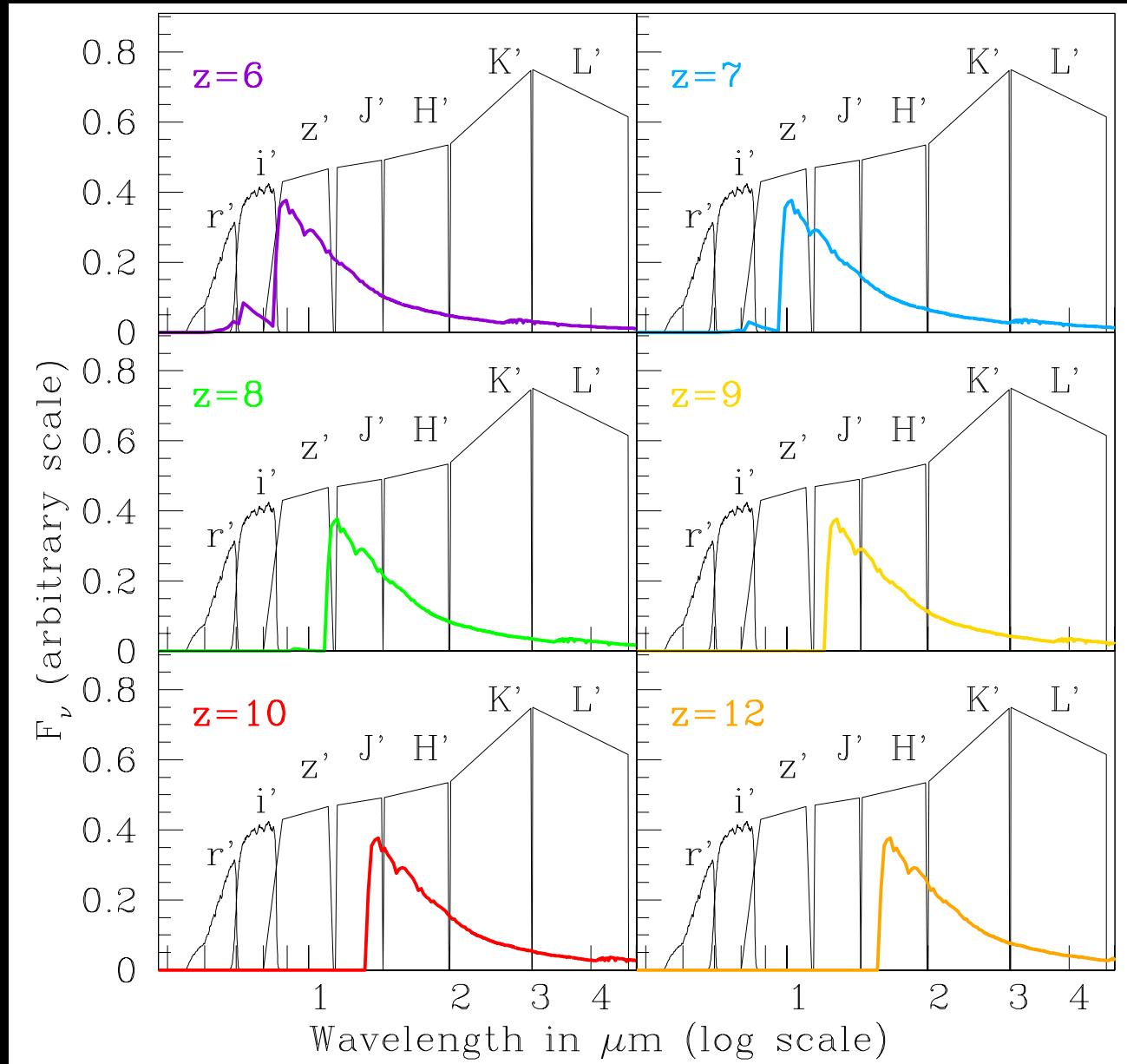
(4) How will JWST Observe First Light and Reionization?



- Detailed Hydrodynamical models (e.g., V. Bromm) suggest that massive Pop III stars may have reionized universe at redshifts $z \lesssim 10-30$ (First Light).
- This should be visible to JWST as the first Pop III stars and surrounding (Pop II.5) star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10 \rightarrow 30$.

