How will JWST measure First Light, Galaxy Assembly & Supermassive Blackhole Growth: New Frontier after HST

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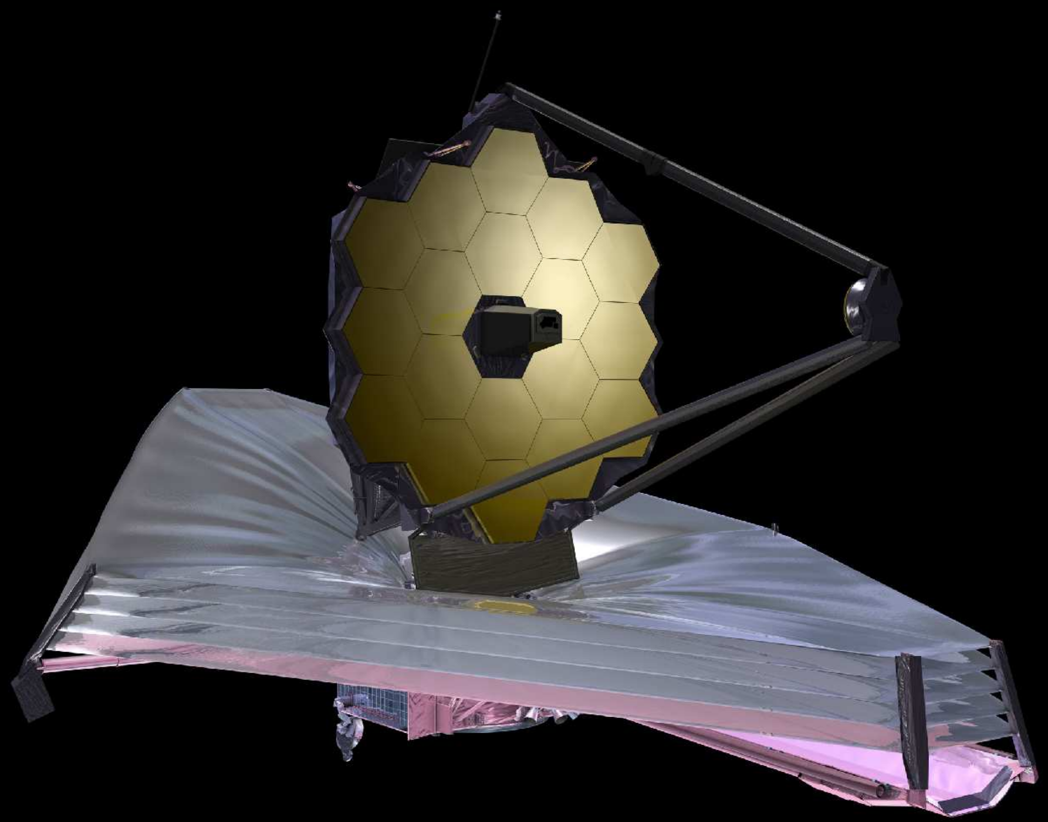


Invited Review at the IAU XXVIII General Assembly — Special Session 9 on "Future Large Scale Facilities"

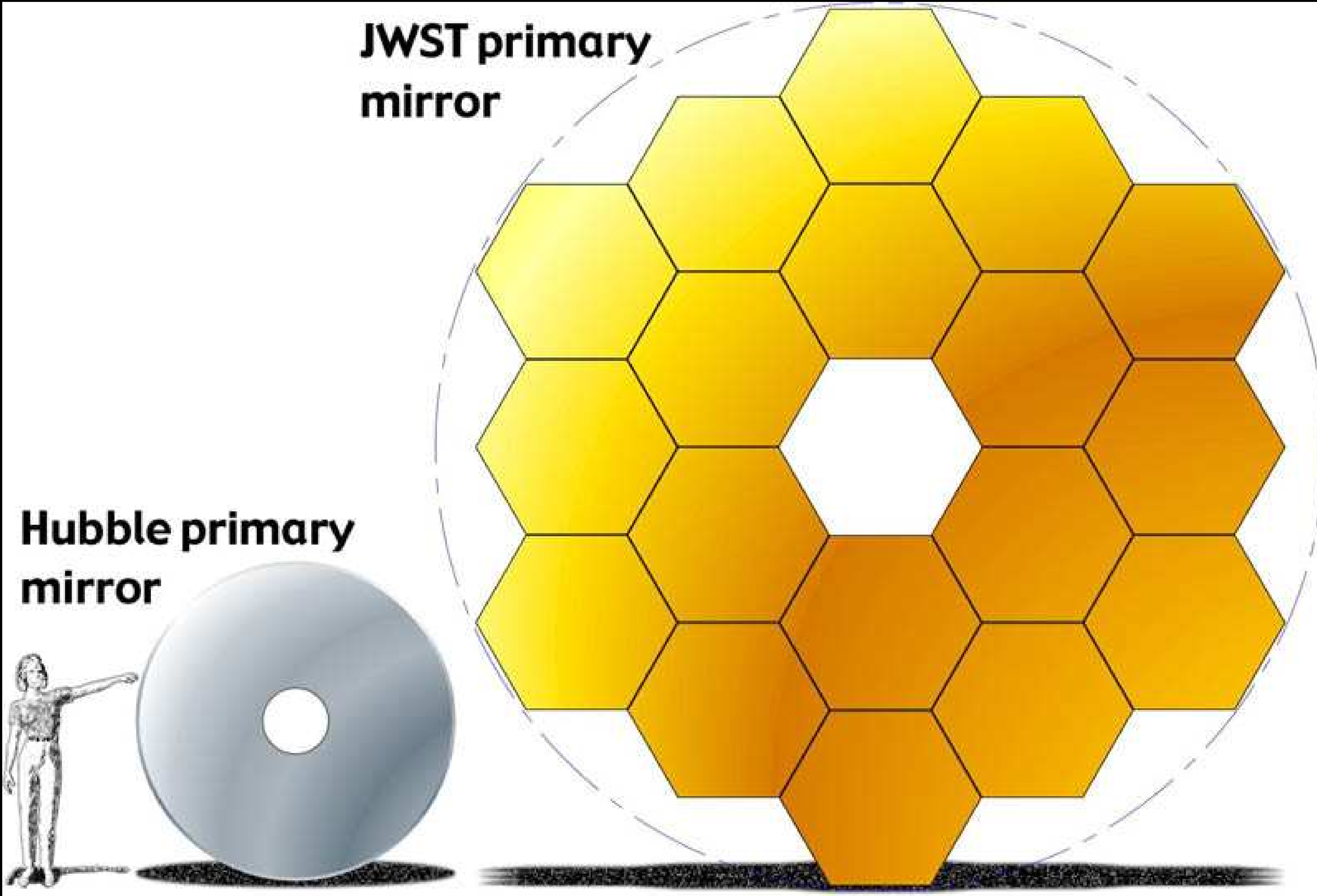
Beijing, China, Tuesday Aug. 28, 2012 — All presented materials are ITAR-cleared. These are my opinions only, not ASU's.

Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).

Outline

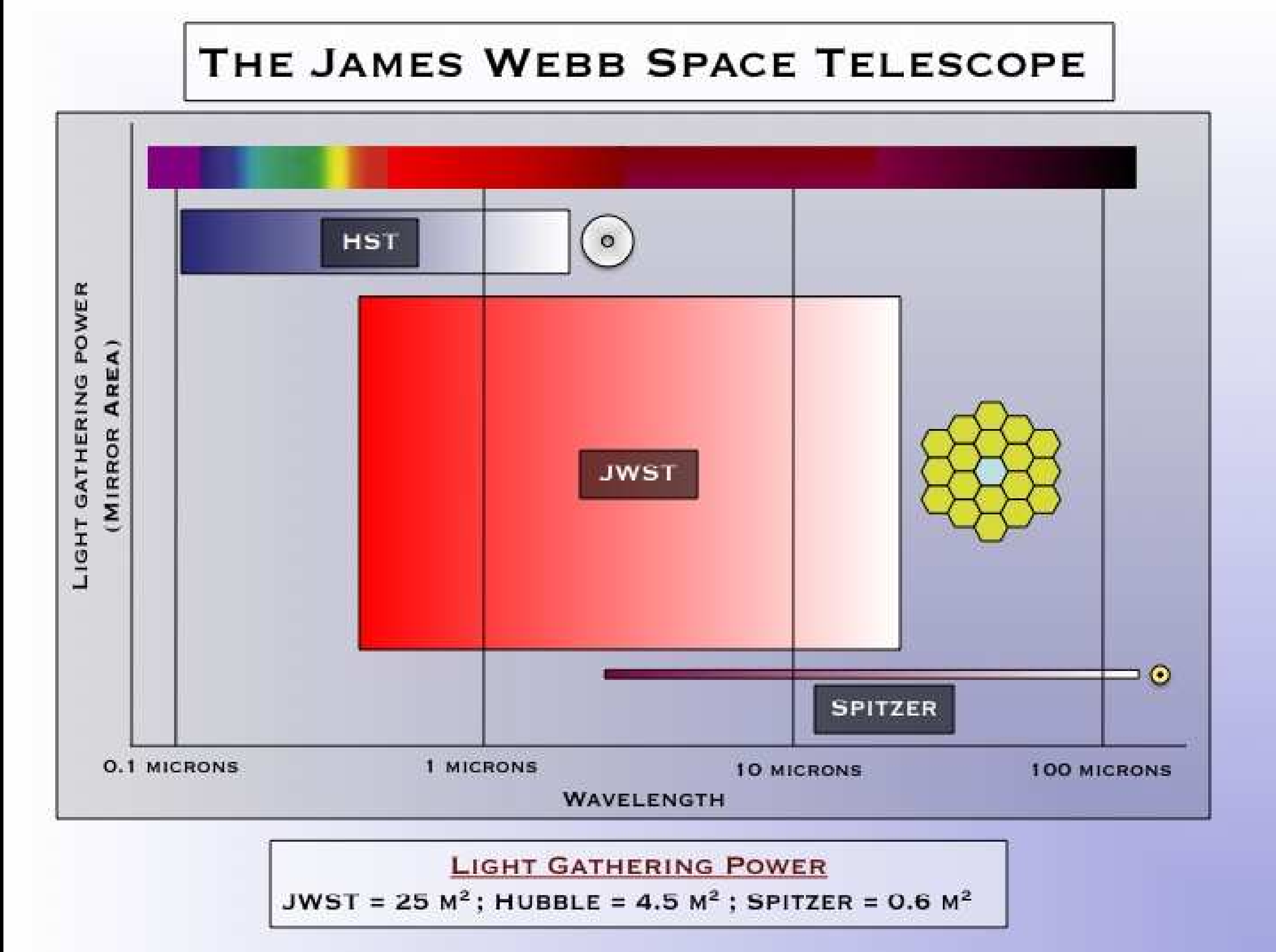
- (1) Recent key lessons from the Hubble Wide Field Camera 3.
- (2) Update on JWST — given in Dr. Mark Clampin's talk.
- (3) JWST Measuring Galaxy Assembly & Supermassive Black-Hole Growth.
- (4) How can JWST measure the Epochs of First Light & Reionization?
- (5) Summary and Conclusions.

Sponsored by NASA/HST & JWST



JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:

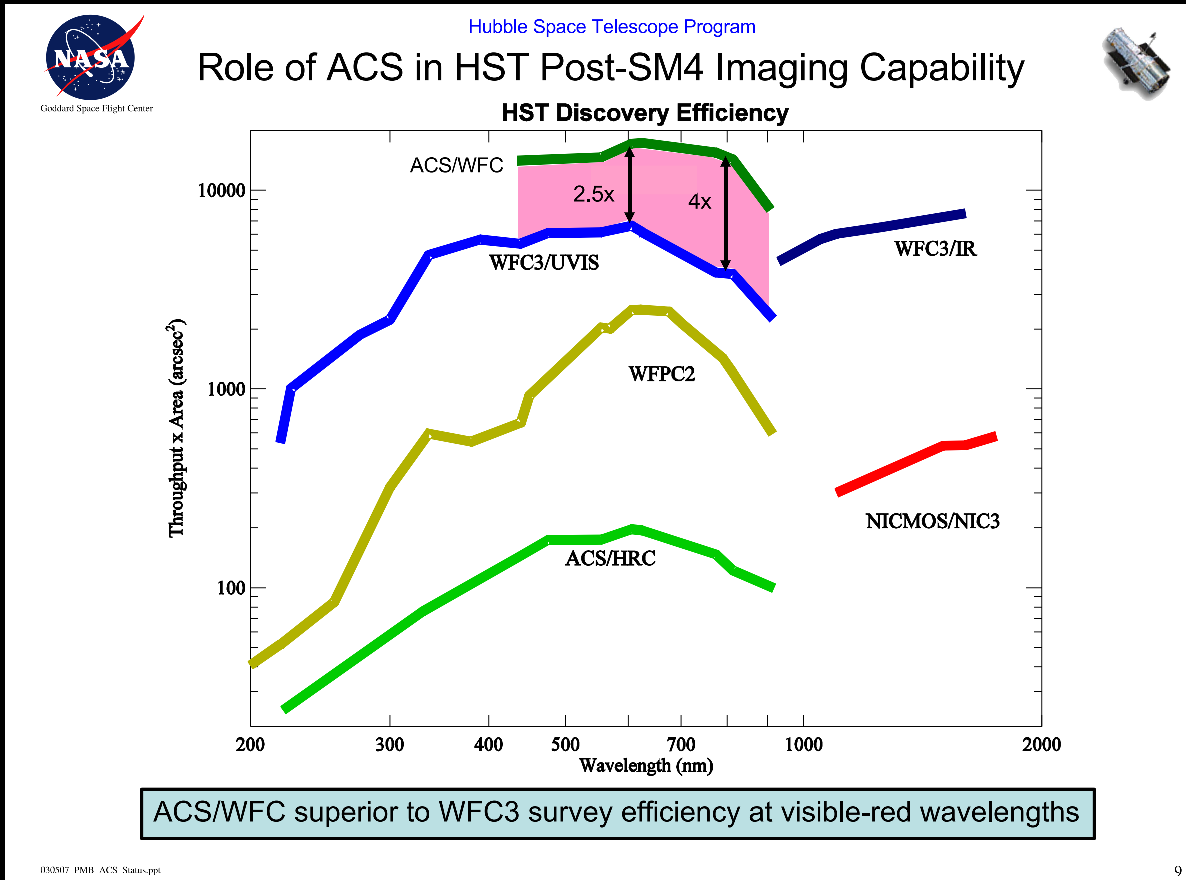
JWST has the same resolution in the near-IR as Hubble in the optical.

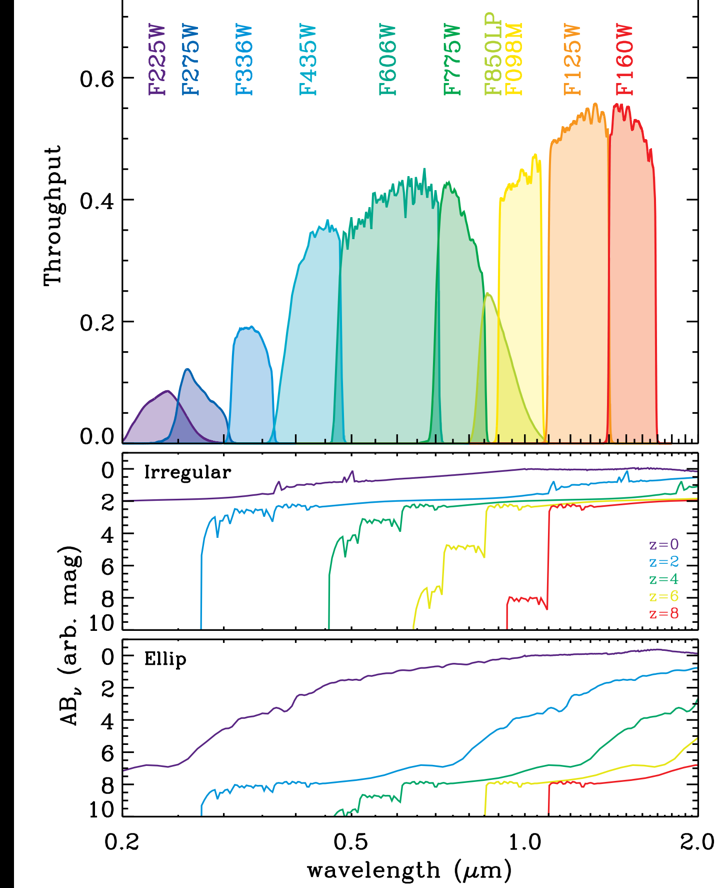


2000 Decadal: JWST is the near–mid-IR sequel to HST and Spitzer:

- Vastly larger $A(\times\Omega)$ than HST in UV-optical and Spitzer in mid-IR.

(1) Recent key lessons from the Hubble Wide Field Camera 3.





WFC3/UVIS unprecedented UV–blue throughput & areal coverage:

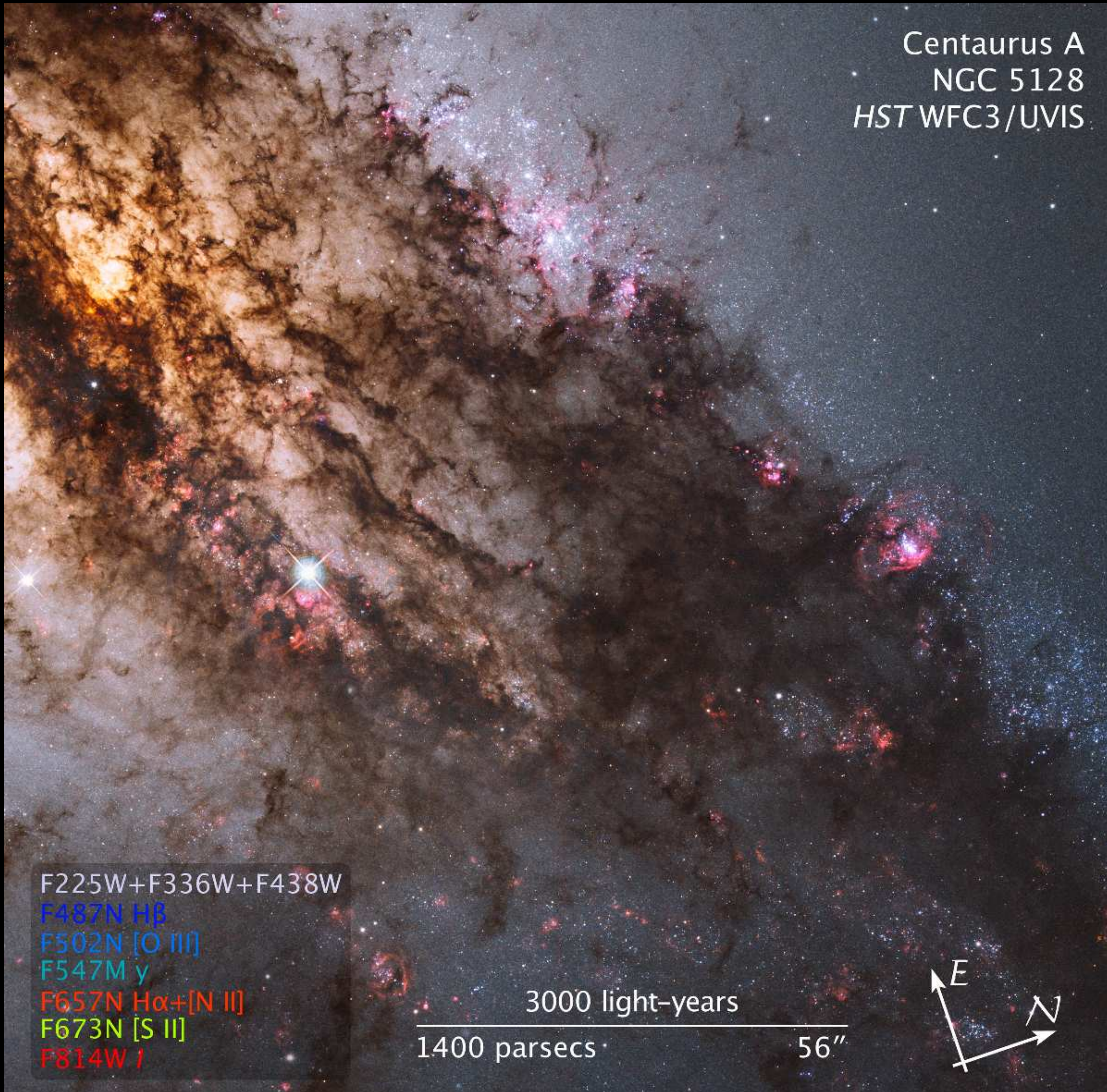
- QE$\gtrsim$70%, 4k$\times$4k array, 0$''\!.$04 pixels, FOV $\simeq$ 2$'\!.$67 $\times$ 2$'\!.$67.

