Observing AGN growth with HST and JWST:

When during galaxy assembly did AGN growth take place?

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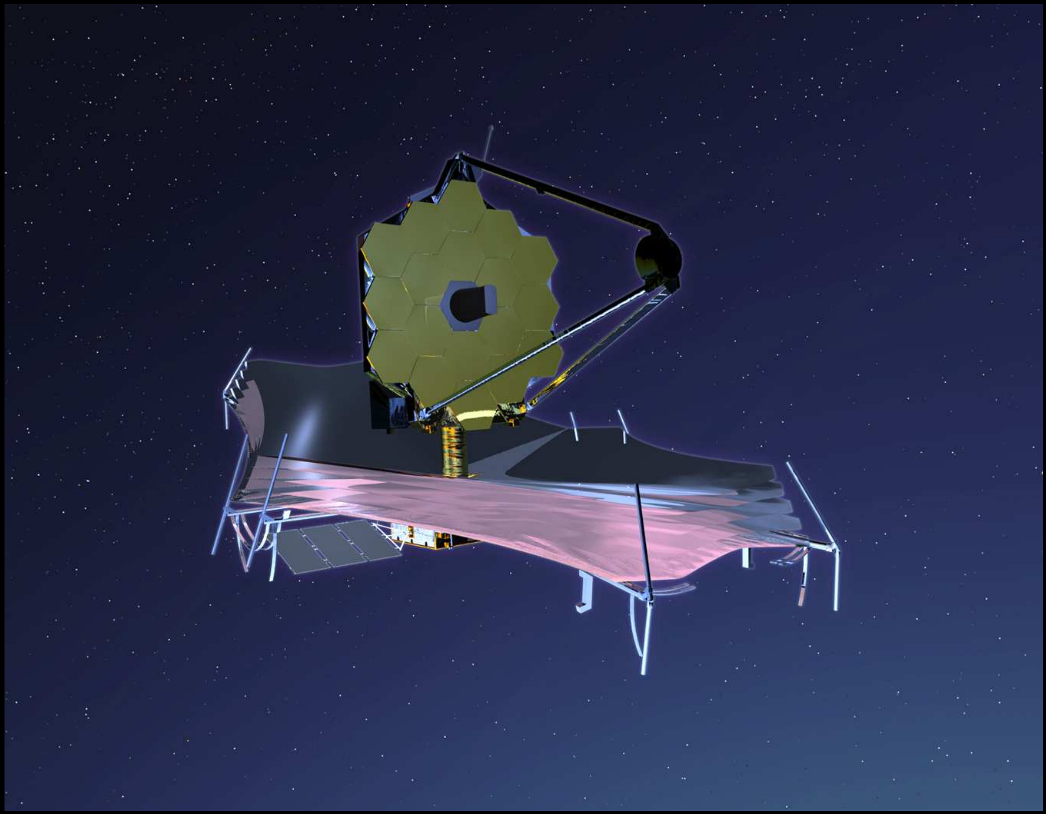
& (Ex) ASU Grad Students: N. Hathi, H. Kim, R. Ryan, M. Rutkowski, A. Straughn, & K. Tamura



Talk at "Key Issues in High-redshift Galaxy/Black Hole Evolution in the ALMA/JWST Era" workshop, Hangzhou, China, We. June 2, 2010

Outline

• (0) Summary of First Light and H-Reionization at z$\gtrsim$6:
What has HST done, and what can JWST do?

• (1) HST/WFC3 & JWST: how did AGN/SMBH-growth go hand-in-hand with Galaxy Assembly?

• (2) (Major) mergers in GOODS & HUDF: Measuring Galaxy Assembly?

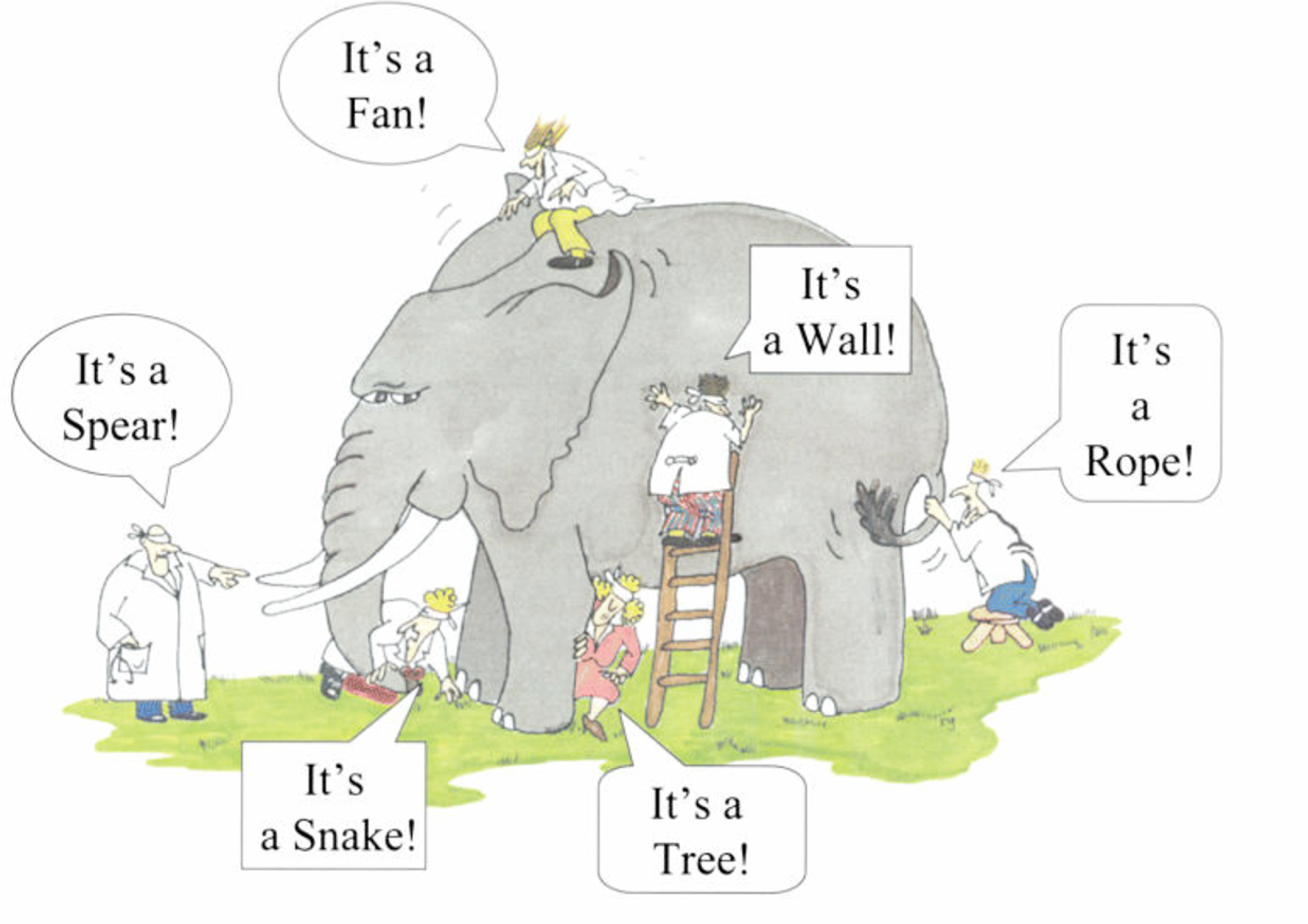
• (3) Variable Objects in the HUDF: A measure of AGN/SMBH-Growth?

• (4) Epoch dependent major merger rate to AB$\lesssim$27 and Chandra N(z).

• (5) SED ages of radio and X-ray host galaxies vs. epoch:
May trace AGN-growth vs. Galaxy Assembly directly.

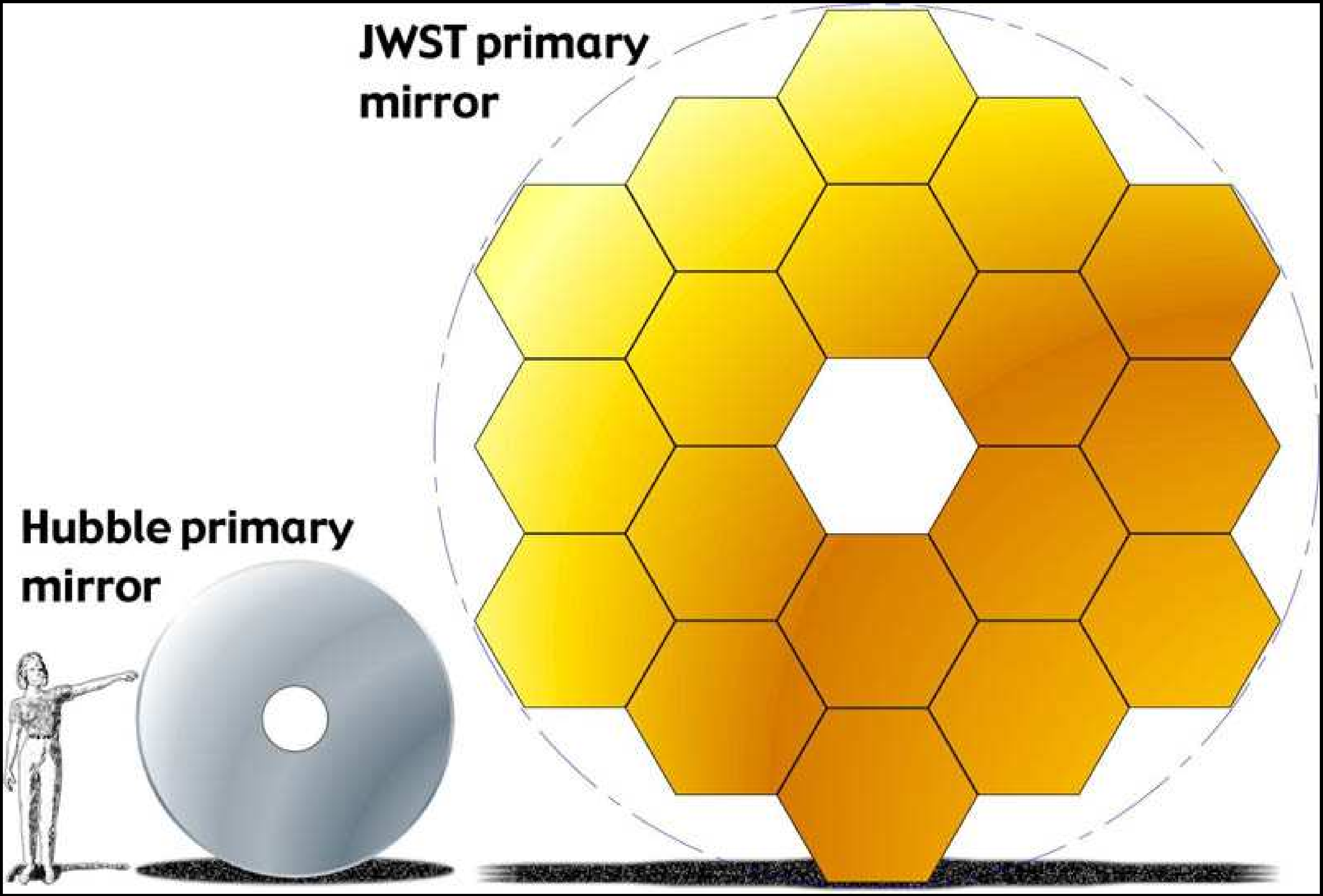
• (6) Summary and Conclusions: Delta t(X-ray/Radio X— field) $\lesssim$1 Gyr.

Sponsored by NASA/JWST; all charts ITAR cleared



AGN are the cosmic elephants that surprise both observers and theorists ... !

(1) JWST: First Light, Reionization, Galaxy Assembly & AGN growth



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

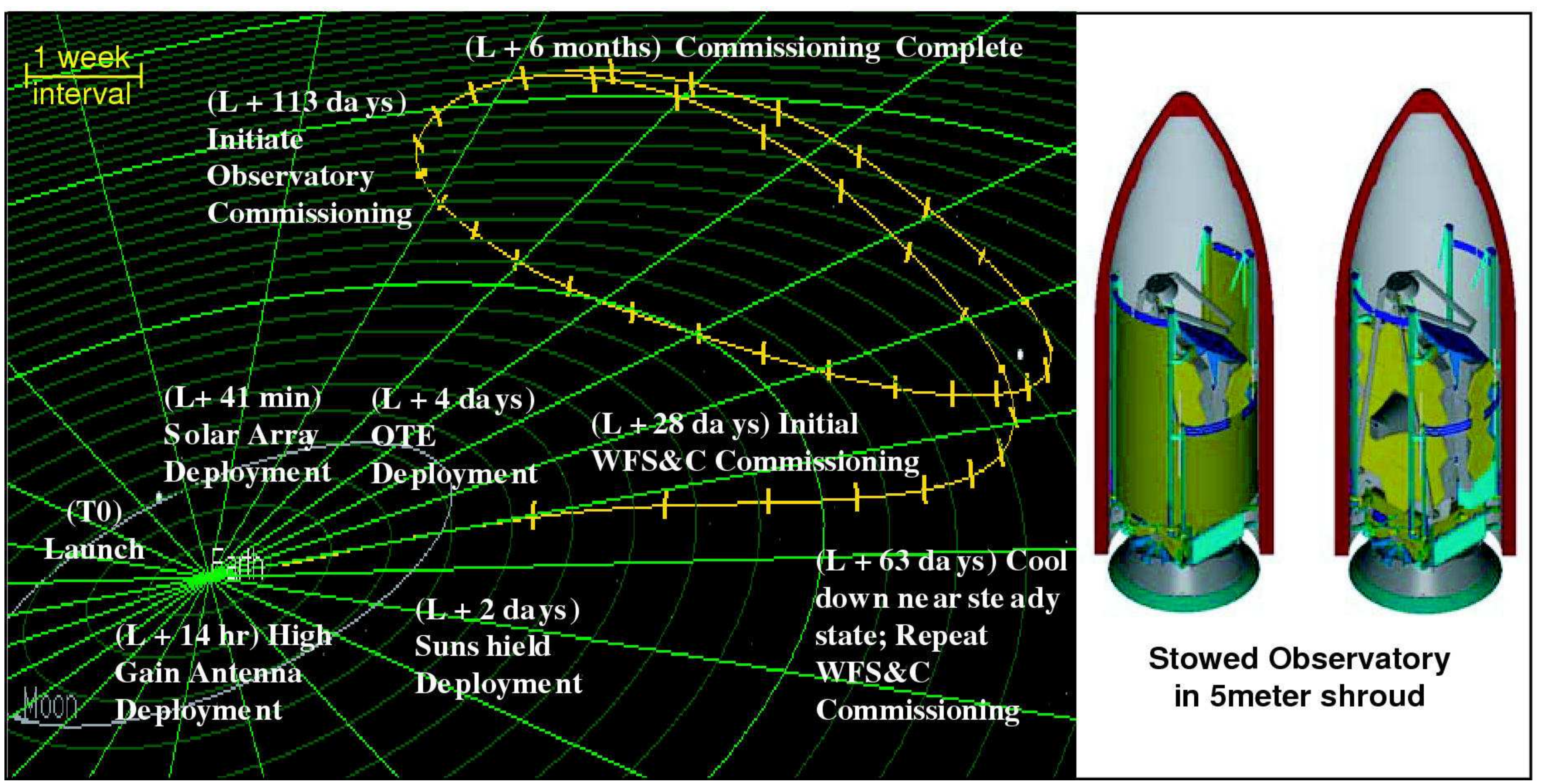
JWST has the same resolution in the near-IR as HST in the optical.

• (1a) 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 0.7 to 29 μm, to be launched in June $\gtrsim$2014.

• 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).

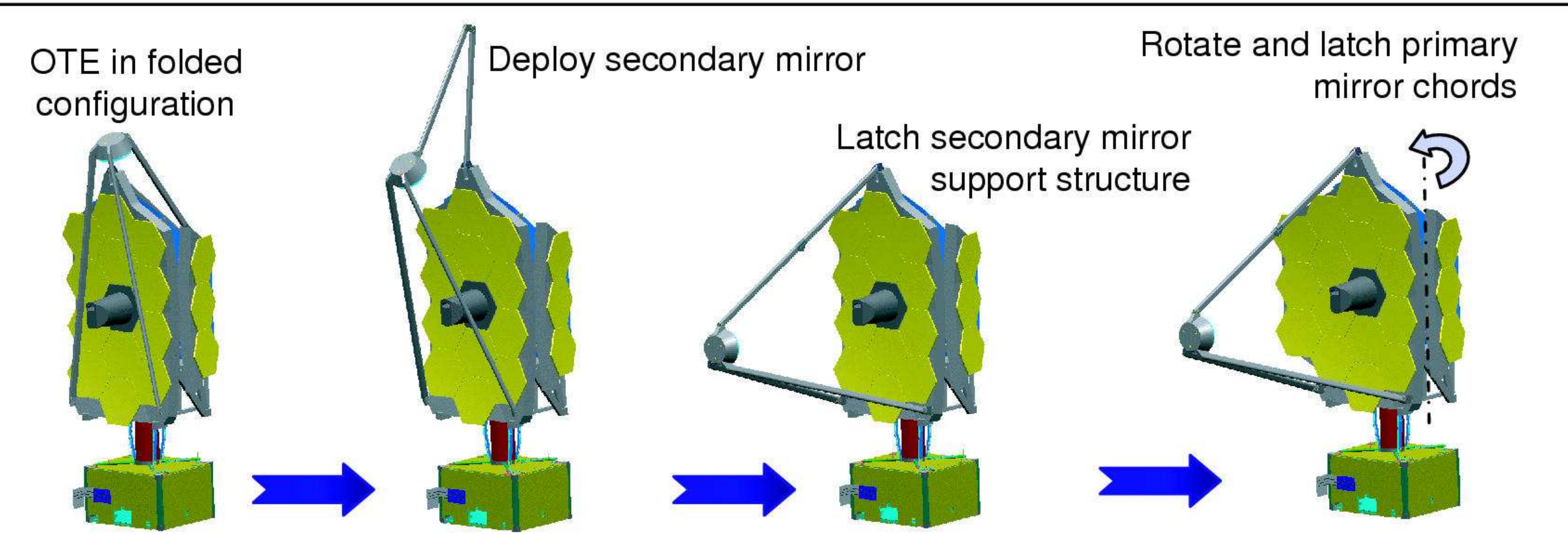
• (1a) How will JWST travel to its L2 orbit?



- After launch in June 2014 with an Ariane-V, JWST will orbit around the the Earth–Sun Lagrange point L2, 1.5 million km from Earth.

- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim$70% of the time, and send data back to Earth every day.

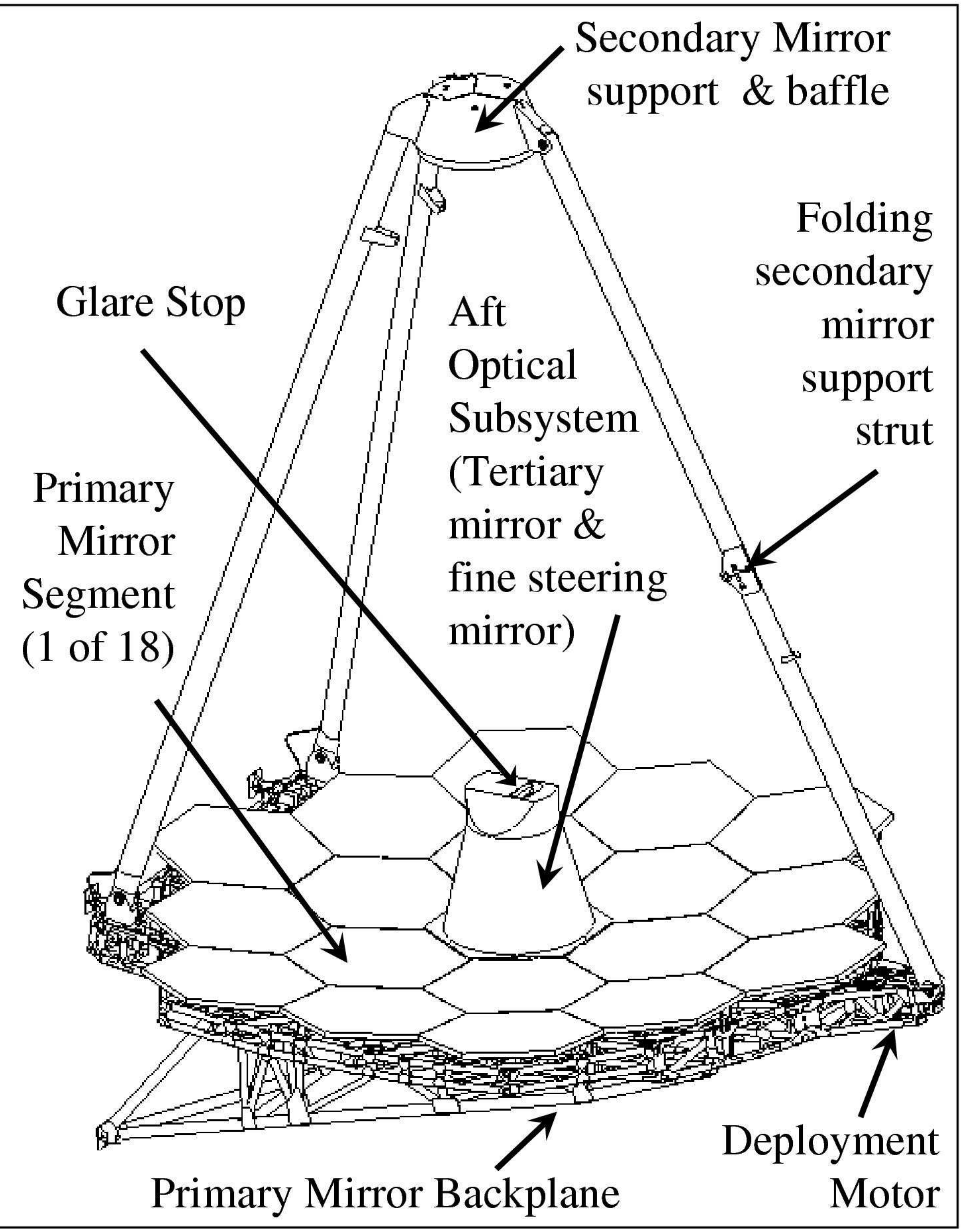
• (1a) How will JWST be automatically deployed?



• 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, 1.5 million km from Earth.

• The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: component and system tests at JSC.

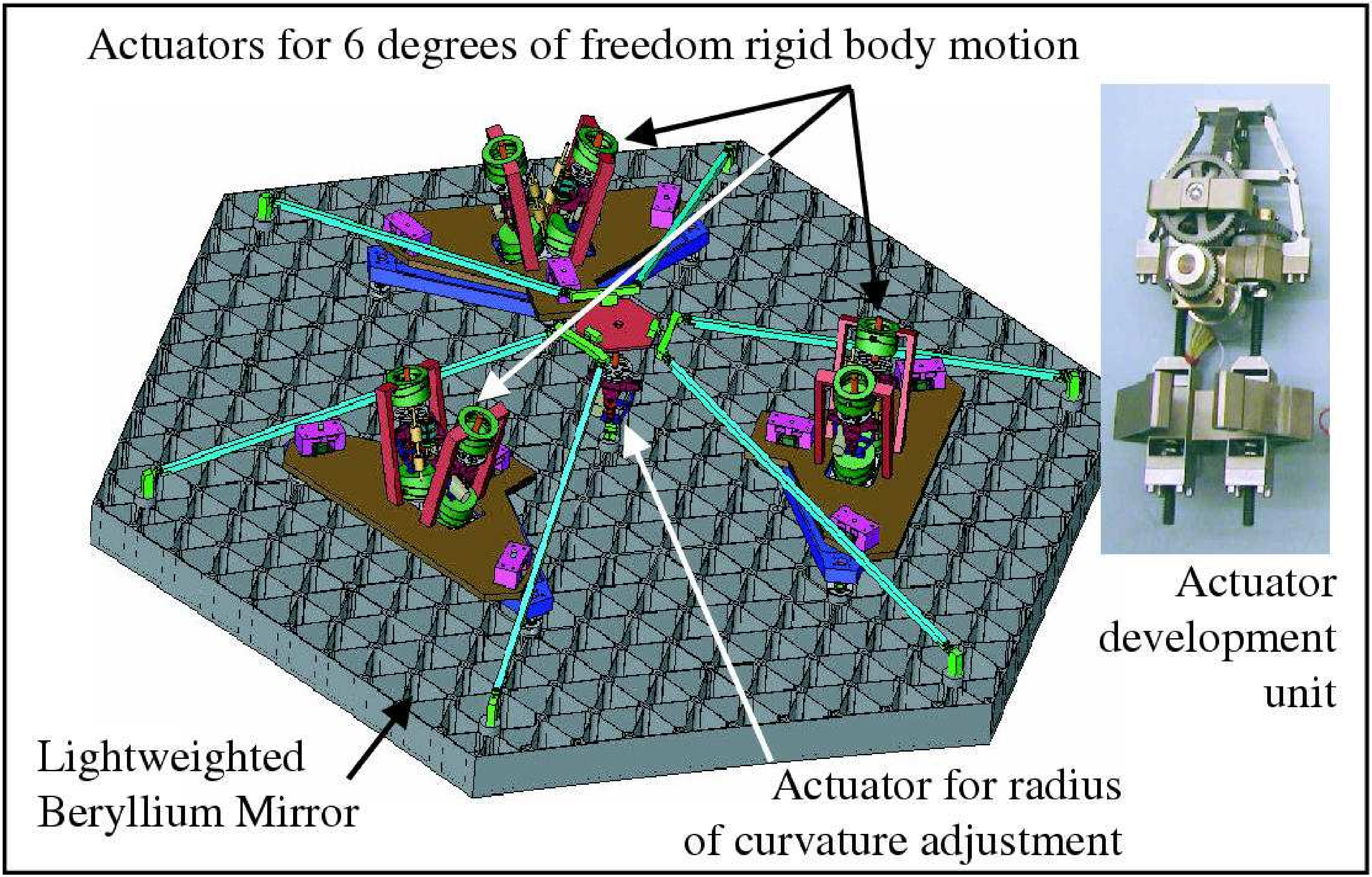
• Component fabrication, testing, & integration is on schedule: 3 out of 18 flight mirrors completely done, and at the 45K 2.0μm diffraction limit!



Ball 1/6-model for WFS: diffraction-limited 2.0 μm images (Strehl$\gtrsim$0.85).

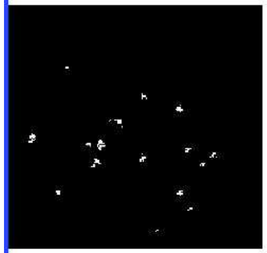
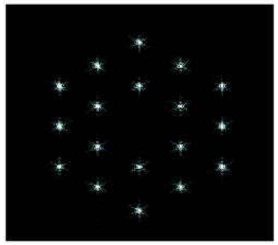
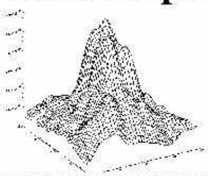
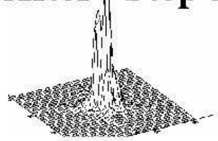
Wave-Front Sensing tested hands-off at 45 K in 1-G at JSC in 2011-2013.

In L2, WFS updates every 10 days depending on scheduling/SC-illumination.



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

Redundant & doubly-redundant mechanisms, quite forgiving against failures

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

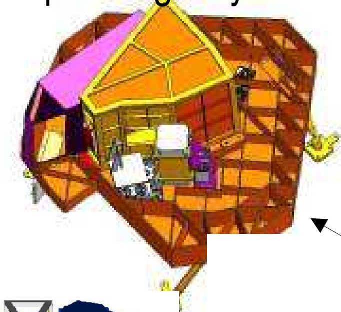
Need WFS-updates every $\sim$10 days, depending on scheduling/SC-illumination.