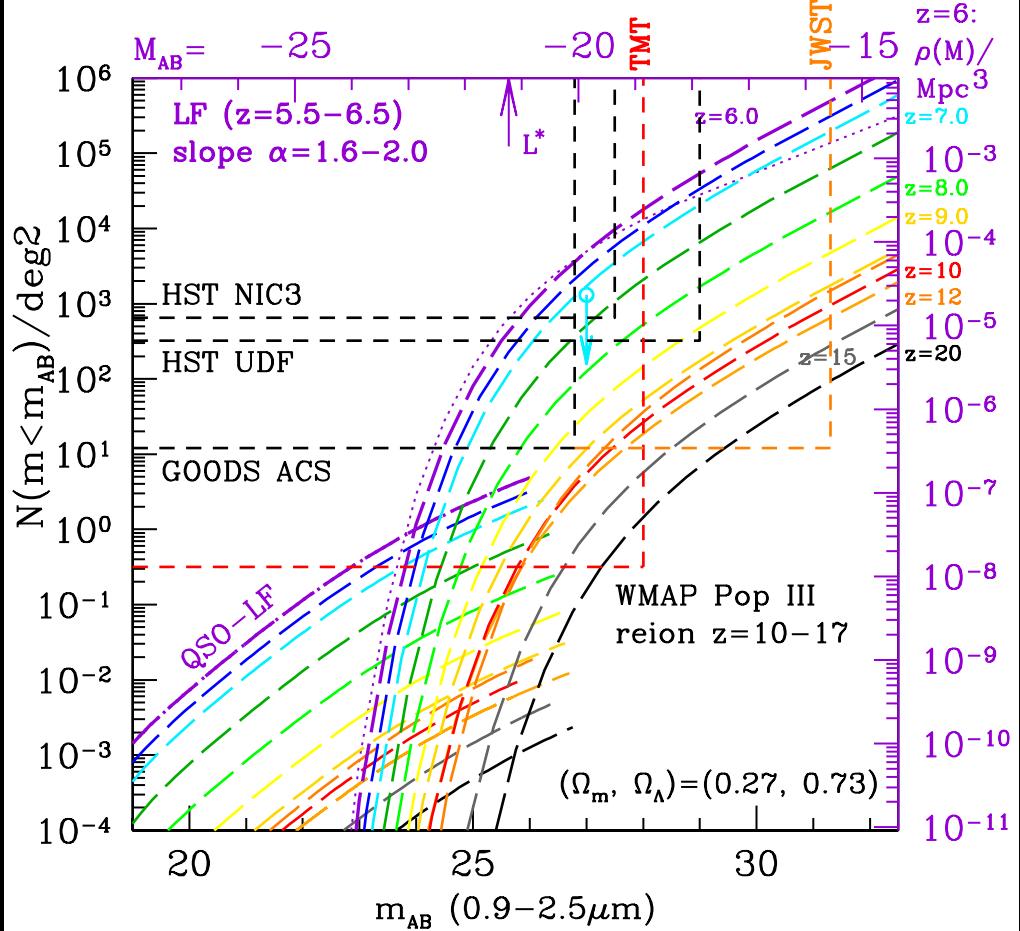
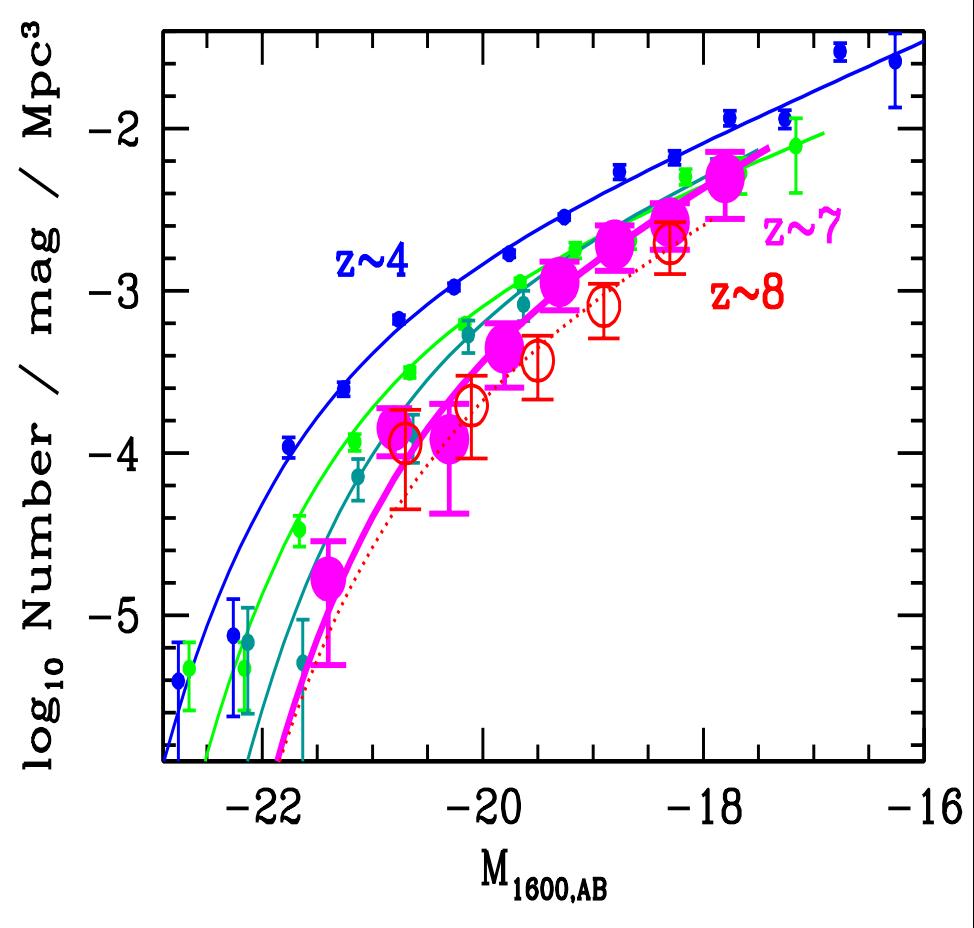
We must make sure we theoretically understand the likely Pop III mass-range, their IMF, their duplicity and clustering properties, their SN-rates, etc.

(4) How will JWST measure First Light & Reionization?

