Observing SMBH growth with HST and JWST:

When during galaxy assembly did AGN growth take place?

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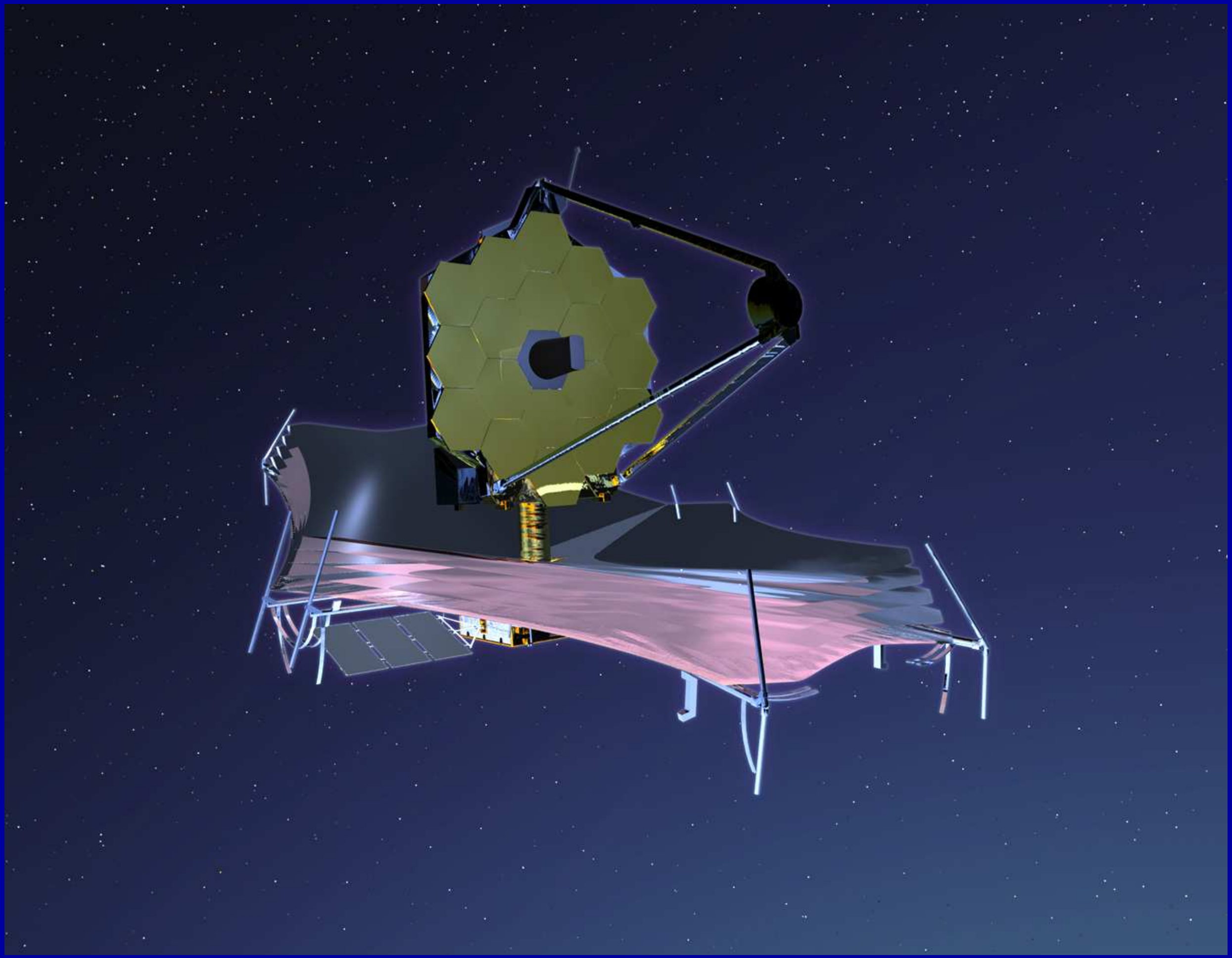
& (Ex) ASU Grad Students: N. Hathi, H. Kim, R. Ryan, M. Rutkowski, A. Straughn, & K. Tamura



Talk at the UT Workshop on "First Stars and Galaxies", Austin, TX; Th. March 11, 2010

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

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

Outline

- (1) Introduction: (How) did AGN/SMBH-growth go hand-in-hand with galaxy assembly? How can HST/WFC3 & JWST measure this?