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

Instrument Overview

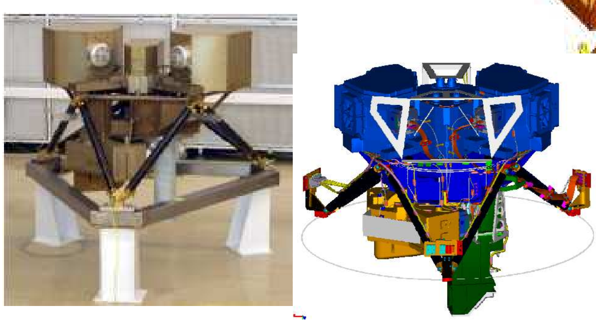
Fine Guidance Sensor (FGS)

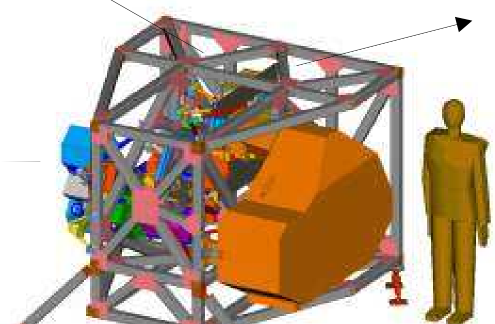
• Ensures guide star availability with >95% probability at any point in the sky
• Includes Narrowband Imaging Tunable Filter
• Developed by Canadian Space Agency & COM DEV

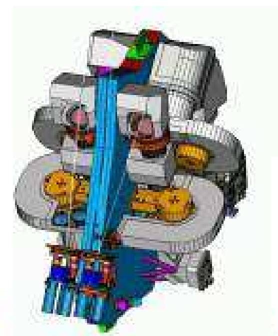


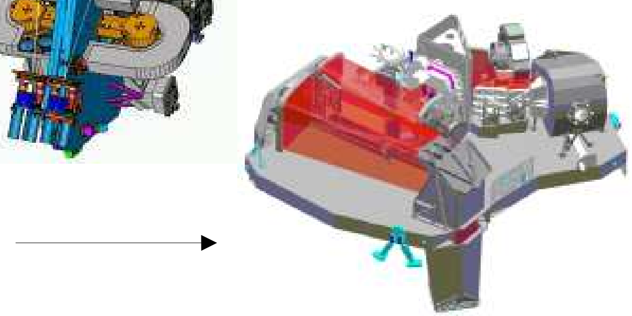
Near Infra-Red Camera (NIRCam)

- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC









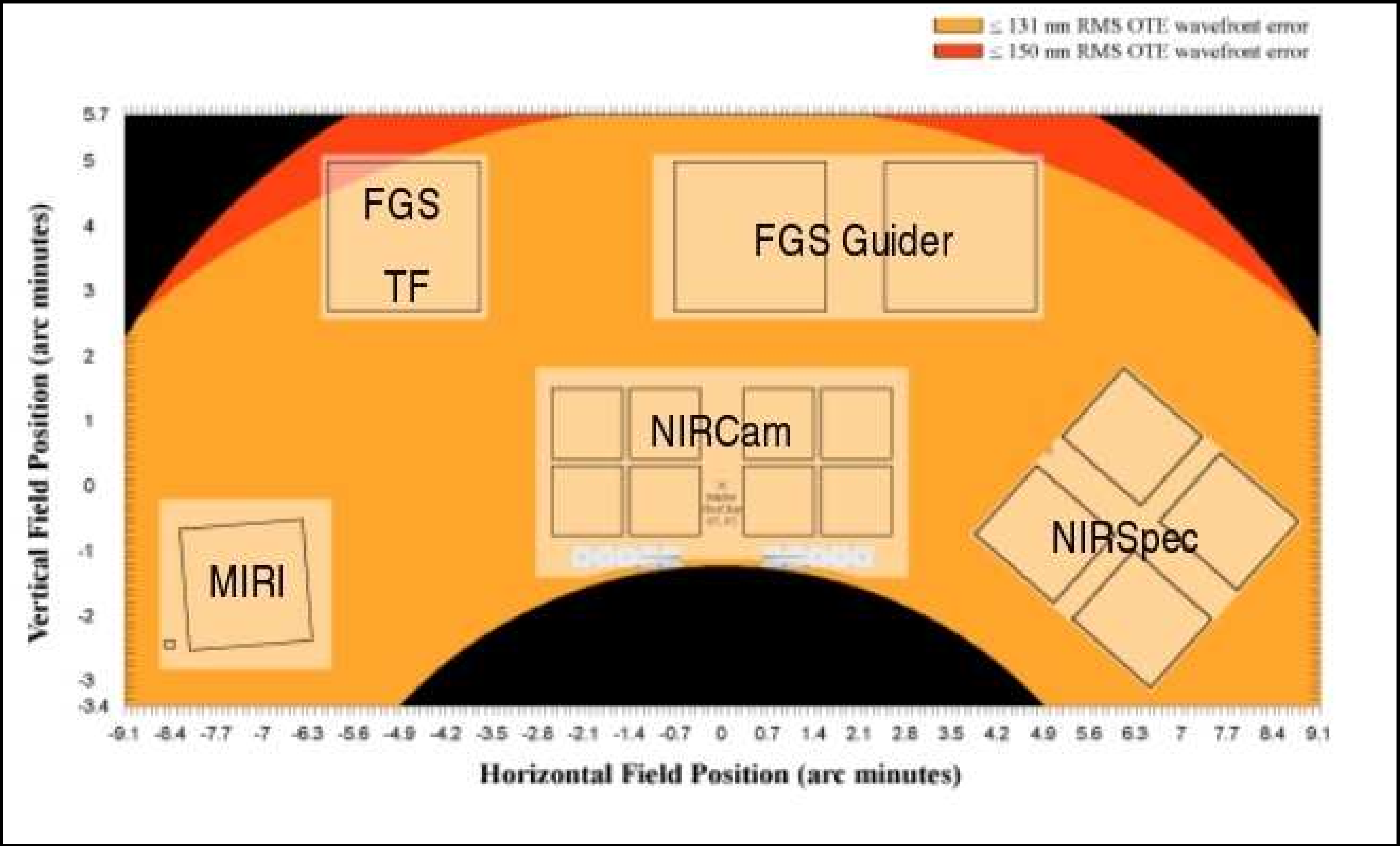
Mid-Infra-Red Instrument (MIRI)

• 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)

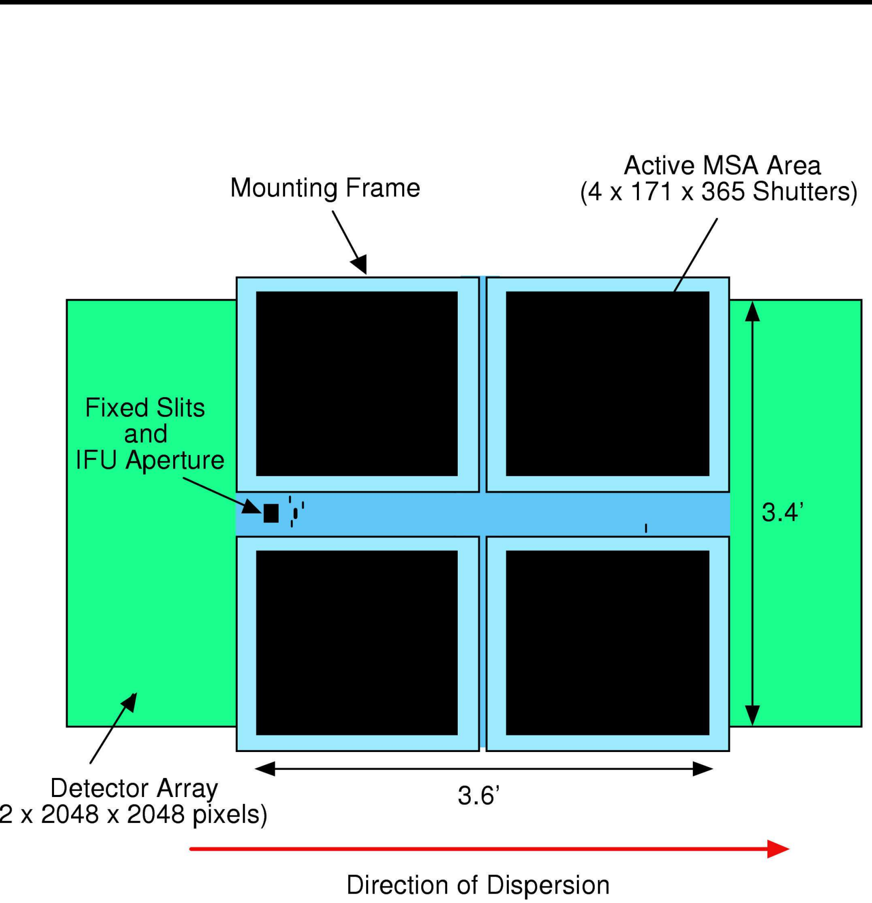
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

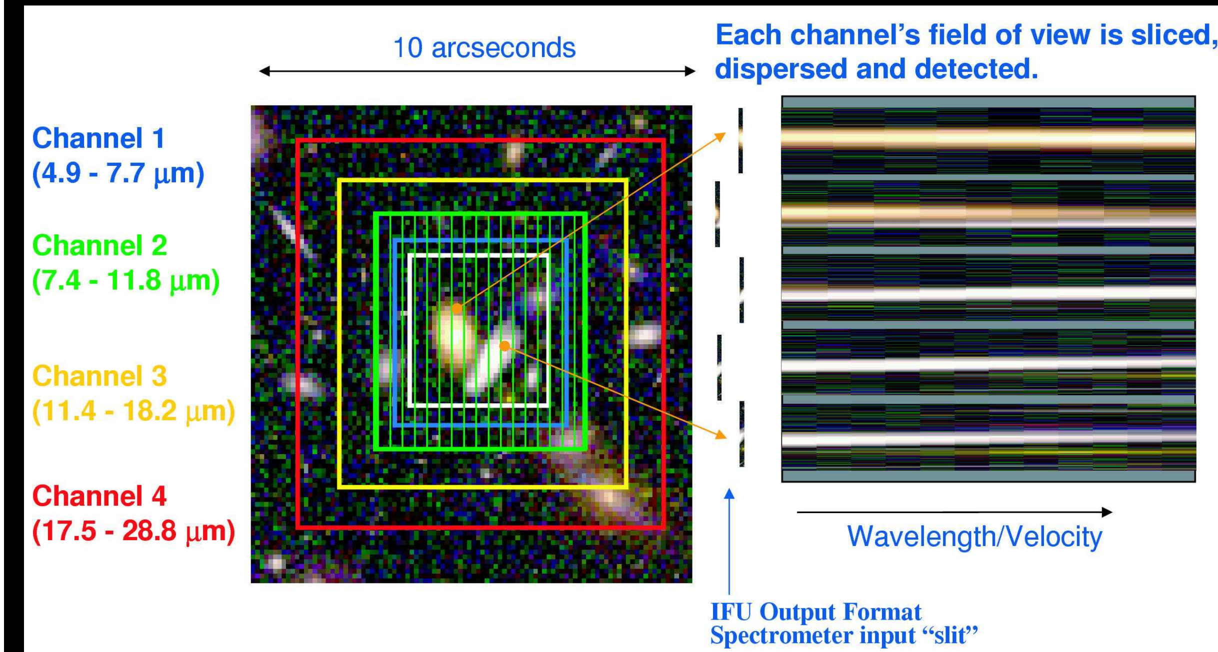
• (1b) What instruments will JWST have?



All JWST instruments can in principle be used in parallel observing mode:

• Currently only being implemented for parallel *calibrations.*





JWST offers significant multiplexing for faint object spectroscopy:

- NIRSpec/MSA with 4×62,415 independently operable micro-shutters (MEMS) that cover $\lambda \simeq 1$–5 μm at R$\simeq$100–1000.

- MIRI/IFU with 400 spatial pixels covering 5–29 μm at R$\sim$2000–4000.

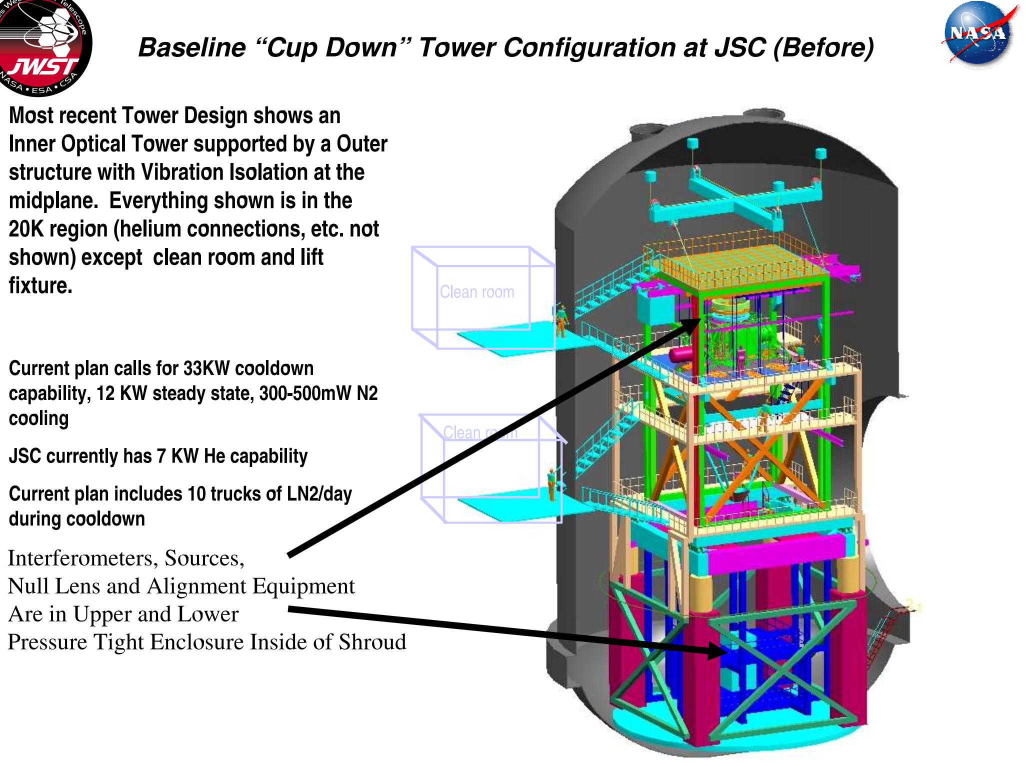
- FGS/TFI that covers a $2\overset{'}{.}2 \times 2\overset{'}{.}2$ FOV at $\lambda \simeq 1.6$–4.9 μm at R$\simeq$100.

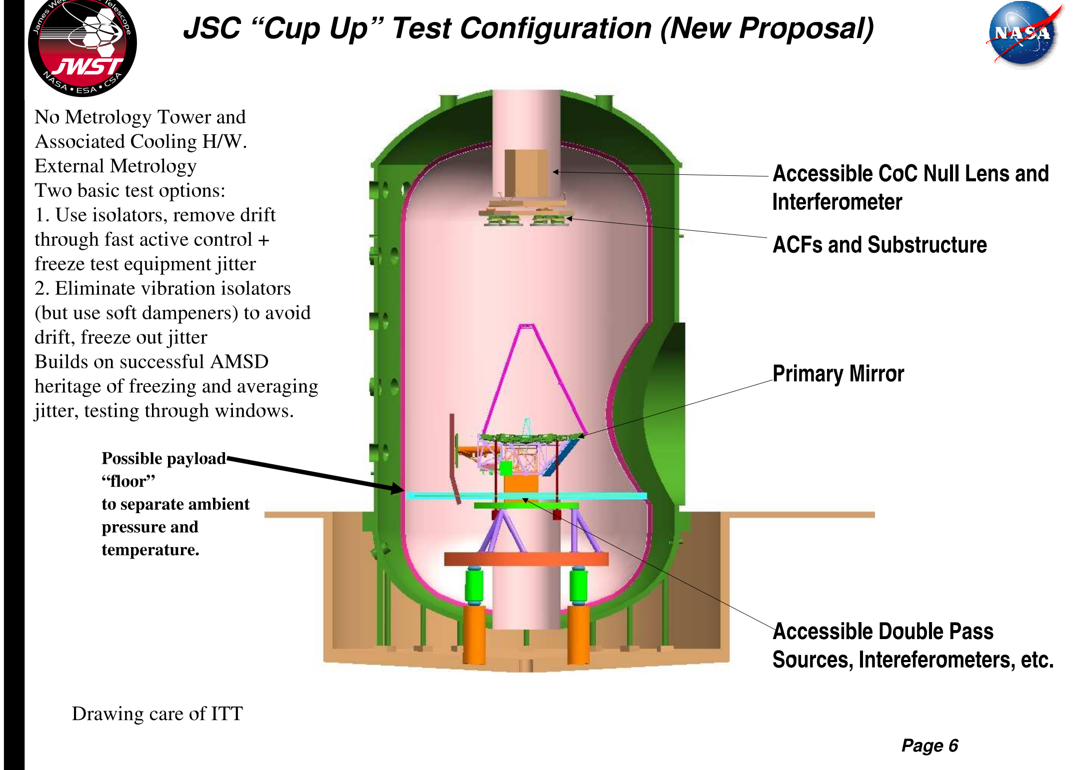
[• NIRCam offers R$\simeq$5 imaging from 0.7–5μm over two $2\overset{'}{.}3 \times 4\overset{'}{.}6$ FOV's.]

Despite NASA's CAN-do approach: Must find all the cans-of-worms ...

Northrop Grumman Expertise in Space Deployable Systems

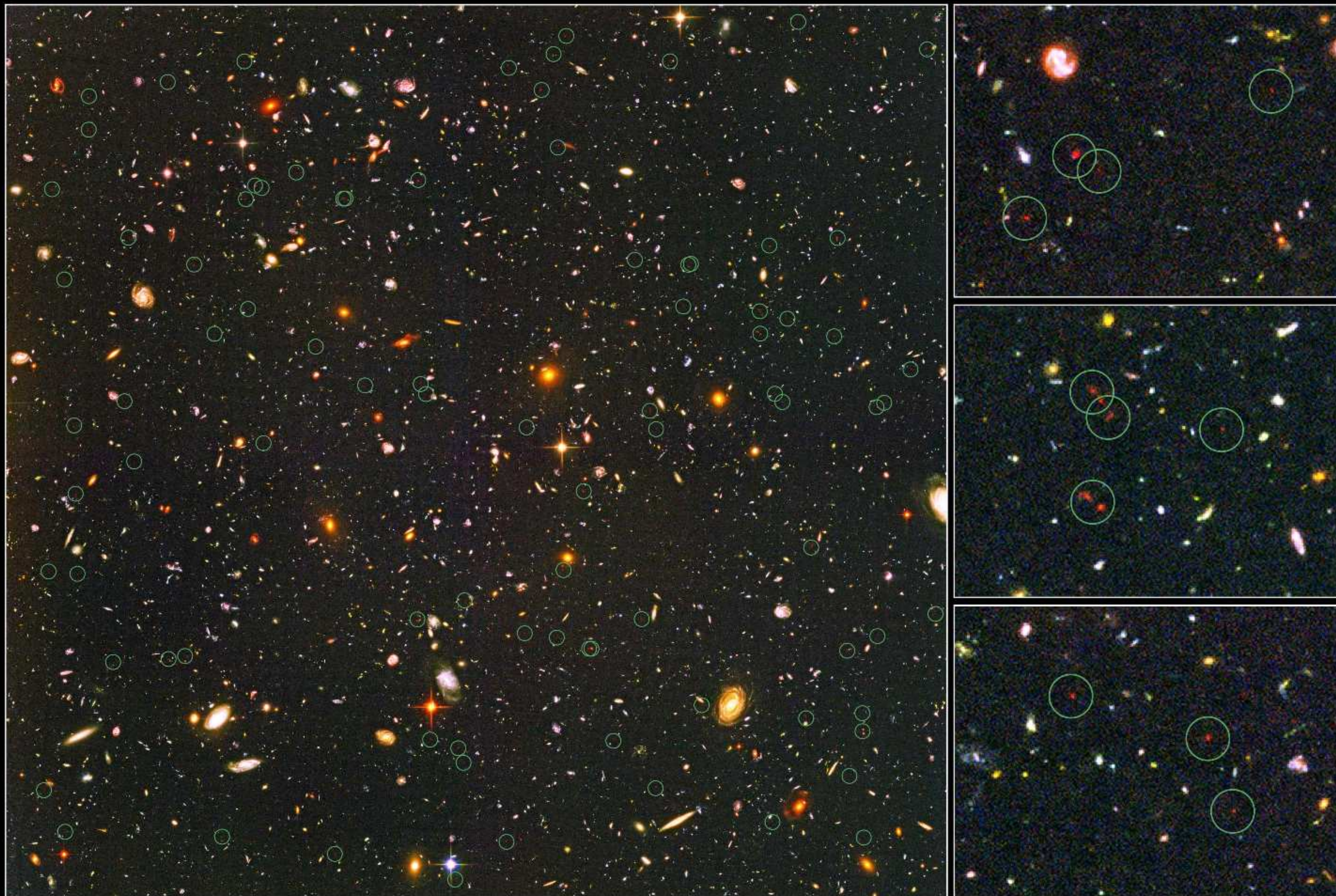
- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements





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.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010: Passes Mission Critical Design Review.



Distant Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

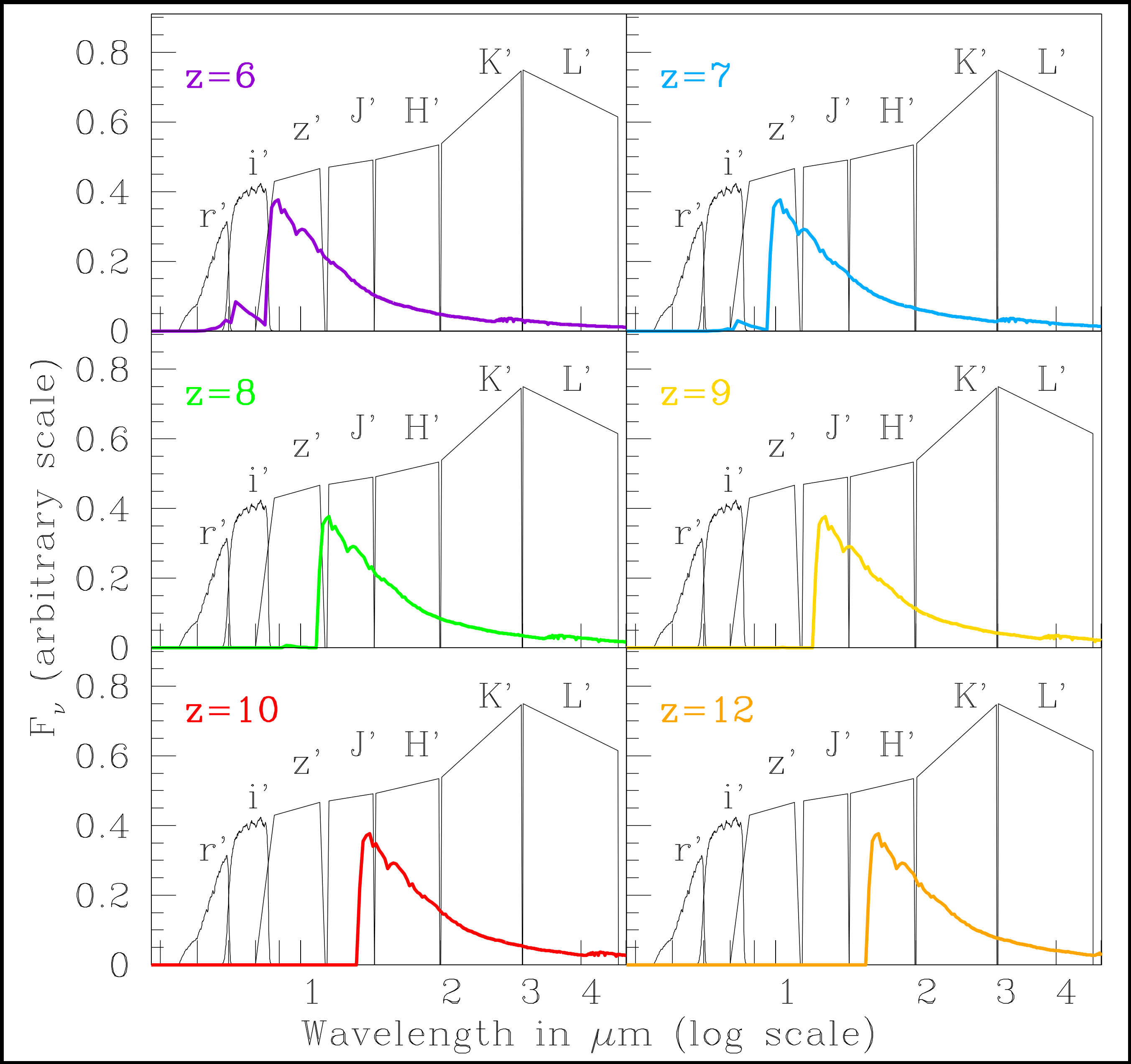
NASA, ESA, R. Windhorst (Arizona State University) and H. Yan (Spitzer Science Center, Caltech) STScI-PRC04-28

In an HUDF^{3} volume at z$\simeq$2–6:

M$_{DM}$ $\sim 10^{12-13}$ $M_{\odot}$, M$_{baryon}$ $\sim 2\times10^{11-12}$ $M_{\odot}$,

M$^{*}_{gxys}$ $\sim 2\times10^{10-11}$ $M_{\odot}$, M$_{SMBH}$ $\sim 4\times10^{7-8}$ $M_{\odot}$.

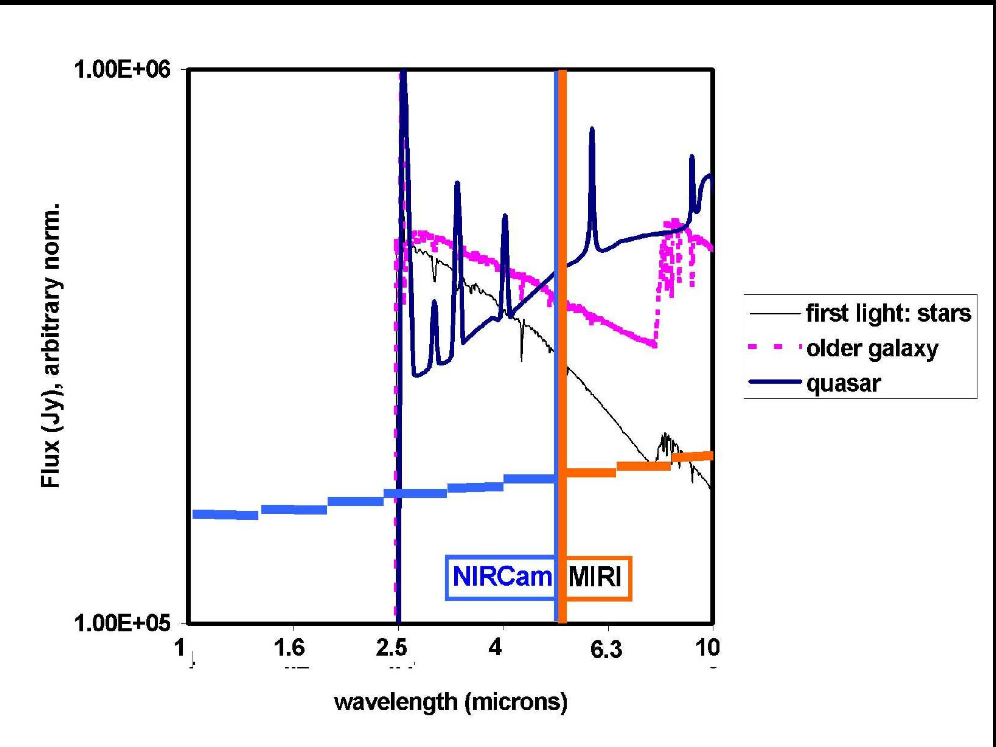
How can HST & JWST measure Galaxy Assembly & SMBH/AGN Growth?

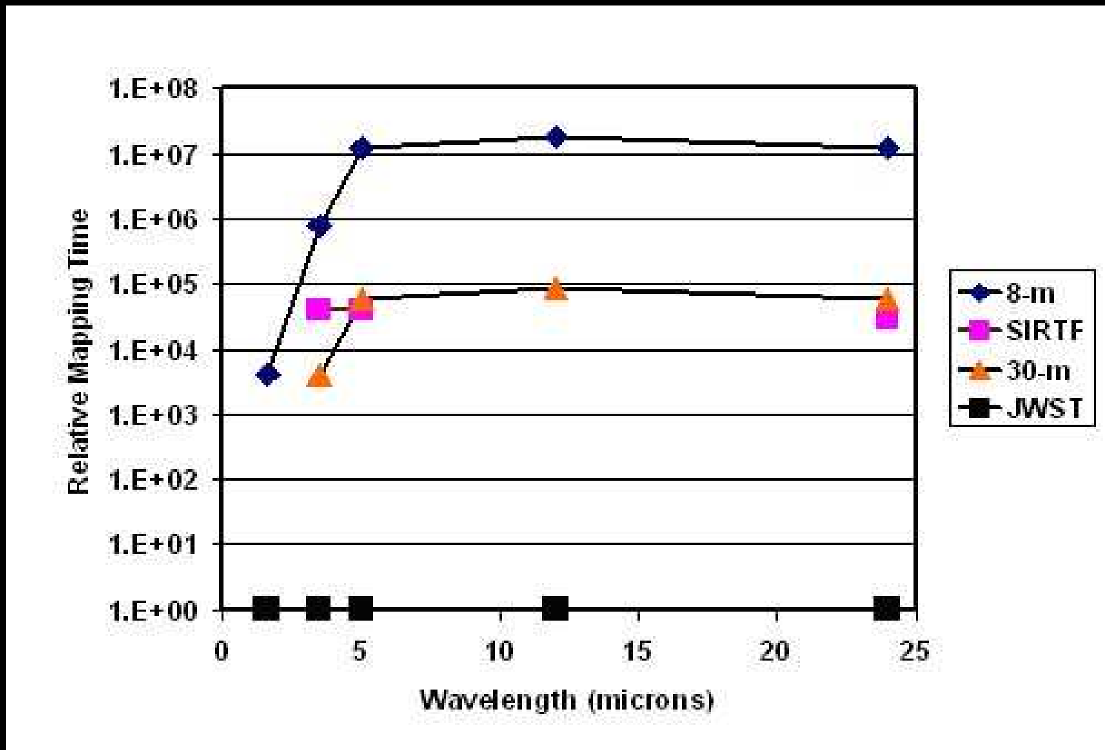


- Can't beat redshift: to see First Light, must observe near–mid IR.

$\Rightarrow$ This is why JWST needs NIRCam at 0.8–5 μm *and* MIRI at 5–29 μm.

• (1b) What sensitivity will JWST have?





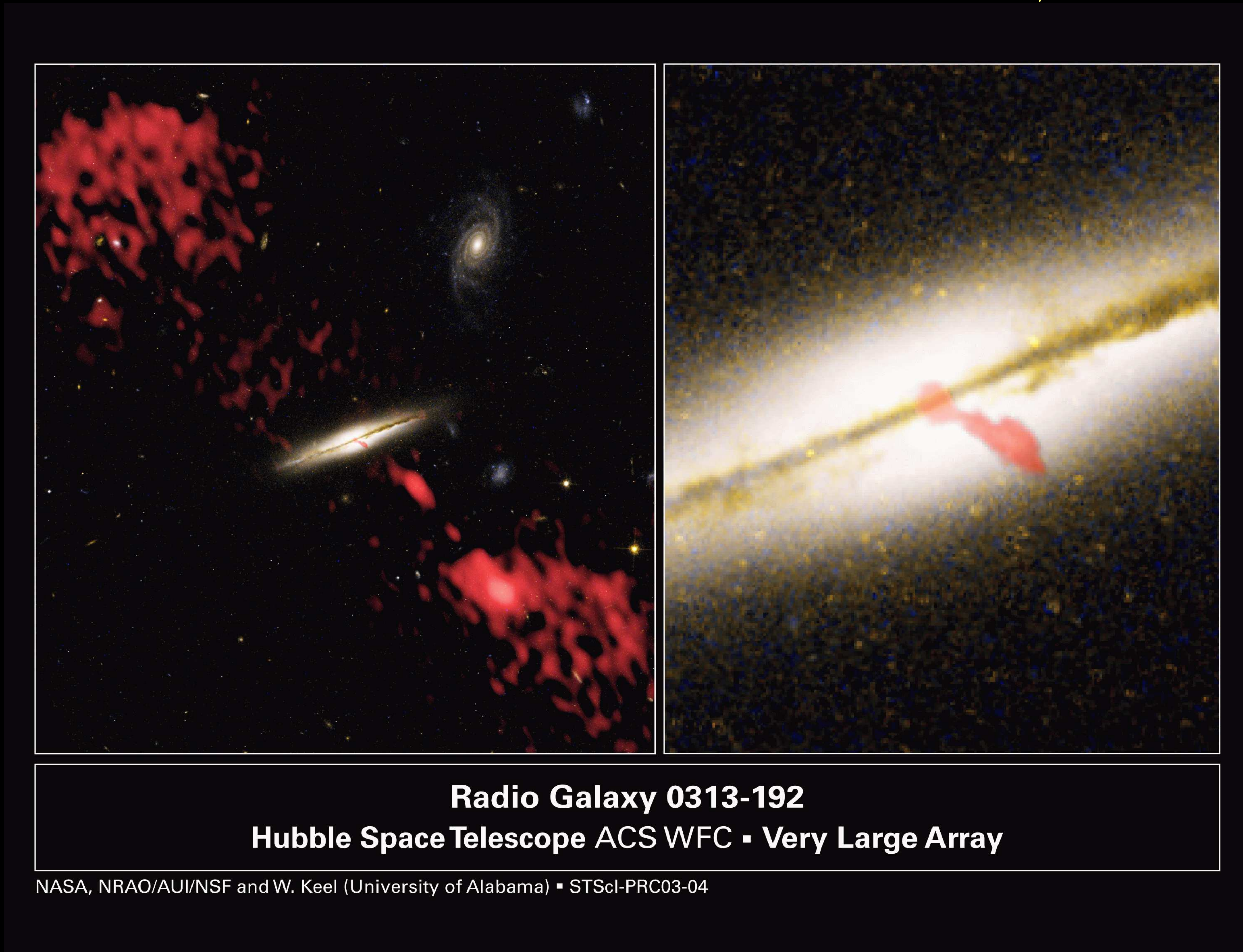
NIRCam and MIRI sensitivity complement each other, straddling $\lambda \simeq 5\ \mu$m.