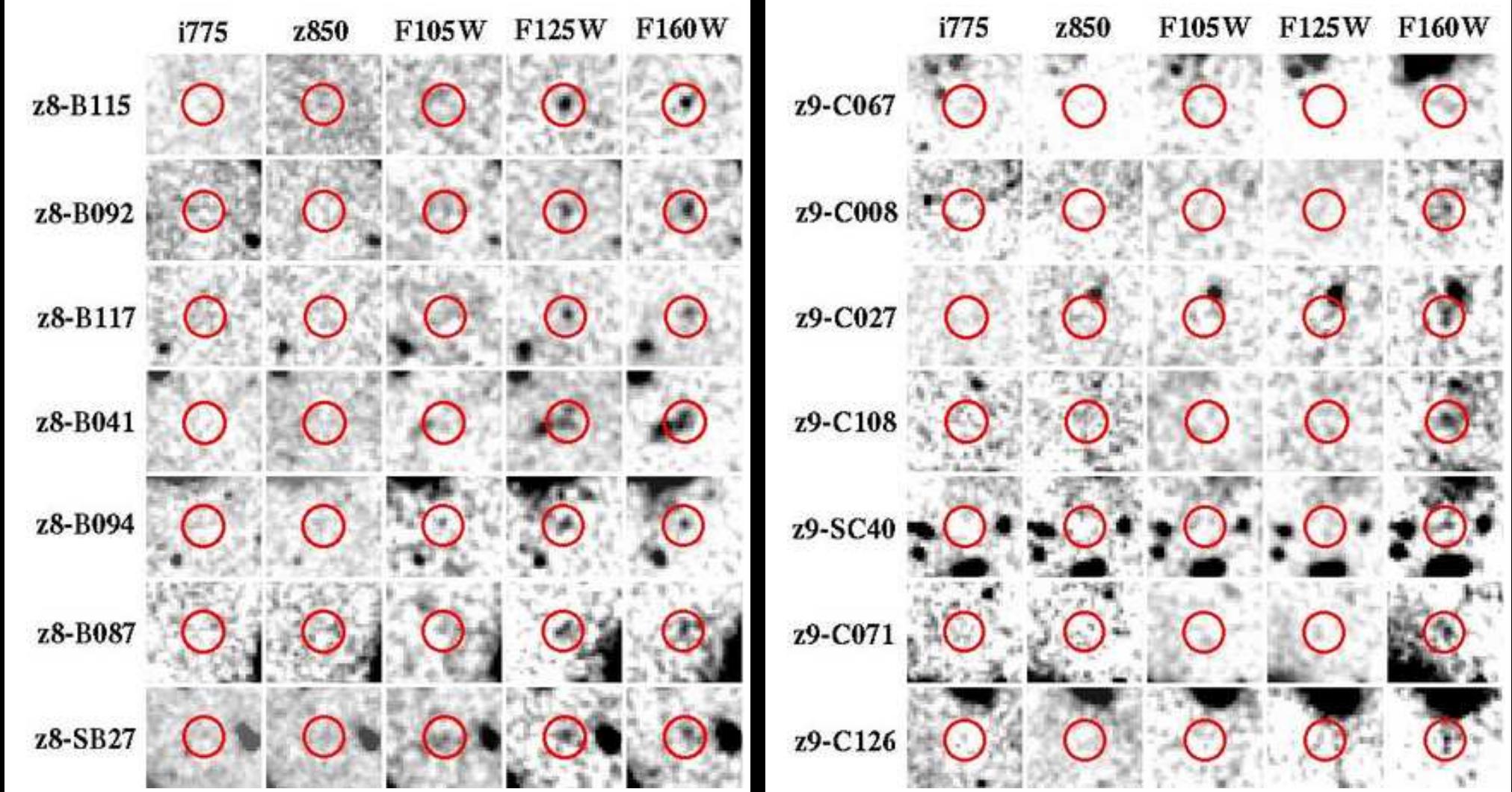


- Can't beat redshift: to see First Light, must observe near–mid IR.
⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm .

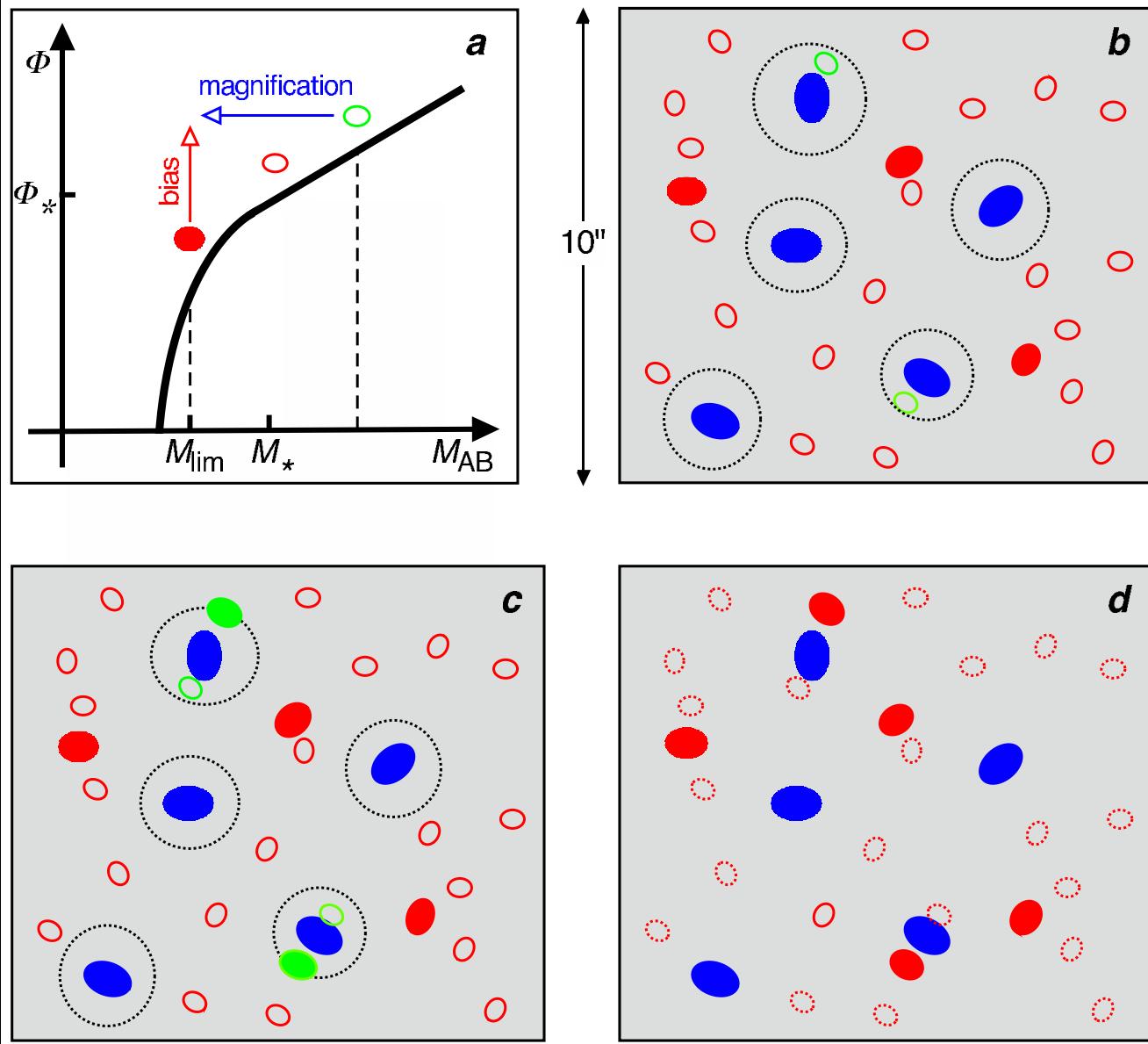




- Objects at $z \gtrsim 9$ are rare (Bouwens⁺ 10; Trenti,⁺ 10; Yan⁺ 10), since volume elt is small, and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ -range (0.7-29 μm).
- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects at $z \lesssim 20$.
- JWST Coronagraphs can also trace super-massive black-holes as faint quasars in young galaxies: JWST needs 2.0 μm diffraction limit for this.