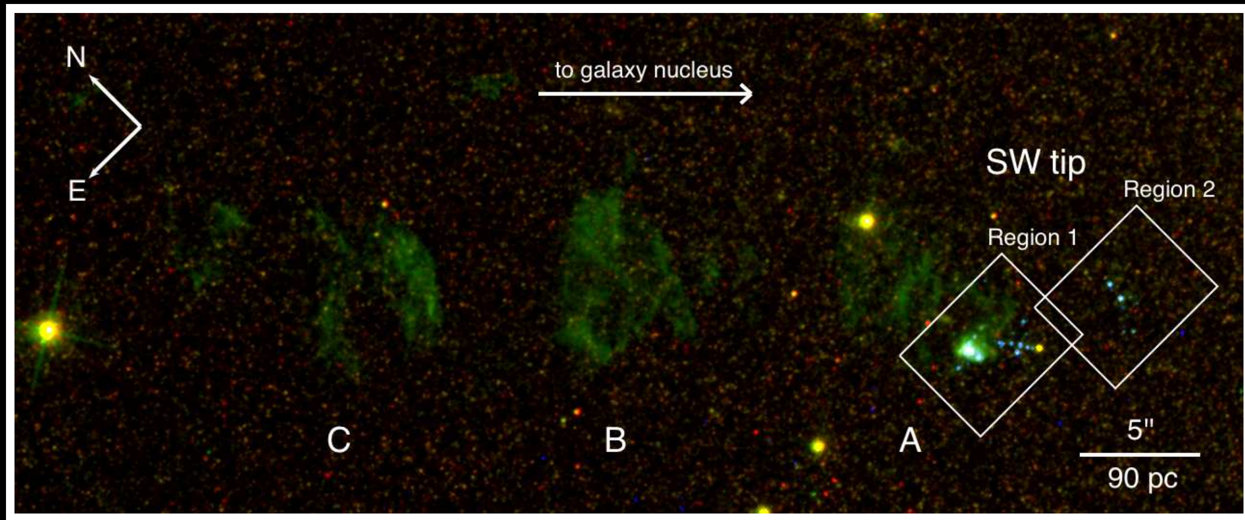
WFC3/IR unprecedented near–IR throughput & areal coverage:

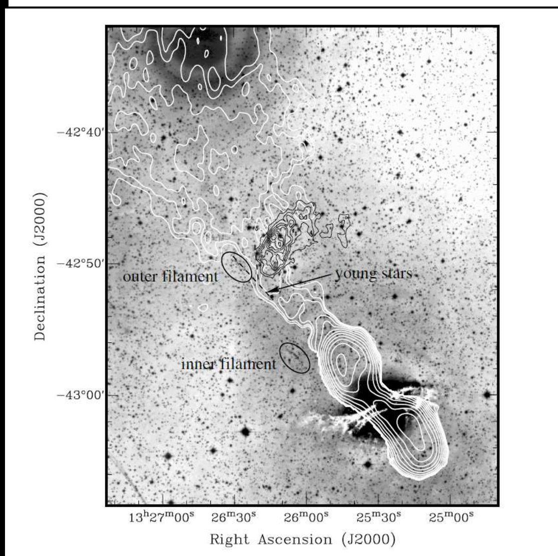
- QE$\gtrsim$70%, 1k$\times$1k array, 0$''\!.$13 pixels, FOV $\simeq$ 2$'\!.$25 $\times$2$'\!.$25.

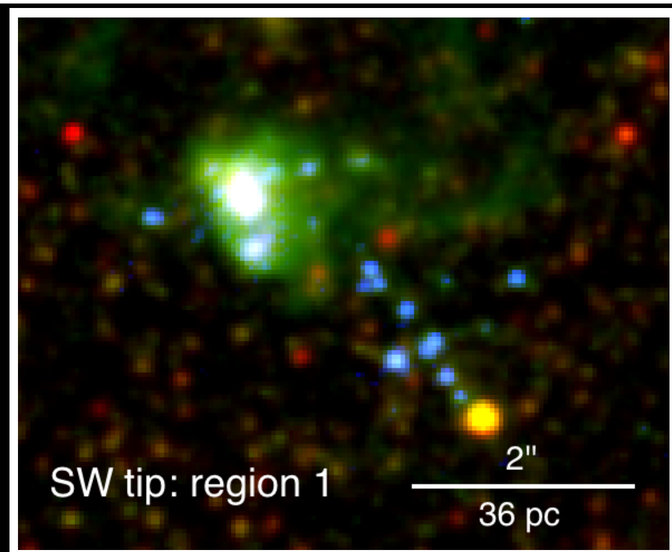
$\Rightarrow$ WFC3 opened major new parameter space for astrophysics in 2009:
WFC3 filters designed for star-formation and galaxy assembly at z$\simeq$1–8.

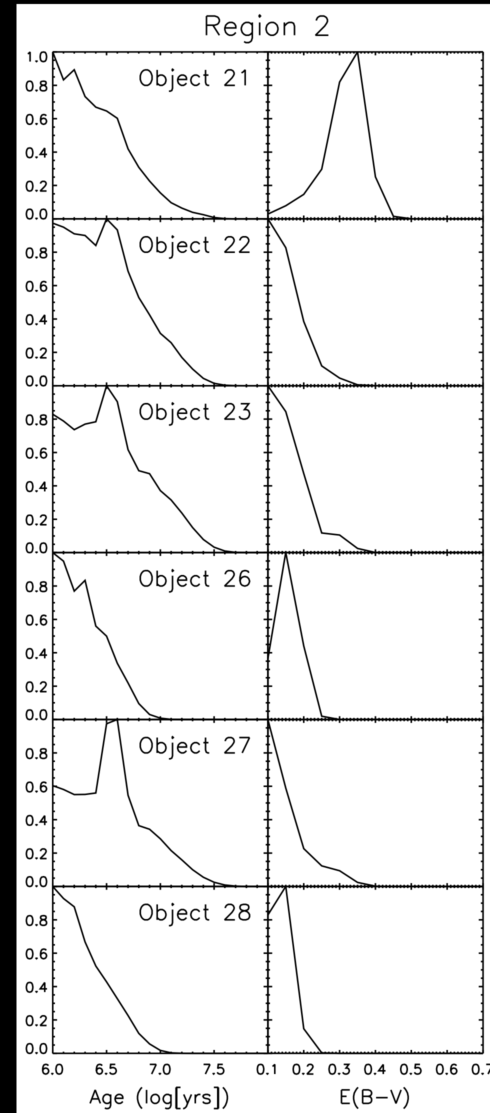
- HST WFC3 and its IR channel a critical pathfinder for JWST science.


Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W *I*
3000 light-years
1400 parsecs
56″
E
N







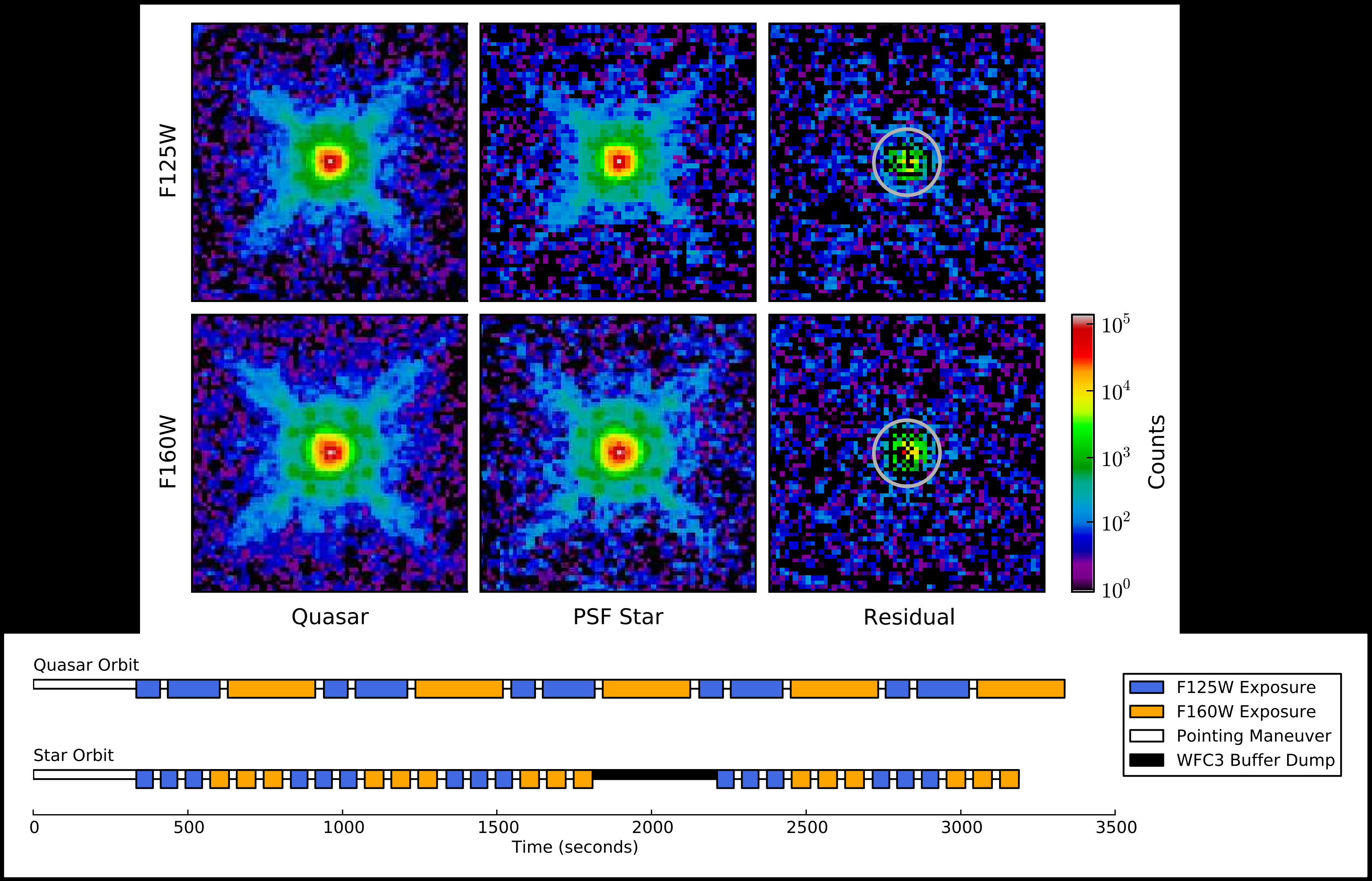


Well determined ages for young (∼2 Myr) stars in Centaurus A jet, with star-formation in jet's wake (Crockett et al. 2012, MNRAS, 421, 1602).

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

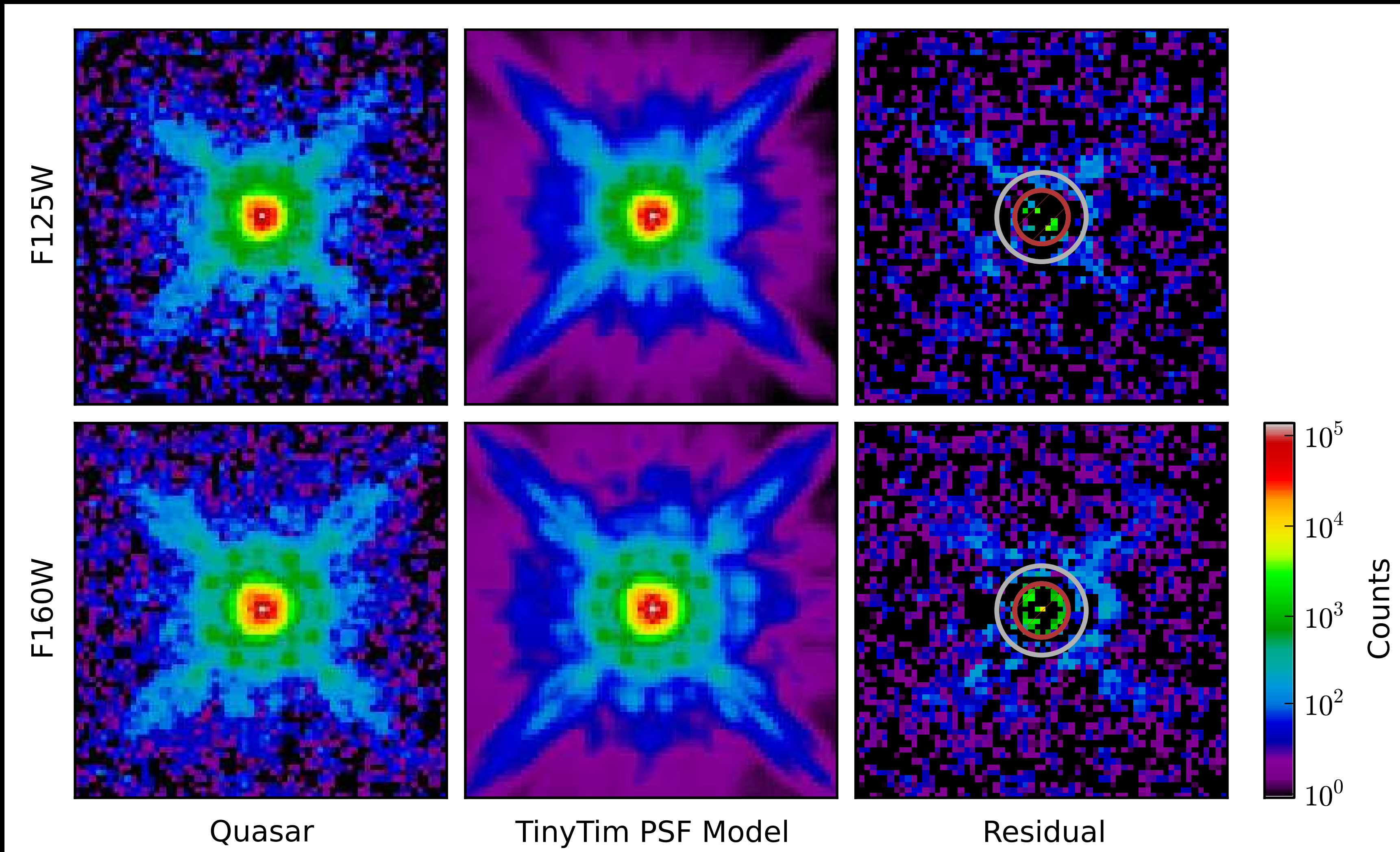
- We must do all we can with HST in UV–blue before JWST flies.

HST WFC3 observations of Quasar Host Galaxies at z≃6 (age≲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× fainter (AB≳23.5 mag at r≳0.″3).

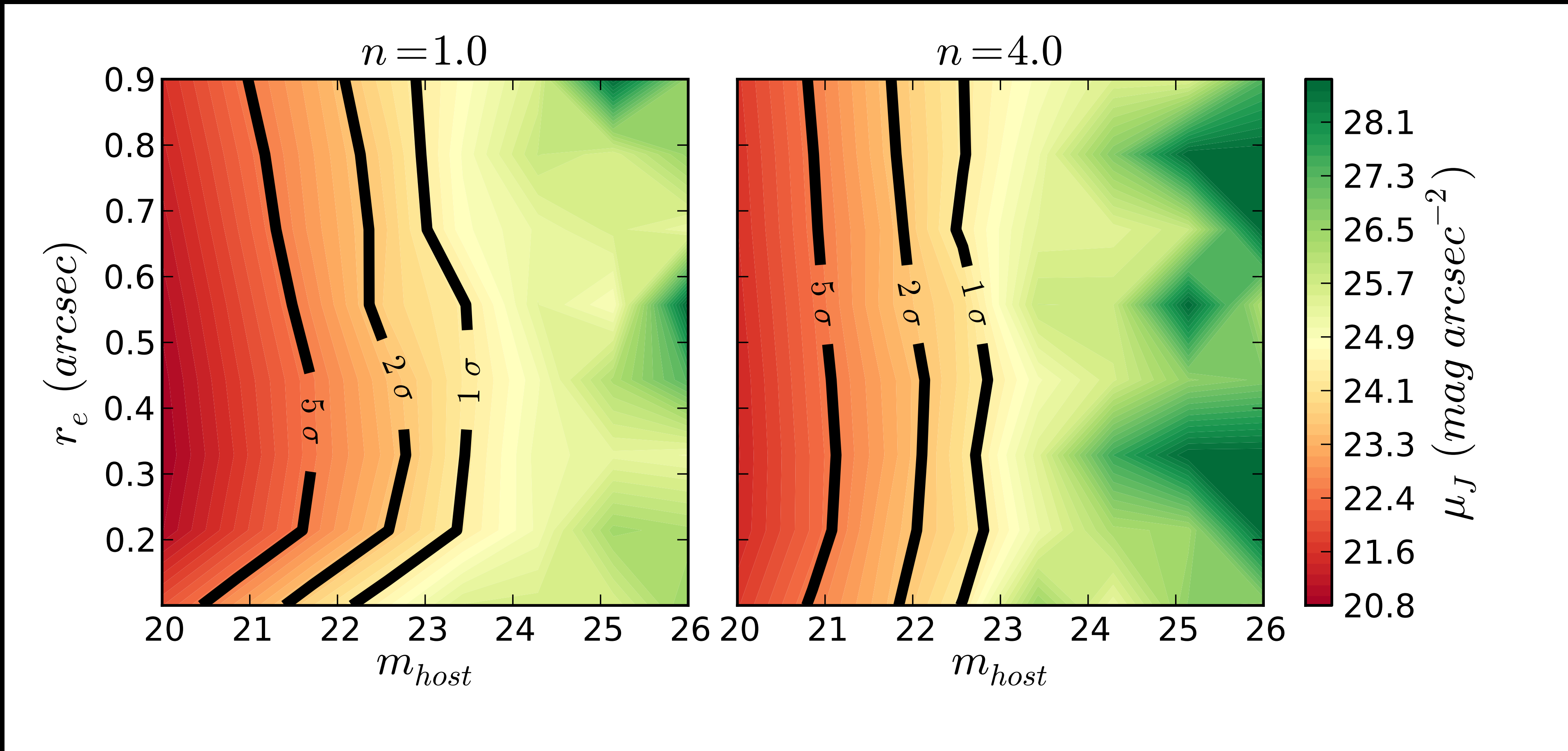
HST WFC3 observations of Quasar Host Galaxies at z≃6 (age≲1 Gyr)



• TinyTim fit of PSF-star + GalFit models QSO nearly to the noise limit: NO z=6.42 host galaxy at AB≳23.5 mag at radius r≃0.″3–0.″5.