Together, they allow objects to be found to z=15–20 in $\sim 10^5$ sec (28 hrs).

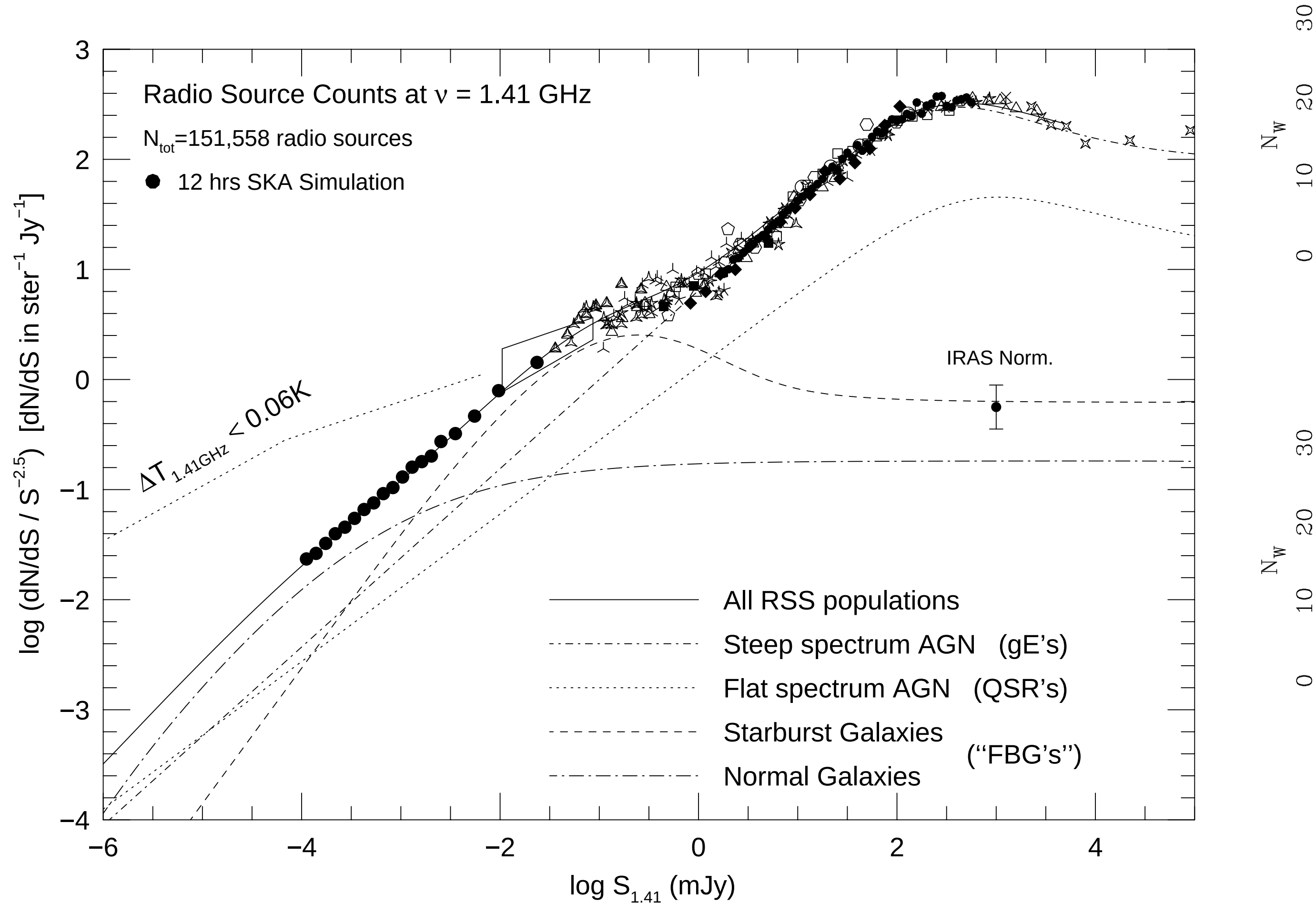
LEFT: NIRCam and MIRI broadband sensitivity to a Quasar, a "First Light" galaxy dominated by massive stars, and a 50 Myr "old" galaxy at z=20.

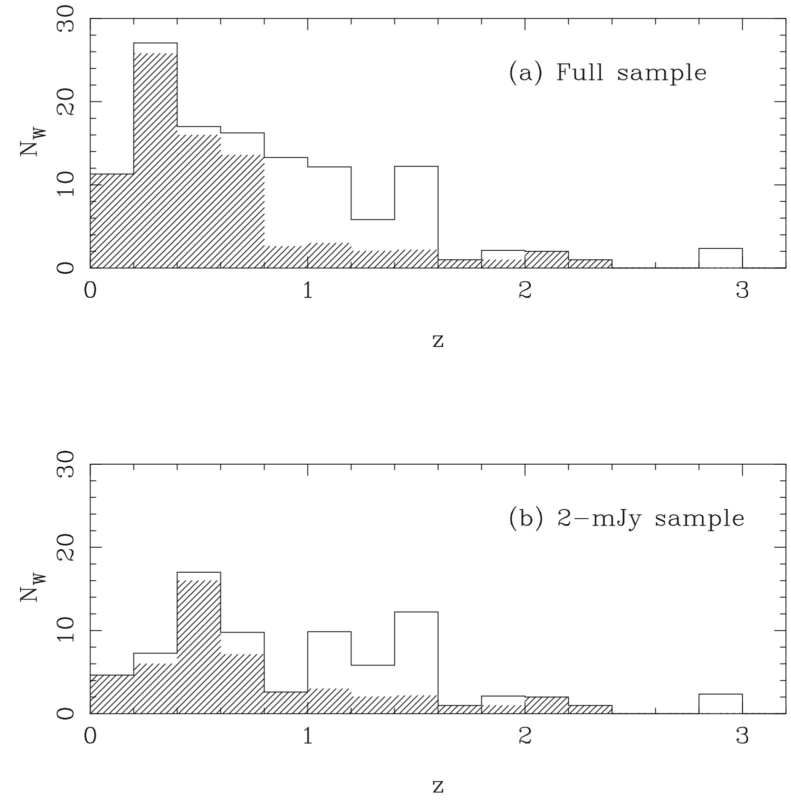
RIGHT: Relative survey time vs. λ that Spitzer, a ground-based IR-optimized 8-m, and a 30-m telescope would need to match JWST.

How can HST & JWST measure Galaxy Assembly & SMBH/AGN Growth?



Question: How long after last (major) merger does AGN activity show?

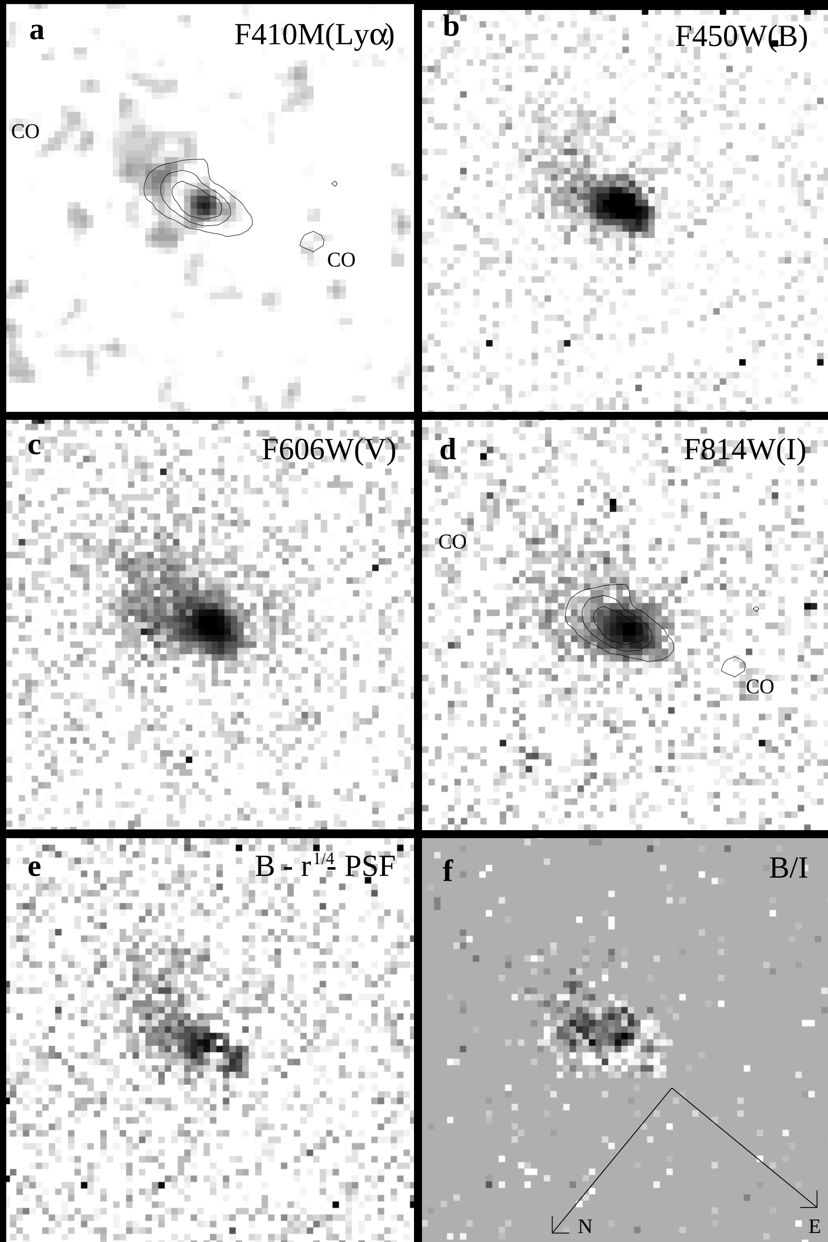




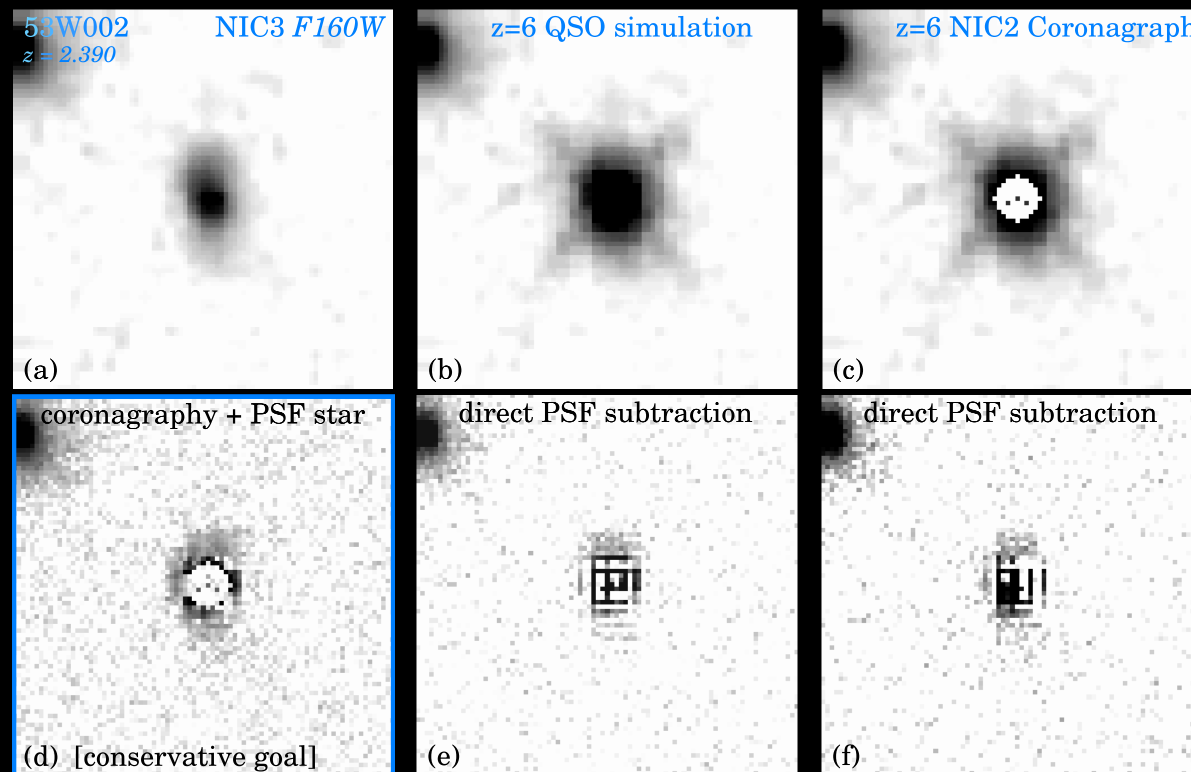
(LEFT) 1.41 GHz source counts (Windhorst et al. 1993, 2003; Hopkins et al. 2000) from 100 Jy to 100 nJy: AGN (monsters) dominate $\gtrsim$1 mJy, starbursts below 1 mJy [12-hr SKA simulation below 10 μJy].

(RIGHT) Redshift distribution of mJy radio sources (Waddington$^+$ 2001):

- Median redshift z_{med} $\lesssim$1 at all flux levels, due to radio K-correction.
- Same in X-rays $\Longrightarrow$ Radio and X-ray poor high-z AGN tracers!

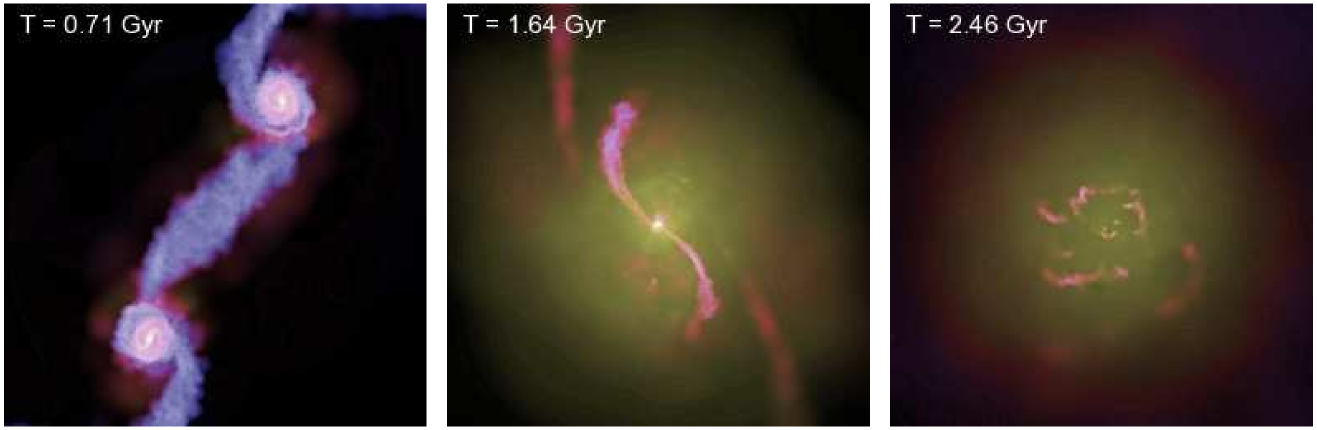


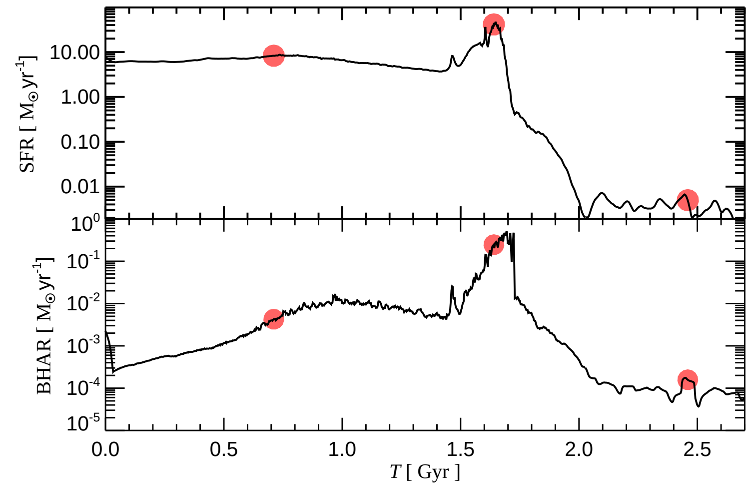
(Left): HST/PC of radio galaxy 53W002 at z=2.39 (Windhorst et al. 1998): rest-UV $r^{1/4}$-law + Lyα & Cont AGN-cloud.



Coronagraph simulation of z=6 SDSS QSO host (using HST/NIC2+Corona). Can measure $>L^*$ AGN-host at z$\gtrsim$6.

- JWST can measure AGN hosts 3 mag fainter in restframe UV-Opt to z$\lesssim$20.
- Such AGN are very rare. JWST must use other ways to trace AGN-growth.



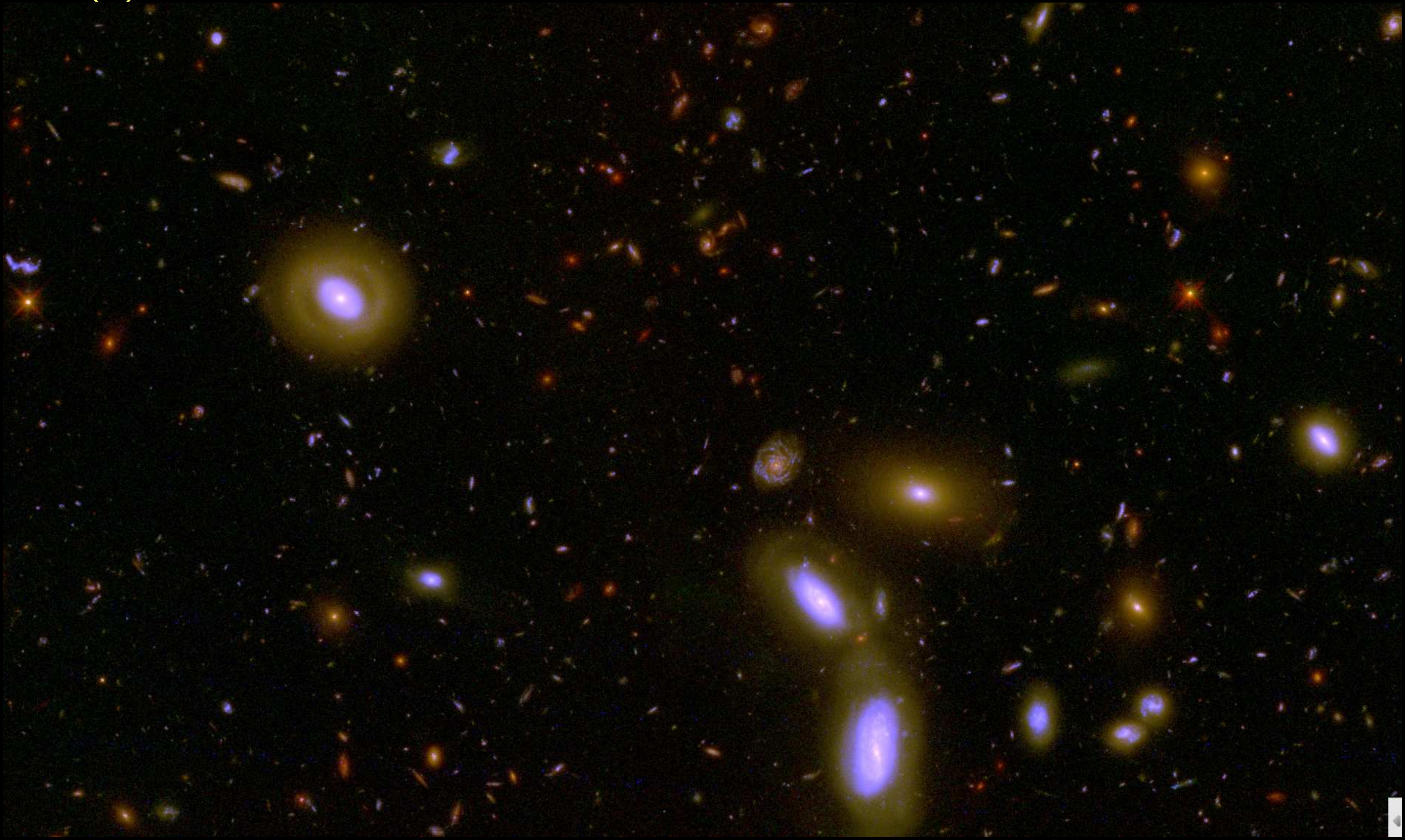


- [LEFT] Simulated merger of two disk galaxies at three different times, including the effects of SMBH growth and AGN feedback by Springel, di Matteo, Hernquist (2005, ApJ, 620, 79). Shown is the gas distribution with color indicating temperature, and brightness indicating gas density.

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

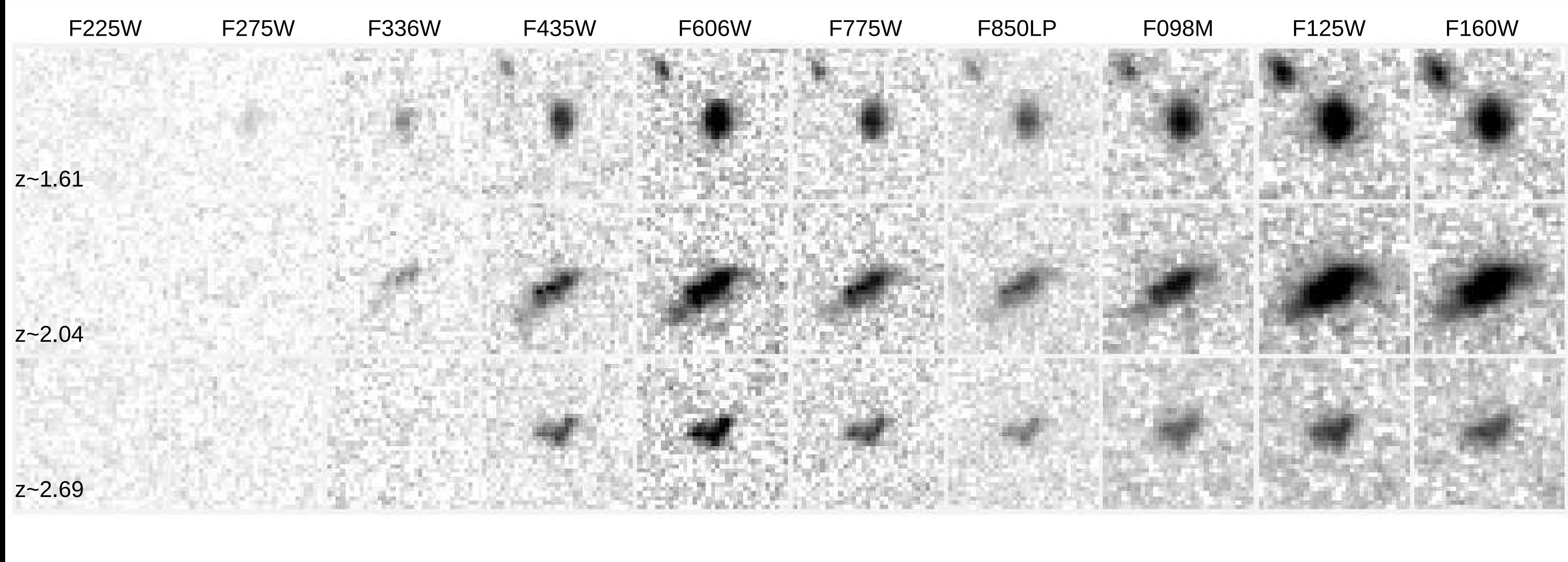
$\Leftrightarrow$ In hydrodynamical simulations, the object resembles a tadpole galaxy $\sim$0.7 Gyr after the merger starts, the AGN is triggered and expels the dust $\gtrsim$1.6 Gyr after the merger starts, $i.e.$, $\gtrsim$1 Gyr after the starburst stage.

- (5) How to directly trace weak AGN growth with WFC3 and JWST

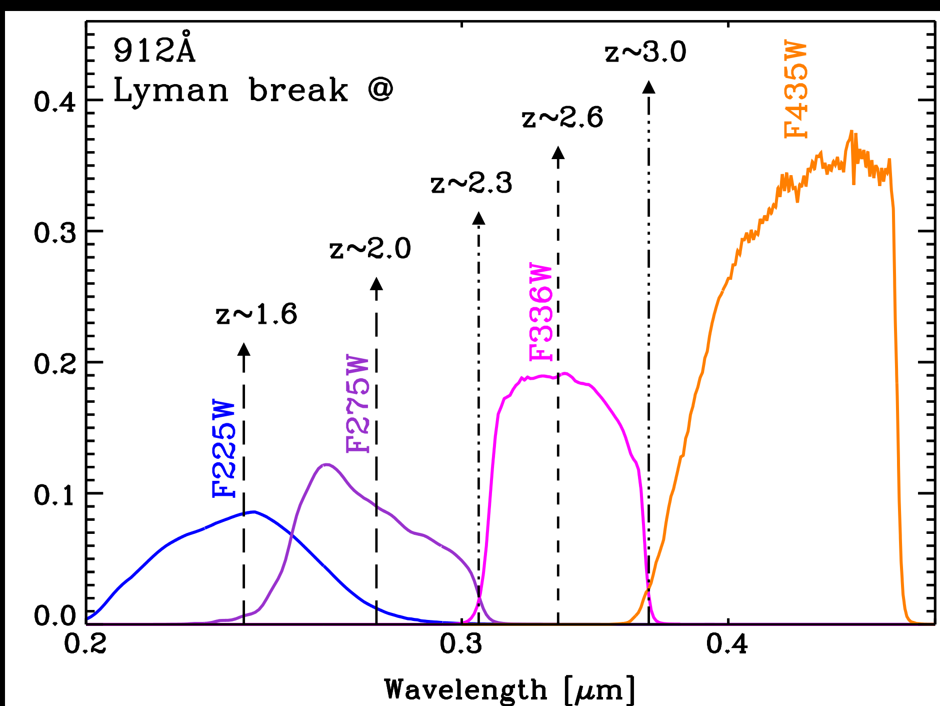


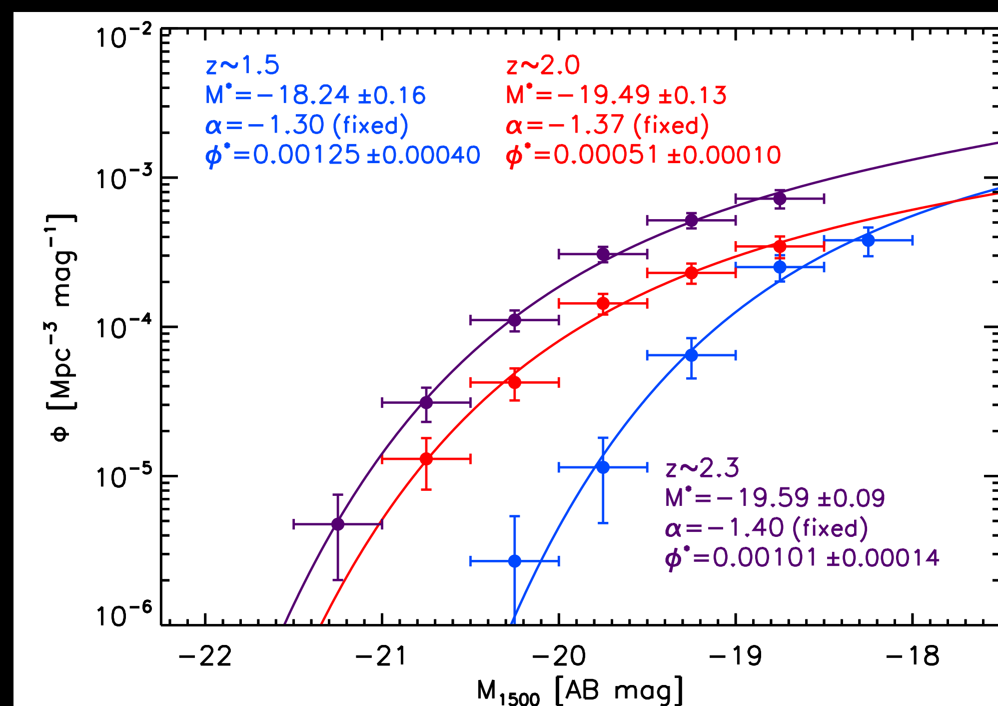
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

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.



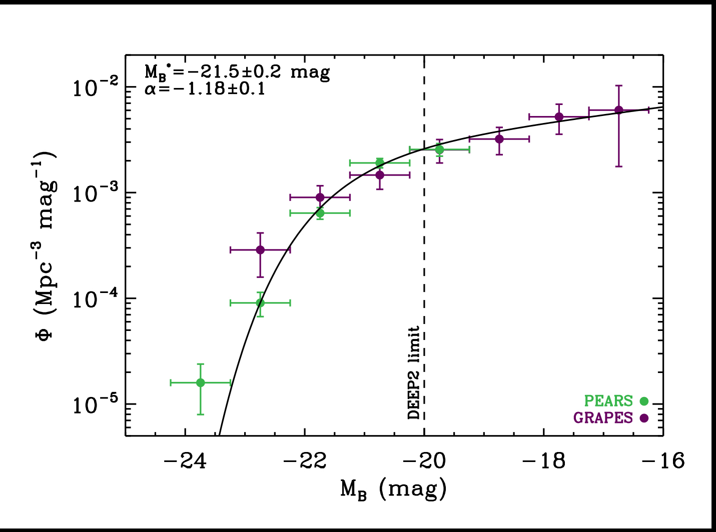
WFC3 Lyman break galaxies at the peak of cosmic SF ($z \simeq 1$-3; Hathi$^+$ 2010)

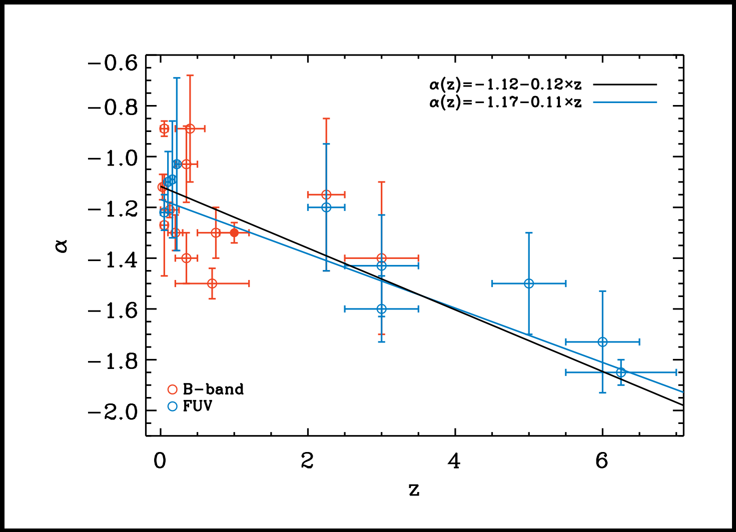


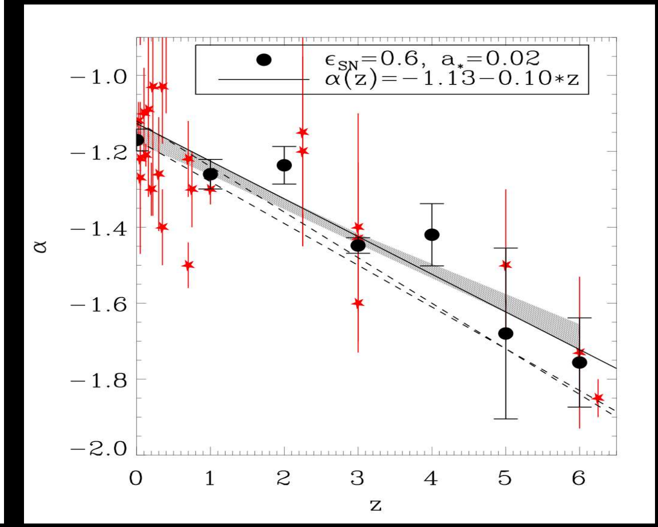


- JWST will similarly measure faint-end LF-slope evolution for $1 \lesssim z \lesssim 12$.