- (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

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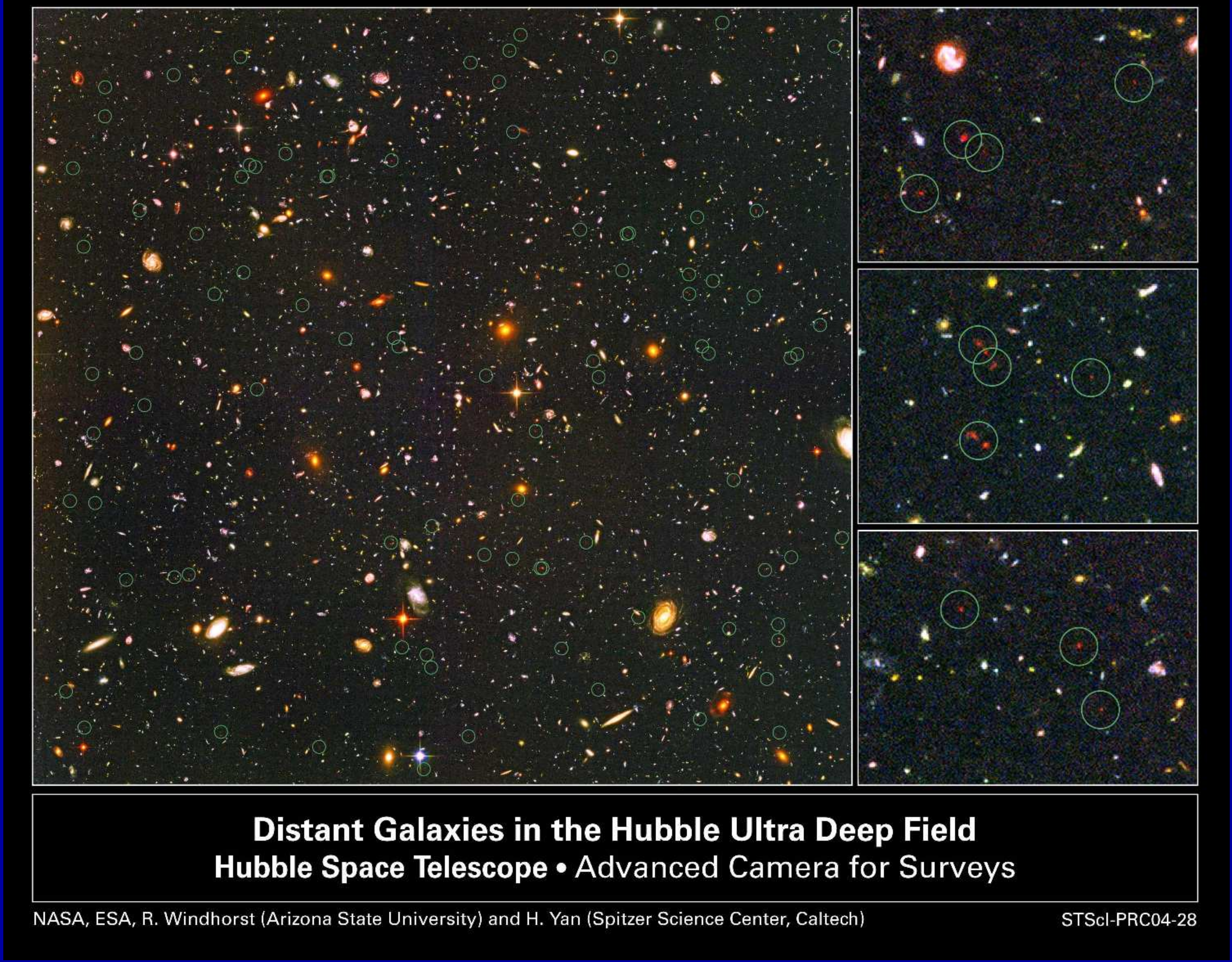
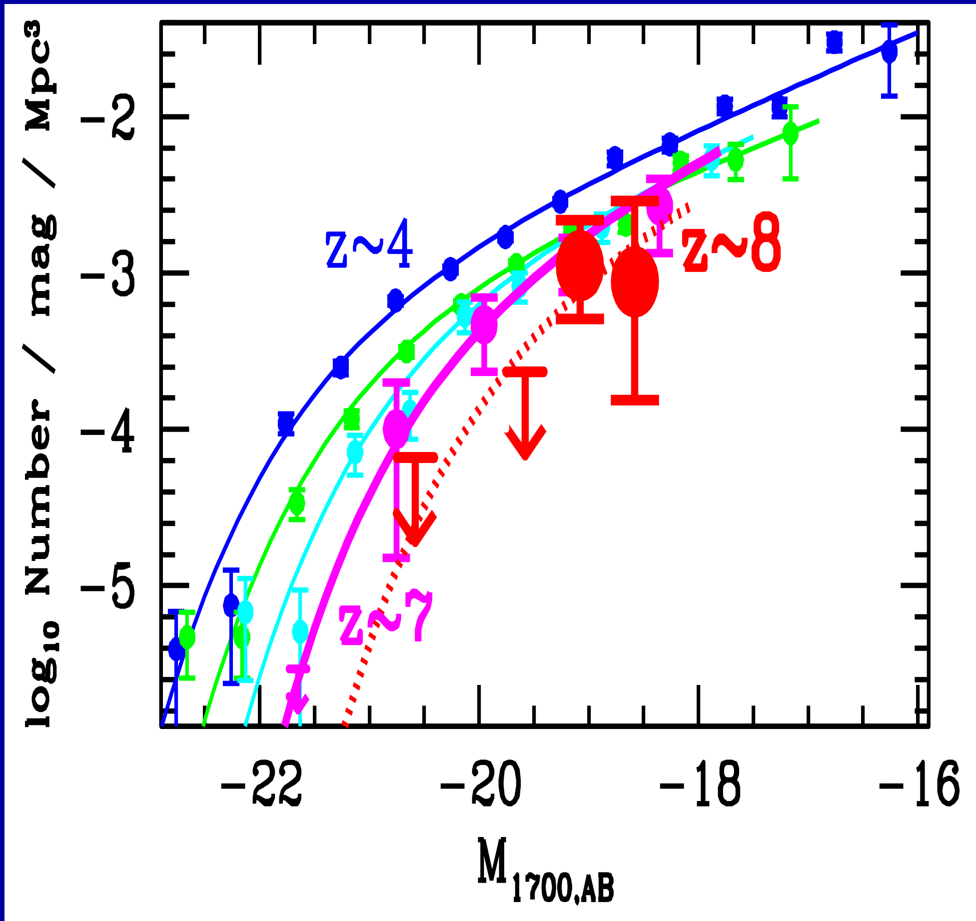
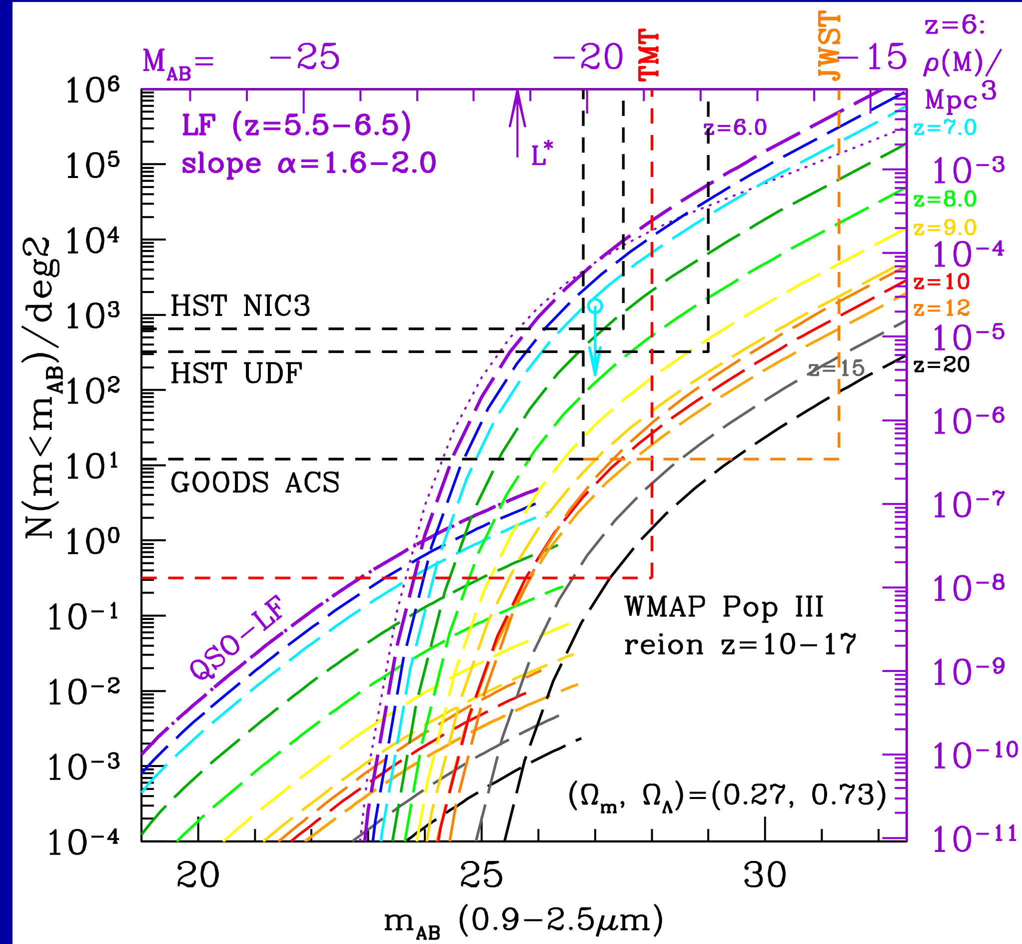