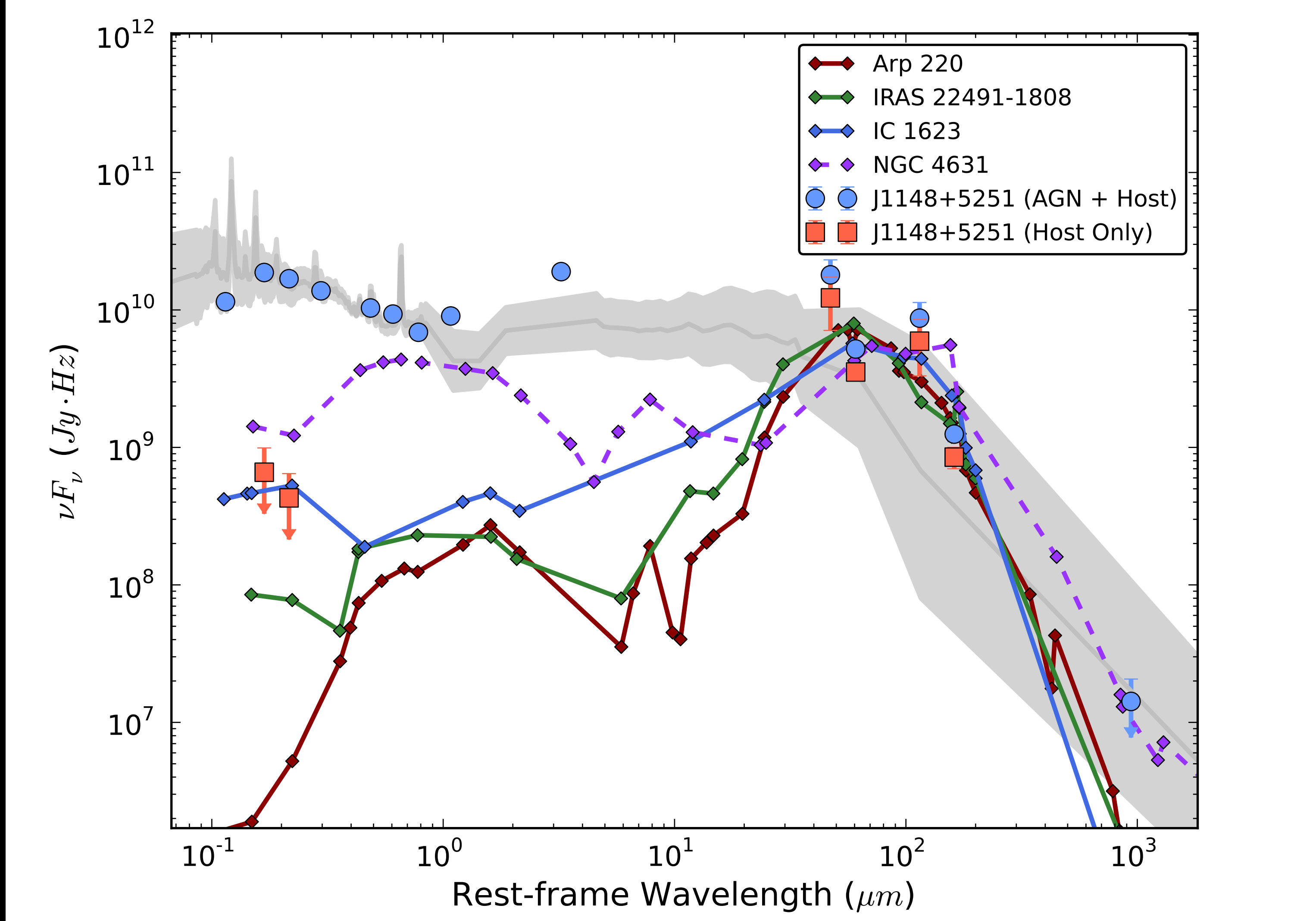
THE most luminous Quasars in the Universe: Are all their host galaxies faint (dusty)? ⇒ Major implications for Galaxy Assembly–SMBH Growth.

HST WFC3 observations of Quasar Host Galaxies at z≃6 (age≲1 Gyr)



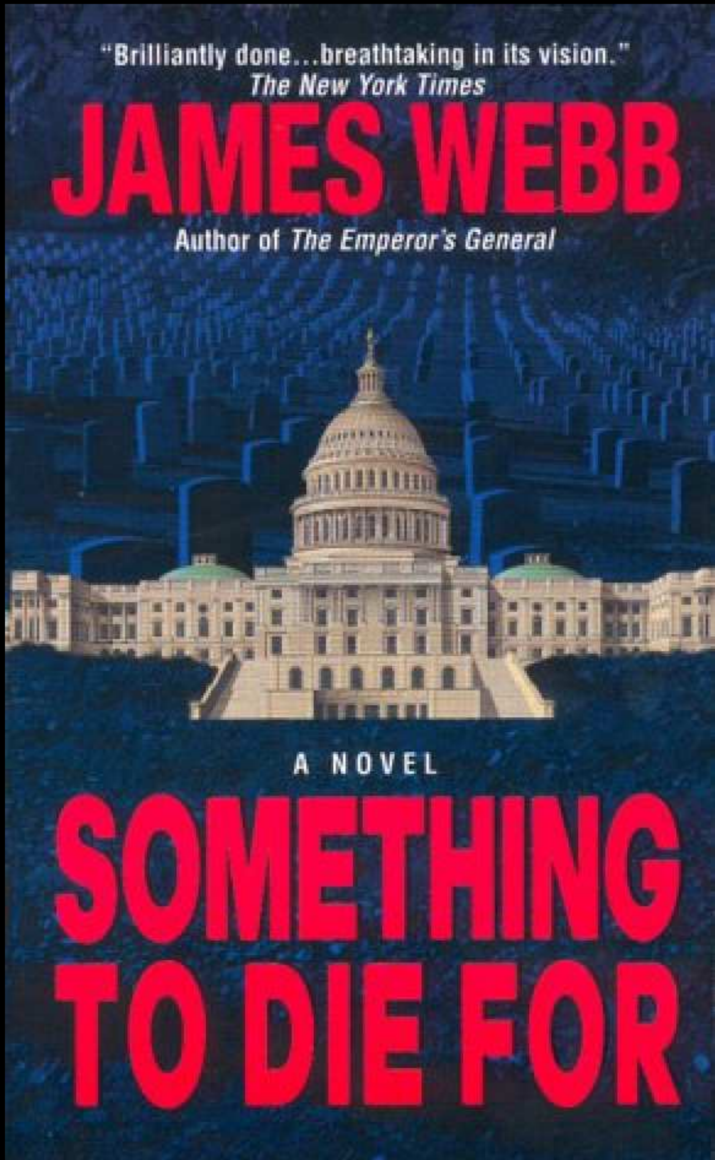
- TinyTim fit of PSF-star + GalFit models of galaxy light-profile, nearly to the noise limit: NO host galaxy at AB≳23.0 mag with $r_e \simeq 0''.5$ (Mechtley et al. 2012, ApJL, 756, L23; astro-ph/1207.3283).

- JWST Coronagraphs can do this 10–100× fainter (and for z≲20, $\lambda \lesssim 28\mu$m) — but need JWST diffraction limit at 2.0μm 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$1 Gyr) normalized at 100μm: Rules out z=6.42 spiral or bluer host galaxy SEDs. (U)LIRGs permitted.
- JWST Coronagraphs can do this 10–100$\times$ fainter (and for z$\lesssim$20, $\lambda\lesssim$28μm).

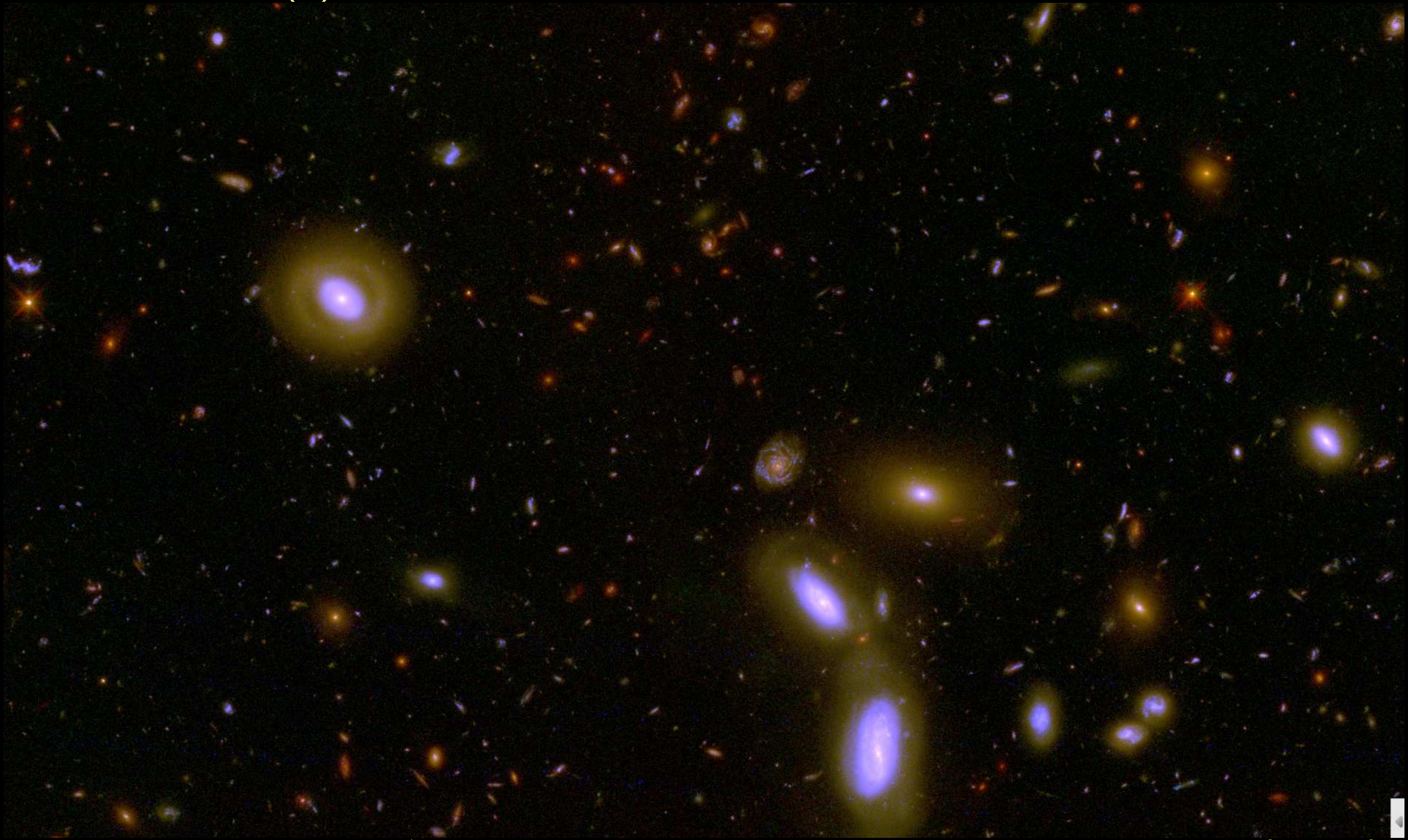
(3) Brief Update of JWST — see Dr. Mark Clampin's talk.



To be used by students & scientists after 2018 ... It'll be worth it.

(RIGHT) Life-size JWST prototype on the Capitol Mall.

• (4) How can JWST measure Galaxy Assembly?

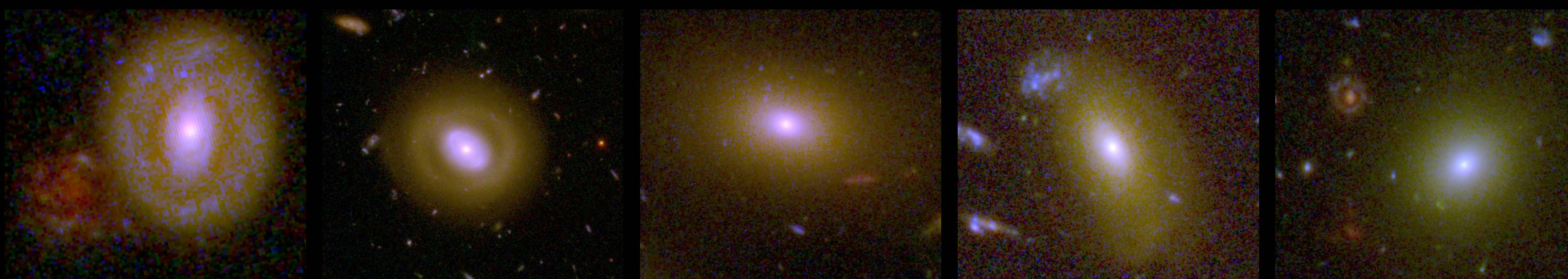


10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5μm, and 0.2–1.2" FWHM at 5–29μm, 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 ($z \simeq 1$–2) is very rich: some resemble the cosmological parameters $\boldsymbol{H_0}$, $\boldsymbol{\Omega}$, $\boldsymbol{\rho_o}$, $\boldsymbol{w}$, and $\boldsymbol{\Lambda}$, resp.

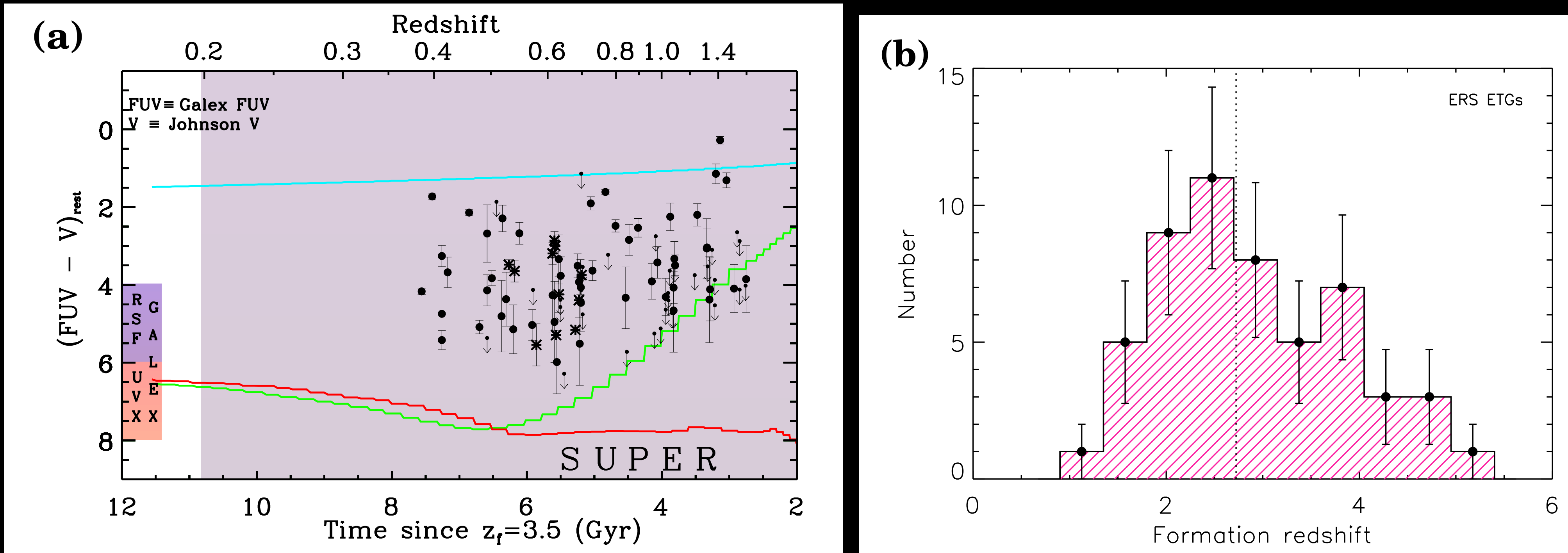


Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

(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 $z \lesssim 1.5$.

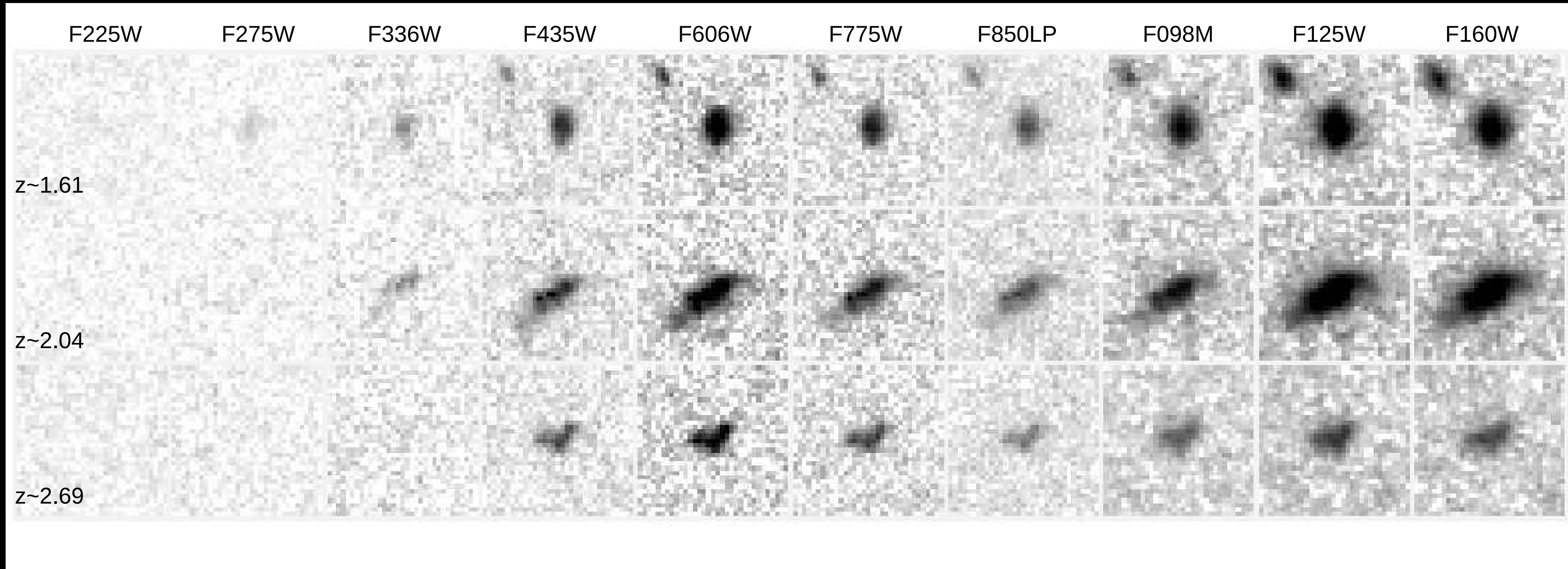


• 10-band WFC3 ERS data measured rest-frame UV-light in nearly all early-type galaxies at $0.3 \lesssim z \lesssim 1.5$ (Rutkowski et al. 2012, ApJS, 199, 4).