Faint-end LF-Slope Evolution (fundamental, like local IMF)





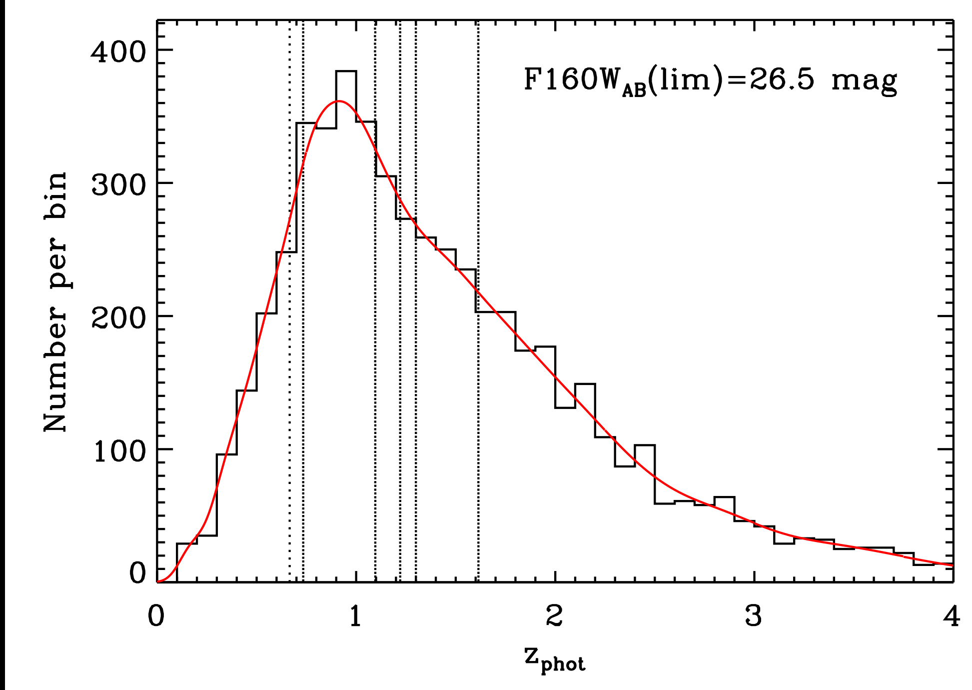


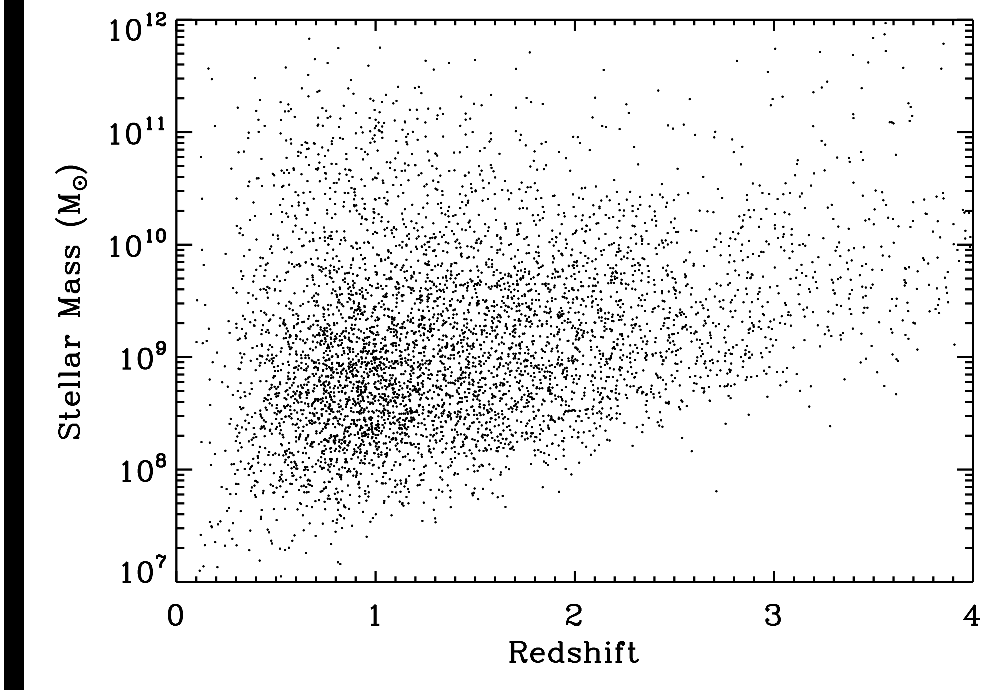
Faint-end LF-slope at z$\gtrsim$1 with accurate ACS grism z's to AB$\lesssim$27 (Cohen et al.; Ryan et al. 2007, ApJ, 668, 839) constrains hierarchical formation:

- 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.





WFC3 ERS 10-band redshift estimates accurate to ∼4% with small systematic errors (Cohen et al. 2010), resulting in a reliable redshift distribution.

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

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

- HUDF shows WFC3 z≃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, dust content, & AGN-growth 3–5 mags fainter from z≃0.5–12, with nanoJy sensitivity from 0.7–5.0 μm.

(5) Radio & X-ray host SED-ages: trace AGN growth directly?

[1] DATA: HST GOODS BVizJHK photometry and VLT JHK + redshifts.

[2] METHOD: SED fitting for 0.12$\lesssim\boldsymbol{\lambda_{rest}}\lesssim$1.6 $\boldsymbol{\mu}$m, using:

- (a) Bruzual-Charlot (2007) stellar population models.
- (b) + AGN power law $\boldsymbol{S_\nu \propto \nu^\alpha}$ bluewards of the IR dust emission.
- VLT redshifts for all objects AB$\lesssim$24–25 (Le Fèvre et al. 2004; Szokoly et al. 2004; Vanzella et al. 2005, 2008; see www.eso.org/science/goods/)

For typical z$\simeq$0.5-1.5, BVizJHK bracket the Balmer+4000Å breaks.

[3] SED fitting:

- Use solar metallicity and Salpeter IMF (most objects at z$\lesssim$2).
- E-folding times $\boldsymbol{\tau}$ in log spaced n=16 grid from 0.01-100 Gyr.
- n=244 ages $\lesssim$ age of Universe at each redshift in WMAP-cosmology.
- Calzetti et al. dust extinction: $\boldsymbol{A_V}$ = [0, 4.0] in 0.2 mag steps (n=21).
- $\boldsymbol{\alpha}$=[0, 1.5] in steps of 0.1 (n=16 values).

[4] Yields $\sim 10^6$ models for 1549 GOODS galaxies with VLT redshifts. Best χ^2 fit stellar mass + possible AGN UV–optical power-law component.

Method follows Windhorst et al. (1991, 1994, 1998), where HST + ground-based UBgriJHK images showed non-negligible AGN components in mJy radio galaxies.

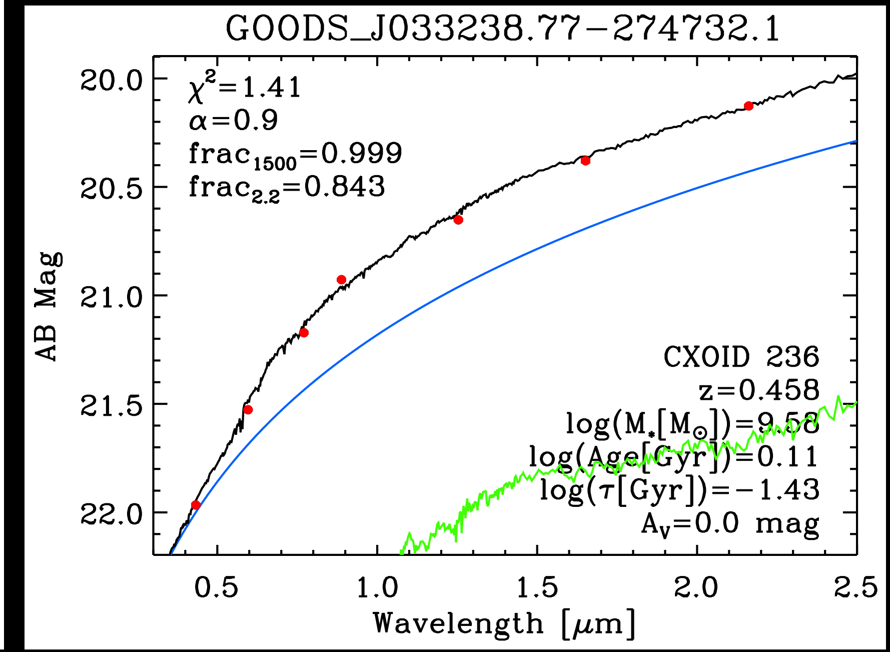
[5] Work in progress on other potential caveats:

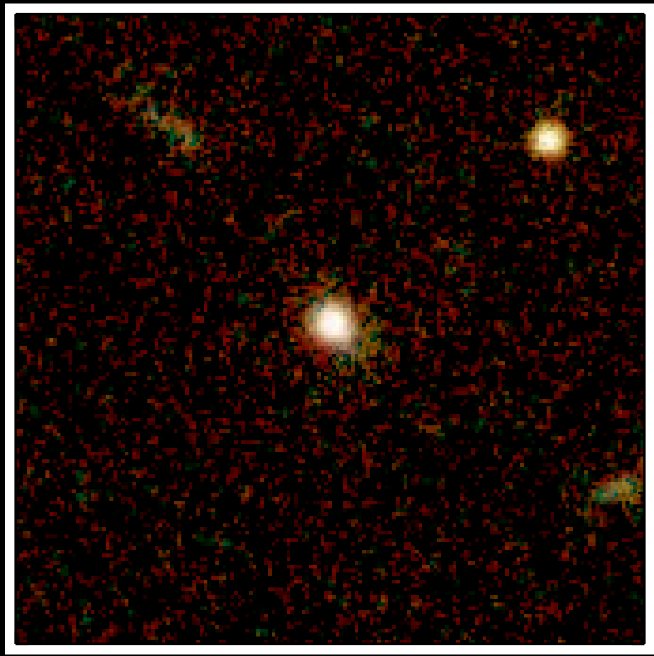
- Young stellar populations have power-law UV spectra (Hathi et al. 2008), and may overestimate UV AGN power-law.

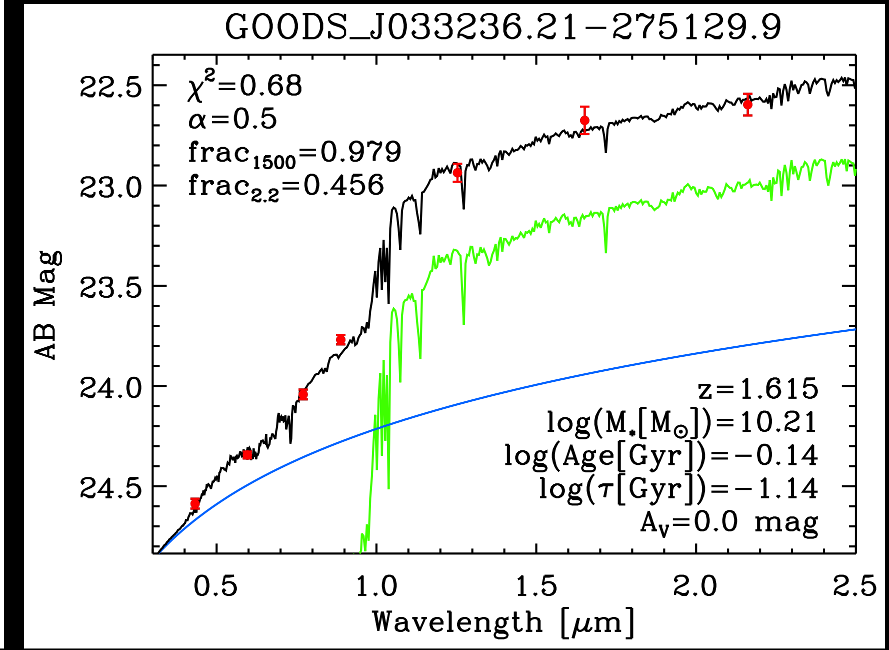
- Include IRAC data and incorporate 1–2 Gyr red AGB population.

- Fit the BC03 stellar SED only to objects where χ^2 doesn't require both.

- Expand to 7000 WFC3 objects with 10-band fluxes to AB=26.5–27 mag.

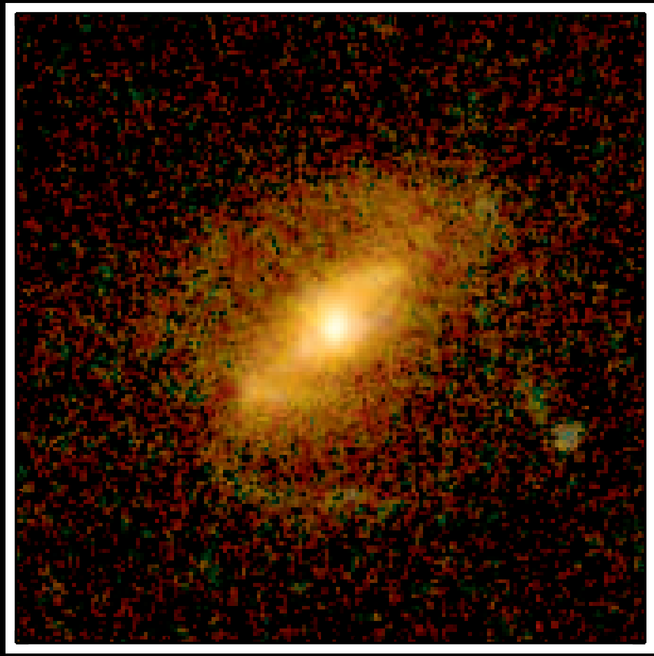


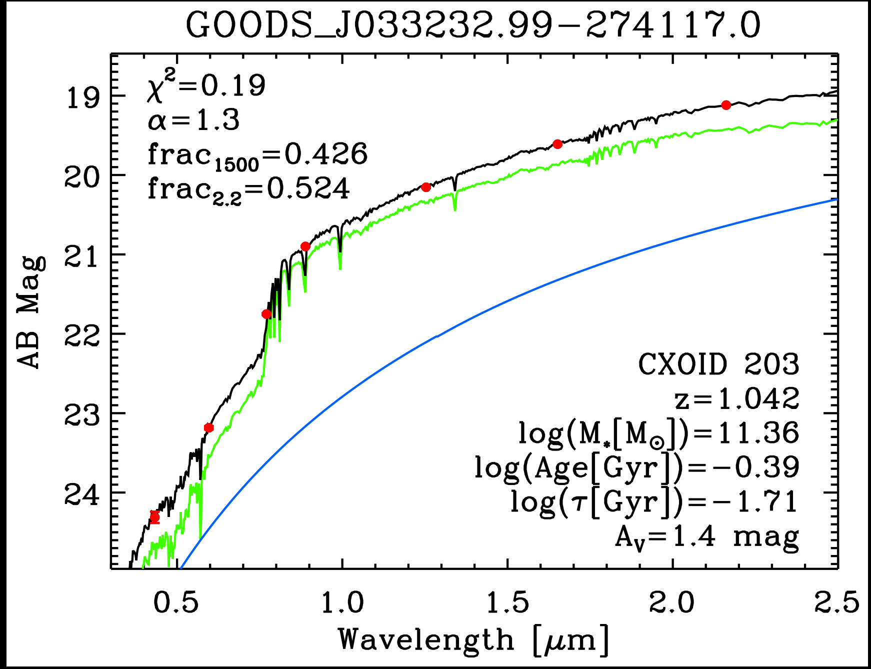


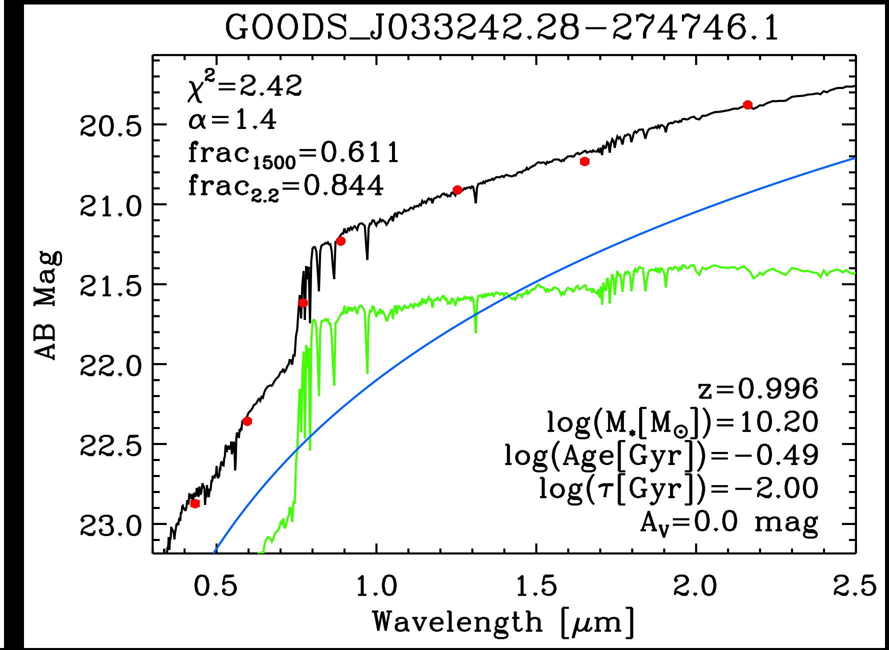


Cohen et al. (2010): GOODS/VLT BVizJHK images

Best fit Bruzual-Charlot (2003) SED + power law AGN.







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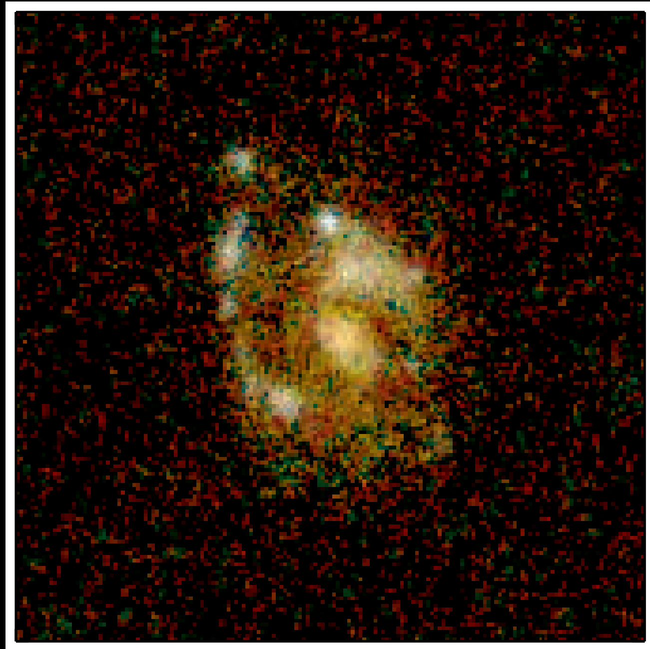
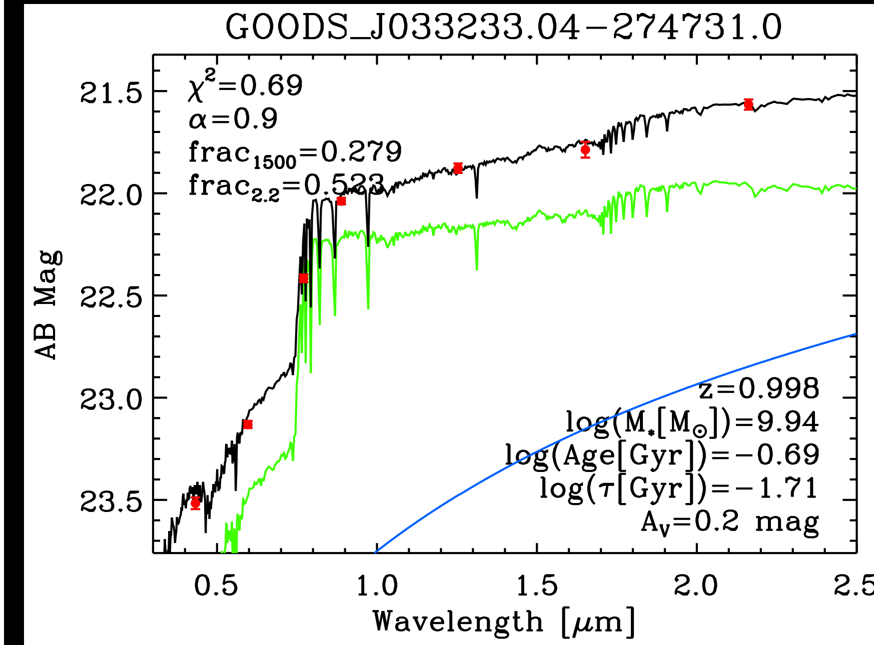
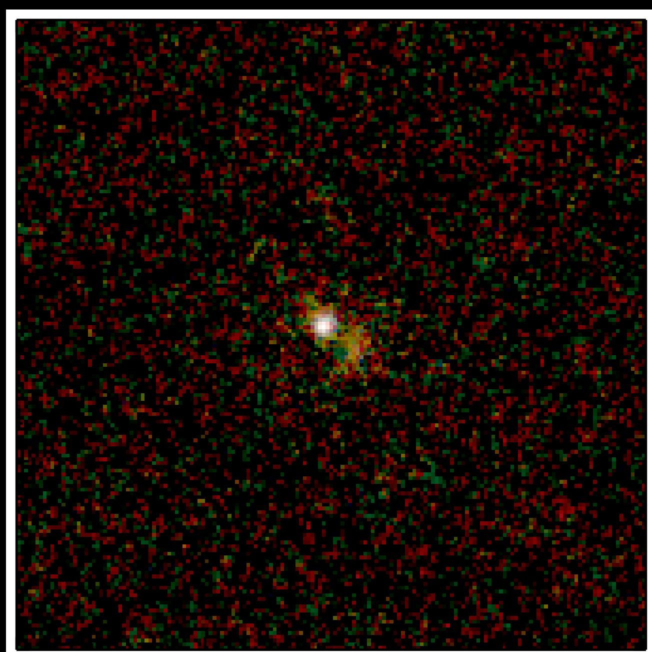
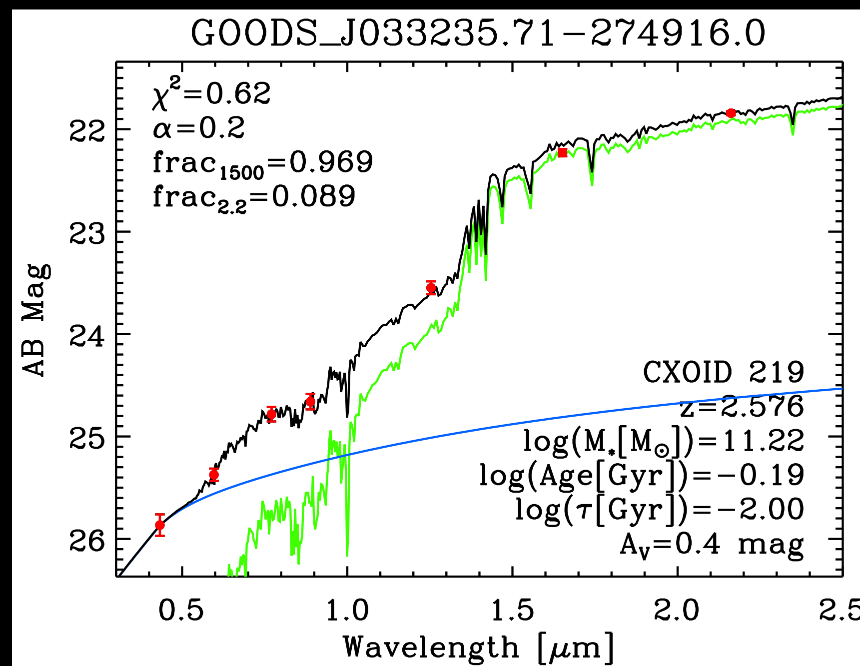


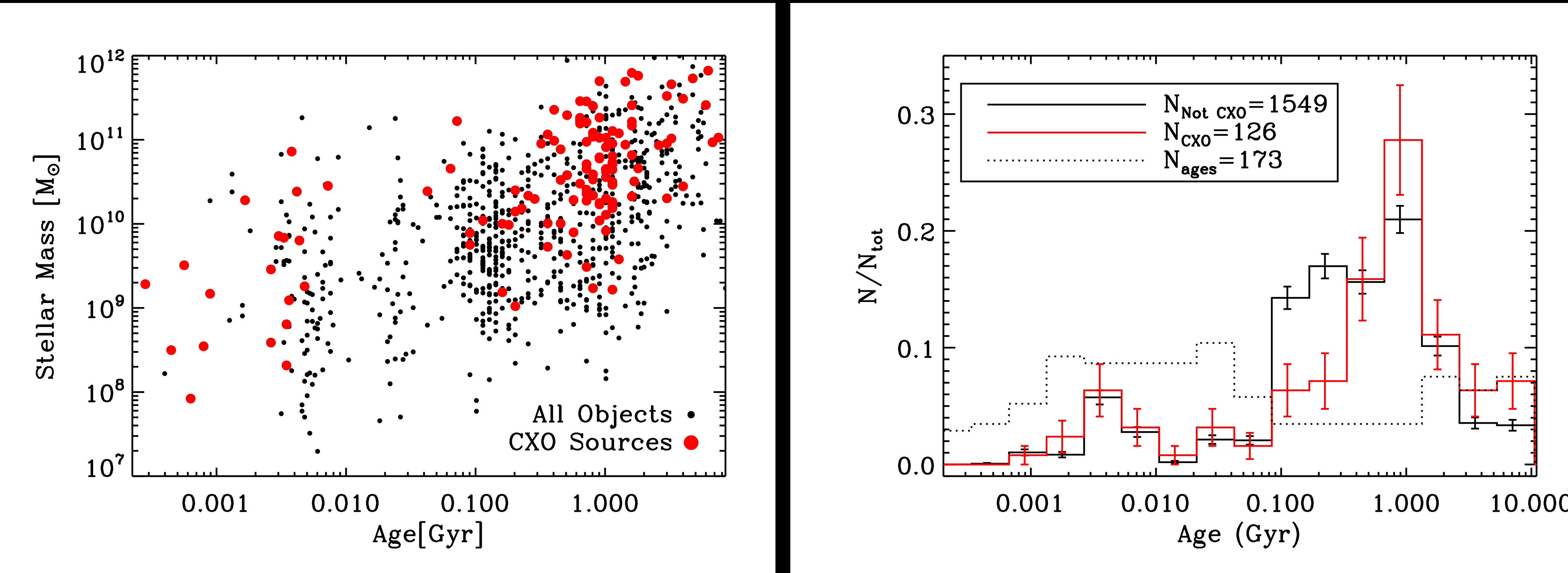






Cohen et al. (2010): GOODS/VLT BVizJHK images

Best fit Bruzual-Charlot (2003) SED + power law AGN.



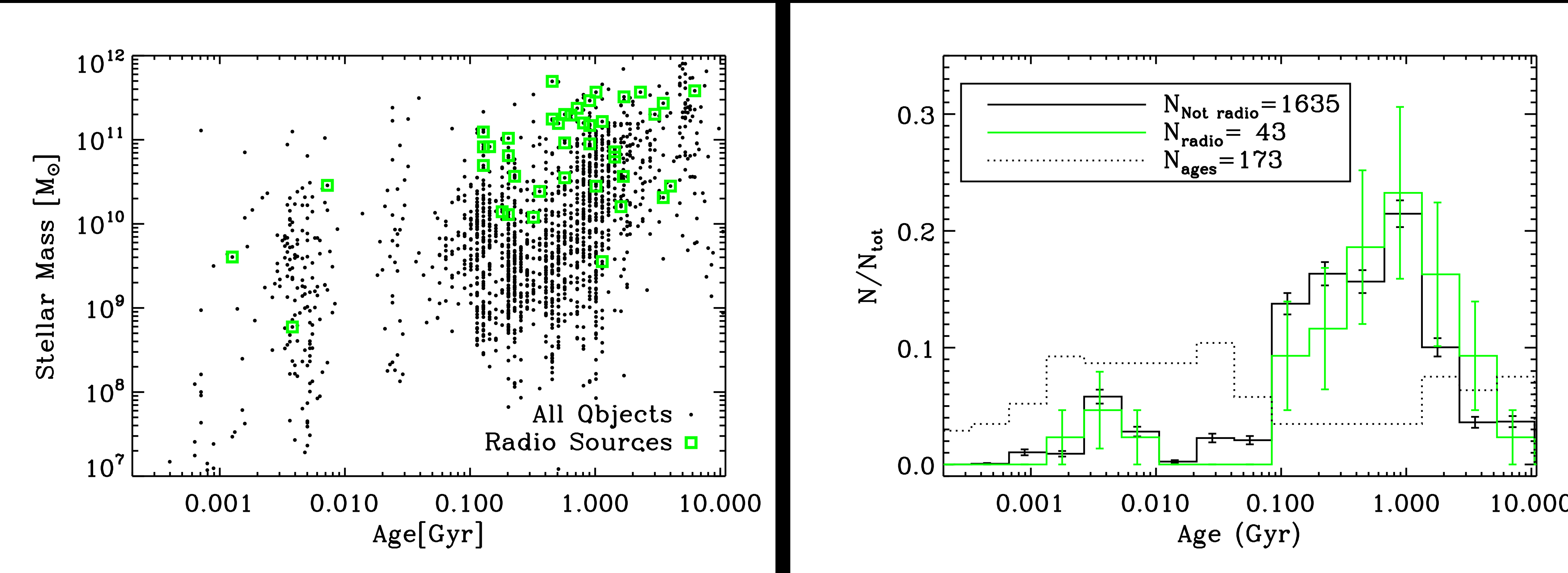
Cohen et al. (2010): Best fit Stellar Mass vs. Age: X-ray and field galaxies.