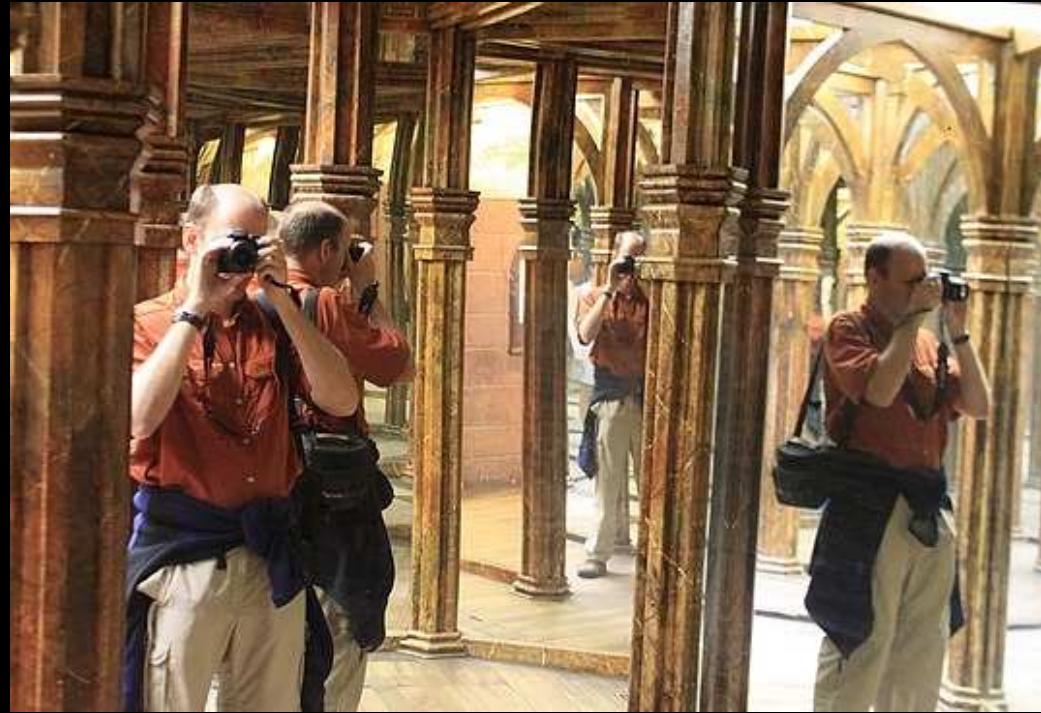


- \sim 10–40% of the HUDF Y-drops and J-drops appear close to bright galaxies (Yan et al. 2010, Res. A.& Ap., 10, 867); see Haojing's talk.
- Expected from gravitational lensing bias by galaxy dark matter halo distribution at $z \approx 1$ –2 (Wyithe et al. 2011, Nature, 469, 181).
- Need JWST to measure $z \approx 9$ –15 LFs, and see if fundamentally different from $z \lesssim 8$. Does gravitational lensing bias boost LF bright-end?



Hard to see the forest for the trees in the first 0.5 Gyrs?:

- Foreground galaxies ($z \simeq 1-2$ or age $\simeq 3-6$ Gyr) may gravitationally lens or amplify galaxies at $z \gtrsim 8-10$ (cosmic age $\lesssim 0.5$ Gyr; Wyithe et al. 2011).
- This could change the landscape for JWST observing strategies.



Two fundamental limitations determine ultimate JWST image depth:

- (1) Cannot-see-the-forest-for-the-trees effect: Background objects blend into foreground neighbors \Rightarrow Need multi- λ deblending algorithms!
 - (2) House-of-mirrors effect: (Many?) First Light objects can be gravitationally lensed by foreground galaxies \Rightarrow Must model/correct for this!
- Proper JWST 2.0 μm PSF and straylight specs essential to handle this.

(5) Conclusions



Prof. Fang started a lot of fireworks, both in astrophysics and in China ...

He inspired next generation of students to build modern astrophysics in China!

(5) Conclusions

(1) HST set stage to measure galaxy assembly in the last 12.7-13.0 Gyrs.

(2) JWST passed Preliminary & Critical Design Reviews in 2008 & 2010.

Management replan in 2010-2011. No technical showstoppers thus far:

- More than 75% of JWST H/W built or in fab, & meets/exceeds specs.

(3) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly & SMBH-growth in detail. JWST will determine:

- Formation and evolution of the first star-clusters after 0.2 Gyr.
- How dwarf galaxies formed and reionized the Universe after 1 Gyr.
- Galaxy Assembly and Super-Massive Black-Hole Growth for $z \lesssim 7-12$.

(4) JWST will have a major impact on astrophysics this decade:

- IR sequel to HST after 2018: Training the next generation researchers.
- JWST helps define next frontier to explore: the Dark Ages at $z \gtrsim 20$.

SPARE CHARTS

- References and other sources of material shown:

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

<http://www.asu.edu/clas/hst/www/ahah/> [Hubble at Hyperspeed Java-tool]

<http://www.asu.edu/clas/hst/www/jwst/clickonHUDF/> [Clickable HUDF map]

<http://www.jwst.nasa.gov/> & <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/fgs>

Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

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

Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

(4) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1-15$

NGC 3310



ESO0418-008



UGC06471-2



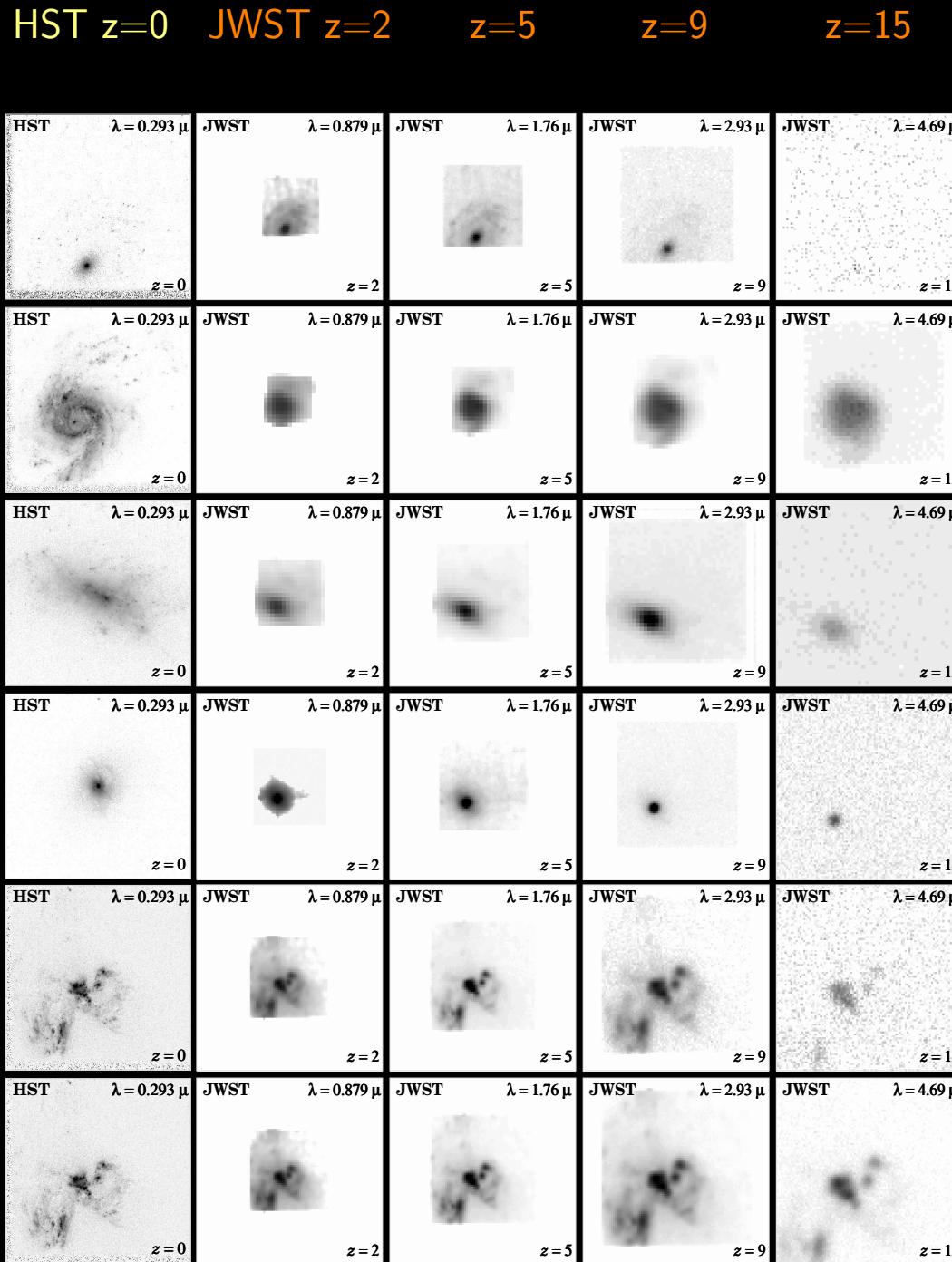
Ultraviolet Galaxies

NASA and R. Windhorst (Arizona State University) • STScI-PRC01-04

HST • WFPC2

- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).
- High-resolution HST ultraviolet images are benchmarks for comparison with very high redshift galaxies seen by JWST.