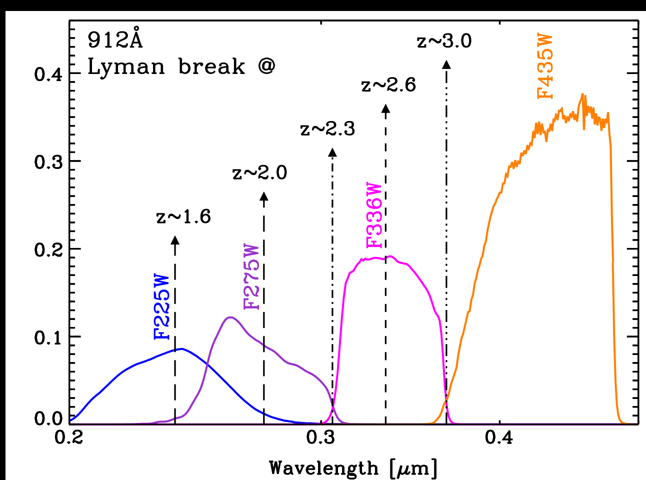
$\Longrightarrow$ Most ETGs have continued residual star-formation after they form.

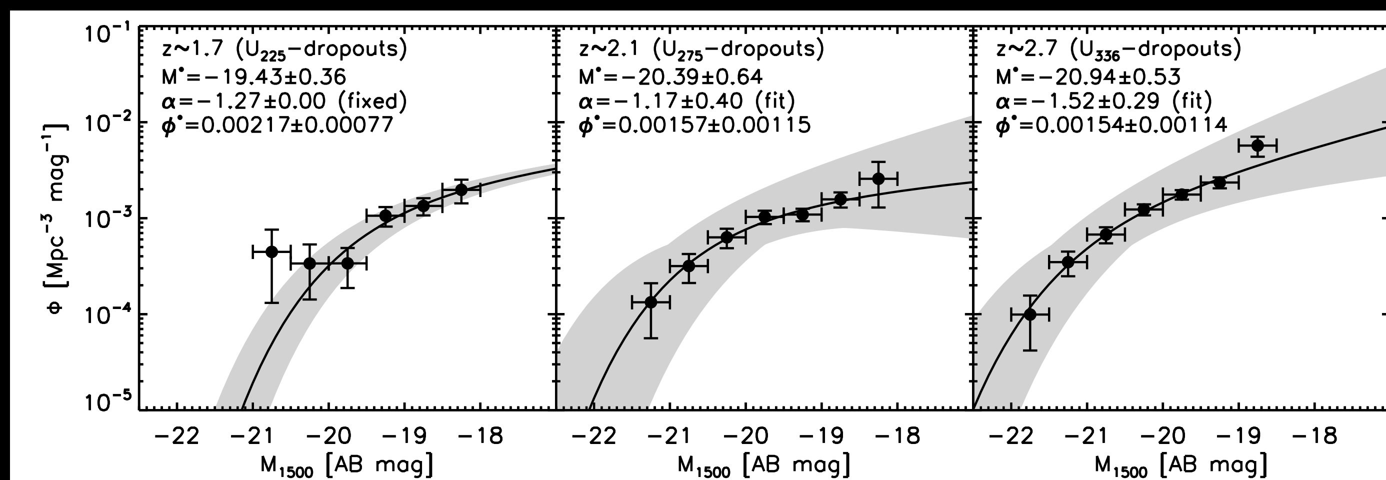
• Can determine their $N(z_{form})$, which resembles the cosmic SFH diagram (*e.g.*, Madau et al. 1996). This can directly constrain the process of galaxy assembly and down-sizing (Kaviraj, Rutkowski et al. 2012, MNRAS).

• JWST will extend Balmer+4000Å-break ages to $z \lesssim 11$.



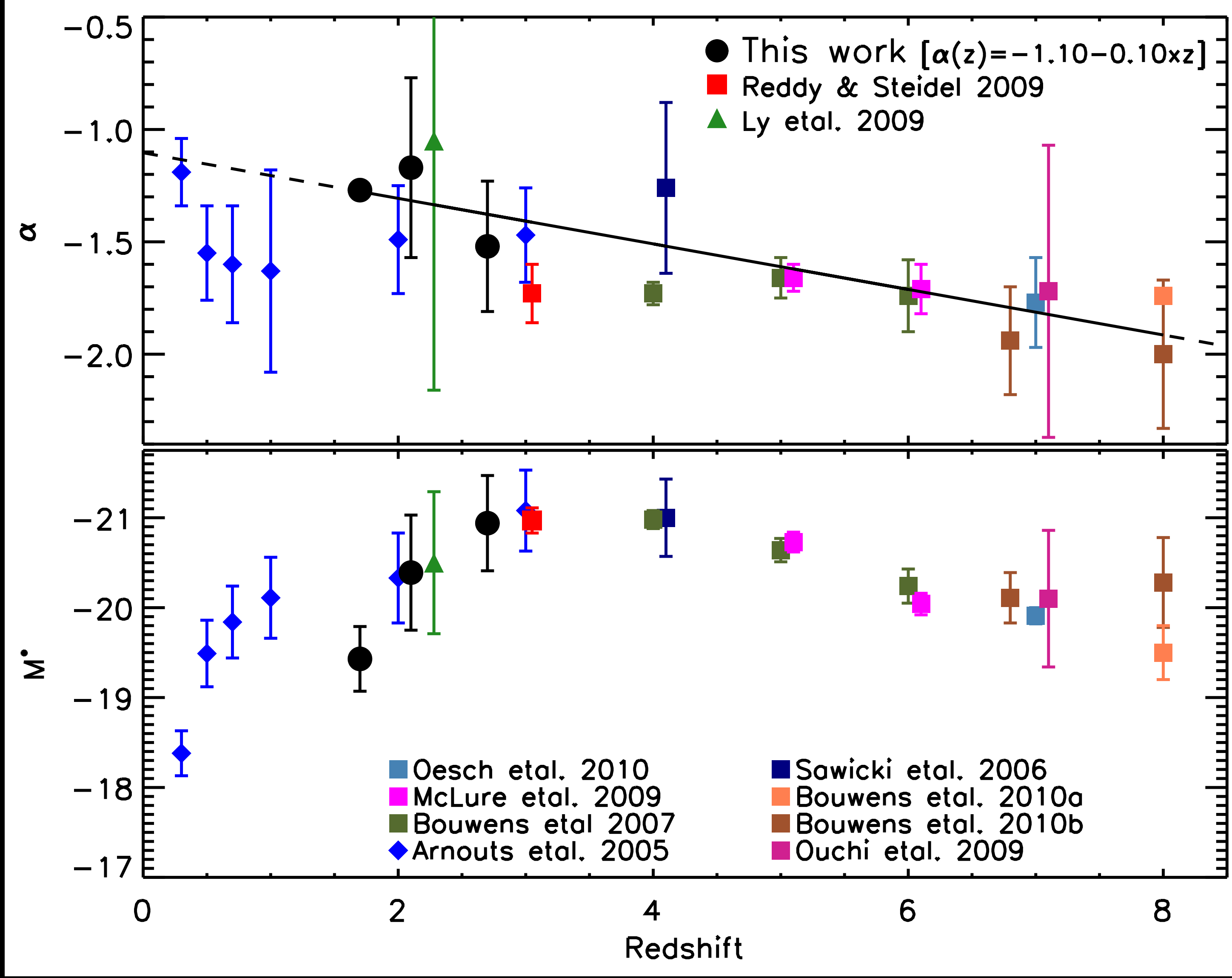
Lyman break galaxies at the peak of cosmic SF (z≃1-3; Hathi ea. 2010)





- JWST will similarly measure faint-end LF-slope evolution for 1≲z≲12.

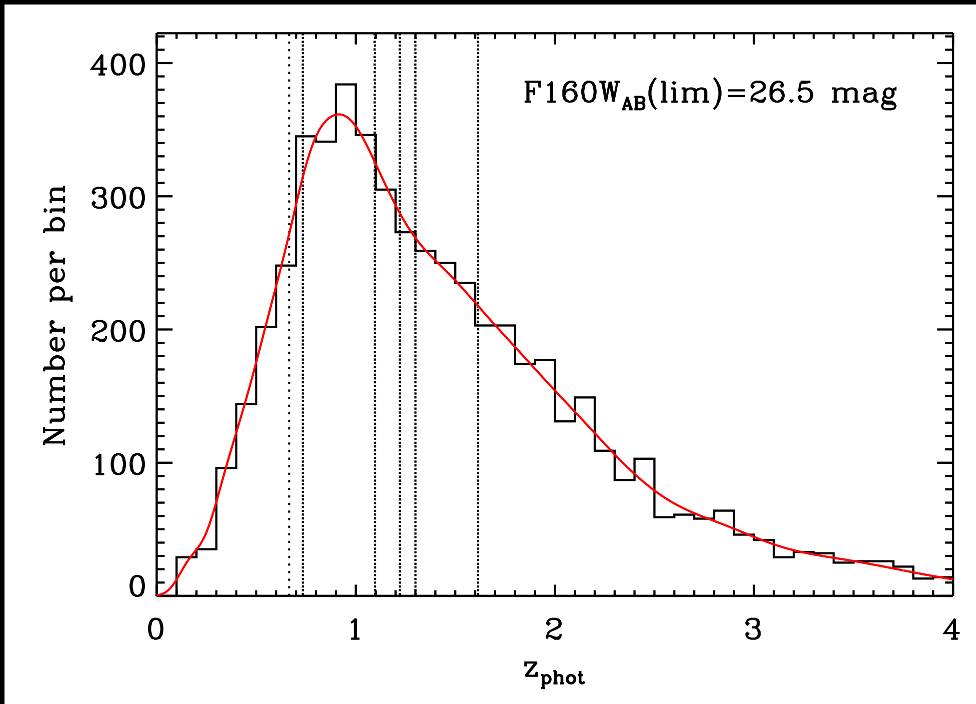
(e.g., Bouwens et al. 2010; Hathi et al. 2012, 2012; Oesch et al. 2010).

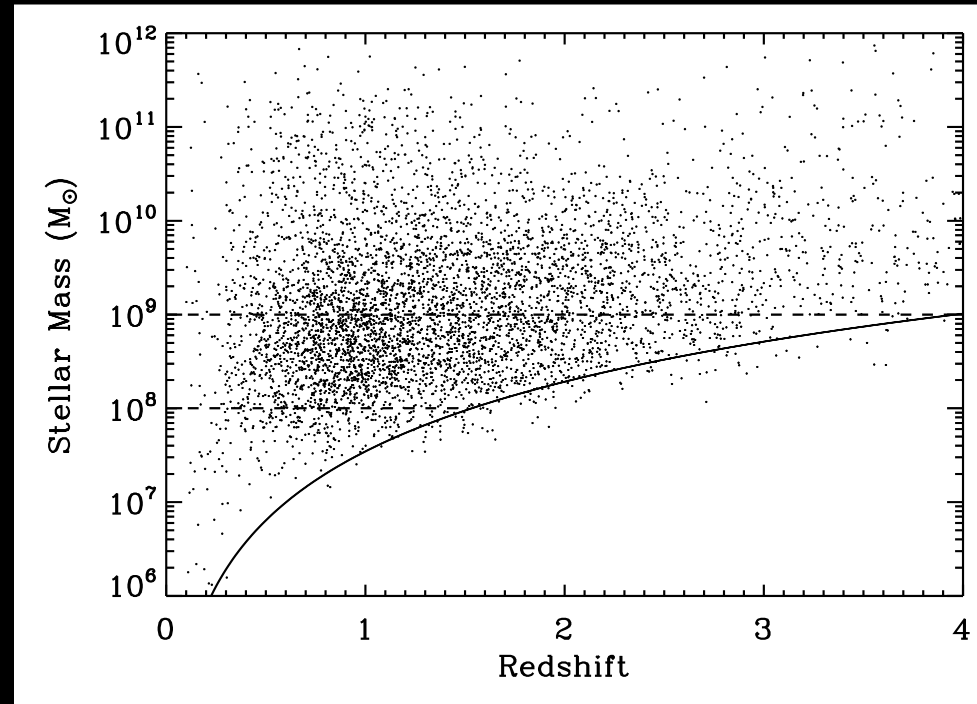


Measured faint-end LF slope evolution (top) and characteristic luminosity evolution (bottom) from Hathi et al. 2010 (ApJ, 720, 1708).

- 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.

$\Rightarrow$ 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?).

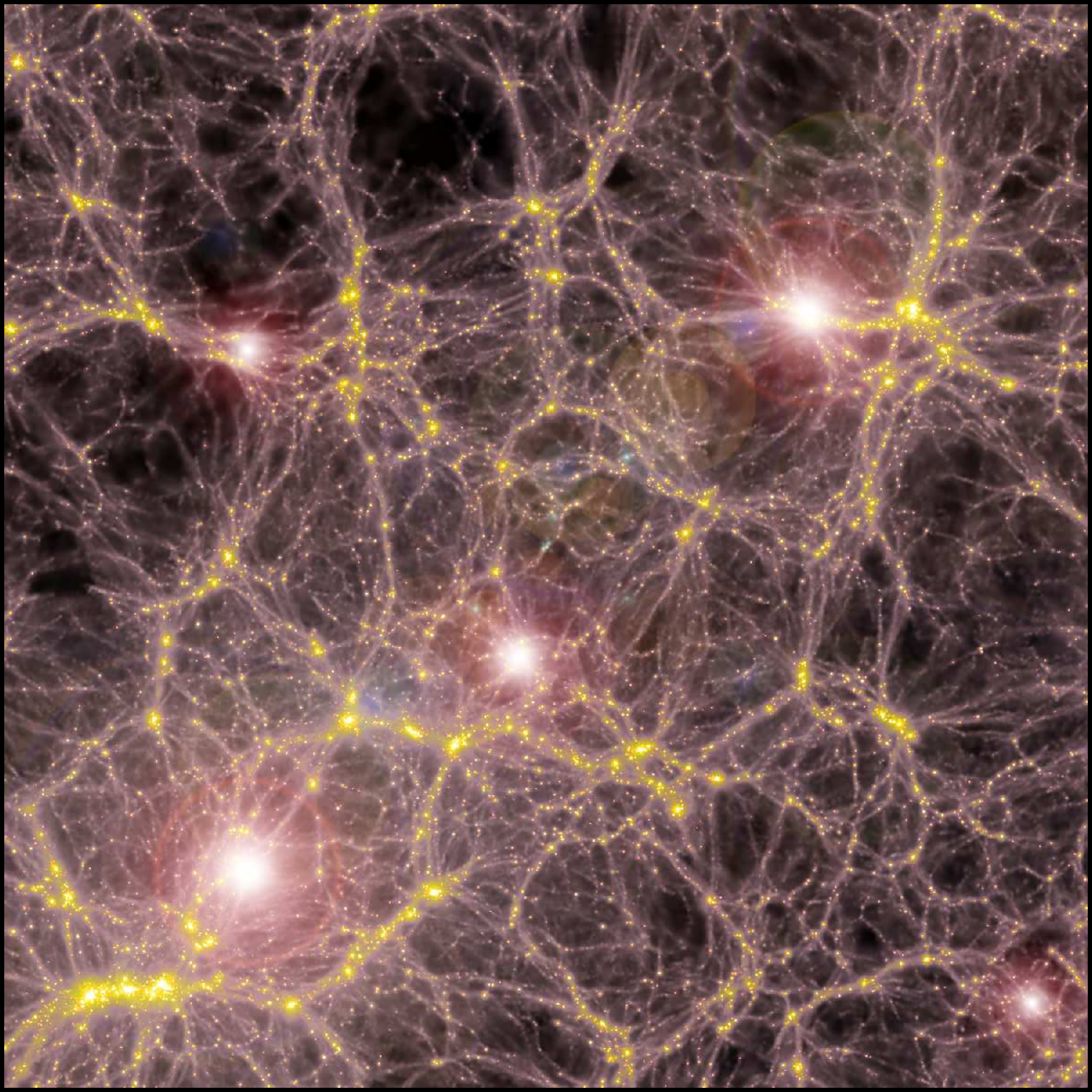
ERS shows WFC3's new panchromatic capabilities on galaxies at z$\simeq$0–7.

• 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 0.7–5μm.

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



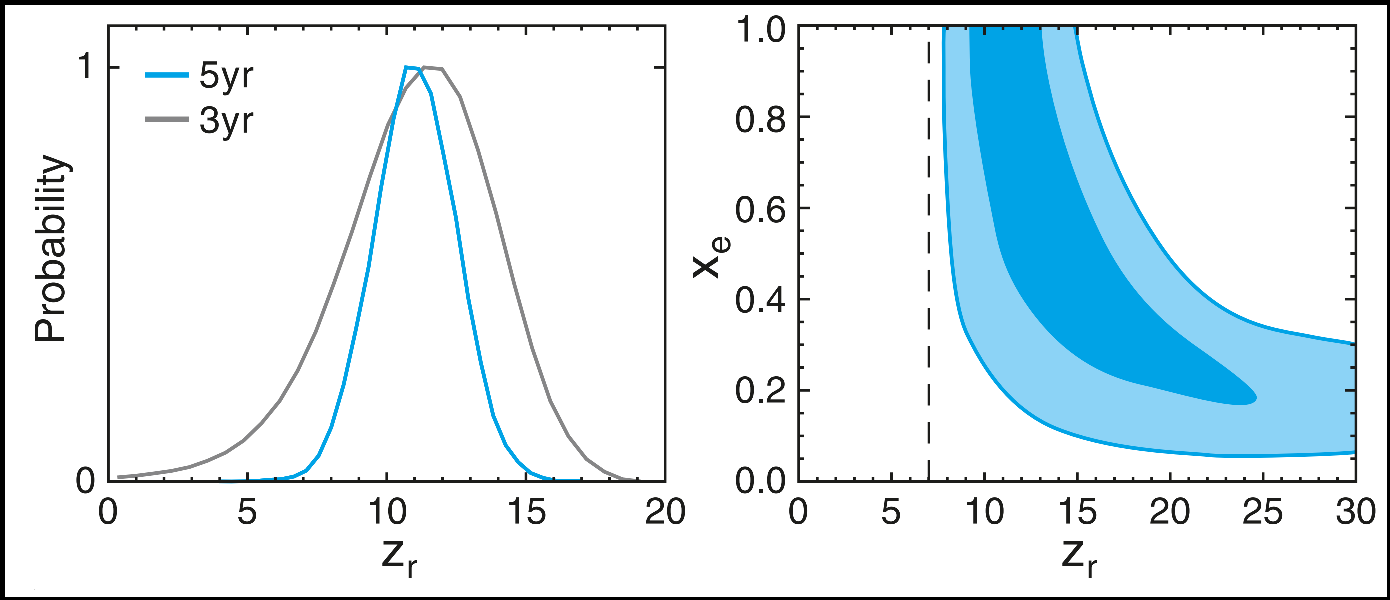
- Detailed Hydrodynamical models (e.g., V. Bromm) suggest that massive Pop III stars may have reionized universe at redshifts $z \lesssim 10$–30 (First Light).

- A 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 $z \simeq 10 \longrightarrow 30$.