In an HUDF^3 volume at z$\simeq$2–6:

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

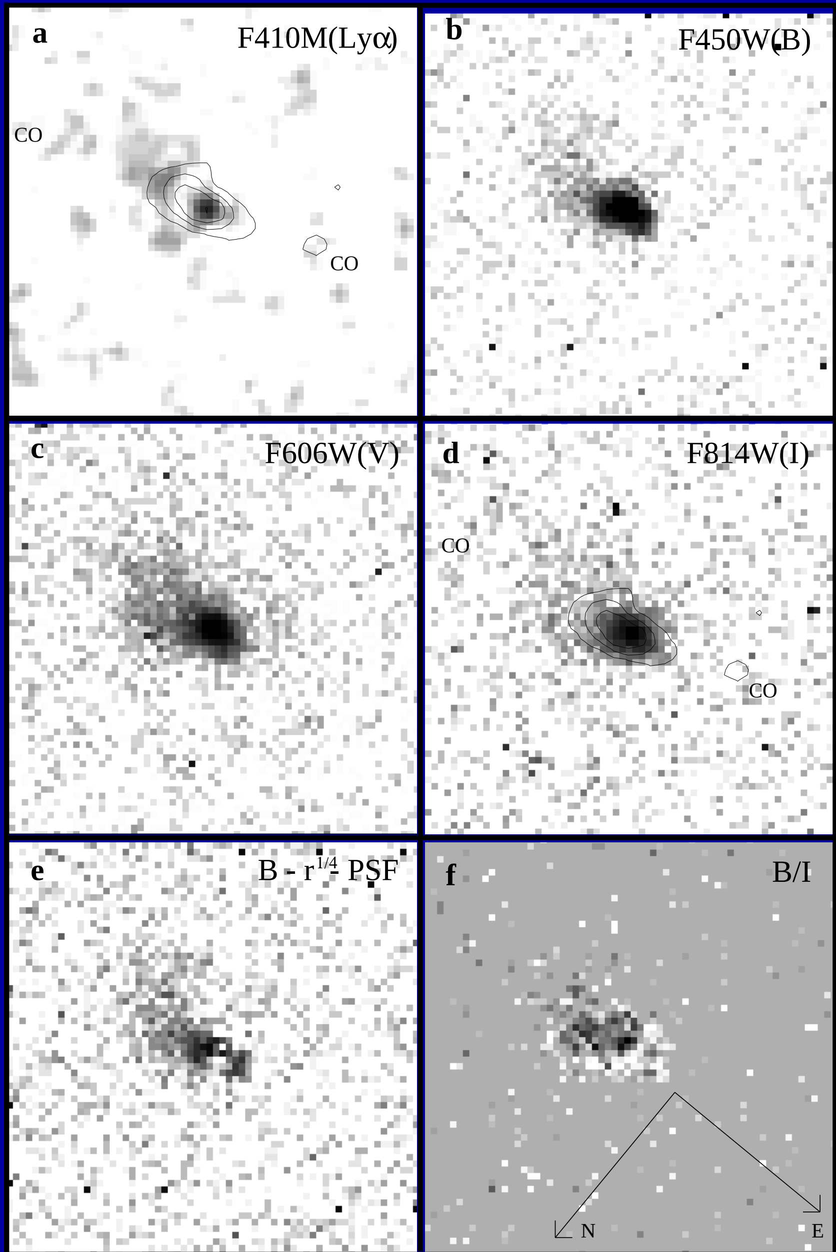
M$^*_{gxys}$ $\sim$ 2$\times$10$^{10-11}$ $M_\odot$, M$_{SMBH}$ $\sim$ 4$\times$10$^{7-8}$ $M_\odot$.