Field galaxies have: Blue cloud of ∼100-200 Myr, Red cloud of $\gtrsim$1–2 Gyr.

- X-ray sources reside in galaxies that are a bit older than the general field population, but by no more than $\lesssim$0.5–1 Gyr on average.

- JWST+WFC3 can disentangle multiple SED + AGN power-law from 15-band photometry to AB=30 mag for z$\lesssim$10.

- JWST can trace AGN-growth, host galaxy masses and ages since z∼10.



Cohen et al. (2010): Best fit Stellar Mass vs. Age: Radio and field galaxies.

Field galaxies have: Blue cloud of ∼100-200 Myr, Red cloud of $\gtrsim$1–2 Gyr.

- Radio galaxies are a bit older than the general field population, but by no more than $\lesssim$0.5–1 Gyr on average.

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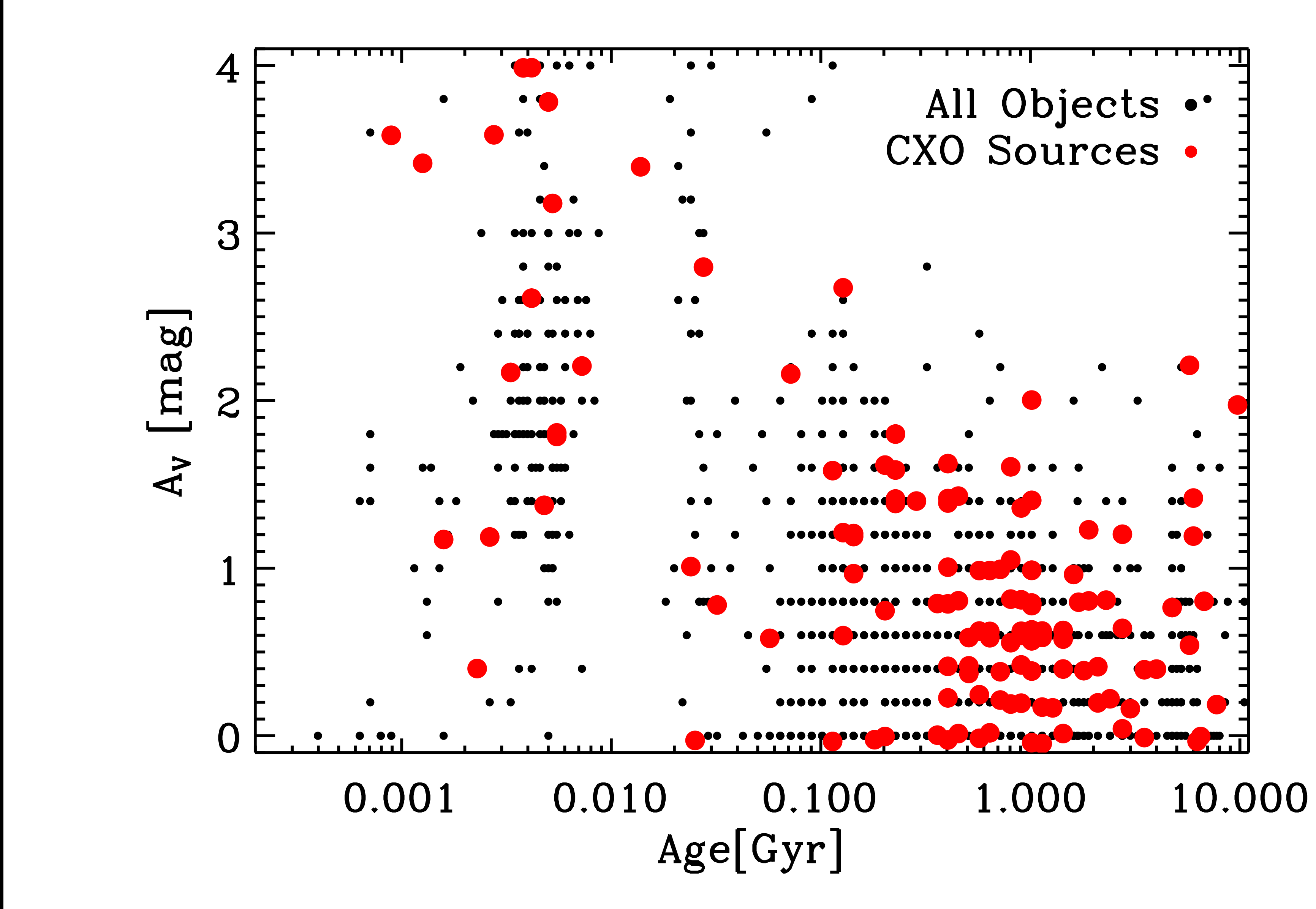
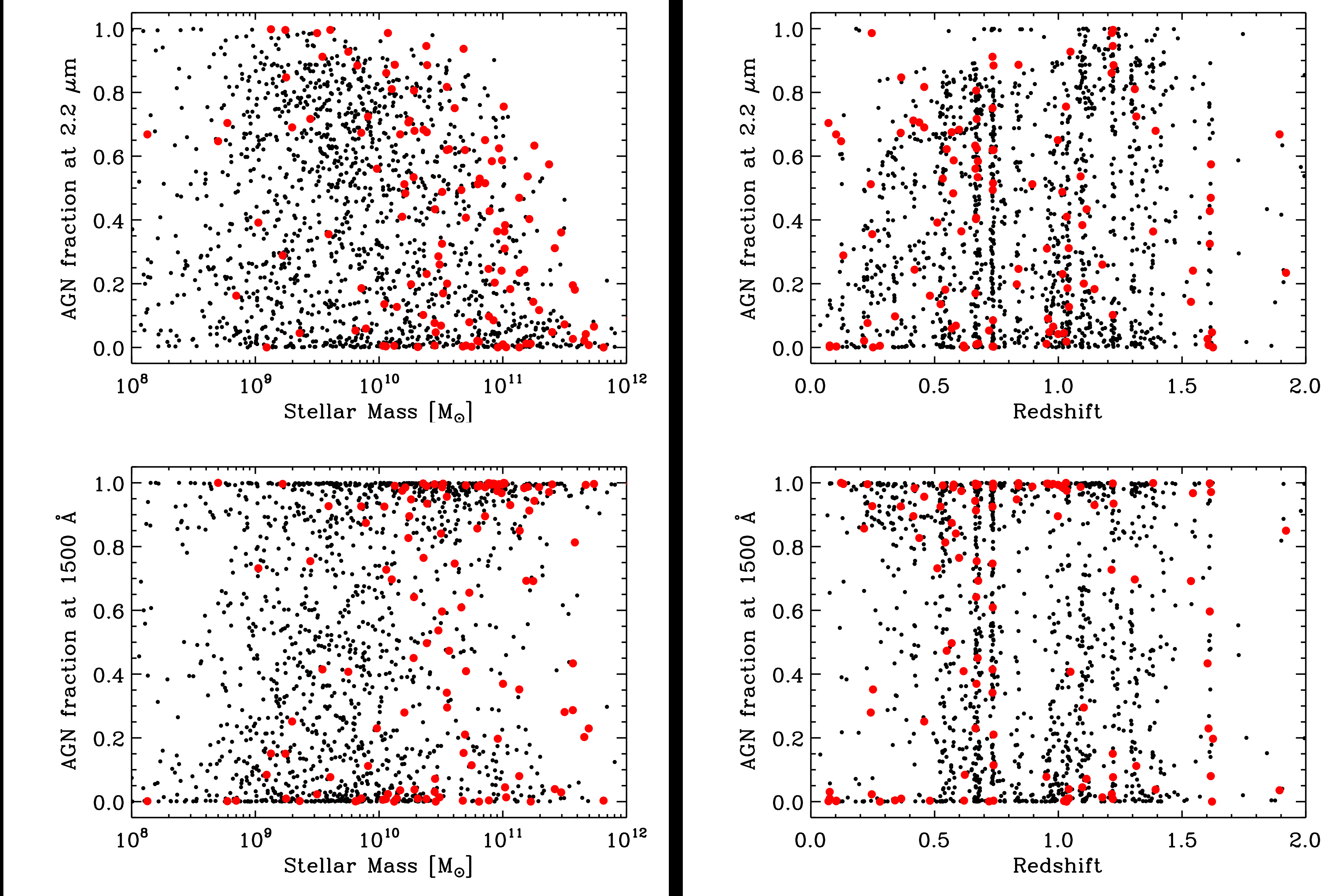


Cohen et al. (2010): Best fit extinction A_V distribution: X-ray and field.

- In Hopkins et al. (2006, ApJS, 163, 1) scenario, dust and gas are expelled *after* the starburst peaks and *before* before the AGN becomes visible.

Older galaxies have less dust after merger/starburst/outflow. But age-Fe/H!



Cohen+ (2010): AGN fraction vs. Stellar Mass and z: X-ray and field gxys.

⇒ Many more with best-fit f(AGN)$\gtrsim$50% to be detected by IXO or SKA!

- JWST can trace power-law SED-fraction for M$\gtrsim 10^8\ M_\odot$ and z$\lesssim$10.

(6) Summary and Conclusions

(1) (Major) Mergers have a redshift distribution very similar to that of field galaxies and are good tracers of the galaxy assembly process.

(2) Variable objects have a redshift distribution similar to that of HUDF field galaxies, and likely trace brief(!) episodes of SMBH growth.

• There is very little overlap between (1) and (2): HUDF mergers likely preceded visible weak-AGN variability.

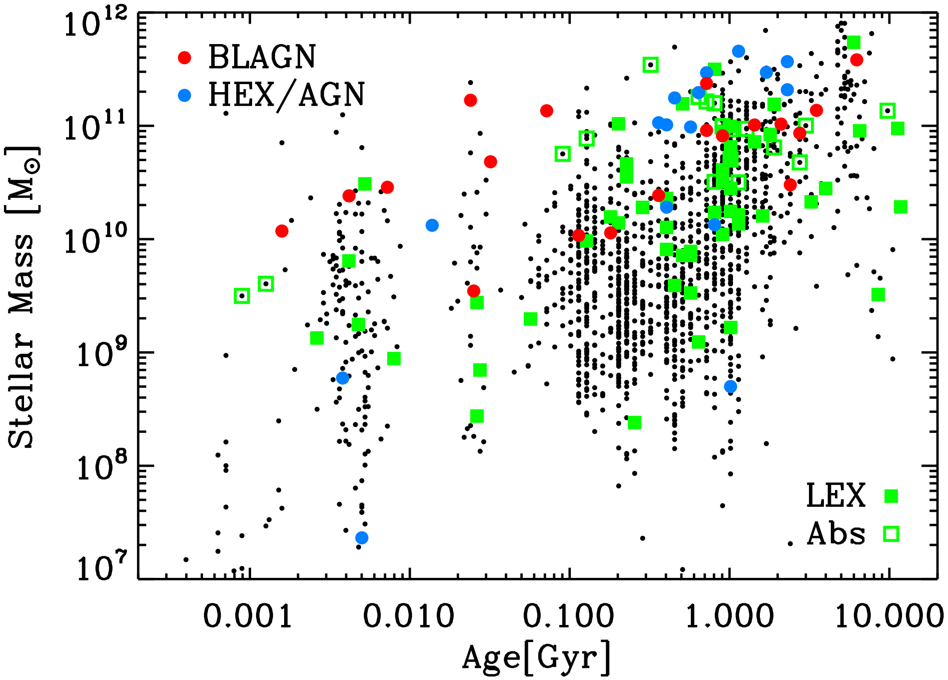
(3) Epoch dependent density of major mergers may precede peak in X-ray selected AGN $\rho(z)$, but by no more than 1–2 Gyr.

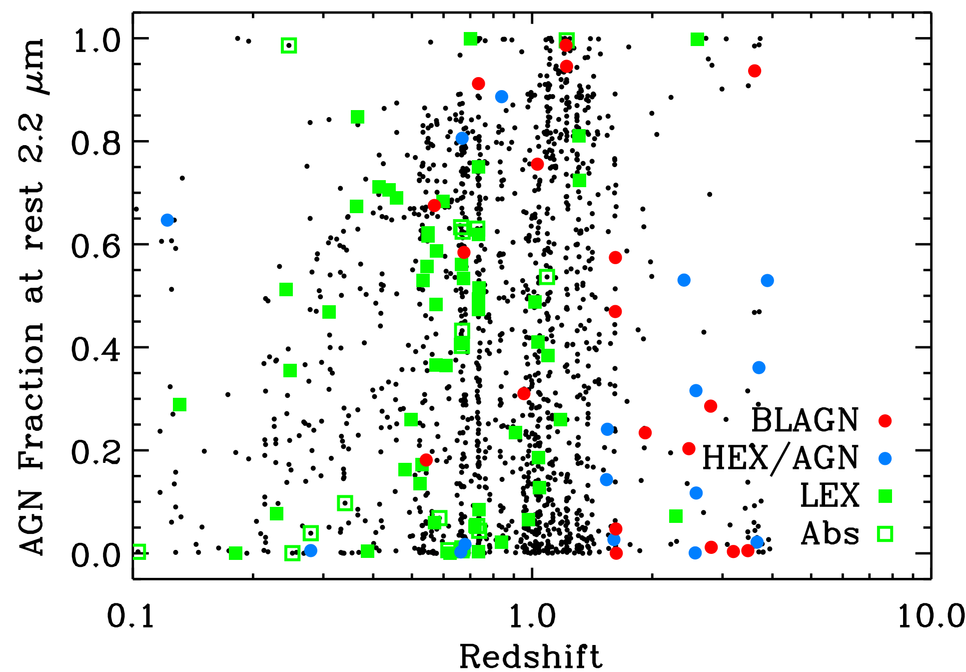
(4) Radio and X-ray selected galaxies are — at z$\simeq$0.5–1.5 — on average 0.5–1 Gyr older than the typical FBG or LBG age of 0.1–0.2 Gyr.

AGN GROWTH STAYS IN PACE WITH GALAXY ASSEMBLY, BUT RADIO / X-RAYS APPEAR $\lesssim$1 Gyr AFTER MERGER/STARBURST.

• JWST can measure this in great detail to AB$\lesssim$31 mag from 0.7–5.0 μm, tracing galaxy assembly and AGN/SMBH-growth since z$\lesssim$10–15.

SPARE CHARTS





Cohen et al. (2010): At all ages, the most massive hosts are QSO-1/2's (based on AGN lines in *optical spectra* by Szokoly et al. 2004):

- This is illustrates the well known L_X-L_{opt} correlation.

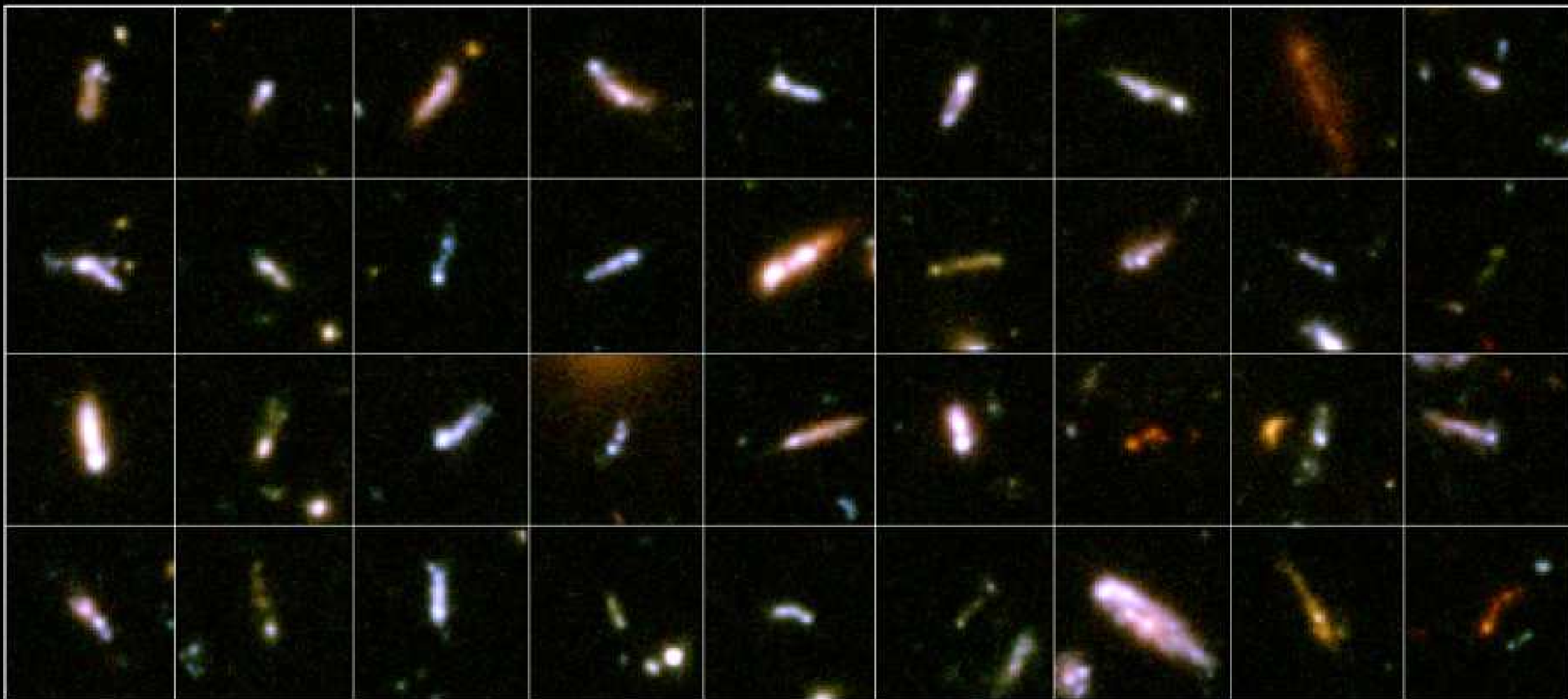
All optical AGN types: emission lines and absorption features.

Most $\gtrsim$0.5–1 Gyr SEDs do not show AGN signatures in optical spectra.

- For majority of AGN-1's: $\lesssim$50% of 2 μm-flux comes from the AGN !?

Many more with best-fit f(AGN)$\gtrsim$50% to be detected by IXO or SKA!

(2) A study of Early-Stage Mergers in the HUDF



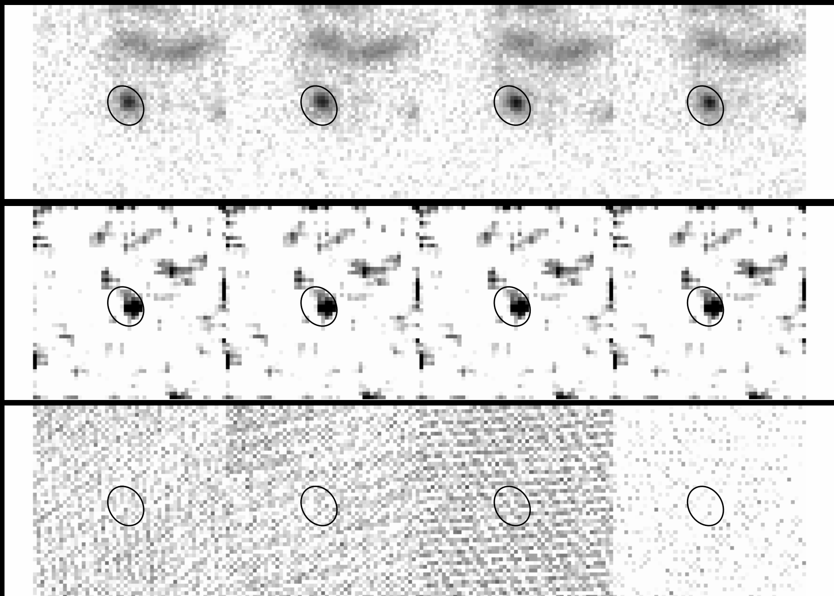
"Tadpole" Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope ▪ ACS/WFC

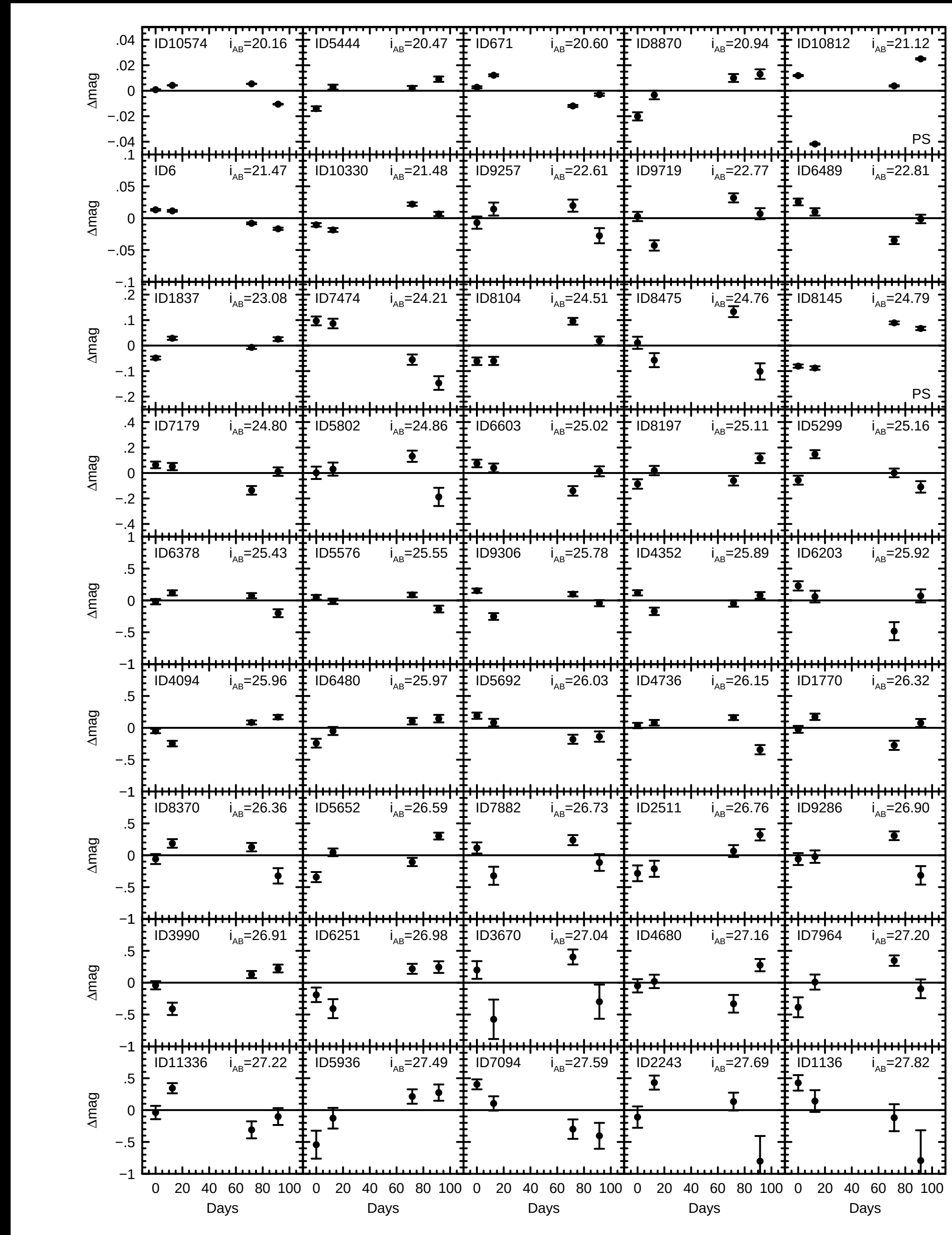
NASA, ESA, A. Straughn, S. Cohen and R. Windhorst (Arizona State University), and the HUDF team (STScI) STScI-PRC06-04

Tadpole galaxies in HUDF: www.hubblesite.org/newscenter/archive/2006/04/

Straughn, A. N., et al. 2006, ApJ, 639, 724 (astro-ph/0511423)

(3) Variable Objects in the HUDF

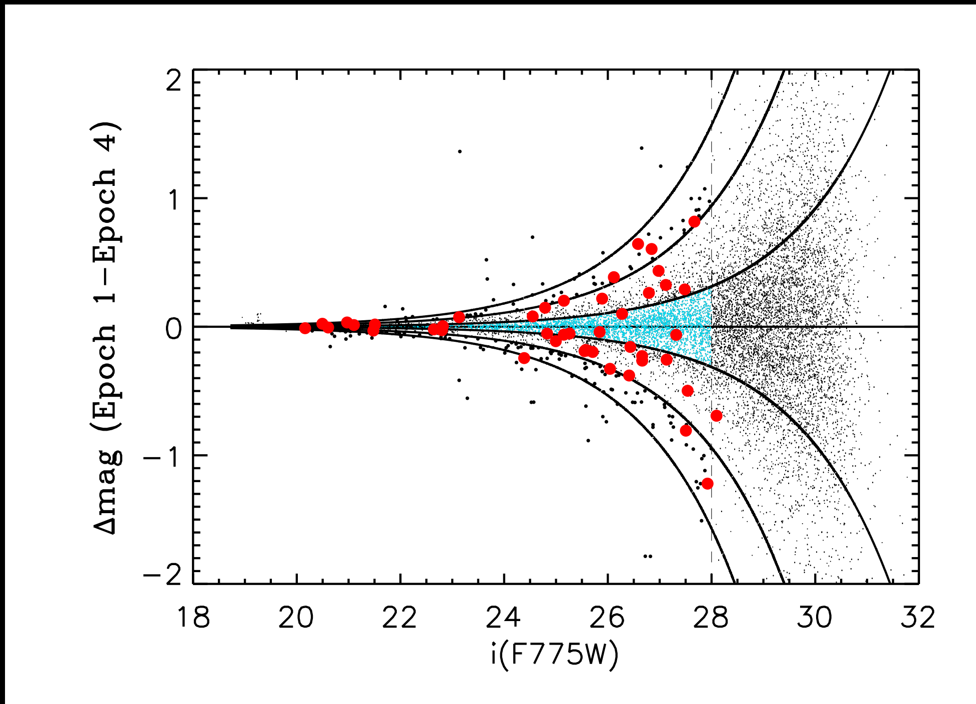


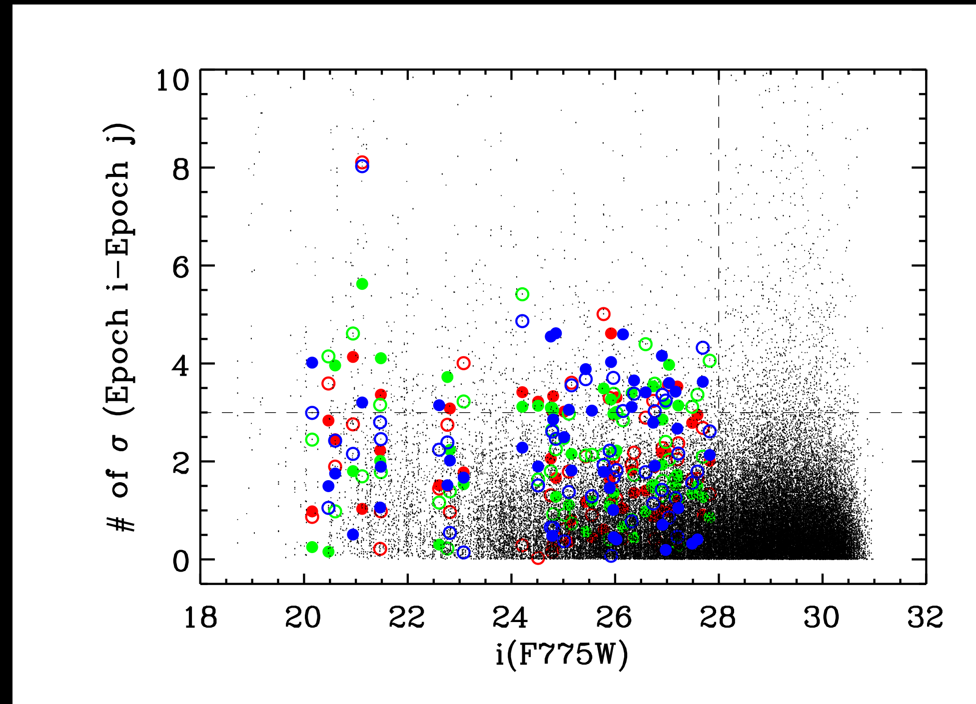


Top: 4 epochs; Middle: Variance map; Bottom: 4 Weight-maps.

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

Light curves: Can detect bright HUDF variable objects on timescales of days–months, even if $|\Delta\text{mag}|(t) \lesssim 1$–$2\%$!





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

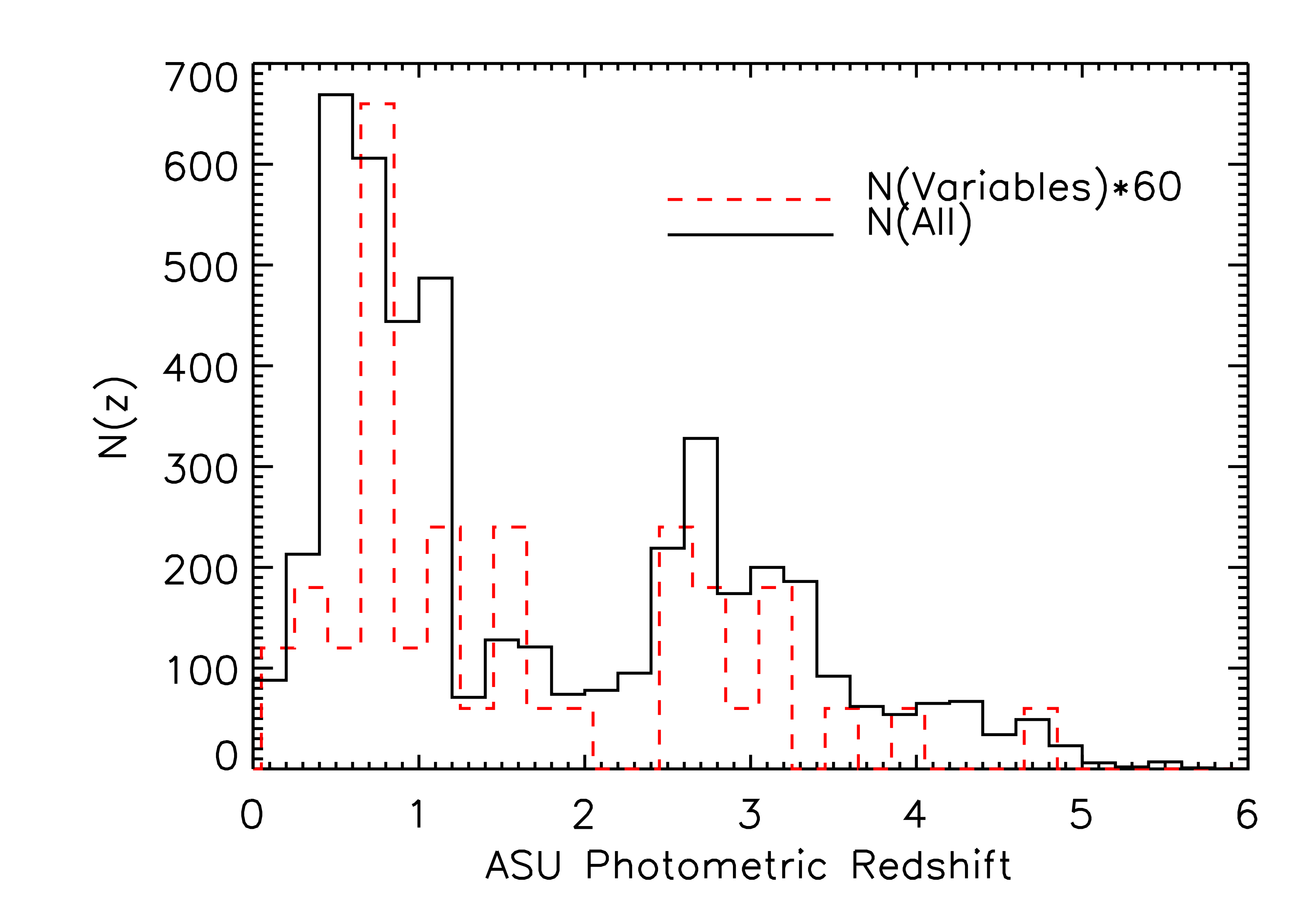
- Objects with |Delta mag|$\geq 3.0\sigma$ in $\geq$2 epoch-pairs are variable.