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

Implications of the (2011) 7-year WMAP results for JWST science:

HST/WFC3 $z \lesssim 7$–9 ⟵ ⟶ JWST $z \simeq 8$–25



The year-7 WMAP data provided much better foreground removal (Dunkley et al. 2009; Komatsu et al. 2011; see also Planck 2013):

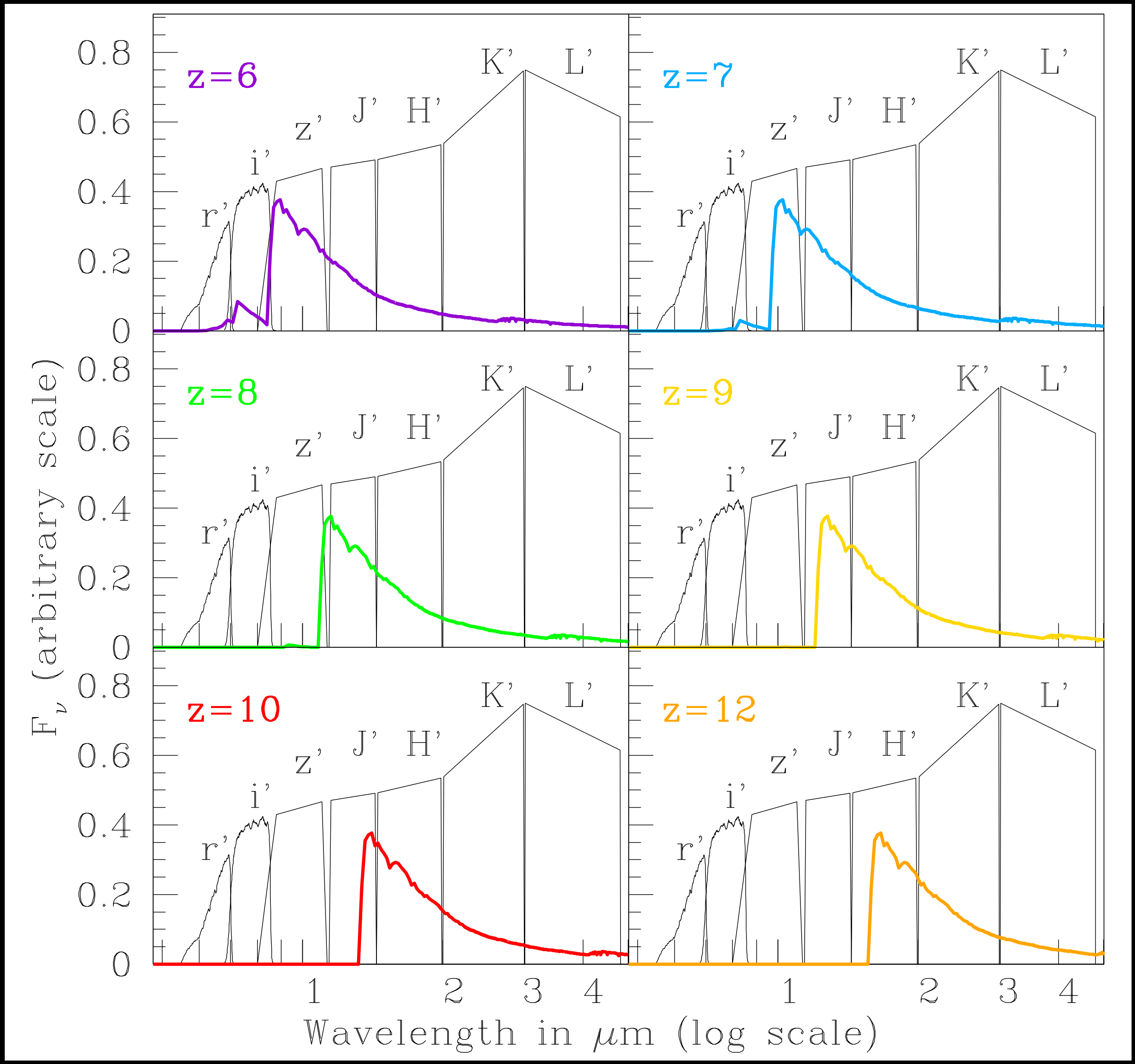
⟹ First Light & Reionization occurred between these extremes:

- (1) Instantaneous at $z \simeq 10.4 \pm 1.2$ ($\tau = 0.087 \pm 0.014$), or, more likely:
- (2) Inhomogeneous & drawn out: starting at $z \gtrsim 20$, peaking at $z \simeq 11$, ending at $z \simeq 7$. The implications for HST and JWST are:

- HST/ACS has covered $z \lesssim 6$, and WFC3 is now covering $z \lesssim 7$–9.
- For First Light & Reionization, JWST must sample $z \simeq 8$ to $z \simeq 15$–20.

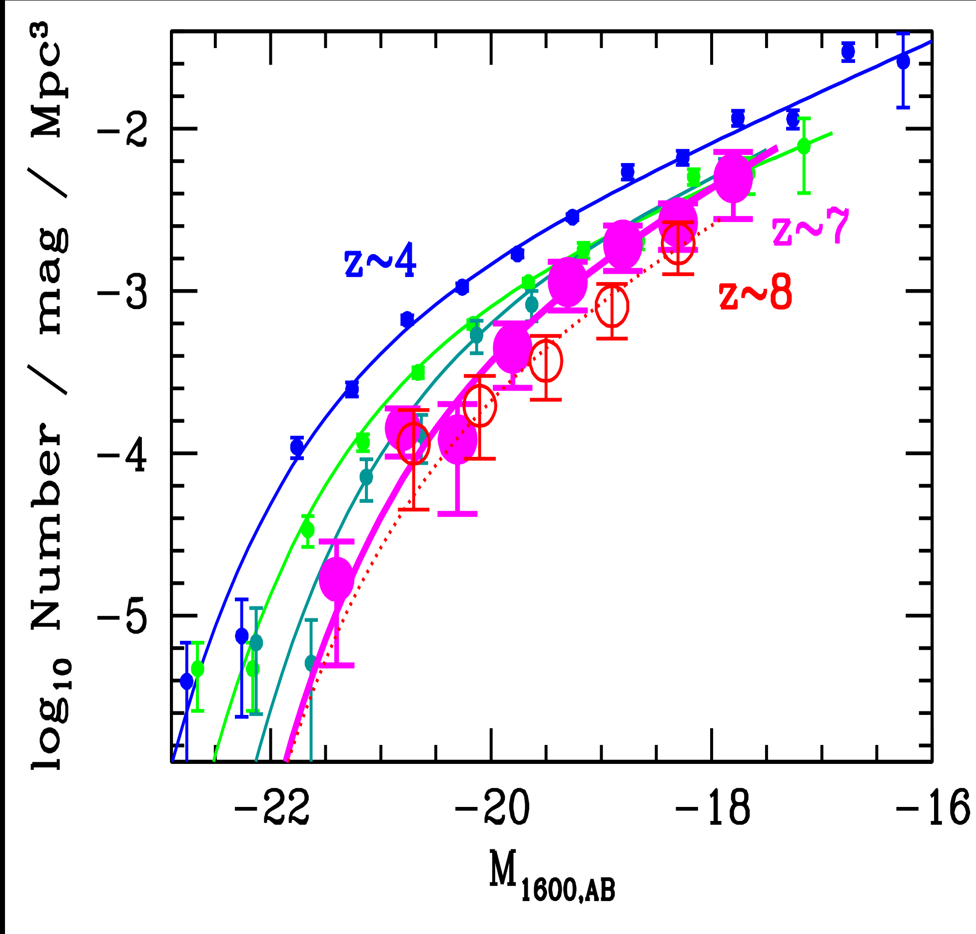
⇒ JWST must cover $\lambda = 0.7$–29 μm, with its diffraction limit at 2.0 μm.

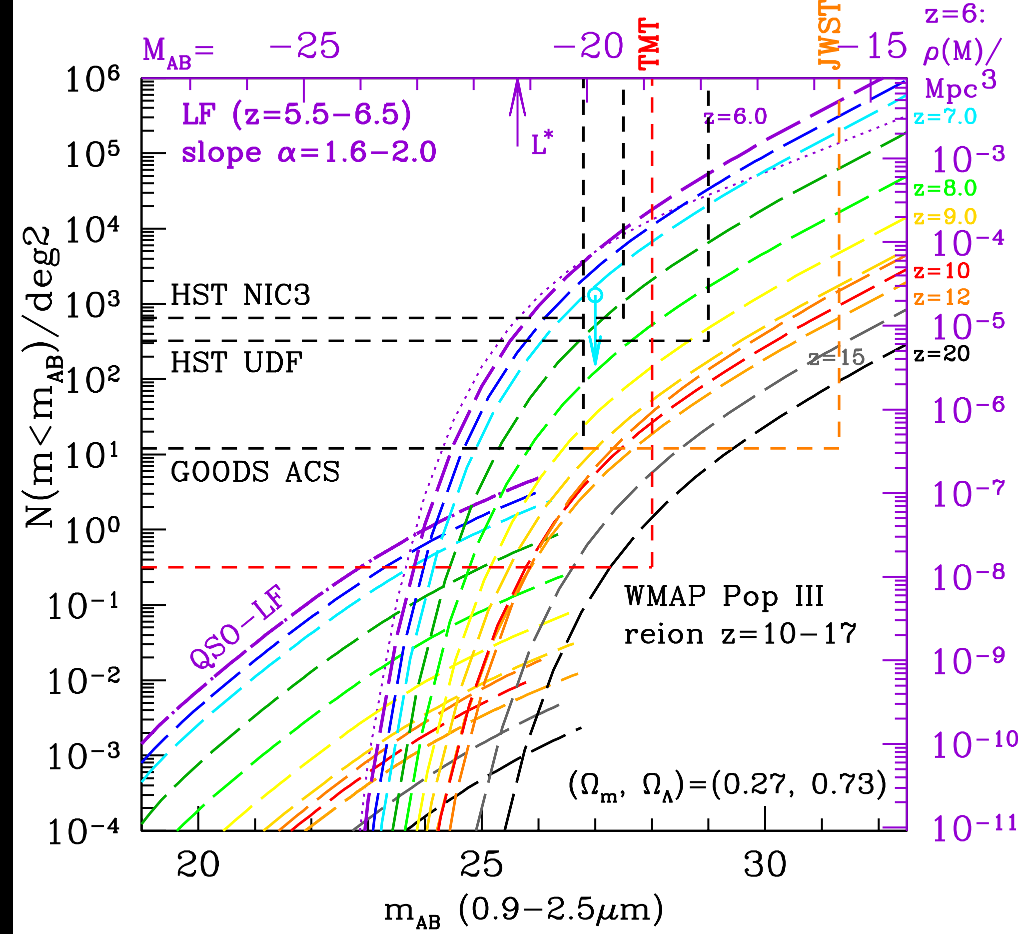
(4) How will JWST measure First Light & Reionization?



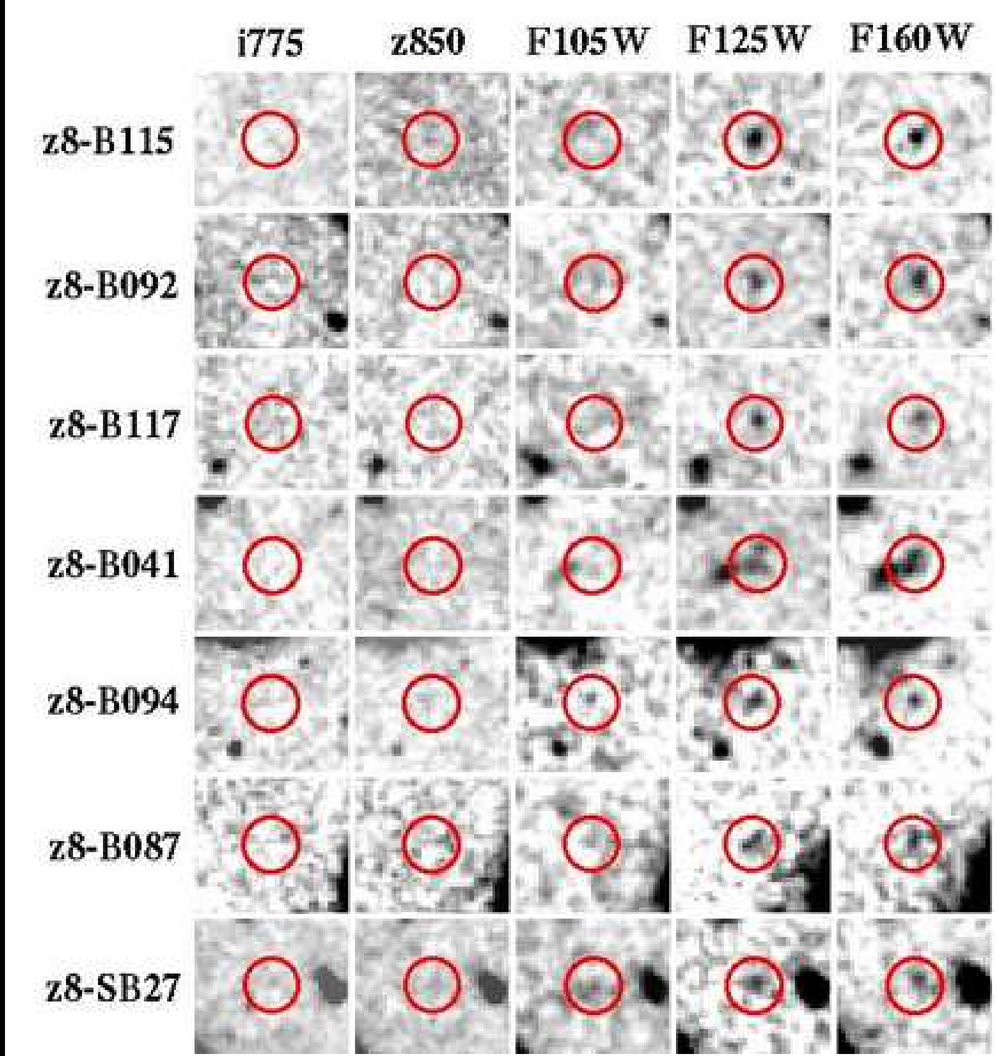
- Can't beat redshift: to see First Light, must observe near–mid IR.

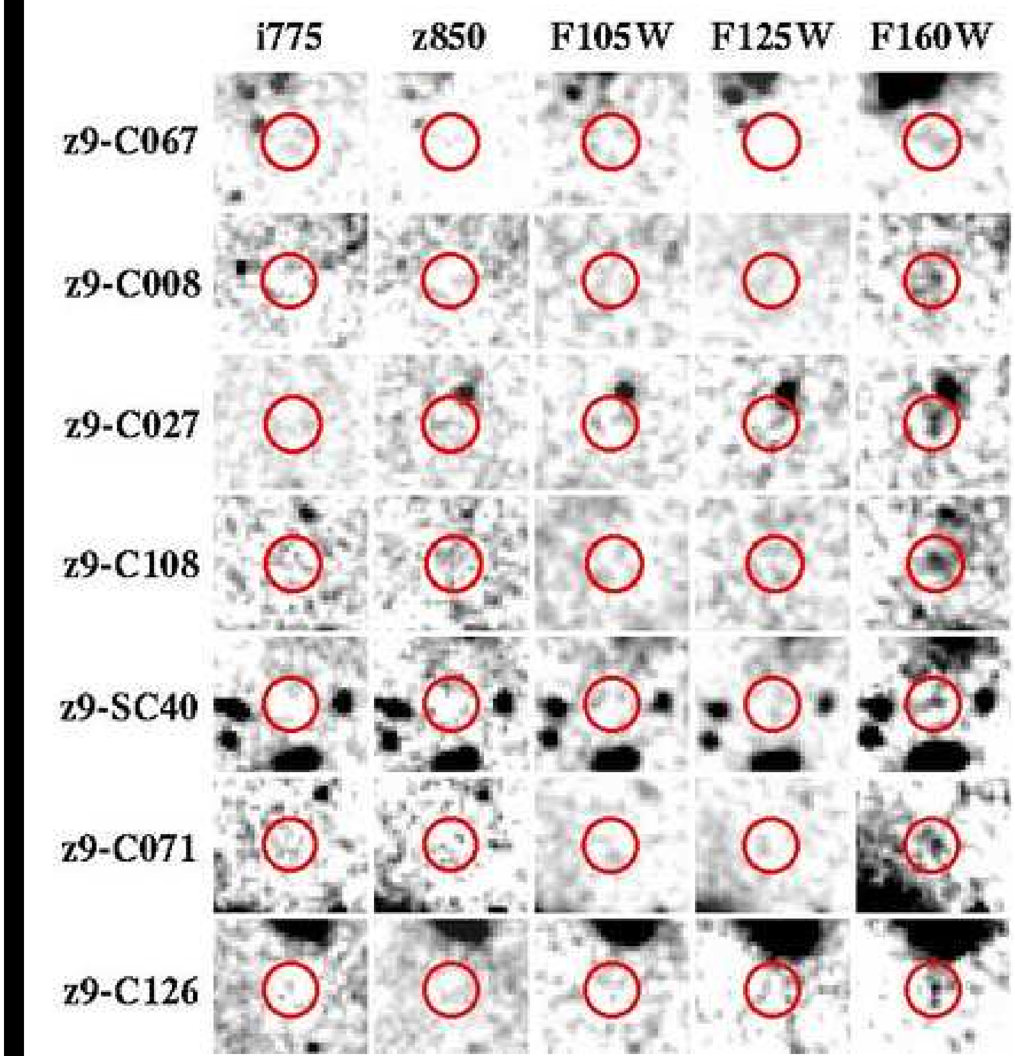
⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.