(4) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1-15$

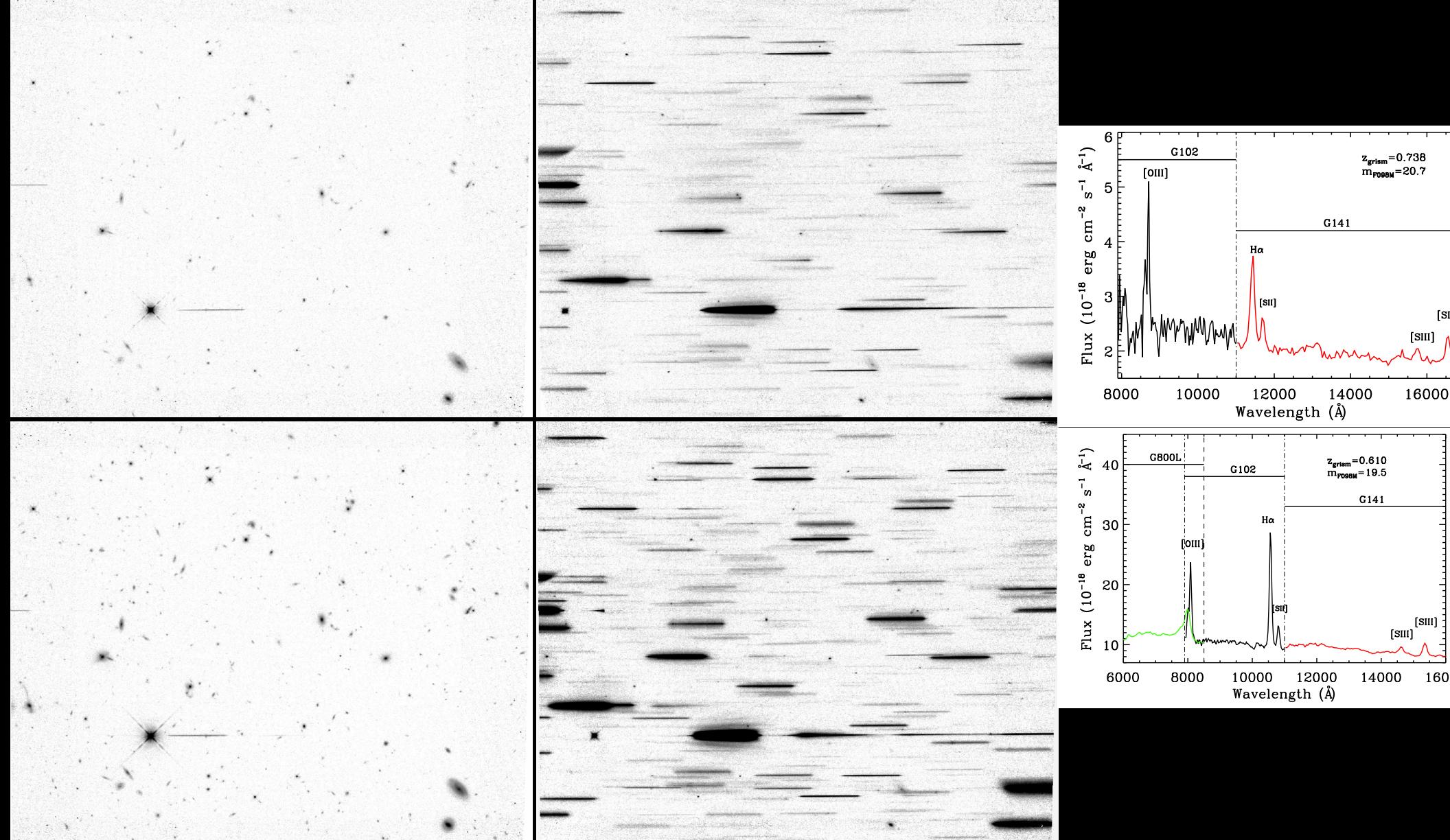


With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

- (1) Most spiral disks will dim away at high redshift, but most formed at $z \lesssim 1-2$.

Visible to JWST at very high z are:

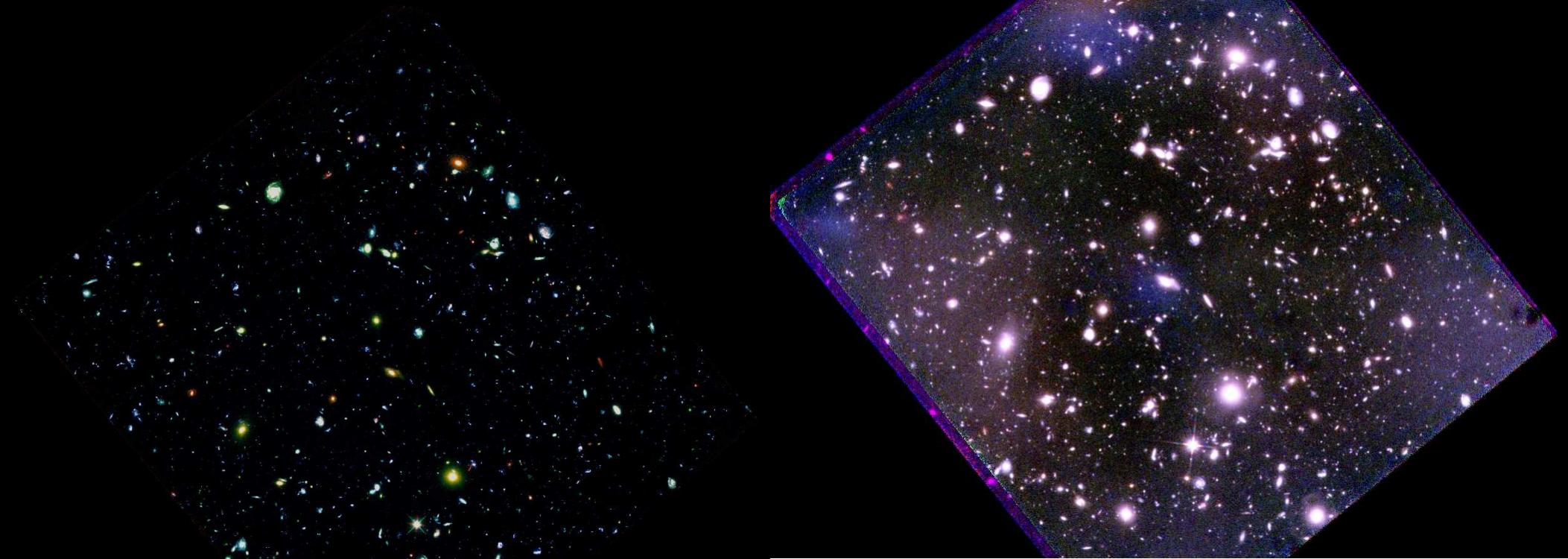
- (2) Compact star-forming objects (dwarf galaxies).
- (3) Point sources (QSOs).
- (4) Compact mergers & train-wrecks.



HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn⁺ 2010)

IR grism spectra from space: unprecedented new opportunities in astrophysics.

- JWST will provide near-IR grism spectra to AB $\lesssim 29$ mag from 2–5.0 μm .