- 3 out of 16 Chandra sources are faint point-like objects variable at $\gtrsim 3.0\sigma$. Other Chandra sources are brighter (early-type) galaxies.

$\Rightarrow$ Variable point sources are valid AGN candidates:

- $\sim$1% of all HUDF galaxies have weak variable AGN.

- 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.

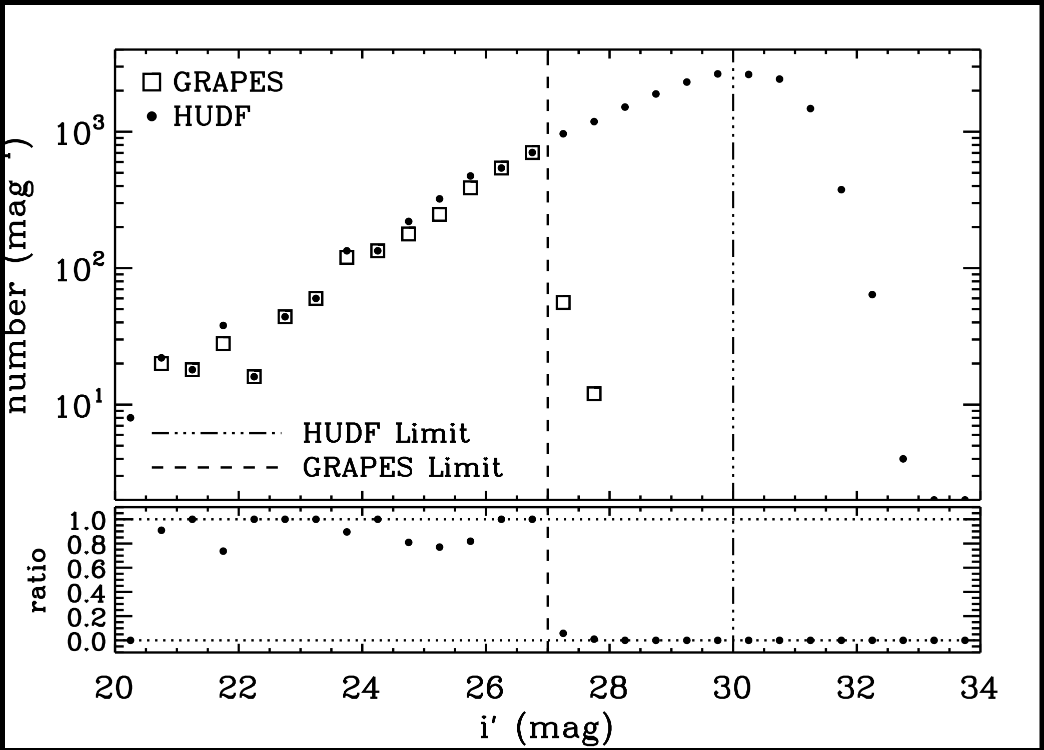


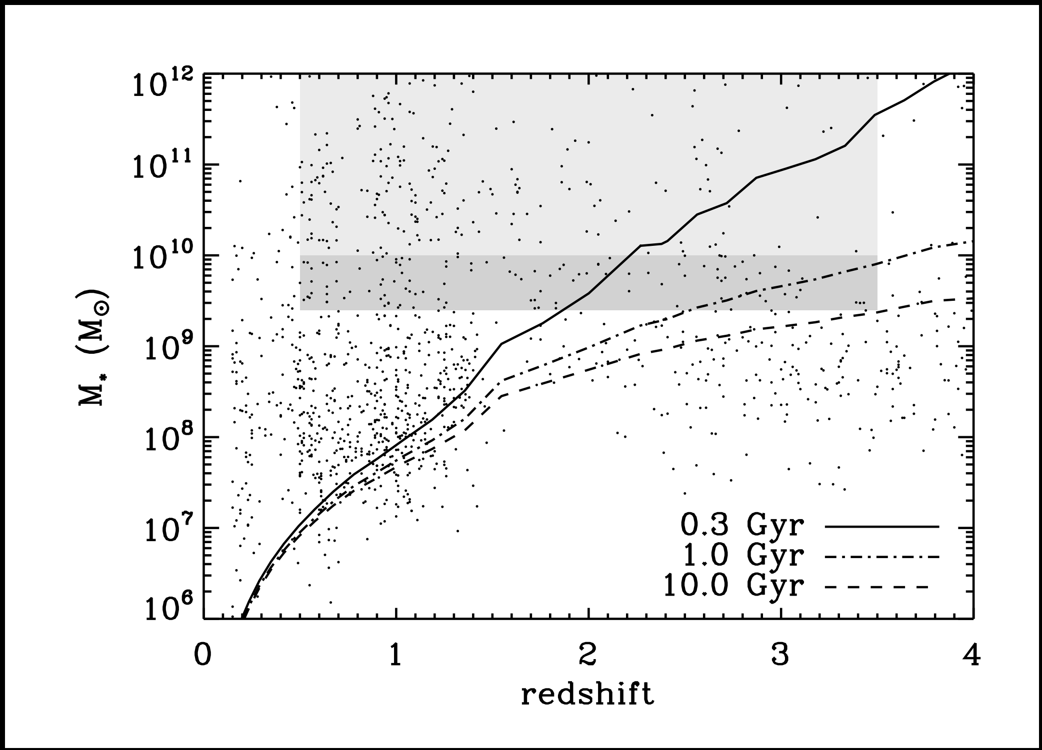
BViz(JH) Photo-z distribution of HUDF field gxys and variable objects:

- Variable objects show a similar N(z) as field galaxies. About 1% of all field galaxies have variable weak AGN at all redshifts.

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

(4) Epoch dependent major merger rate to AB≲27 mag.





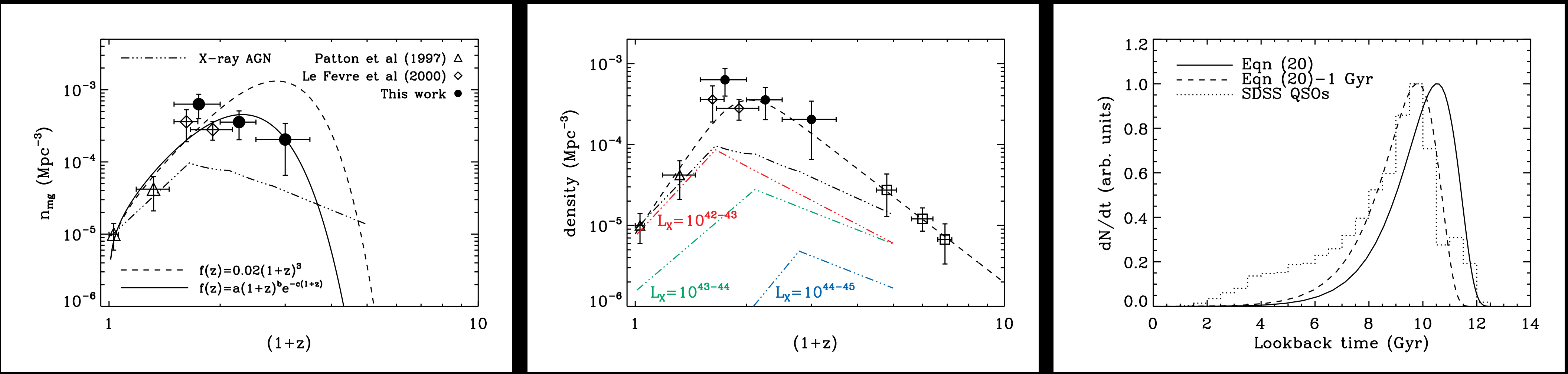
Ryan et al. (2007): HST/ACS grism pair-fraction(z) — sample selection:

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

Mass completeness limit for z≲2 from flux limits/SED fitting:

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

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

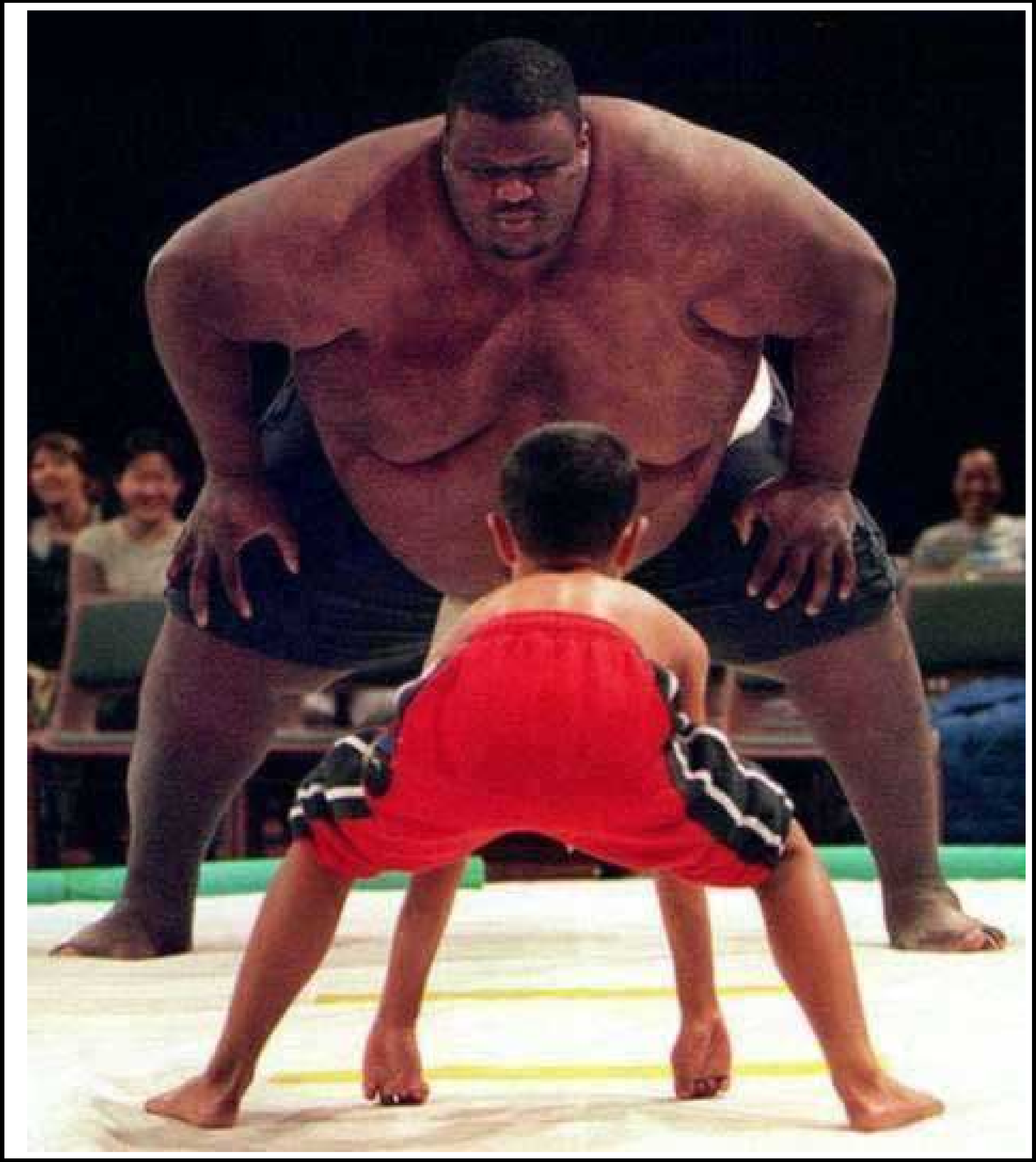


Ryan et al. (2007, 2008): HST/ACS grism epoch-dependent galaxy pair-fraction for AB$\lesssim$27, z$\lesssim$6: spectro-photo-z's for both objects in pair. Merger samples are very complex to select (Lotz et al. 2009).

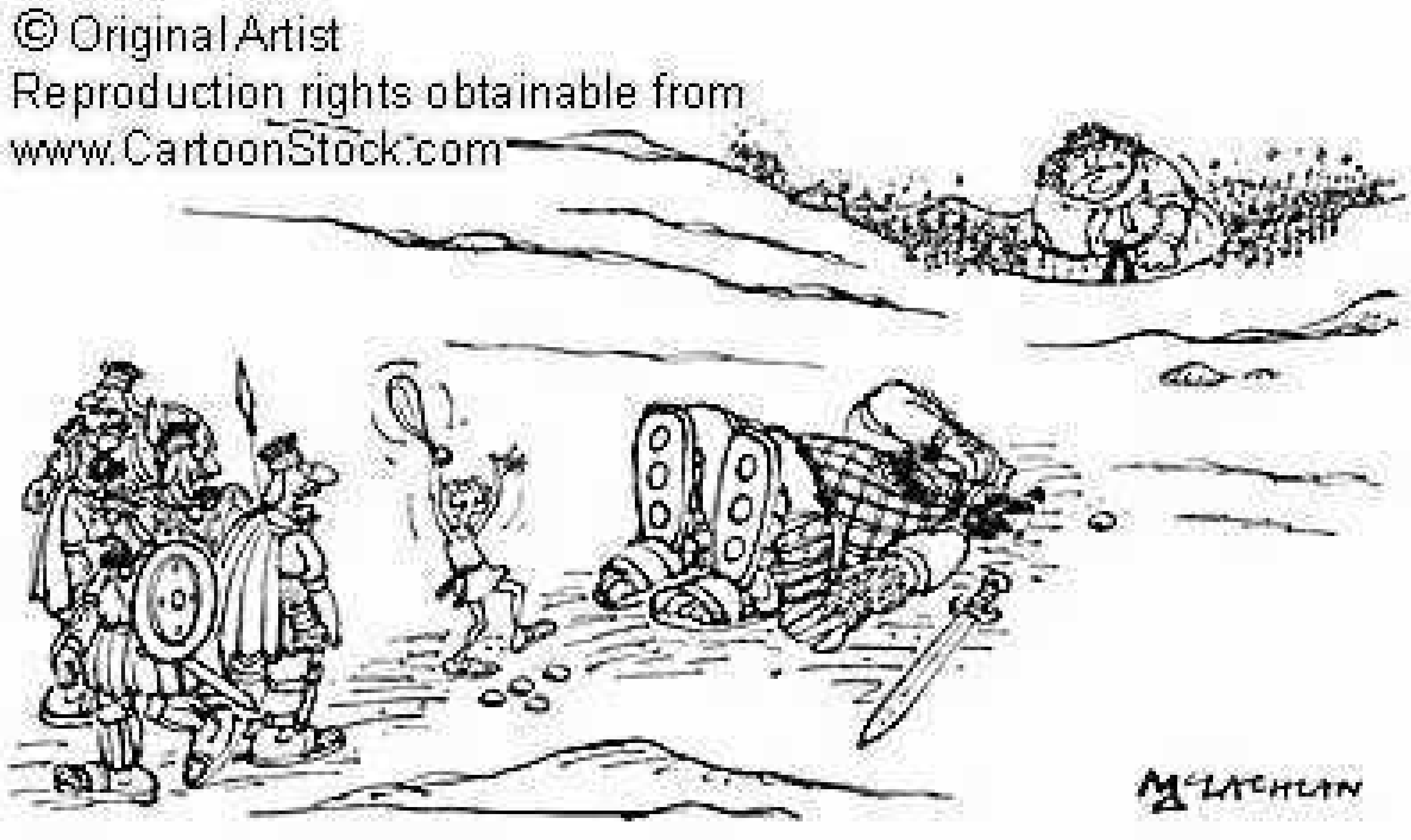
Galaxy major ($0.25 \leq M_2/M_1 \leq 1$) merger density compared to Chandra SDSS QSO density vs. z: Similar curves, but with a $\sim$1 Gyr offset??

$\Rightarrow$ May support the hierarchical models: There could be a $\sim$1 Gyr delay between major mergers and visible SMBH feeding — weak AGN.

• JWST will be able to do this 3 mag fainter, from 0.7–5.0 μm, sampling rest-frame UV-optical for z$\simeq$0–20.



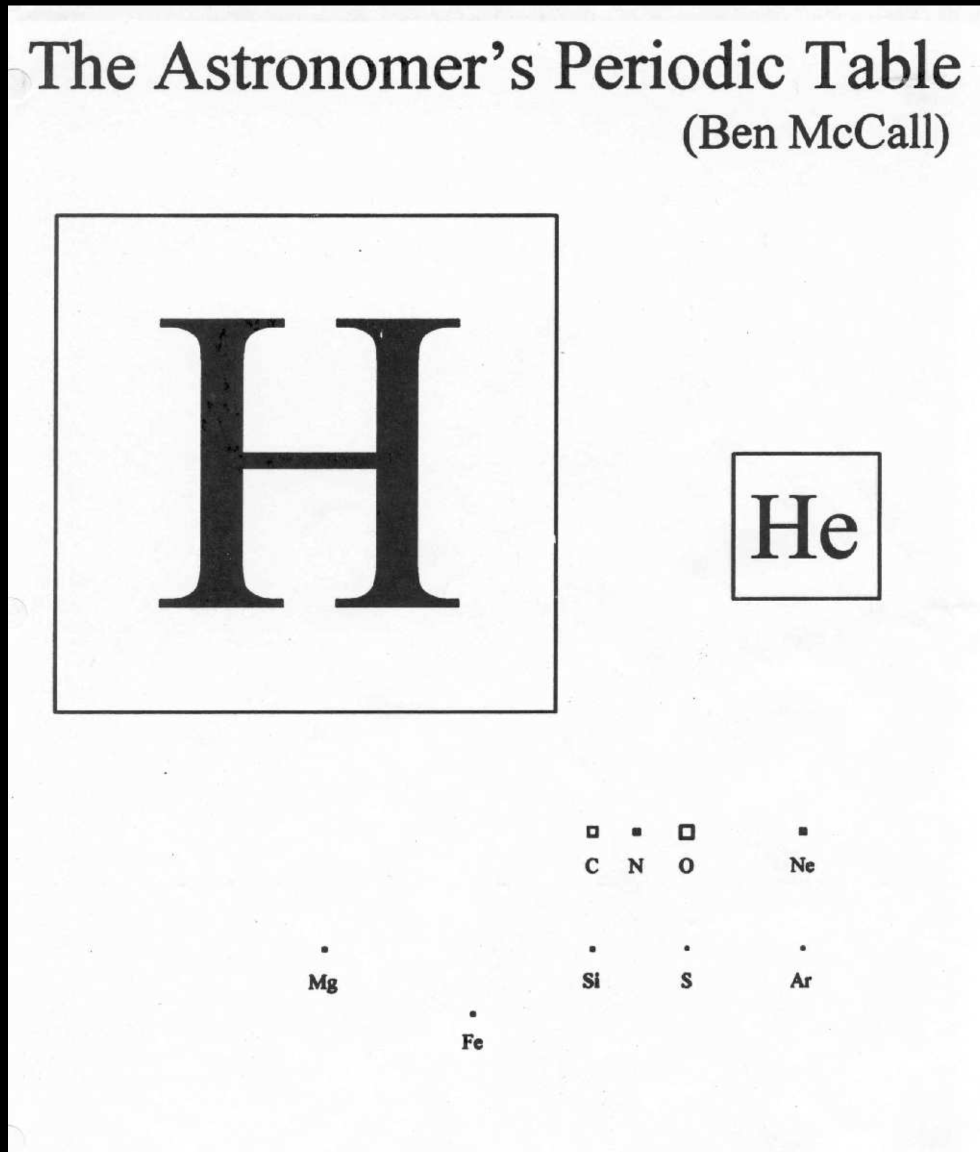
At the end of H-reionization, dwarfs had beaten the Giants, but ...



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

What comes around, goes around ...

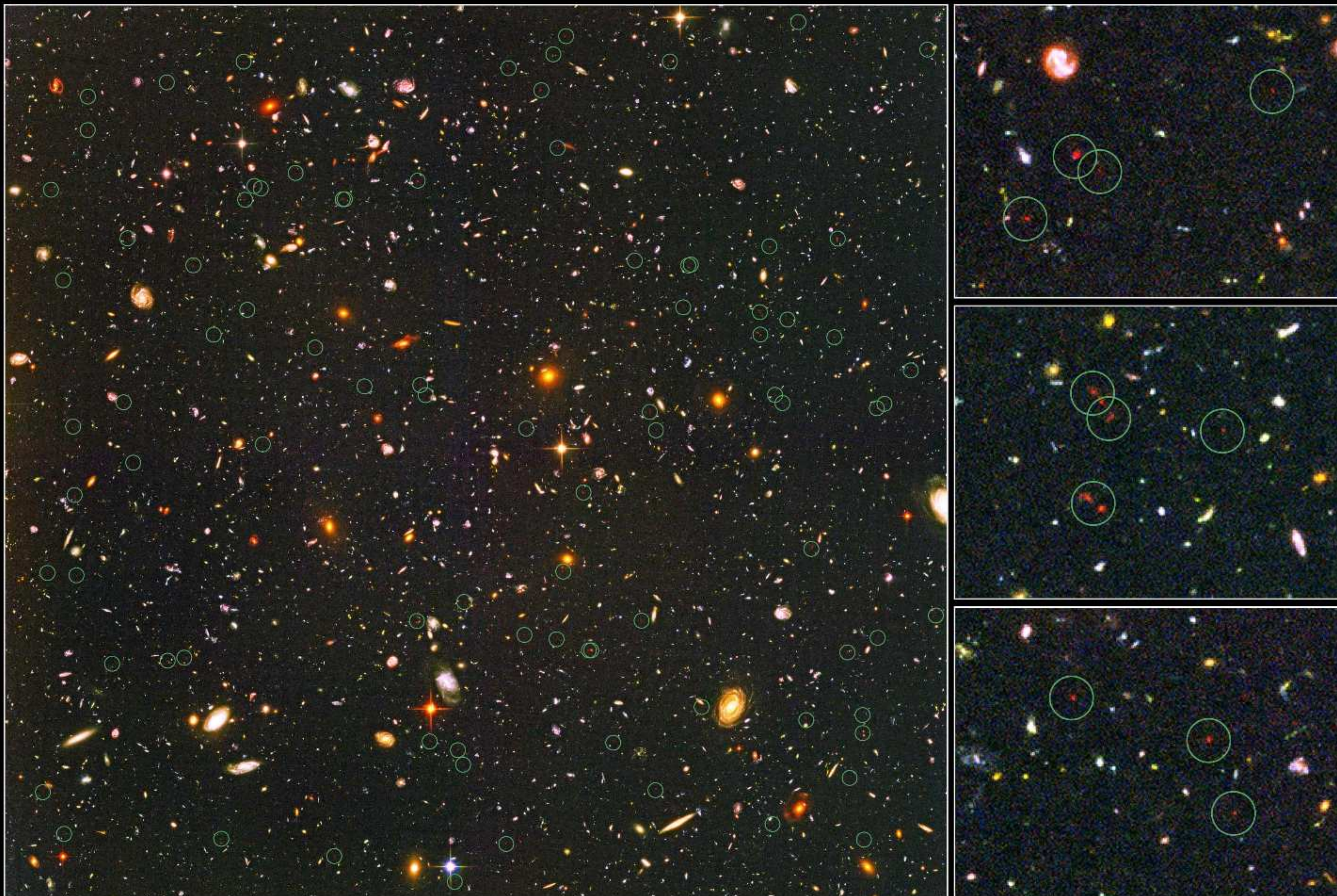
The Universe was reionized (at least) TWICE:



[Astronomers periodic table — with cosmic abundances included:]

- SF in dwarfs galaxies likely caused H-reionization at $z \simeq 12 \longrightarrow z \simeq 7$.
- Hard-UV of QSO's and weak AGN likely caused He-reionization at $z \simeq 3$.

First Light & Reionization: what has HST done & what can JWST etc do?

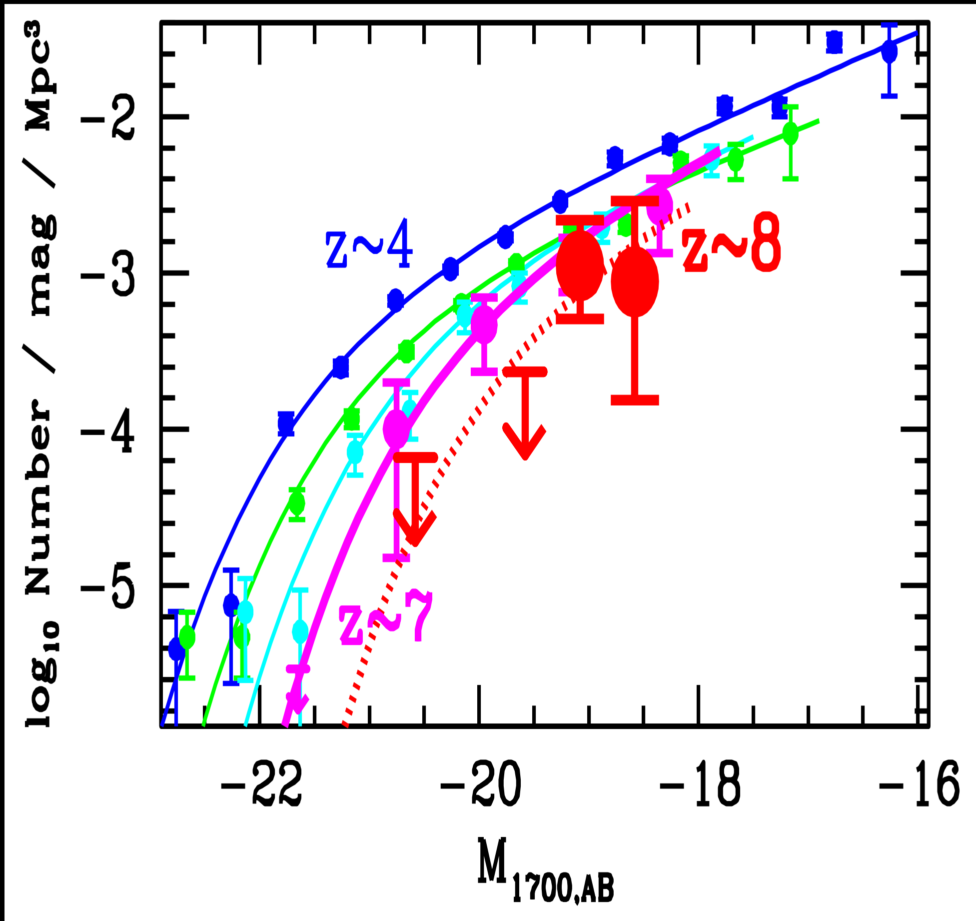


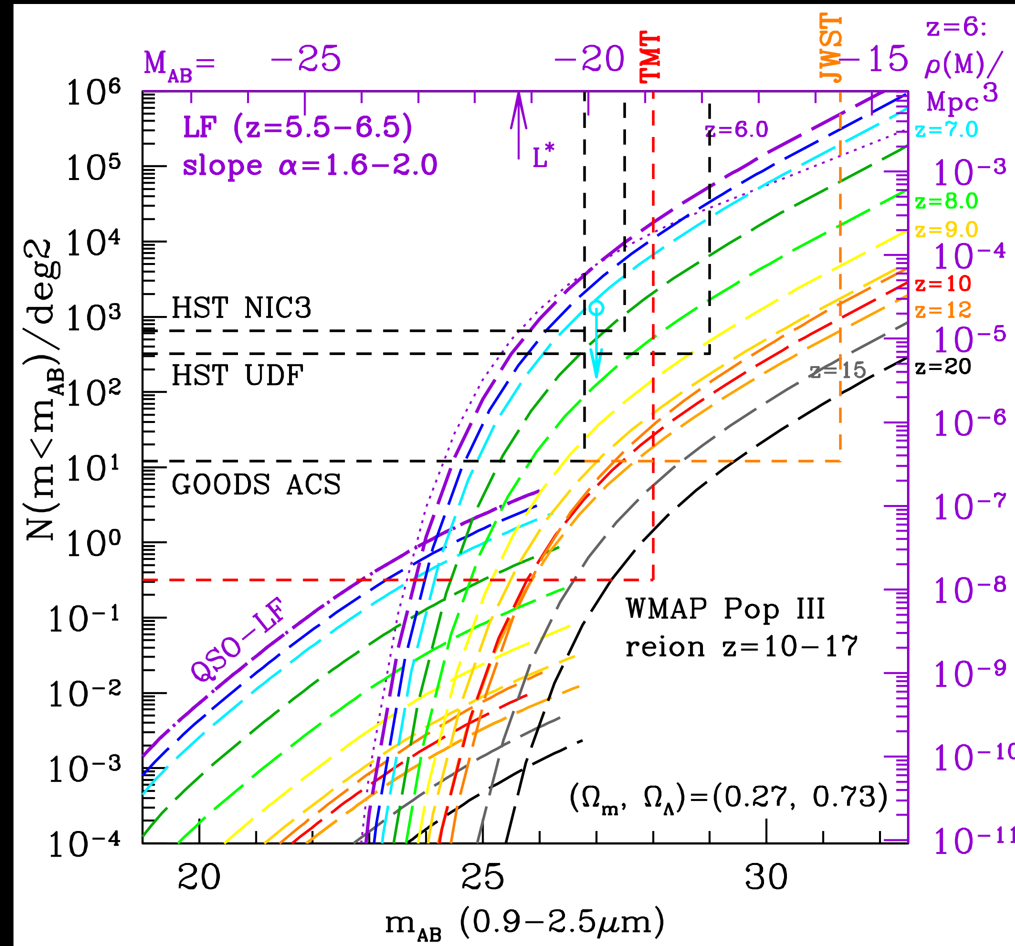
Distant Galaxies in the Hubble Ultra Deep Field

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, R. Windhorst (Arizona State University) and H. Yan (Spitzer Science Center, Caltech)

STScI-PRC04-28



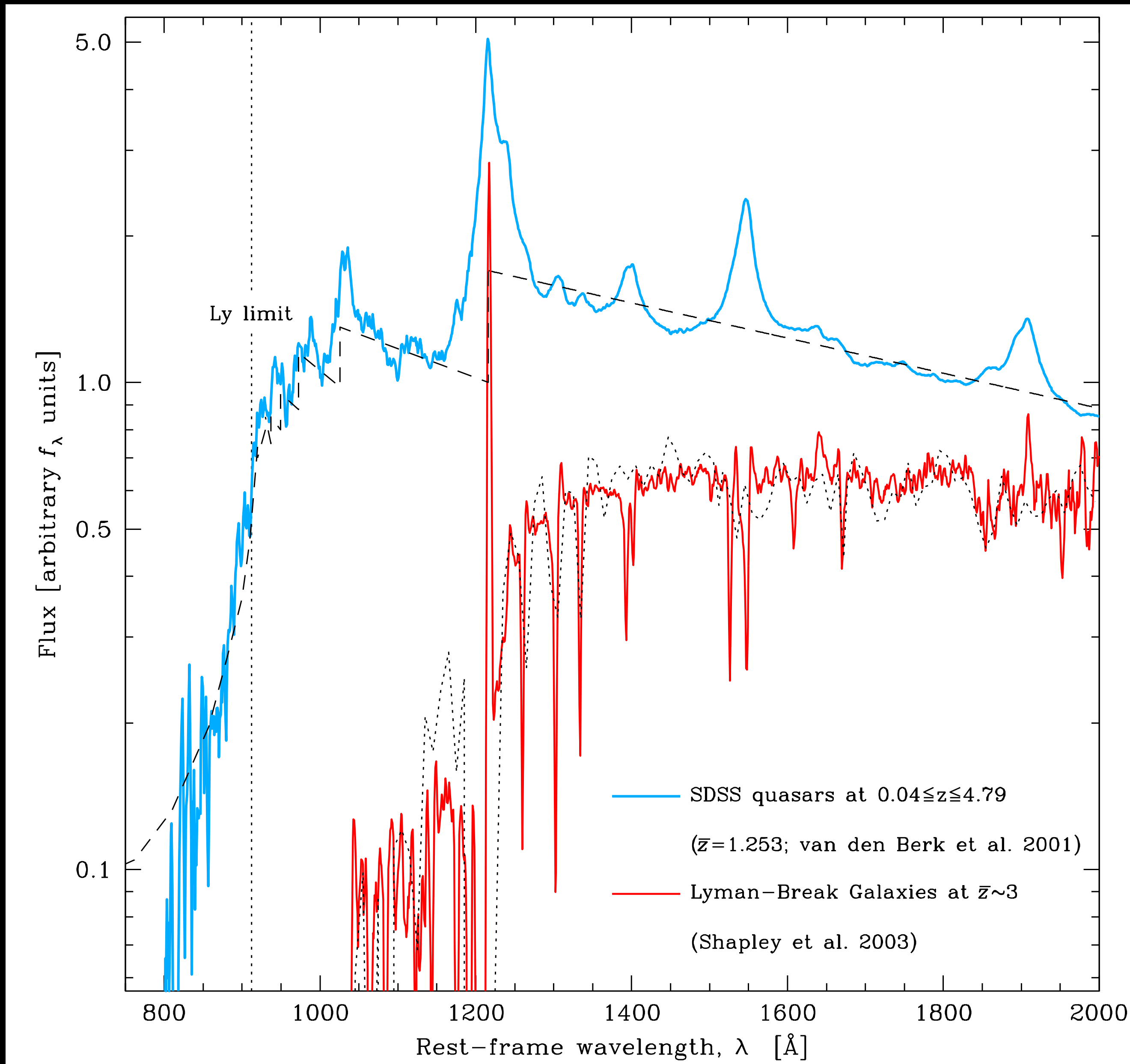


• Objects at z$\gtrsim$9 are rare (Bouwens+ 2010, Yan+ 2010), since volume element is small and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ-range (0.7-29 μm).