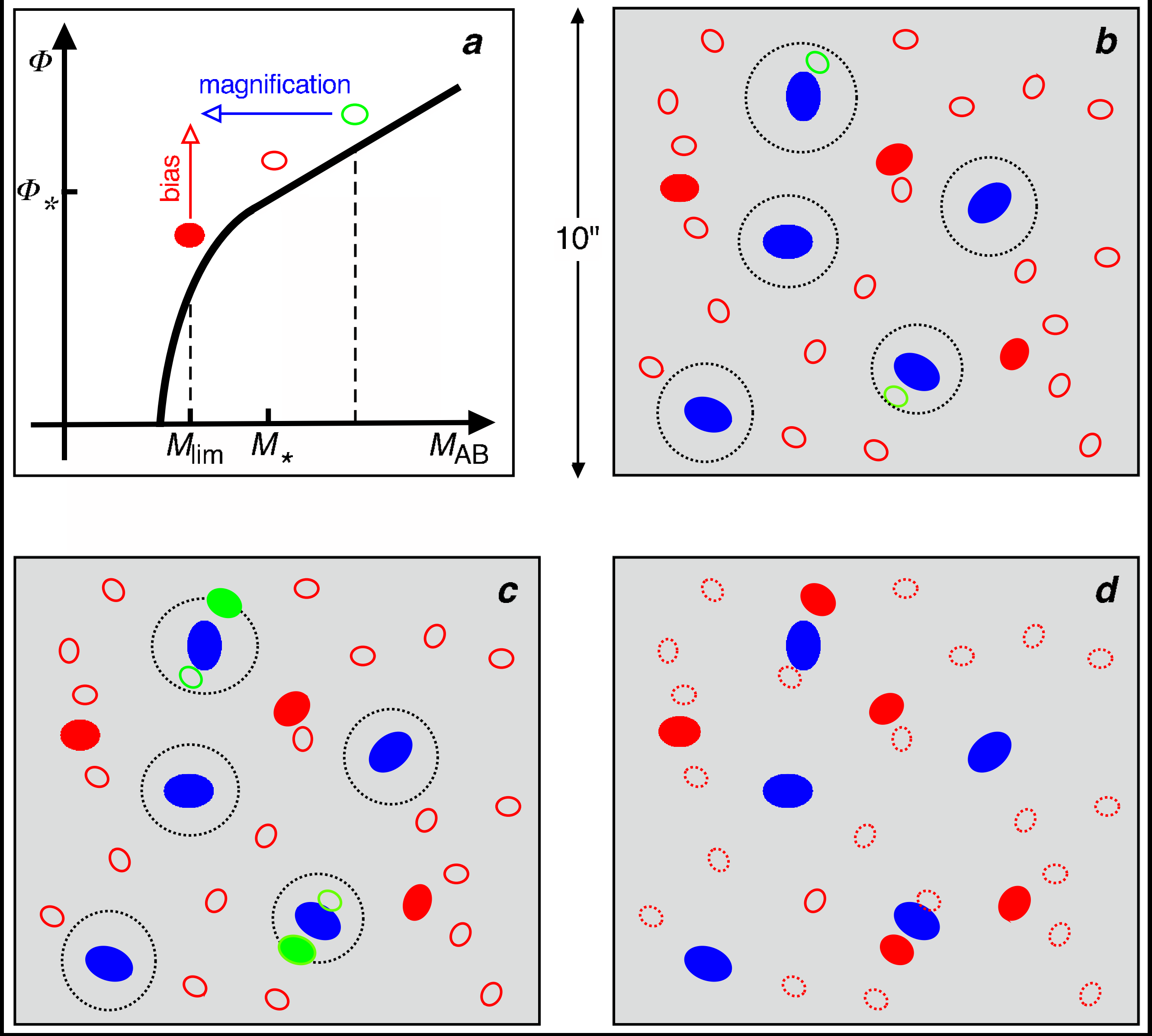


- Objects at z≳9 are rare (Bouwens+ 10; Trenti,+ 10; Yan+ 10), since volume elt is small, and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ-range (0.7-29 μm).
- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch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



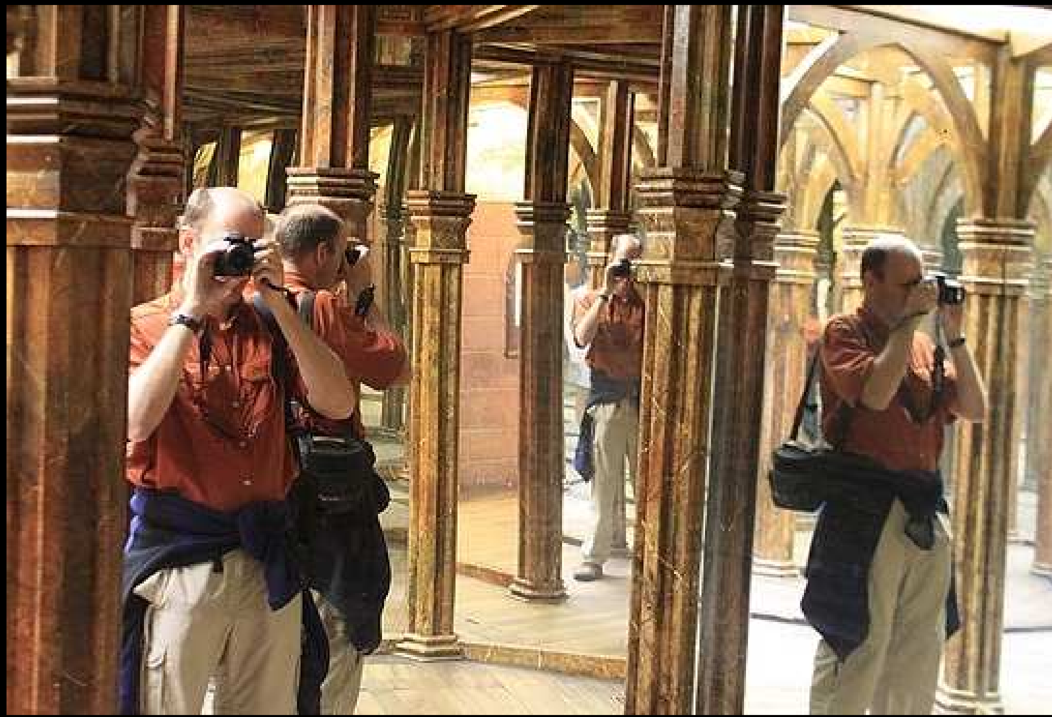


- ∼10–40% of the HUDF Y-drops and J-drops appear close to bright galaxies (Yan et al. 2010, Res. Astr. & Ap., 10, 867).
- Expected from gravitational lensing bias by galaxy dark matter halo distribution at $z\simeq 1$–2 (Wyithe et al. 2011, Nature, 469, 181).
- Need JWST to measure $z\simeq 9$–15 LFs, 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 2.0μm PSF and straylight specs essential to handle this.

(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

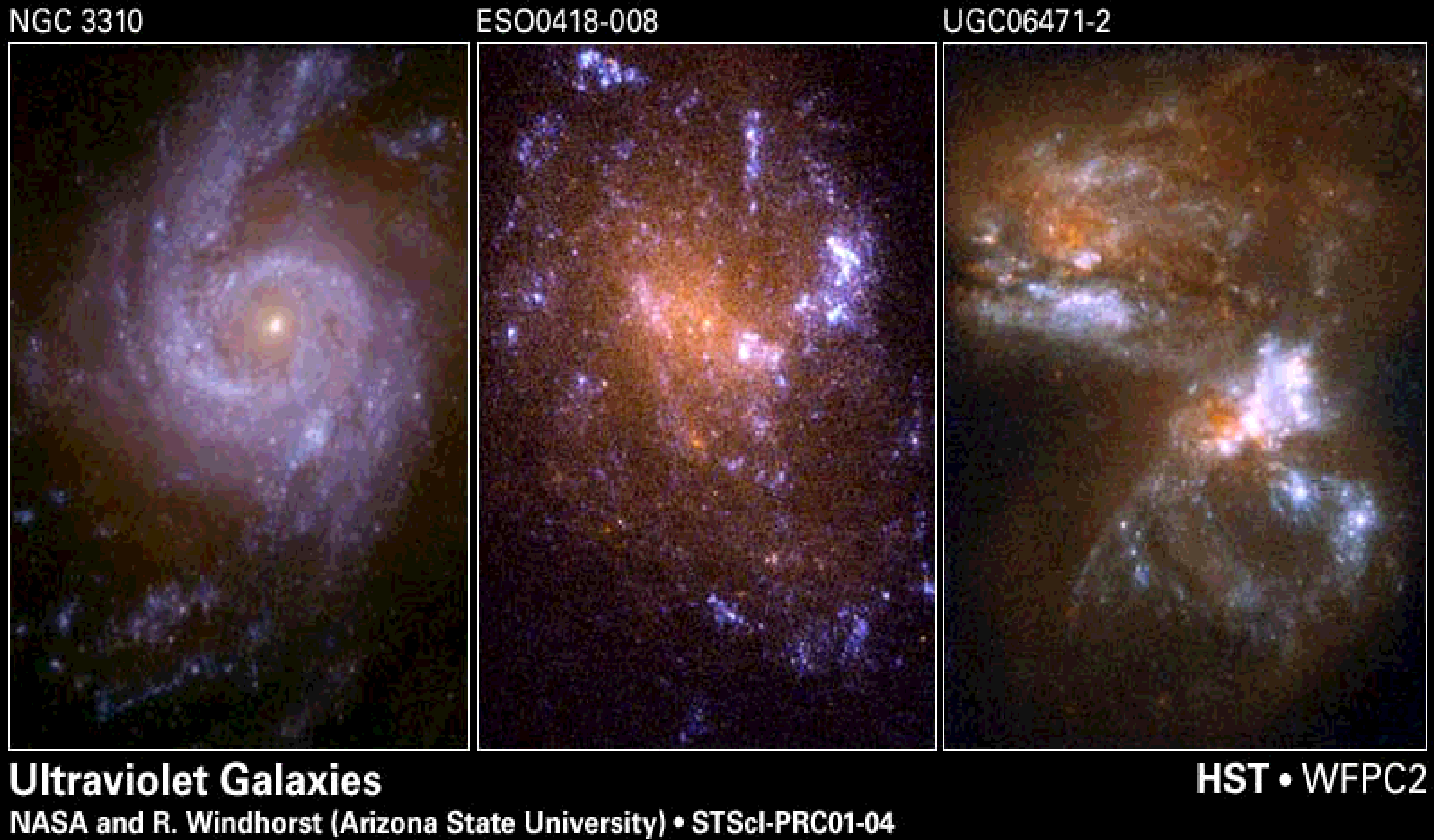
Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

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).

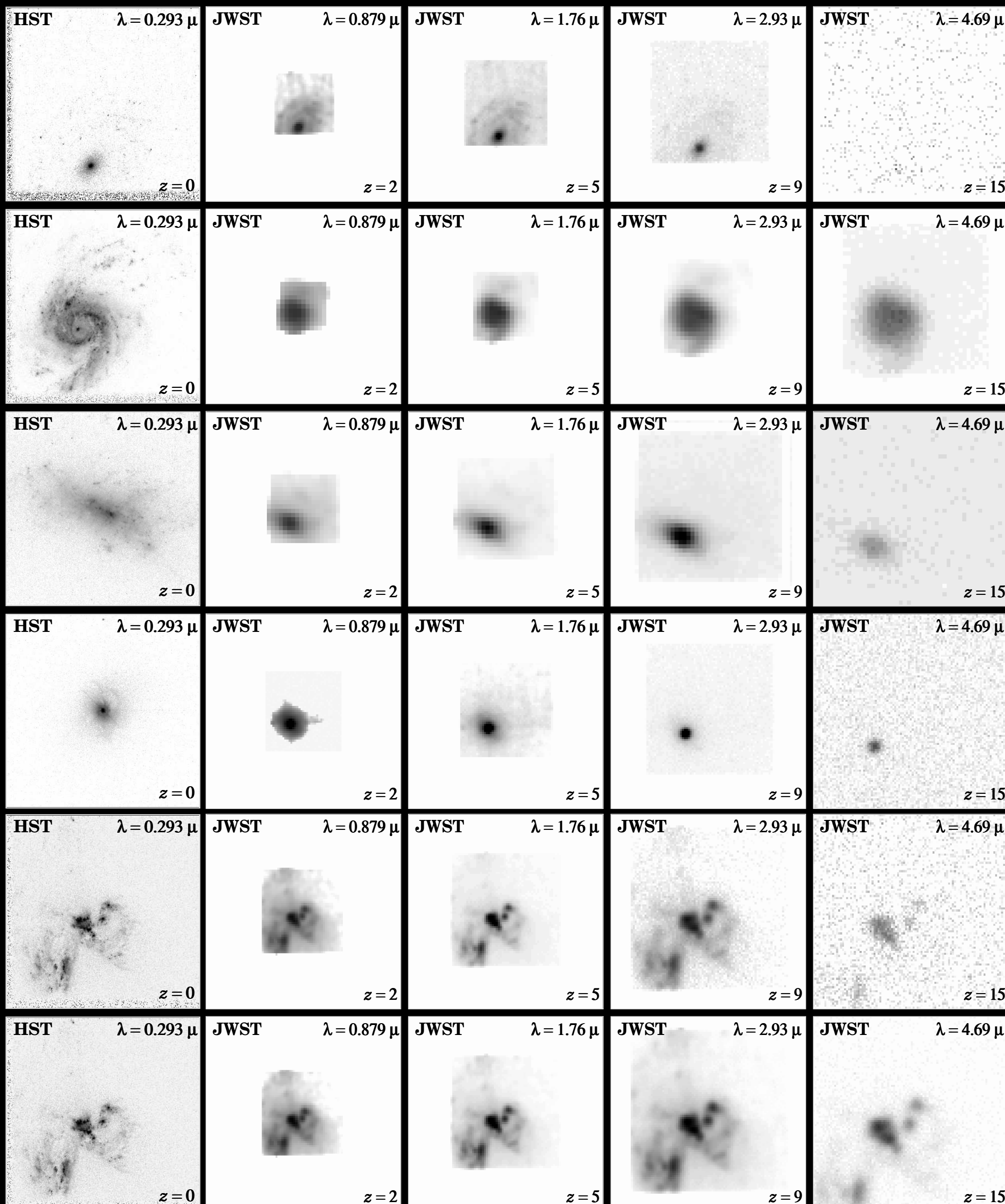
(4) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1$–15



- 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≃1–15

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

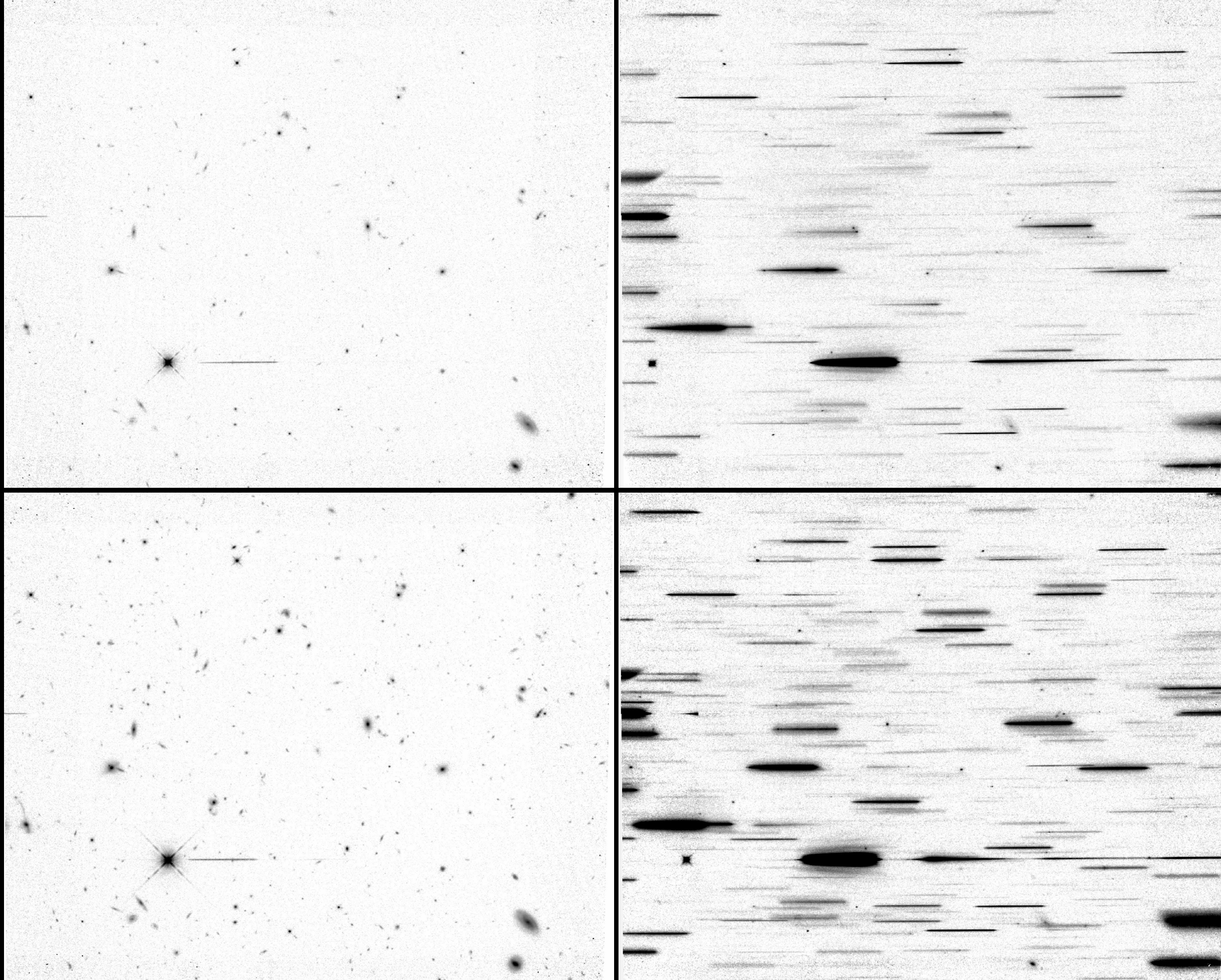


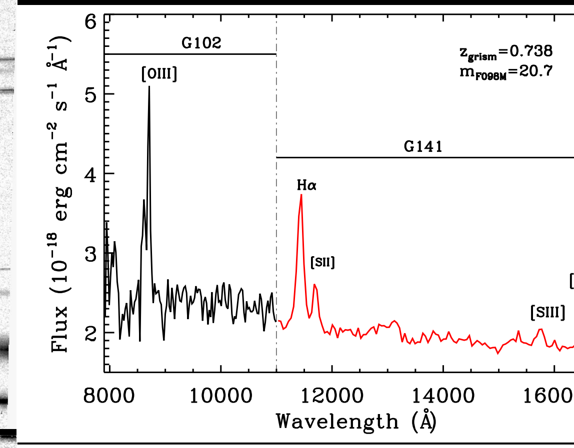
With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

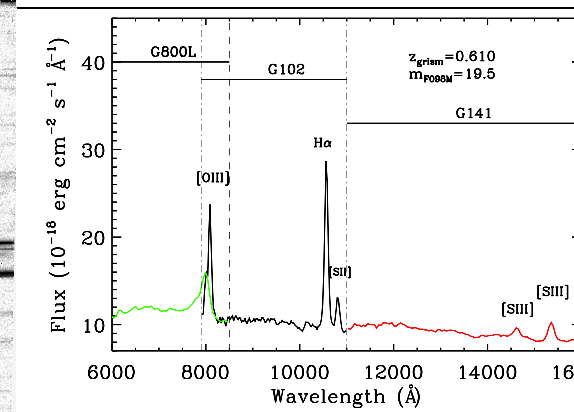
- (1) Most spiral disks will dim away at high redshift, but most formed at z≲1–2.