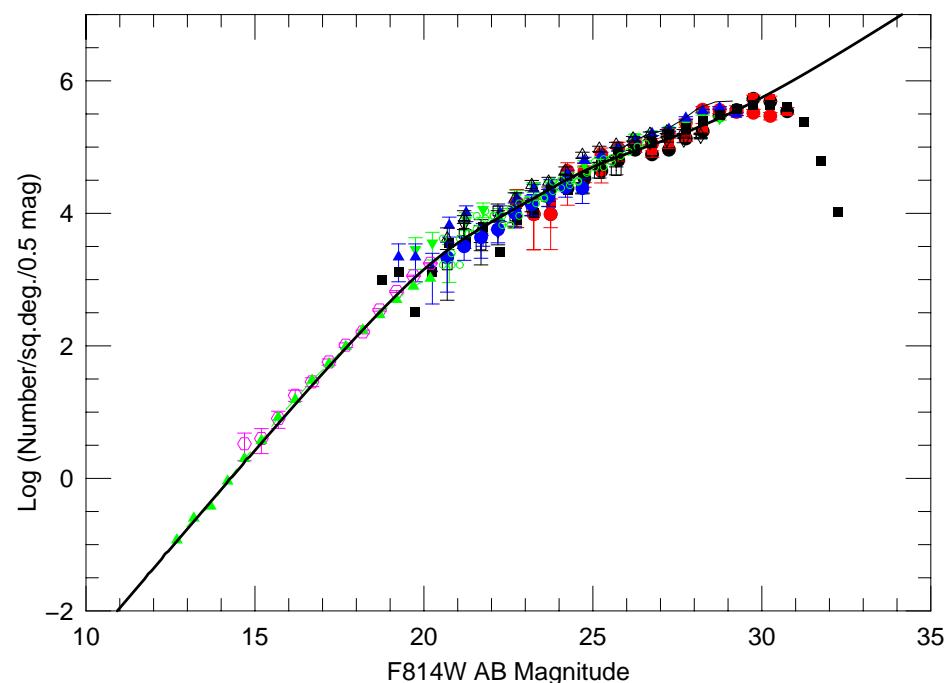
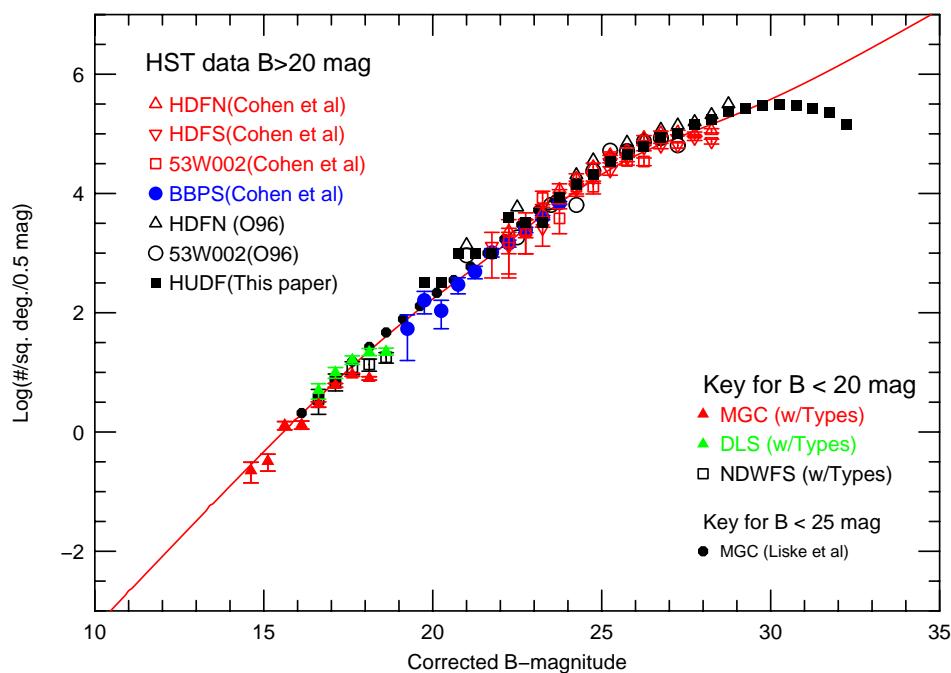
(Left) 128-hr HST/WFC3 IR-mosaic in HUDF at $1\text{--}1.6\mu\text{m}$ (YJH filters; Bouwens et al 2010, Yan et al. 2010; +85-hr by R. Ellis in 09/2012).

(Right) Same WFC3 IR-mosaic, but stretched to $\lesssim 10^{-3}$ of Zodical sky!

- The CLOSED-TUBE HST has residual low-level systematics: Imperfect removal of detector artifacts, flat-fielding errors, and/or faint straylight.

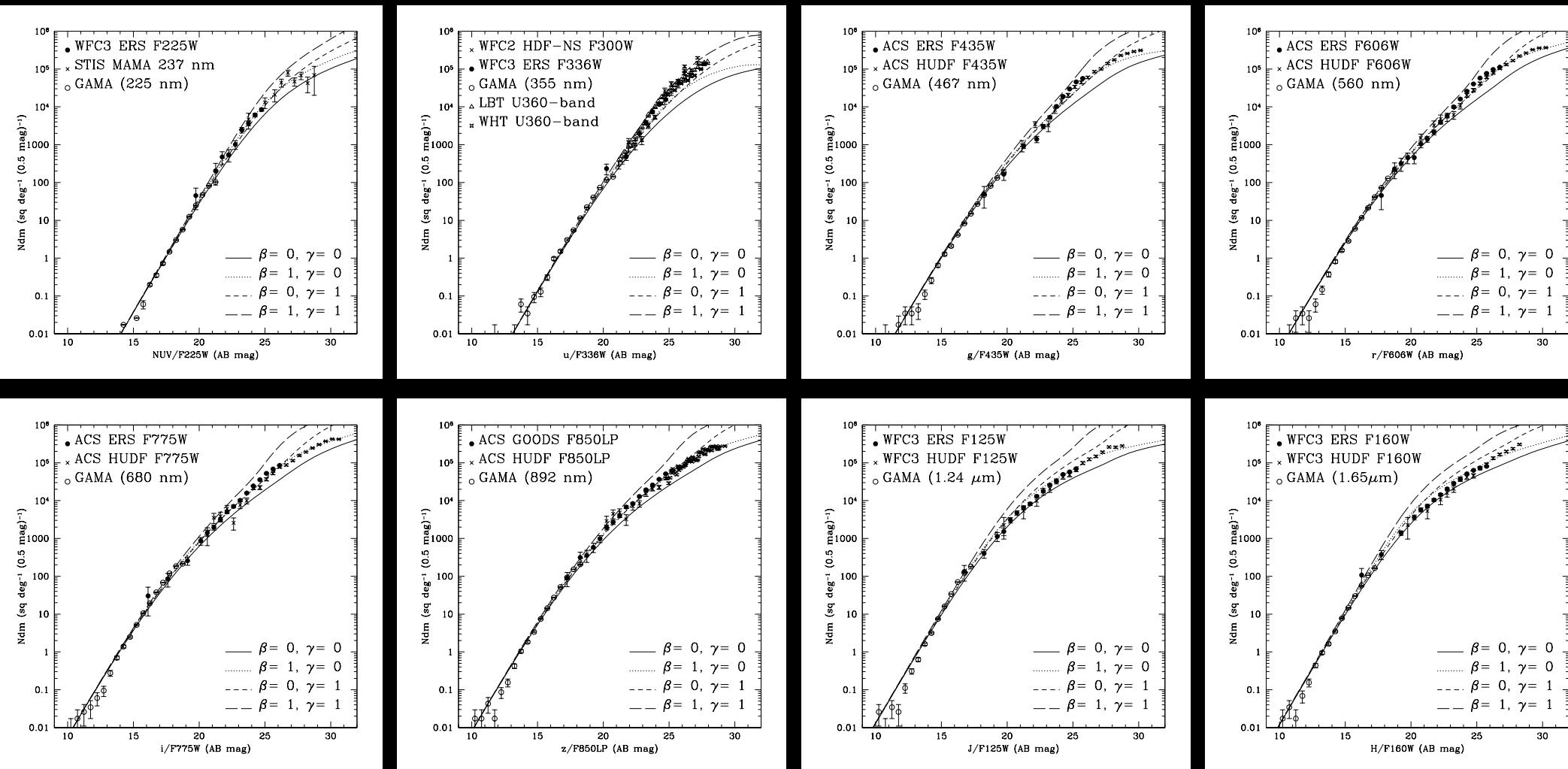
⇒ The open JWST architecture needs very good baffling and rogue path mitigation to do ultradeep JWST fields (JUDF's) to 10^{-4} of sky.