• With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.

• To study co-evolution of SMBH-growth and proto-bulge assembly for z$\lesssim$10–15 requires new AGN finding techniques for JWST.

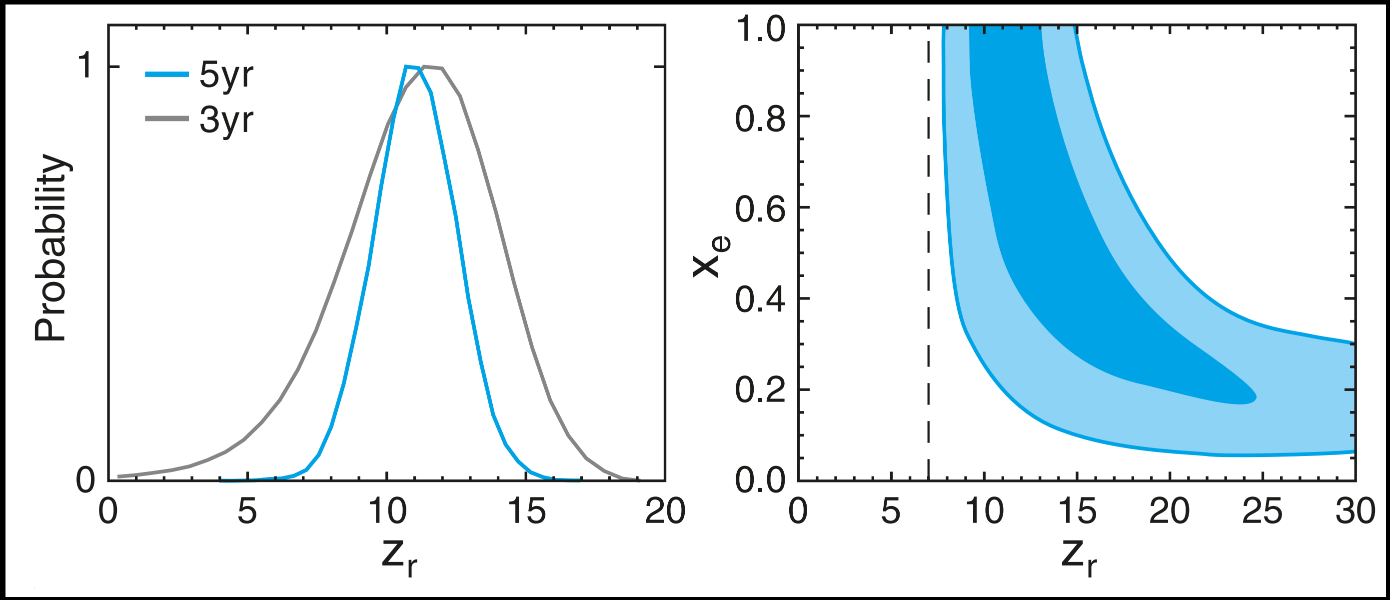
Caveat: Can the Hard-UV of weak AGN outshine Dwarf Galaxies?



- 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.

Implications of the (2010) 7-year WMAP results for JWST science:

HST/WFC3 $z \lesssim 7$–9 $\longleftarrow$ $\longrightarrow$ JWST $z \simeq 8$–25



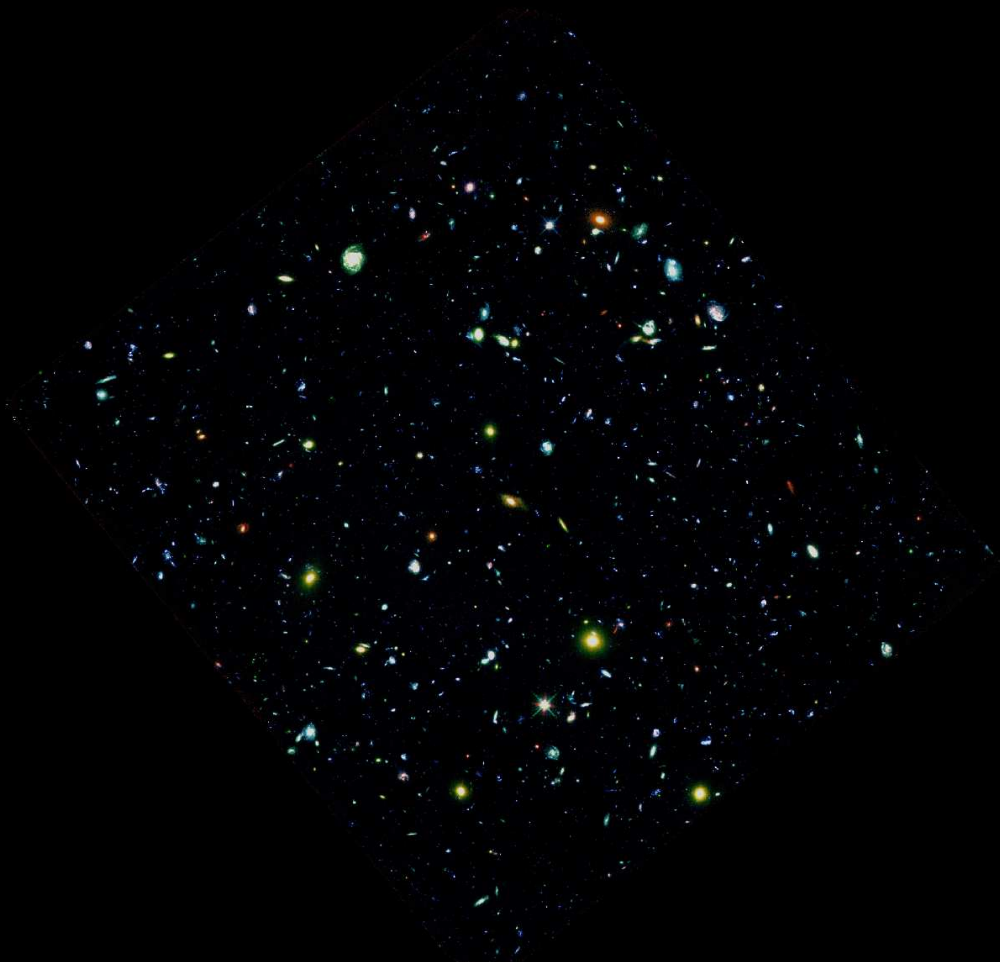
The year-7 WMAP data provided much better foreground removal (Dunkley et al. 2009; Komatsu et al. 2009, 2010; astro-ph/1001.4538)

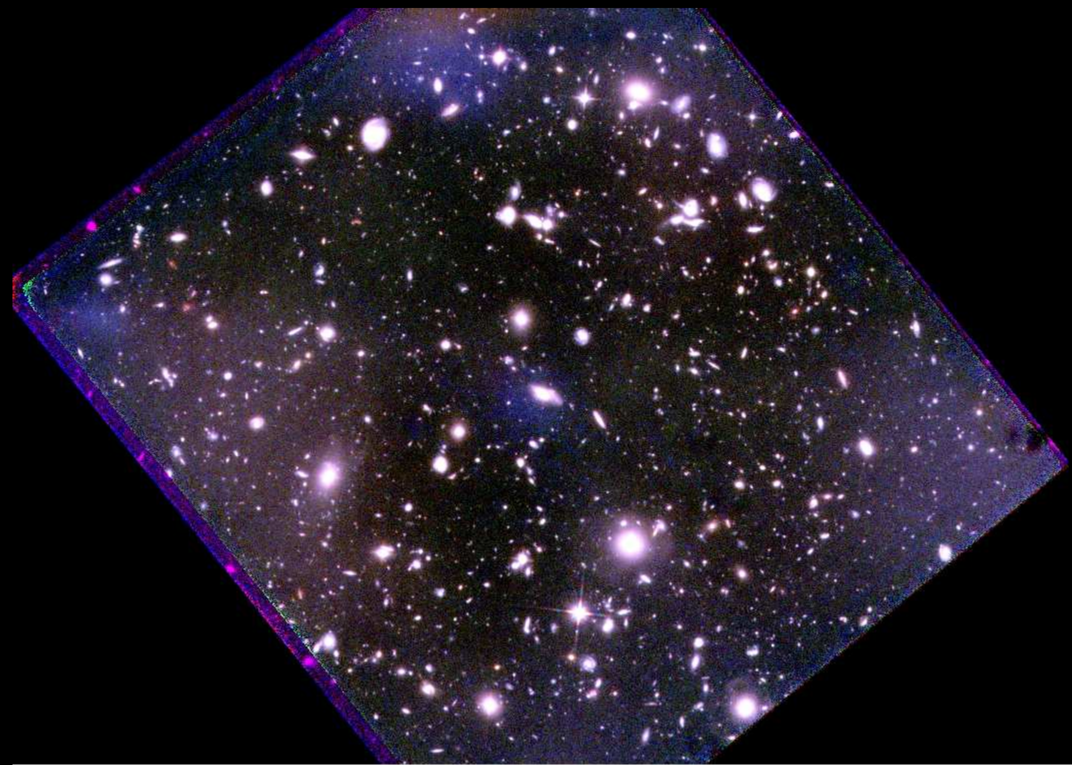
$\Longrightarrow$ First Light & Reionization occurred between these extremes:

- (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.

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

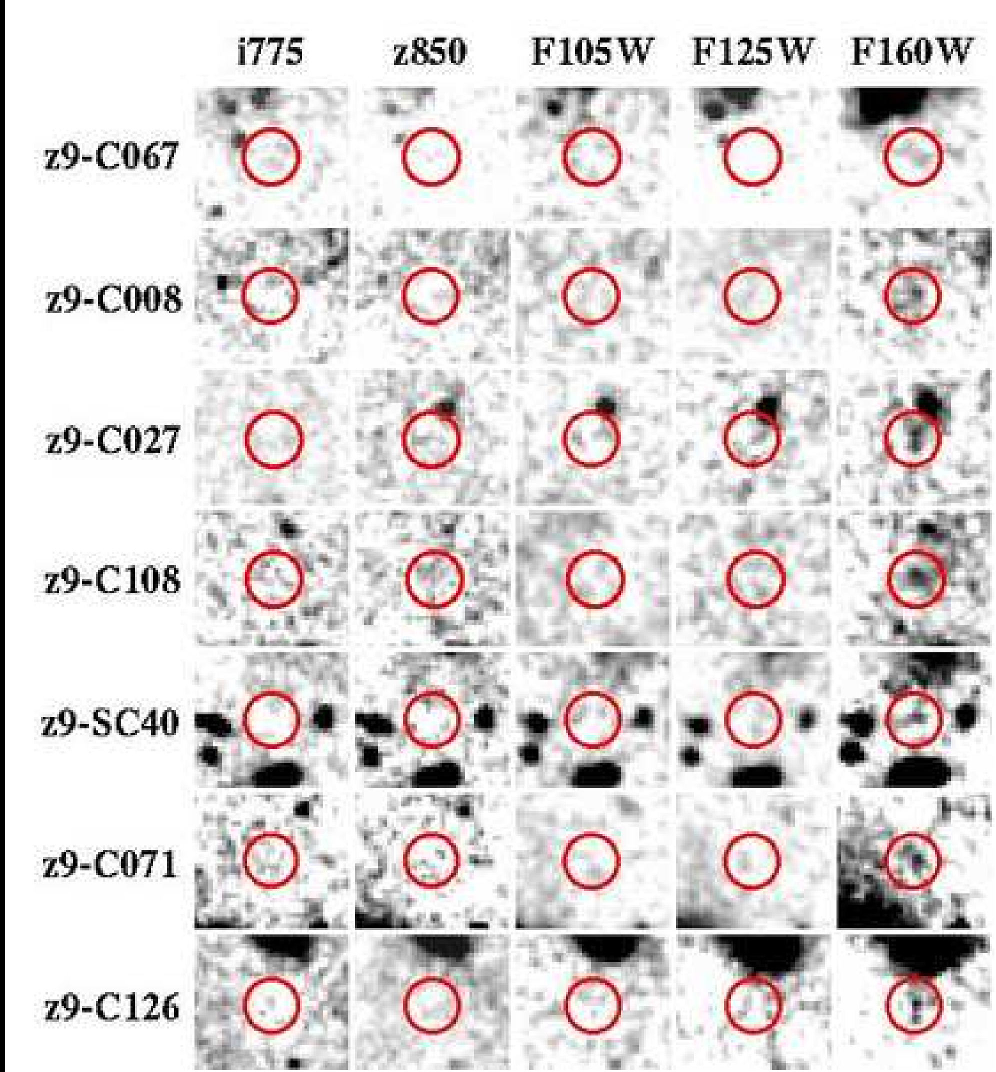


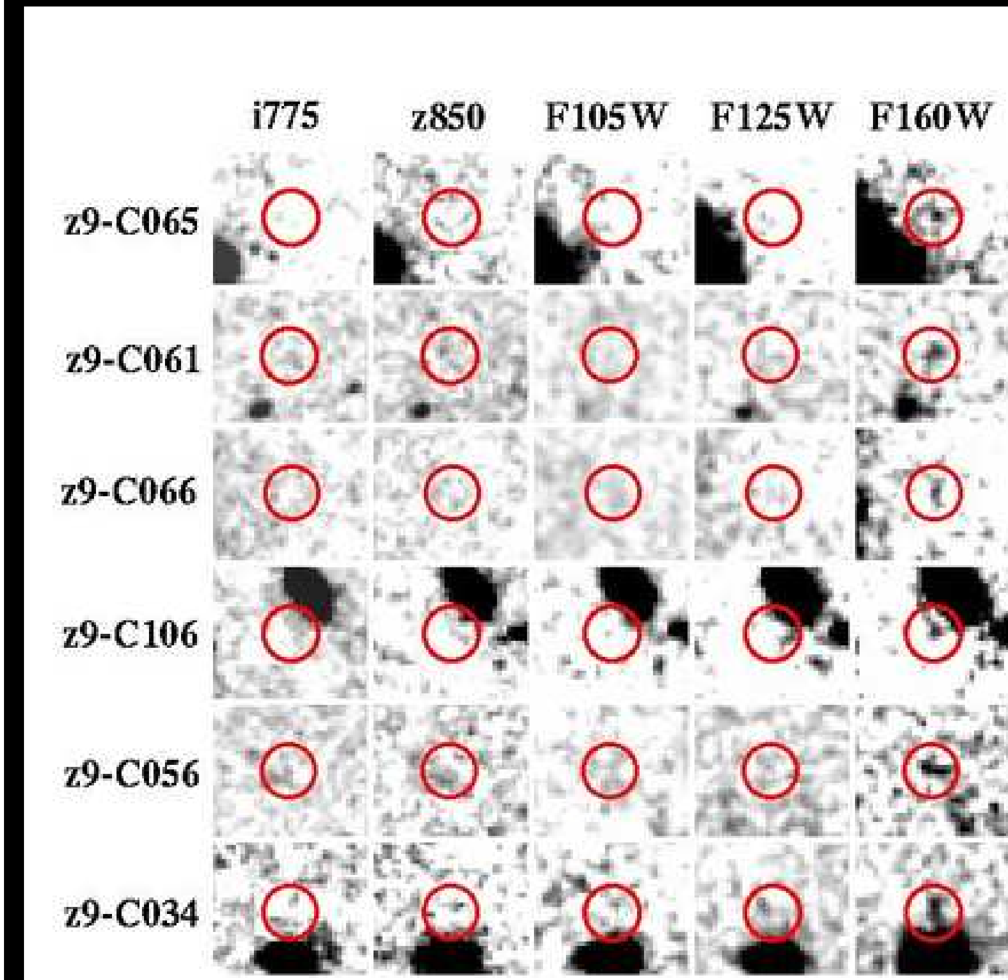


(Left) HST/WFC3 IR-mosaic in YJH in the HUDF: Bouwens et al (2010), Yan et al. (2009; astro-ph/0910.0077).

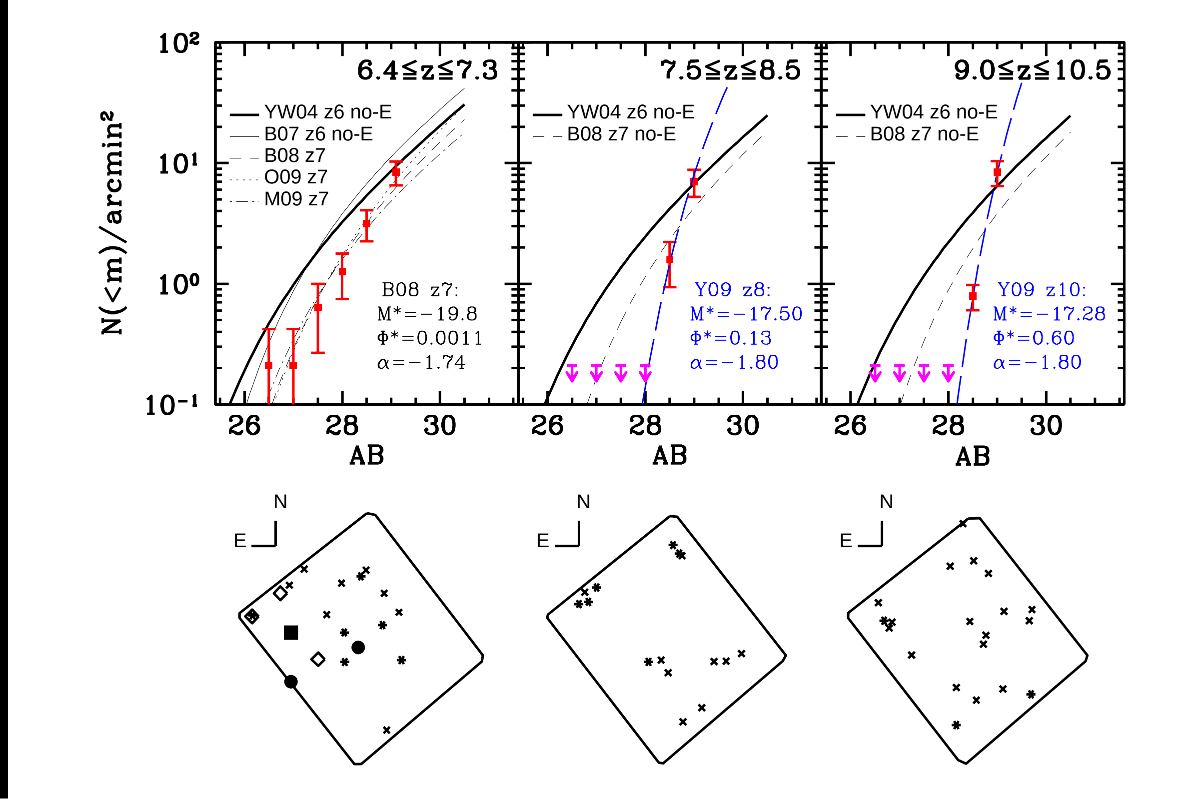
(Right) Same WFC3 IR-mosaic, but stretched to $\lesssim 10^{-3}$ of Zodi sky!!

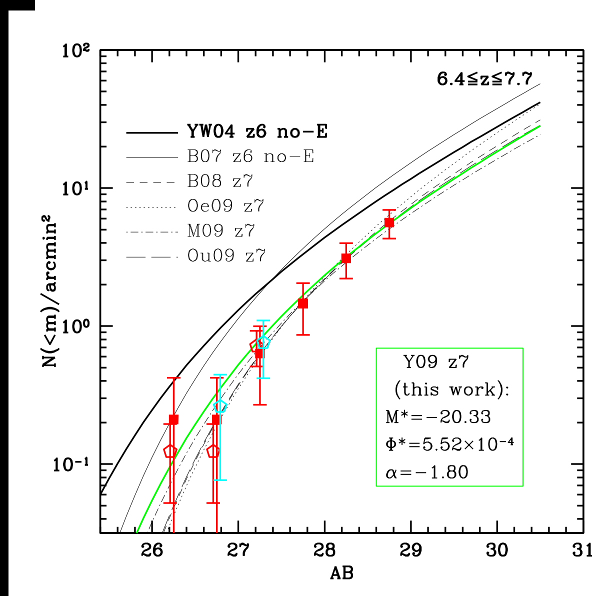
- The CLOSED-TUBE HST has residual low-level systematics: imperfect removal of detector artifacts, flat-fielding errors, and/or faint straylight.
- The open JWST architecture needs perfect baffling and rogue path mitigation to do ultradeep JWST fields (JUDF's) to 10^{-4} of sky.

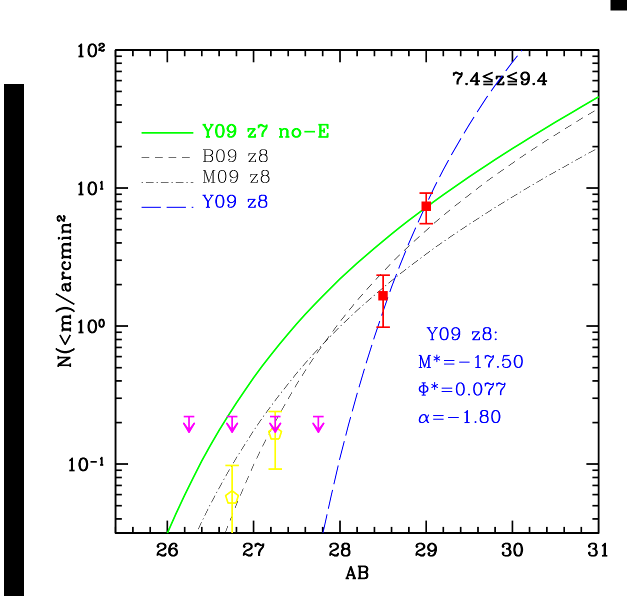




- Our simulations show that ∼50% of the J-drops close to bright galaxies are real (unlike Bouwens 2010), see Yan et al. 2010 (astro.0910.0077).
- Assume only 33% of J-drops are real *and* at z$\gtrsim$9. Together with the HUDF and ERS upper limits to AB$\lesssim$28 mag, the z∼9 LF is still steep!
- Need JWST to measure z$\gtrsim$9 LF, and see if it's fundamentally different from the z$\lesssim$8 LFs. Does a pop-III driven IMF cause a power-law LF?

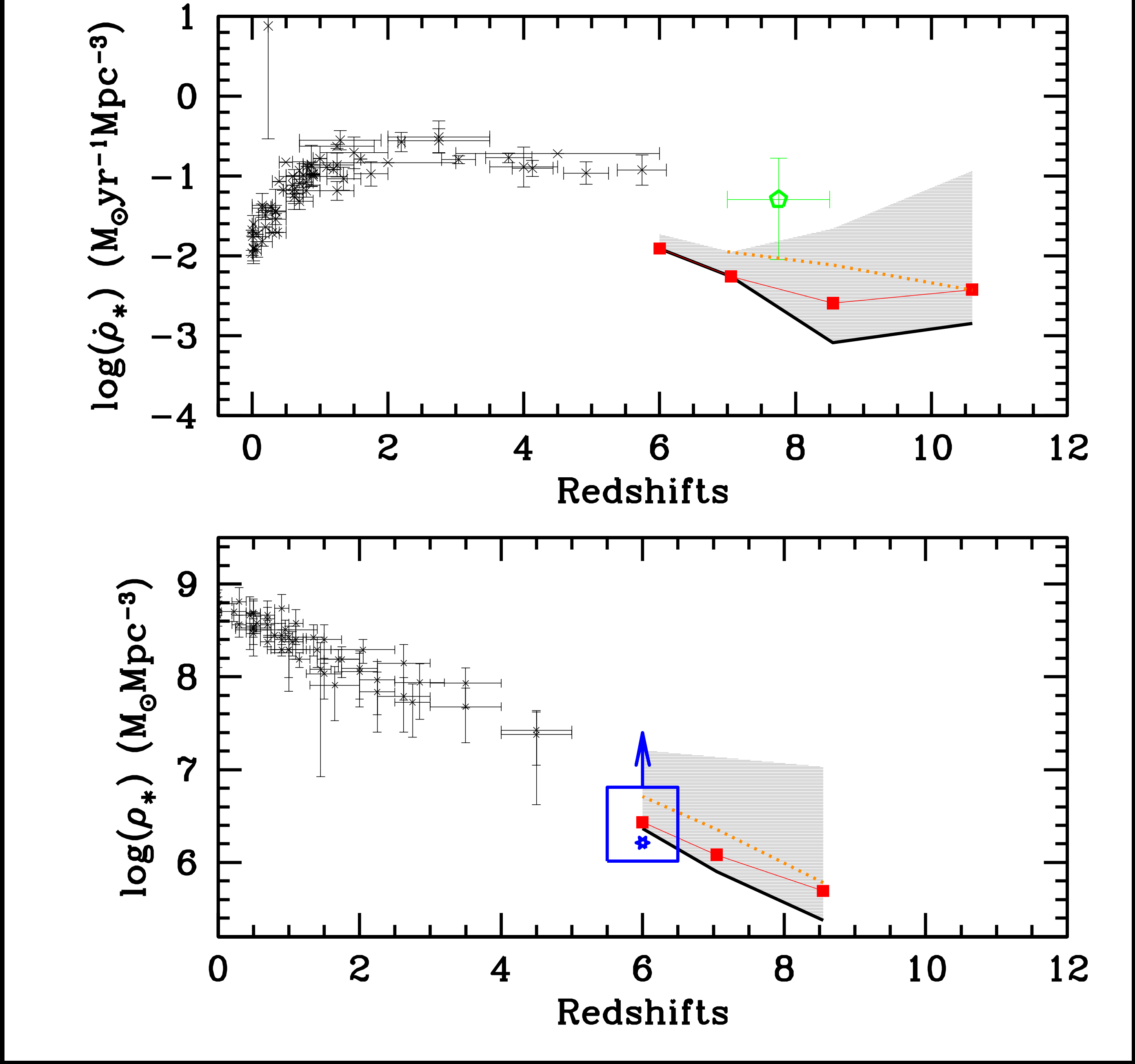






Update of Yan et al. 2009 (astro.0910.0077) HUDF with WFC3 ERS data:

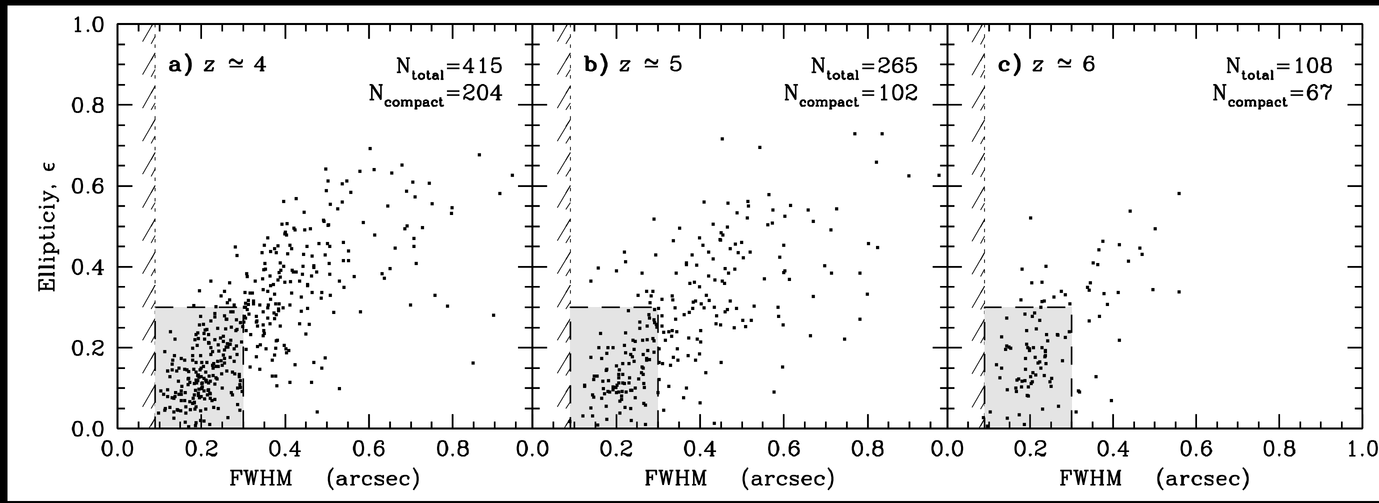
- $z=7$ LF more firm (see Bouwens), $z=8$ LF refined, $z=9.5$ UL's still stand.