Visible to JWST at very high z are:

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



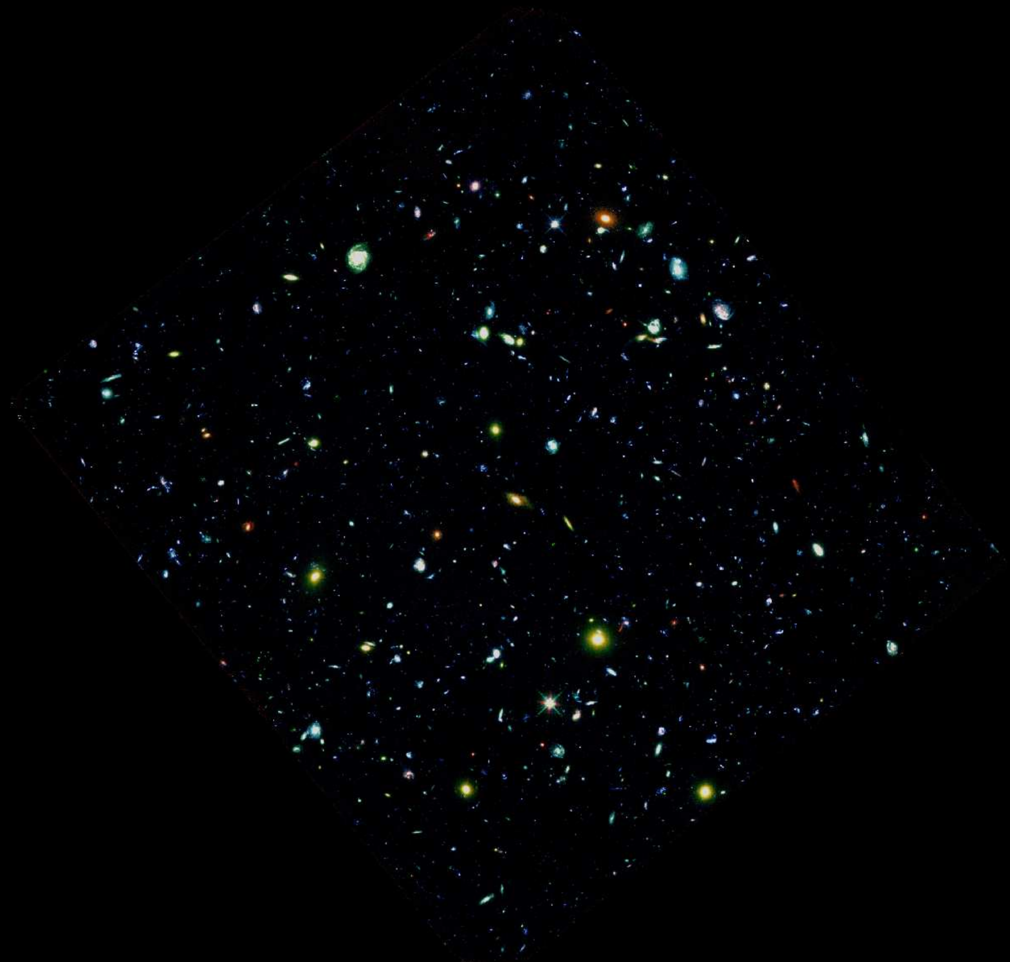


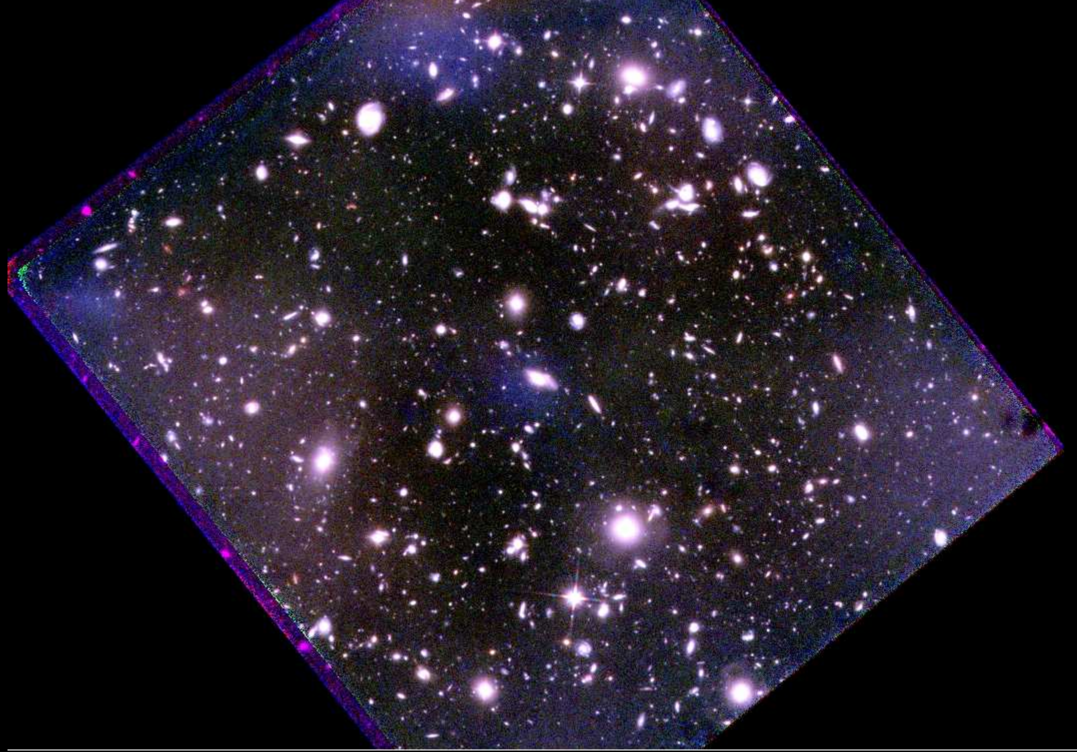


HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn^{+} 2010)

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.





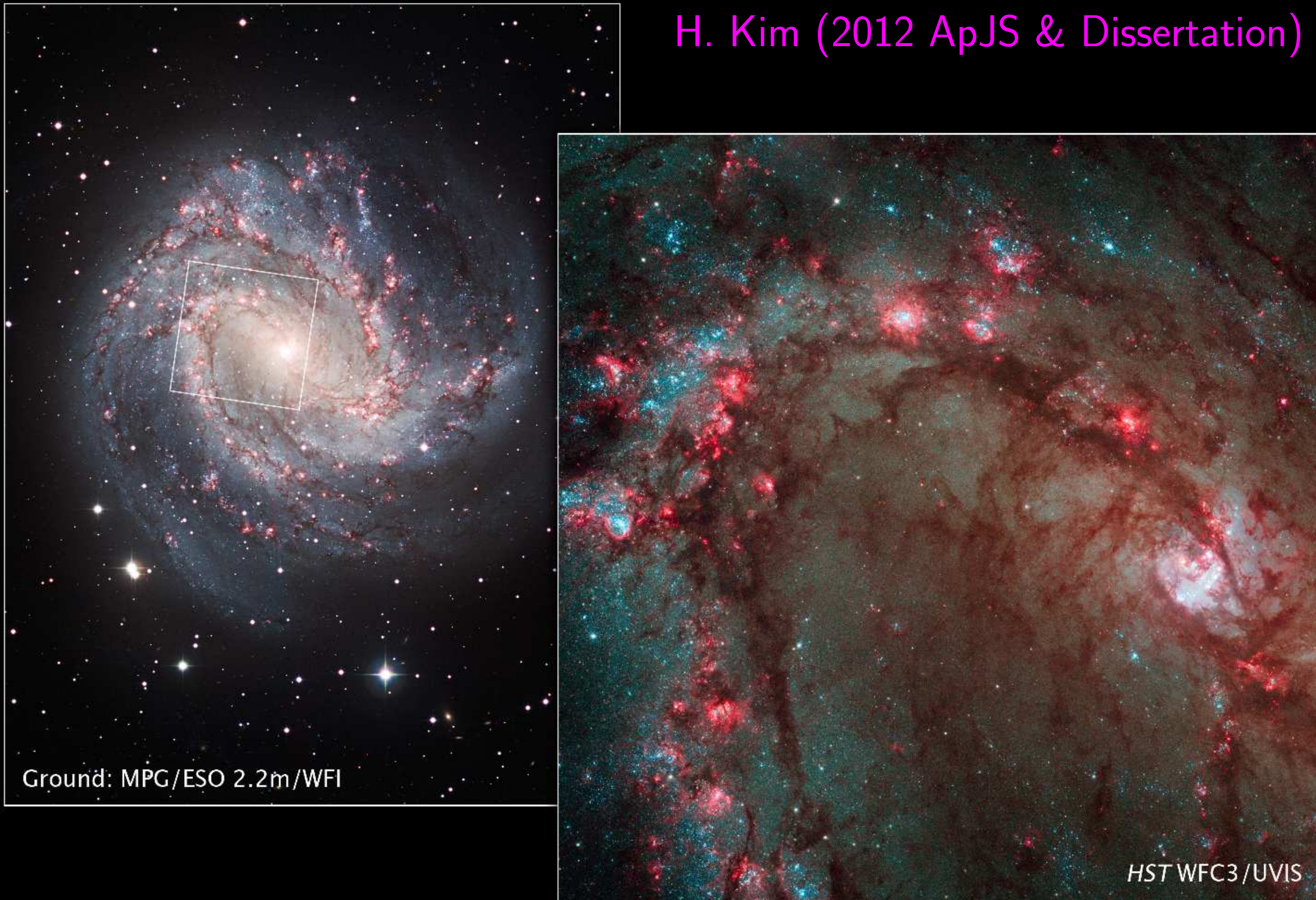
(Left) 128-hr HST/WFC3 IR-mosaic in HUDF at 1–1.6μm (YJH filters; Bouwens et al 2010, Yan et al. 2010; +85-hr by R. Ellis in 09/2012).

(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.

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

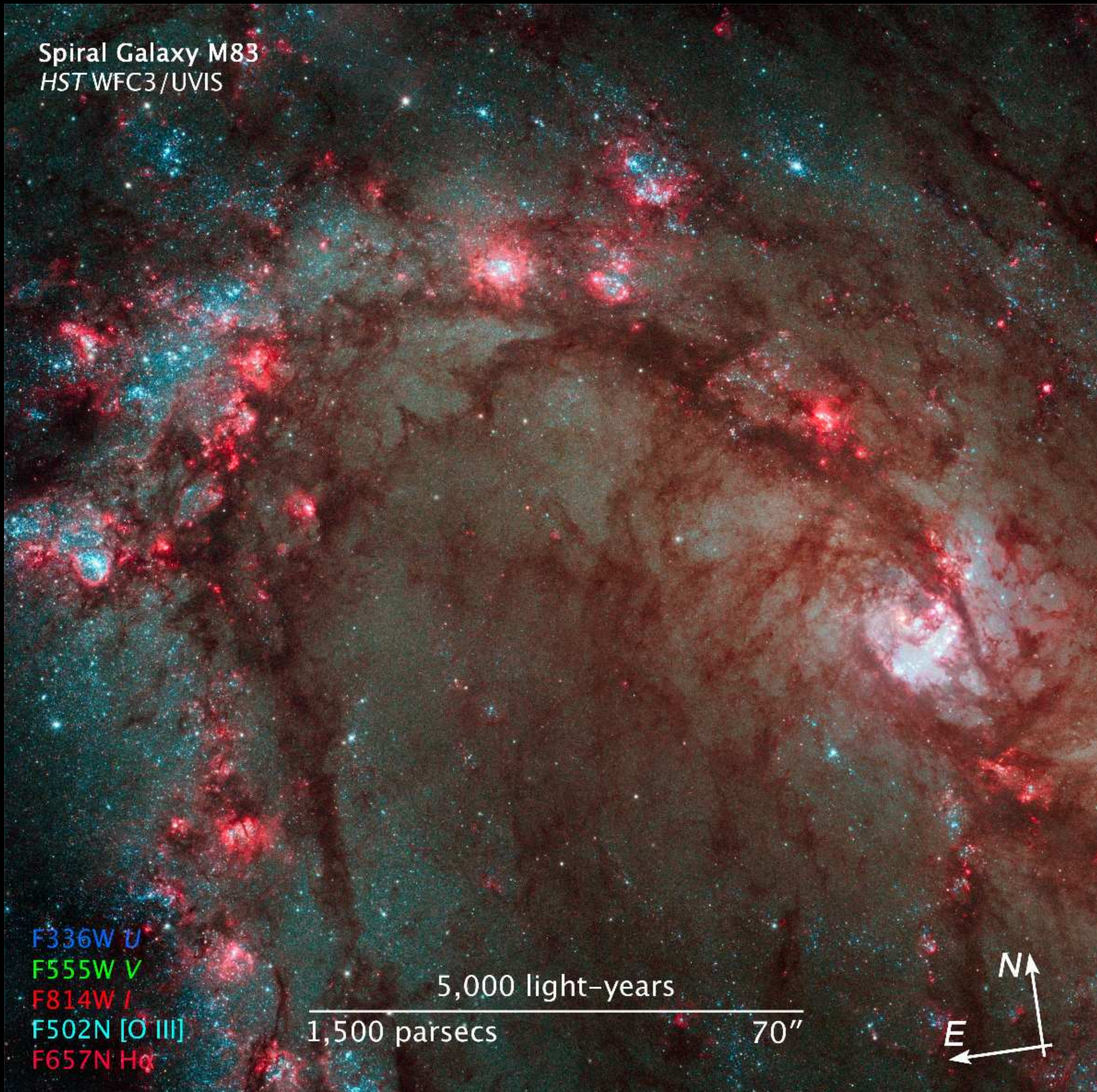
H. Kim (2012 ApJS & Dissertation)

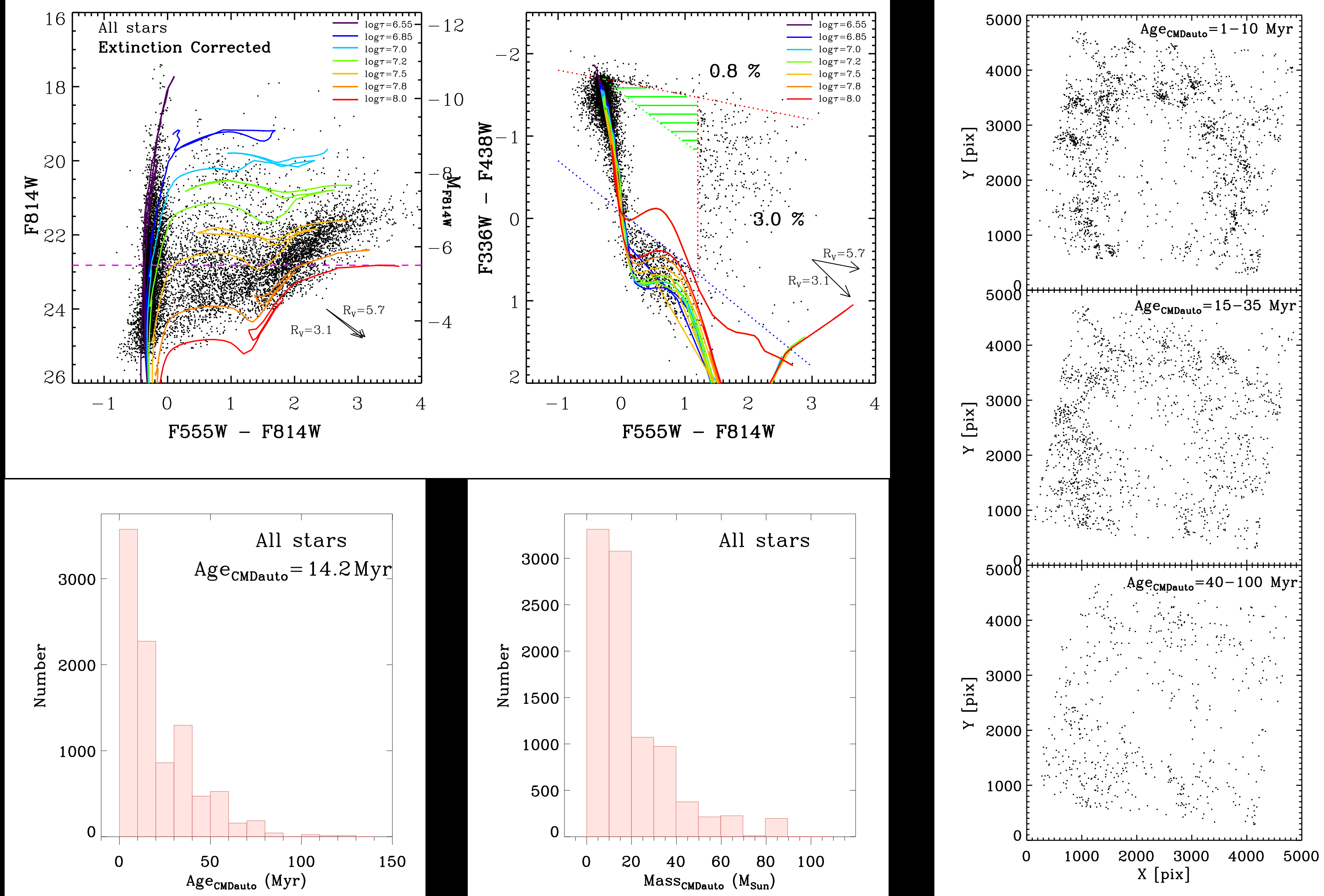


Spiral Galaxy M83

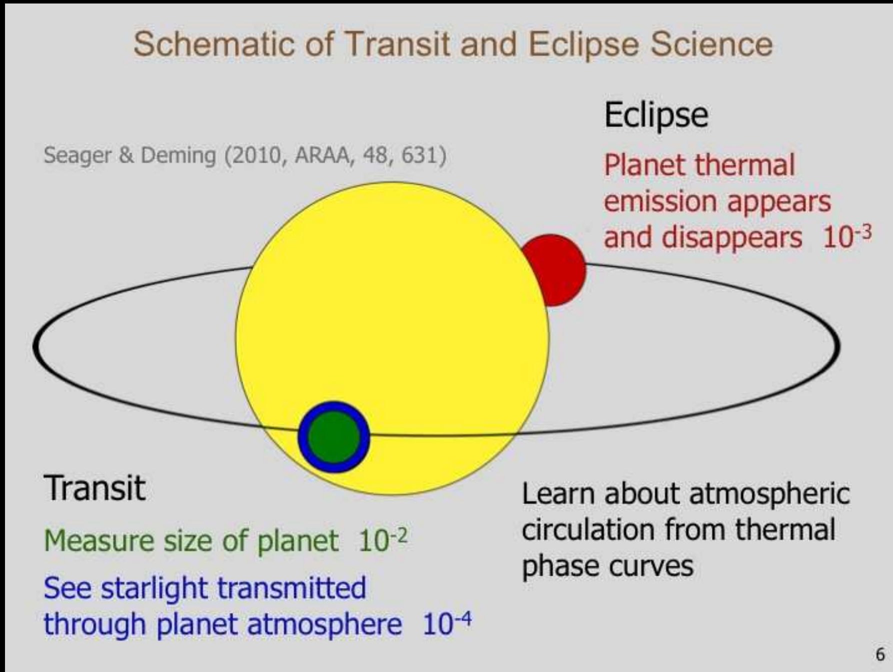
Hubble Space Telescope ▪ WFC3/UVIS

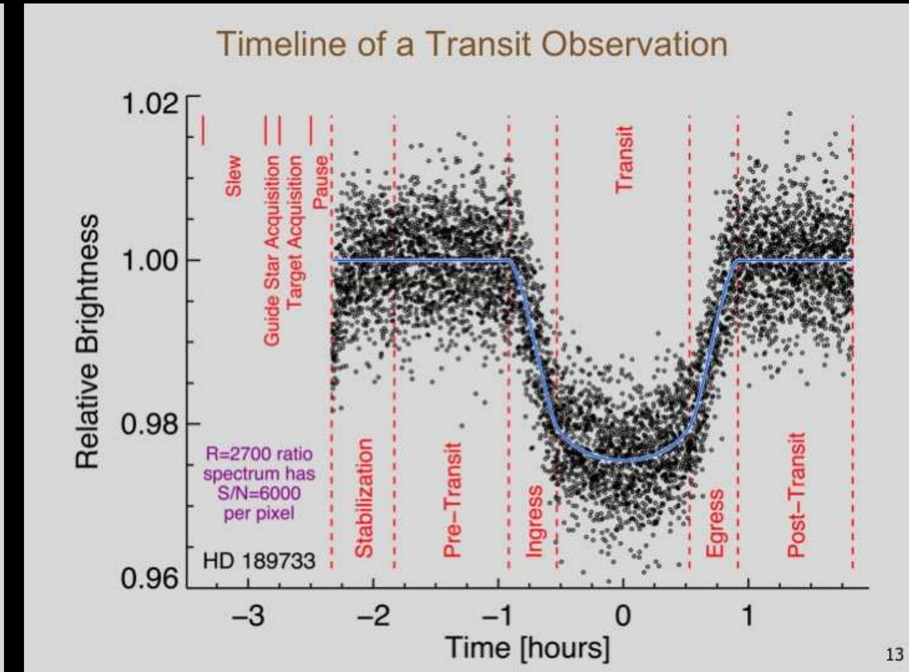
NASA, ESA, R. O'Connell (University of Virginia), the WFC3 Science Oversight Committee, and ESO STScI-PRC09-29