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

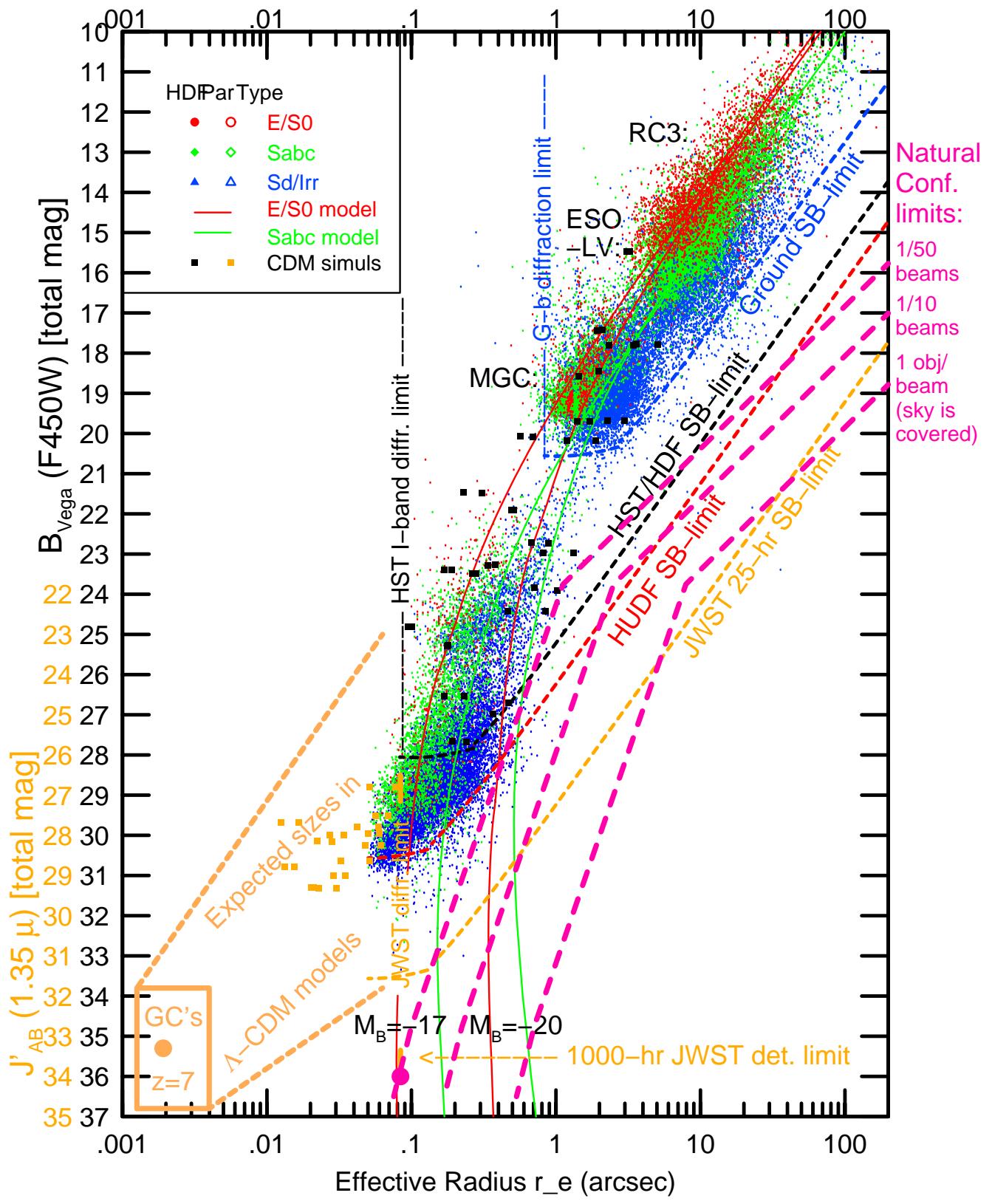


- HUDF galaxy counts (Cohen et al. 2006): expect an integral of $\gtrsim 2 \times 10^6$ galaxies/ deg^2 to AB=31.5 mag ($\simeq 1$ nJy at optical wavelengths). JWST and SKA will see similar surface densities to $\simeq 1$ and 10 nJy, resp.
- ⇒ Must carry out JWST and SKA nJy-surveys with sufficient spatial resolution to avoid object confusion (from HST: this means FWHM $\lesssim 0\farcs08$).
- ⇒ Observe with JWST/NIRSpec/MSA and SKA HI line channels, to disentangle overlapping continuum sources in redshifts space.

Panchromatic Galaxy Counts from $\lambda \simeq 0.2$ – $2\mu\text{m}$ for AB \simeq 10–30 mag



Data: GALEX, ground-based GAMA, HST ERS ACS+WFC3 + HUDF ACS+WFC3 (e.g., Windhorst et al. 2011, ApJS 193, 27):
 Filters: F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F098M/F105W, F125W, F160W.
 • No single Lum.+Dens evol model fits over 1 dex in λ and 8 dex in flux.



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

- (1) Apparent galaxy sizes decline from the RC3 to the HDF 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 causing 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. 2008, Advances in Space Research, Vol. 41, 1965, (astro-ph/0703171) “High Resolution Science with High Redshift Galaxies”