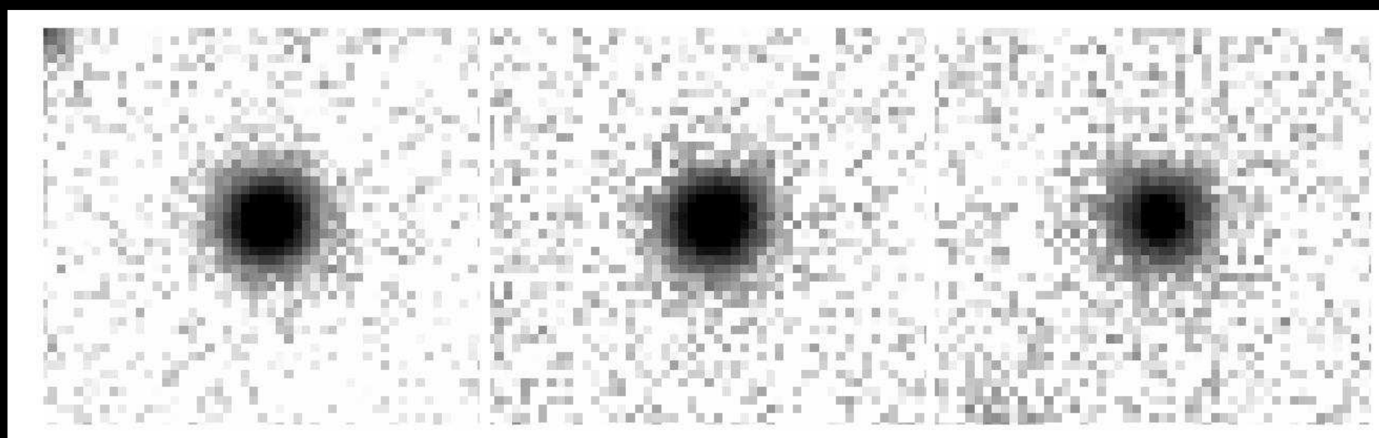


The current WFC3 uncertainties on J-drops are large enough that at z$\gtrsim$8, a wide range of possibilities is allowed (Yan et al. 2010; astro.0910.0077).

- Need JWST to fully measure the LF and SFR for 8$\lesssim$z$\lesssim$15.

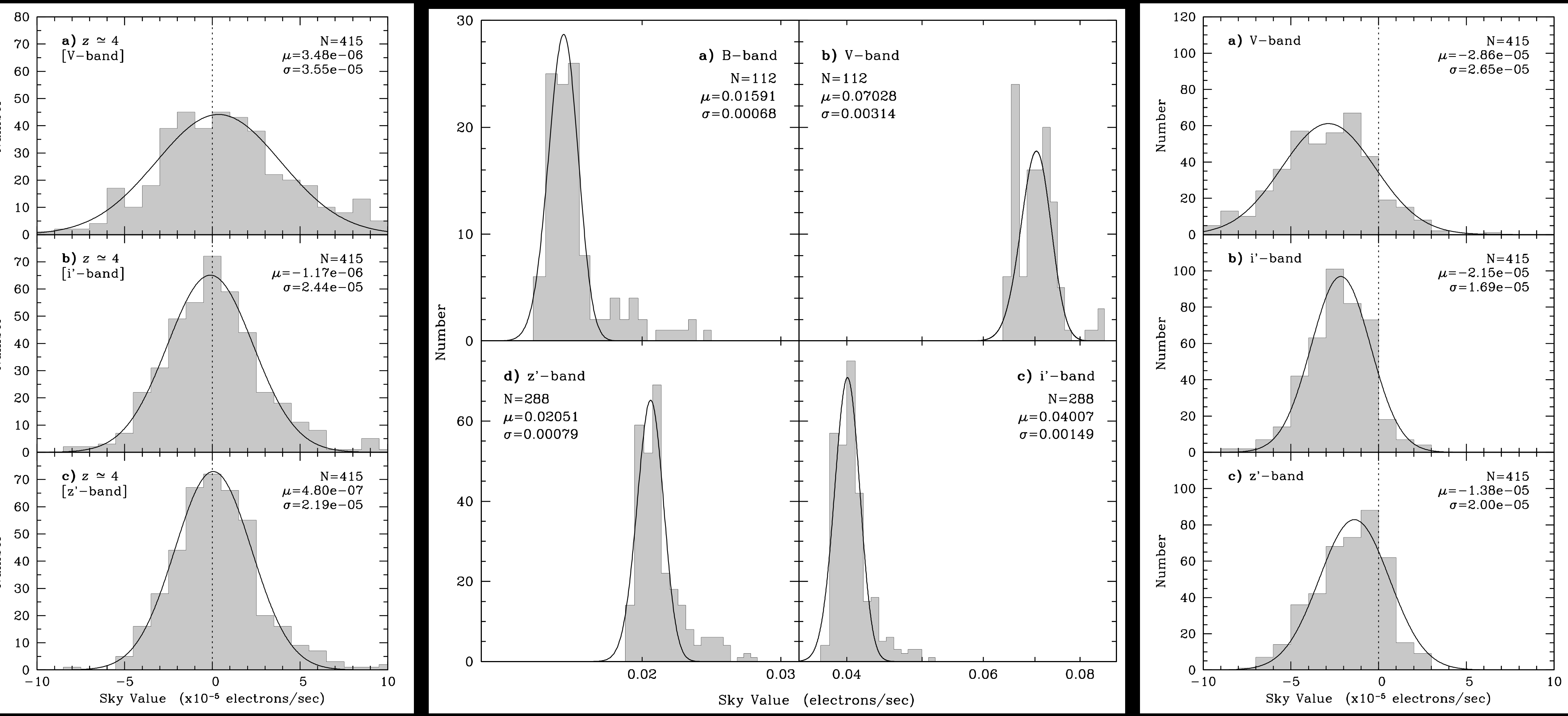
HUDF Zodi: Dynamical ages of Dwarf Galaxies at z≃4–6?





- Select all isolated, nearly unresolved ($2r_e \lesssim 0\farcs3$), 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. (Hathi et al. 2008, AJ 135, 156).
- If these compact, round objects are intrinsically comparable, each stack has the S/N of ∼4300 HST orbits (≃240 JWST hrs; Hathi et al. 2008)!

Zodi BViz sky-values in HUDF to 0.2% of sky



(LEFT): Modal Viz sky-values in the Multi-Drizzled HUDF: LOCAL sky-subtraction (Hathi et al. 2008, AJ 135, 156).

(MIDDLE): Modal BViz sky-values in the HUDF: NOT sky-subtracted.

(RIGHT): Modal Viz sky's in the Multi-Drizzled HUDF: GLOBAL sky-subtr.

- HUDF sky-subtraction error$\simeq$(2–3)$.\mathbf{10^{-3}}$ or AB$\simeq$29.0–30.2 mag/arcsec$^{\mathbf{2}}$

Zodi BViz sky-values in HUDF to 0.2% of sky

Table 1. Measured sky values in $BVi'z'$ (filters) for the HUDF

HUDF Filter	Number of Exposures	Mean Sky Value[a] (e^-/s) and rms error[b]	Sky SB[c] (AB mag arcsec^{-2})	Sky Color[c] (AB mag)	1σ Sky-Subtraction error (AB mag arcsec^{-2})
B	112	0.015909 ± 0.000065	23.664 ± 0.003	$(B-V)_{\rm sky}$=0.800	29.85 ± 0.05
V	112	0.070276 ± 0.000297	22.864 ± 0.002	$(V-i')_{\rm sky}$=0.222	30.15 ± 0.15
i'	288	0.040075 ± 0.000088	22.642 ± 0.002	$(i'-z')_{\rm sky}$=0.065	29.77 ± 0.20
z'	288	0.020511 ± 0.000047	22.577 ± 0.003	$(V-z')_{\rm sky}$=0.287	28.95 ± 0.05

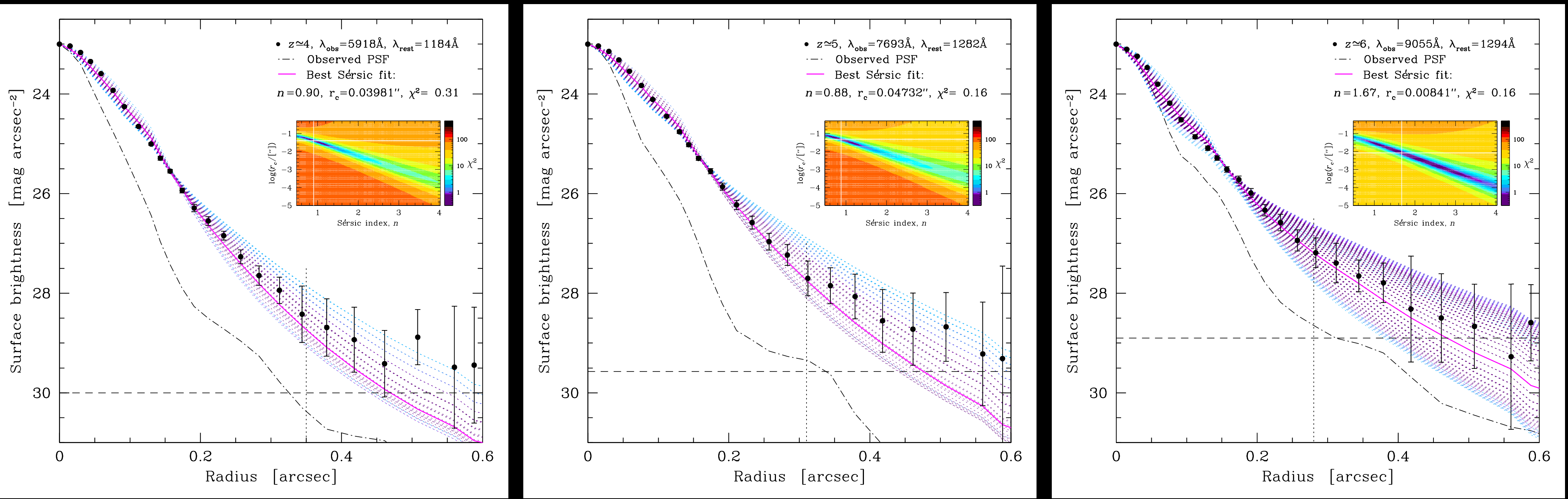
[a]From Fig. 4 in Hathi, N. P., et al. 2008, AJ, 135, 156 (astro-ph/0710.0007)

[b]Error is standard deviation of the mean ($\sigma/\sqrt{N}$)

[c]Sky surface brightness values and colors are consistent with the solar colors in AB mag of (V-i')=0.19, (V-z')=0.21 and (i'-z')=0.01 [except for bluest color (B-V)], and is dominated by the zodiacal background.

- 400 HUDF orbits in BViz (Hathi et al. 2008, AJ, 135, 156):
- HUDF sky-subtraction error≃(2–3).10^{-3} or AB≃29.0–30.2 mag/arcsec^2
- JWST can do this in 20 hrs, reaching AB≃31–32 mag/arcsec^2 in ≳500 hrs?

HUDF Zodi: Light profiles of Dwarf Galaxies at z≃4–6



Best fit Sersic profile of 1680 ACS V-band orbit stack: n=0.90 at z≃4

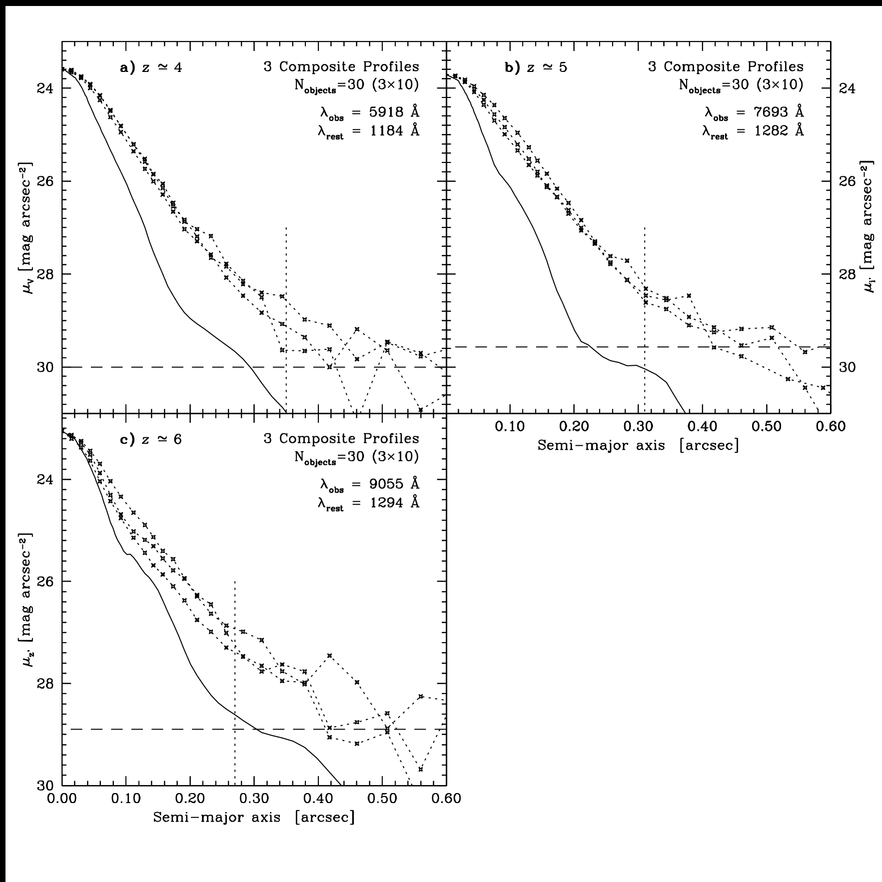
Best fit Sersic profile of 4320 ACS i-band orbit stack: n=0.88 at z≃5

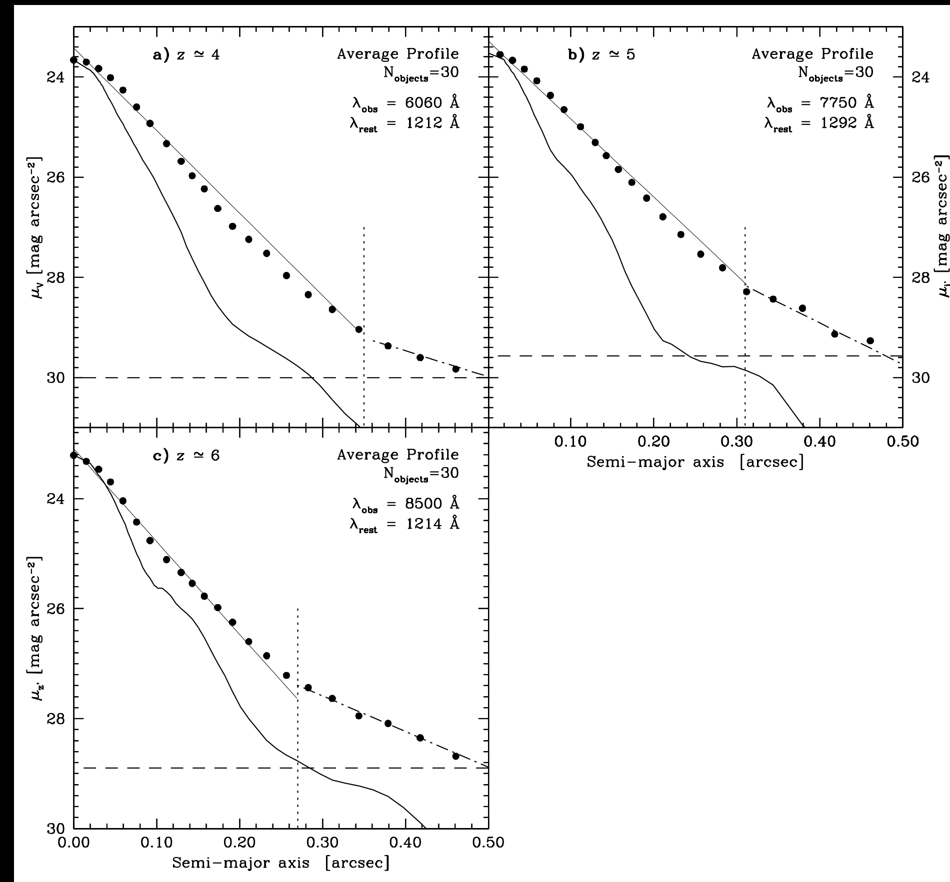
Best fit Sersic profile of 4320 ACS z-band orbit stack: n=1.67 at z≃6

⇒ Dwarf galaxies at z≃4–6 are disk dominated! (Hathi et al. 2008).

- JWST can do this to $\mathbf{10^{-4}}$, or AB≃31.0–32.0 mag/arcsec$^{\mathbf{2}}$ to z≲15,
- *provided* that JWST straylight/rogue path is kept to a minimum: well below Zodi and only has low spatial frequencies.

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



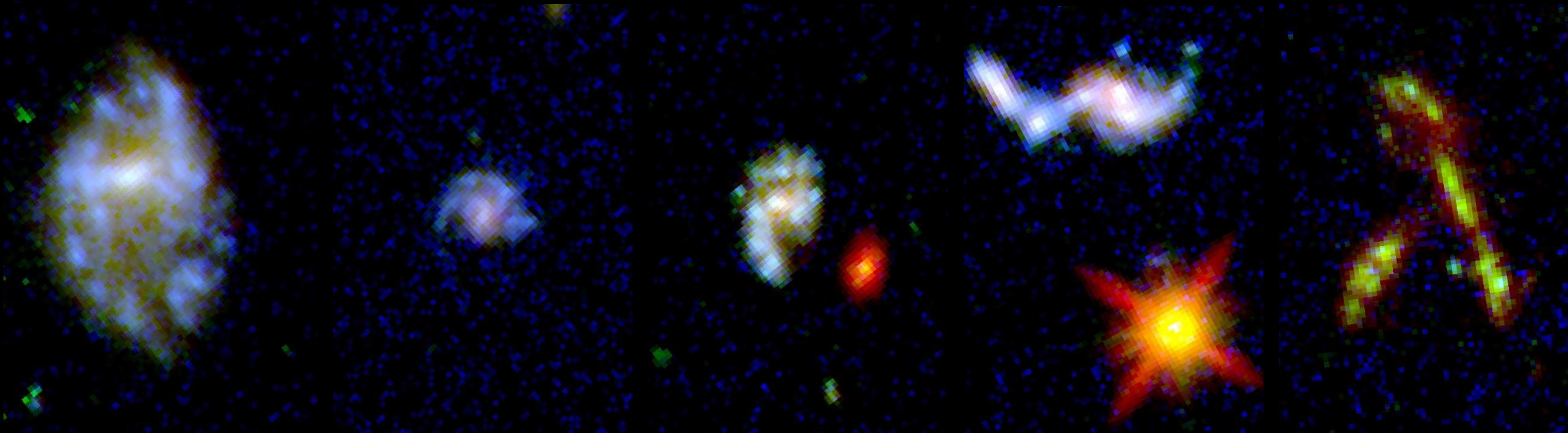


- HUDF sky-subtraction error is 2–3.10^{-3} or AB≃29.0–30.2 mag/arcsec^2
- Average 4300-orbit compact, round dwarf galaxy light-profile at z≃6–4 deviates from best fit Sersic n≃1.0 law (incl. PSF) at r≳0″.27–0″.35.
- If interpreted as virial radii in hierarchical growth, these imply dynamical ages of τ_{dyn}≃0.1-0.2 Gyr at z≃6–4 for the enclosed masses.

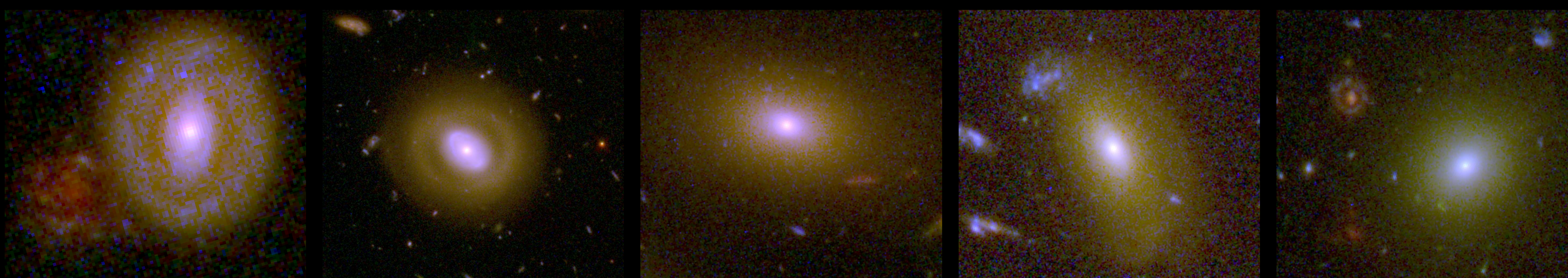
⇔ comparable to SED ages (Hathi$^+$ 2008, AJ 135, 156).

⇒ Star-formation that finished global reionization at z≃6 started at ≳7.

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.

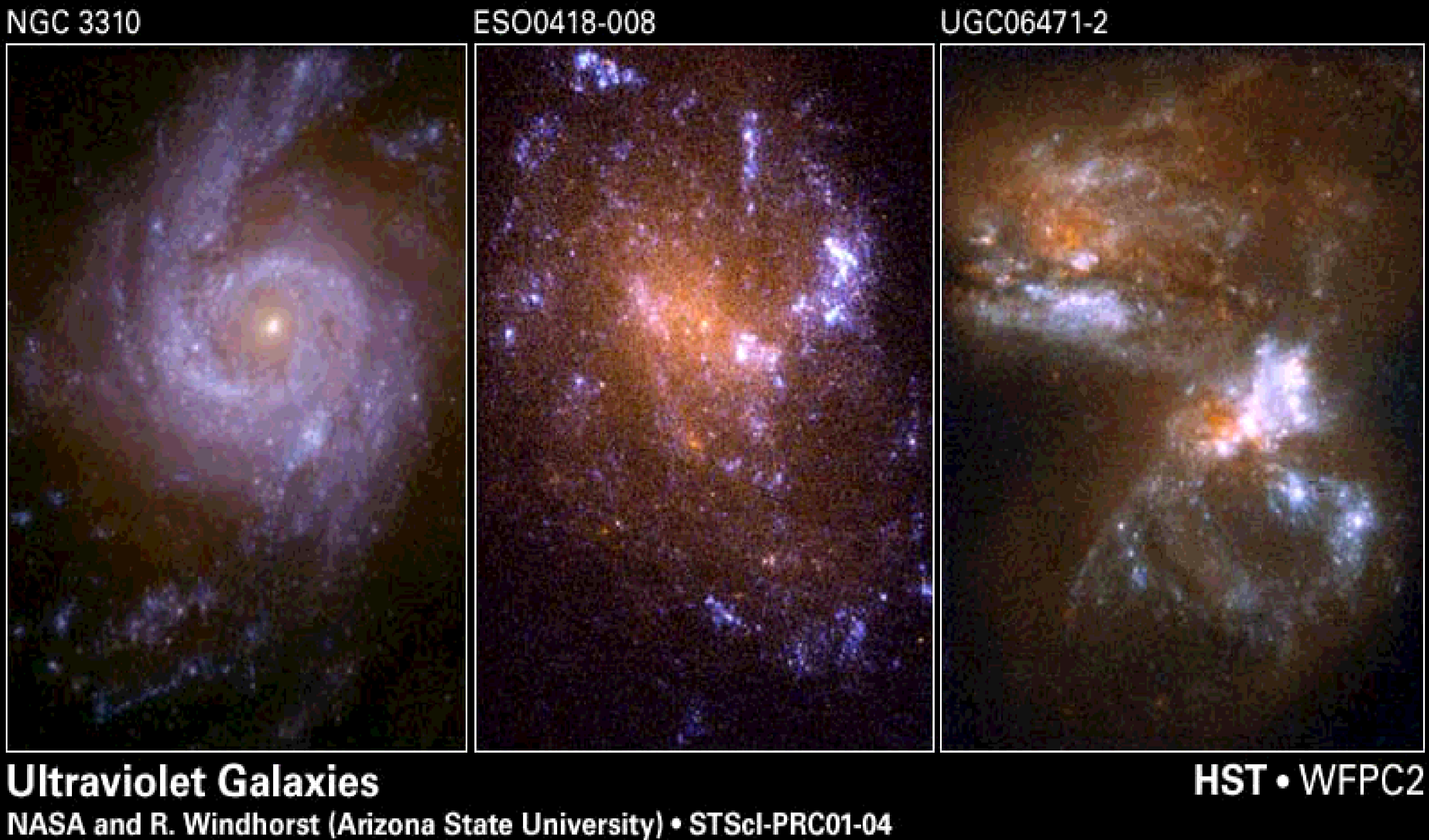


Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

(Rutkowski et al. 2010) $\Longrightarrow$ "Red and dead" galaxies aren't dead!

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

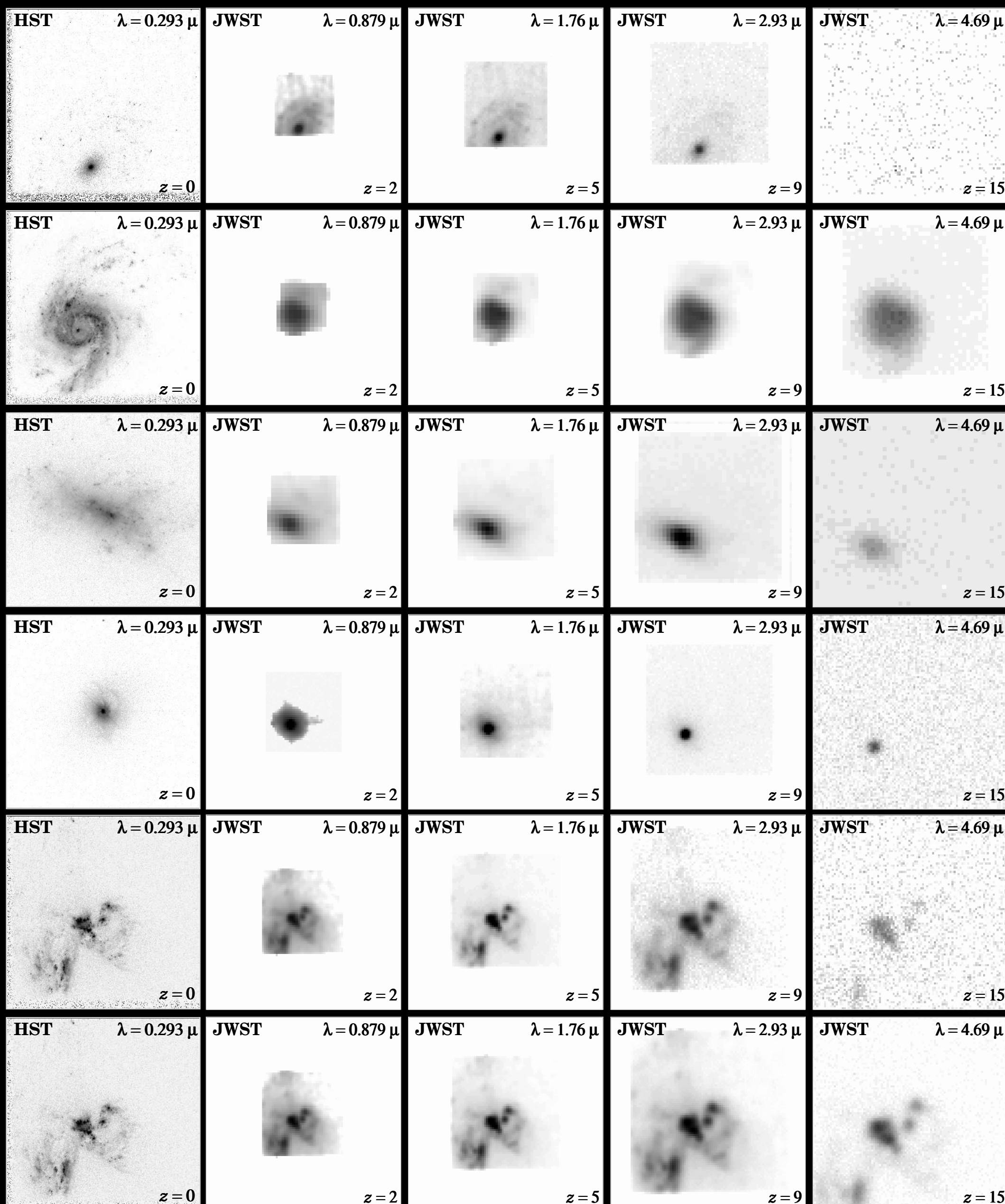
(6) Predicted Galaxy Appearance for JWST at $z \simeq 1$–15



- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often copious amounts of dust imprinted.
- High-resolution HST UV images are benchmarks for comparison with very high redshift galaxies seen by JWST, enabling quantitative analysis of the restframe-λ dependent structure, B/T, CAS, SFR, mass, dust, etc.

(6) Predicted Galaxy Appearance for JWST at z≃1–15 (w/ C. Conselice)

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



With proper restframe UV-optical benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of

cosmic time:

- (1) Most disks will SB-dim away at high z, but most formed at z≲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.

- References and other sources of material shown:

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

www.asu.edu/clas/hst/www/ahah/ [Hubble at Hyperspeed 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://jwst.gsfc.nasa.gov/faq_scientists.html

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

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

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

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

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. 2007, Advances in Space Research, 42, p. 1965 (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"