Spiral Galaxy M83
HST WFC3/UVIS
F336W U
F555W V
F814W I
F502N [O III]
F657N Hα
5,000 light-years
1,500 parsecs
70″
N
E

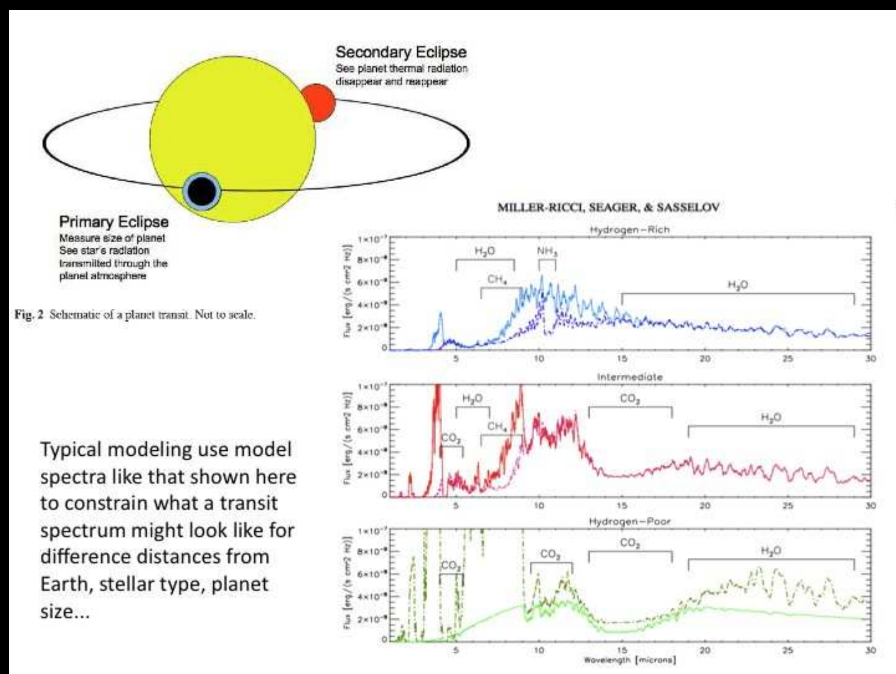


Well determined dust-corrected ages for stars in M83, with formation and dissipation along/across spiral arms (Hwihyun Kim et al. 2012, ApJS).
JWST can do this in much dustier environments and for older stellar populations. But must do all we can with HST in UV–blue before JWST flies!

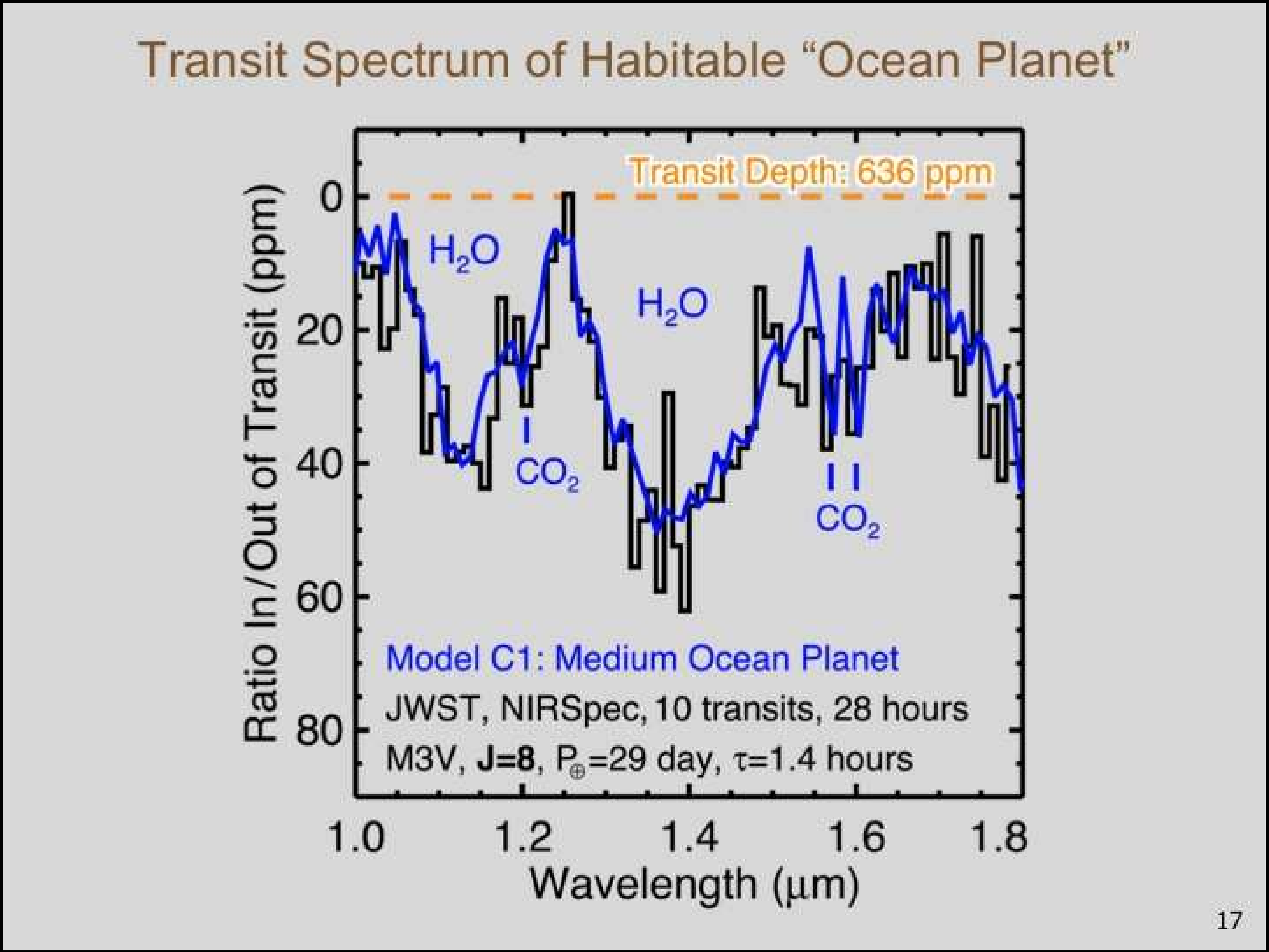




JWST can do very precise photometry of transiting Earth-like exoplanets.

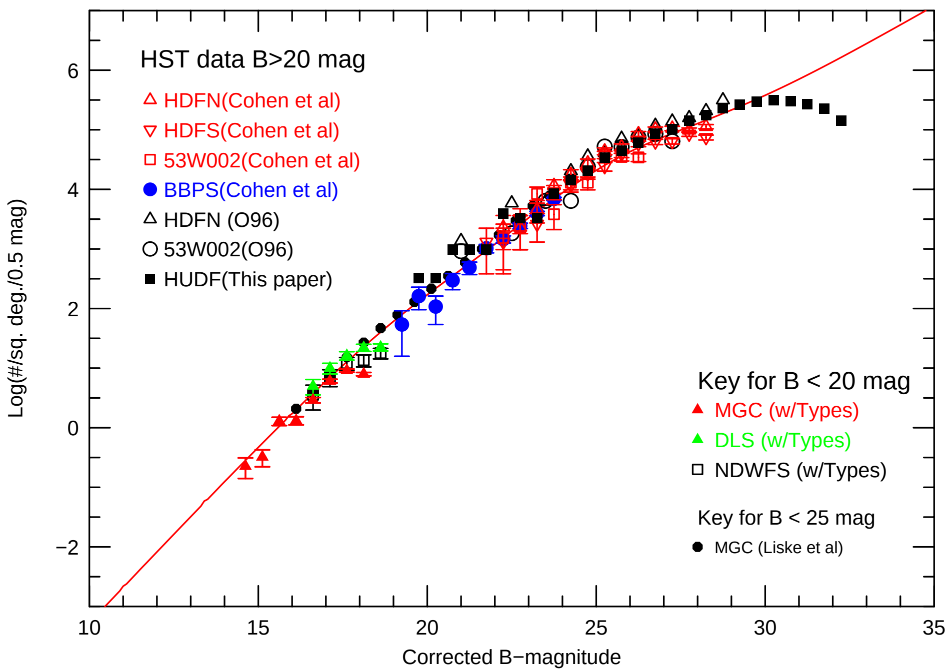


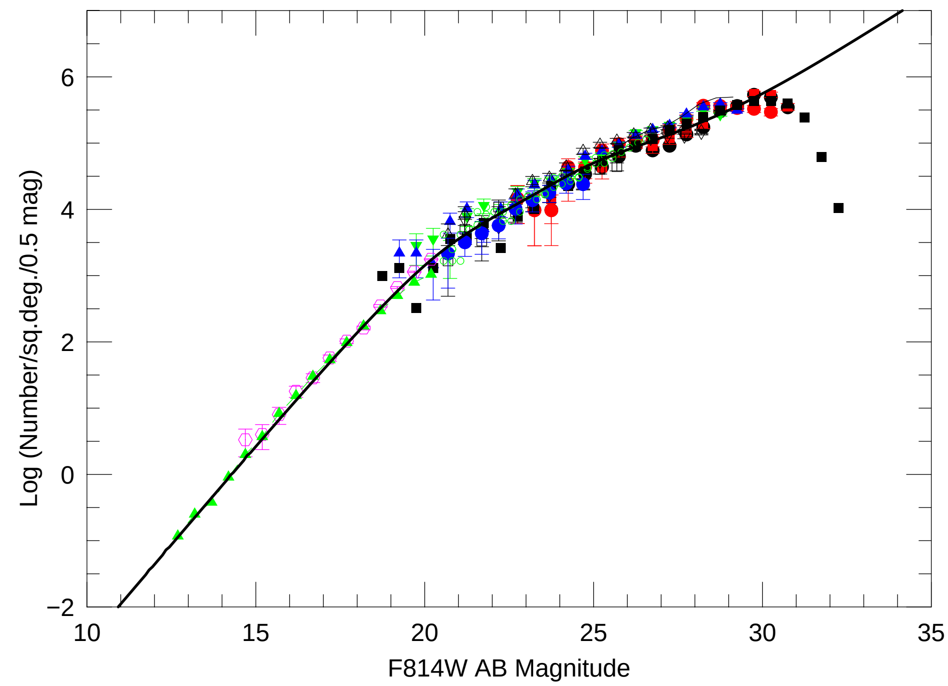
JWST IR spectra can find water and CO_2 in (super-)Earth-like exoplanets.



JWST IR spectra can find water and CO_2 in transiting Earth-like exoplanets.

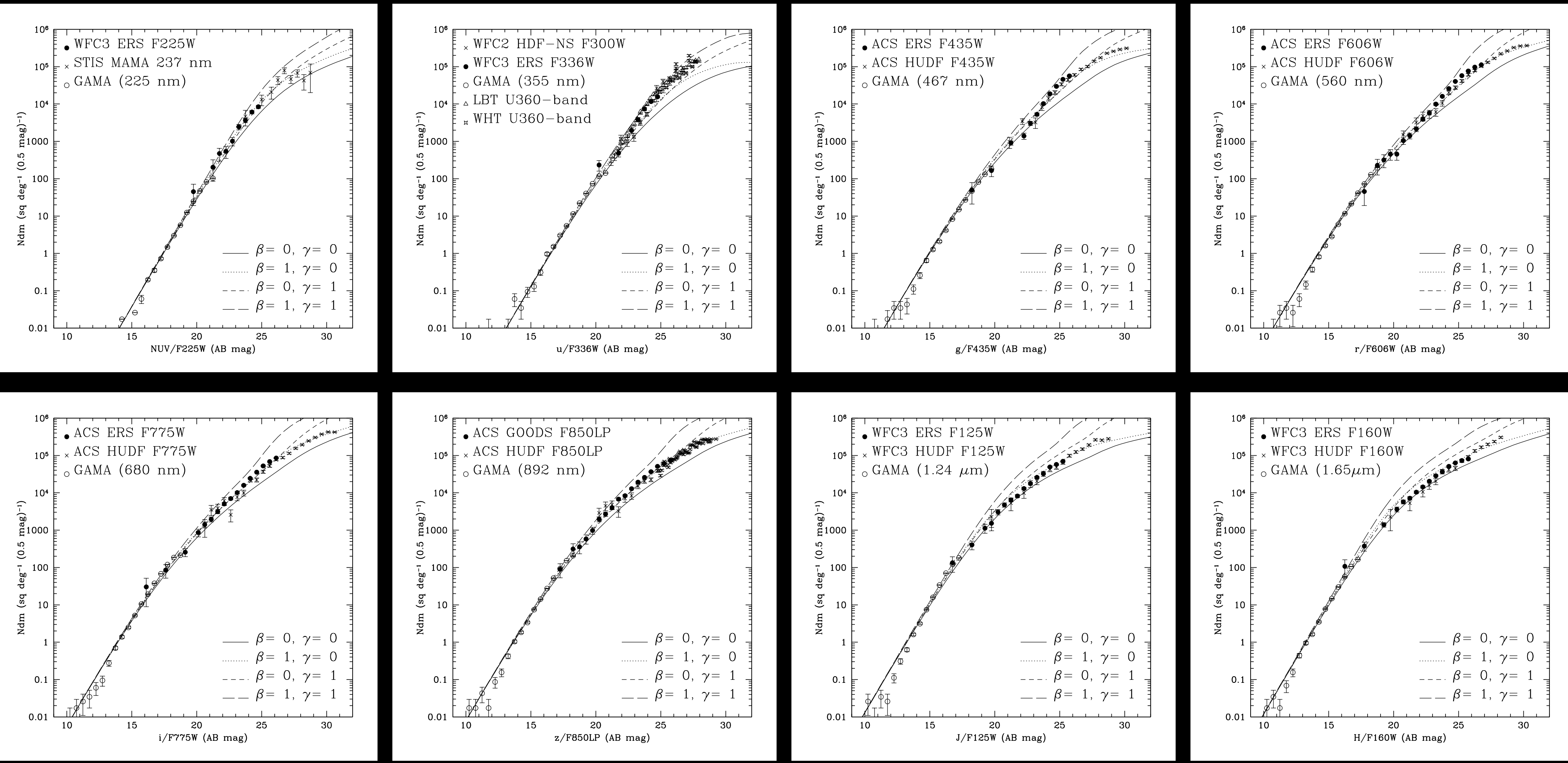
Appendix 1: will JWST (& SKA) reach the Natural Confusion Limit?





- 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$\lesssim 0\farcs08$).
- $\Rightarrow$ Observe with JWST/NIRSpec/MSA and SKA HI line channels, to disentangle overlapping continuum sources in redshifts space.

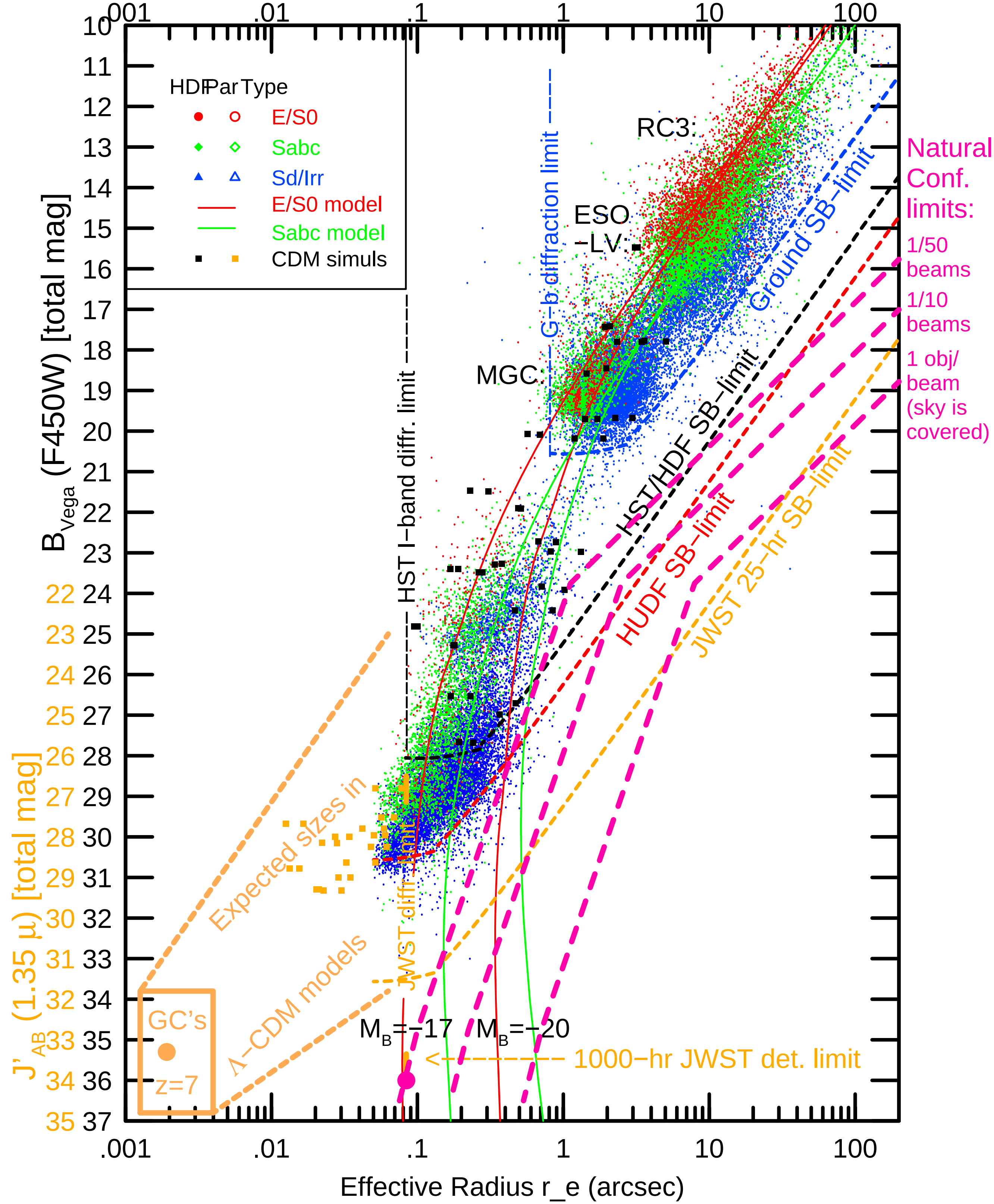
Panchromatic Galaxy Counts from $\lambda \simeq 0.2$–$2\mu m$ for AB$\simeq$10–30 mag



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.



HDF Par Type
E/S0
Sabc
Sd/Irr
E/S0 model
Sabc model
CDM simuls
RC3:
ESO
−LV:
MGC:
G−b diffraction limit
HST I−band diffr. limit
Ground SB−limit
HST/HDF SB−limit
HUDF 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
Λ−CDM 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)

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 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"