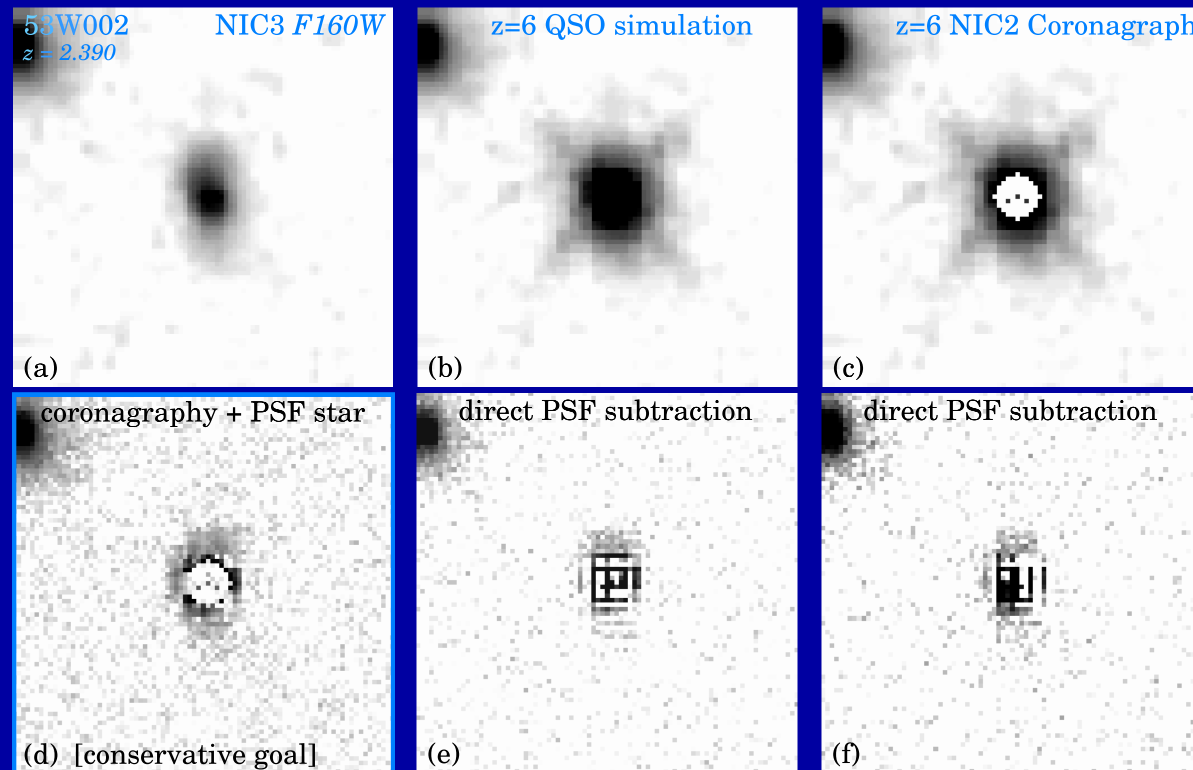




- Objects at $z \gtrsim 9$ are rare (Bouwens^{+} 2010, Yan^{+} 2010), since volume element is small and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ-range (0.7-29 μm).
- With proper survey strategy (area AND depth), JWST can trace the entire reionization 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.

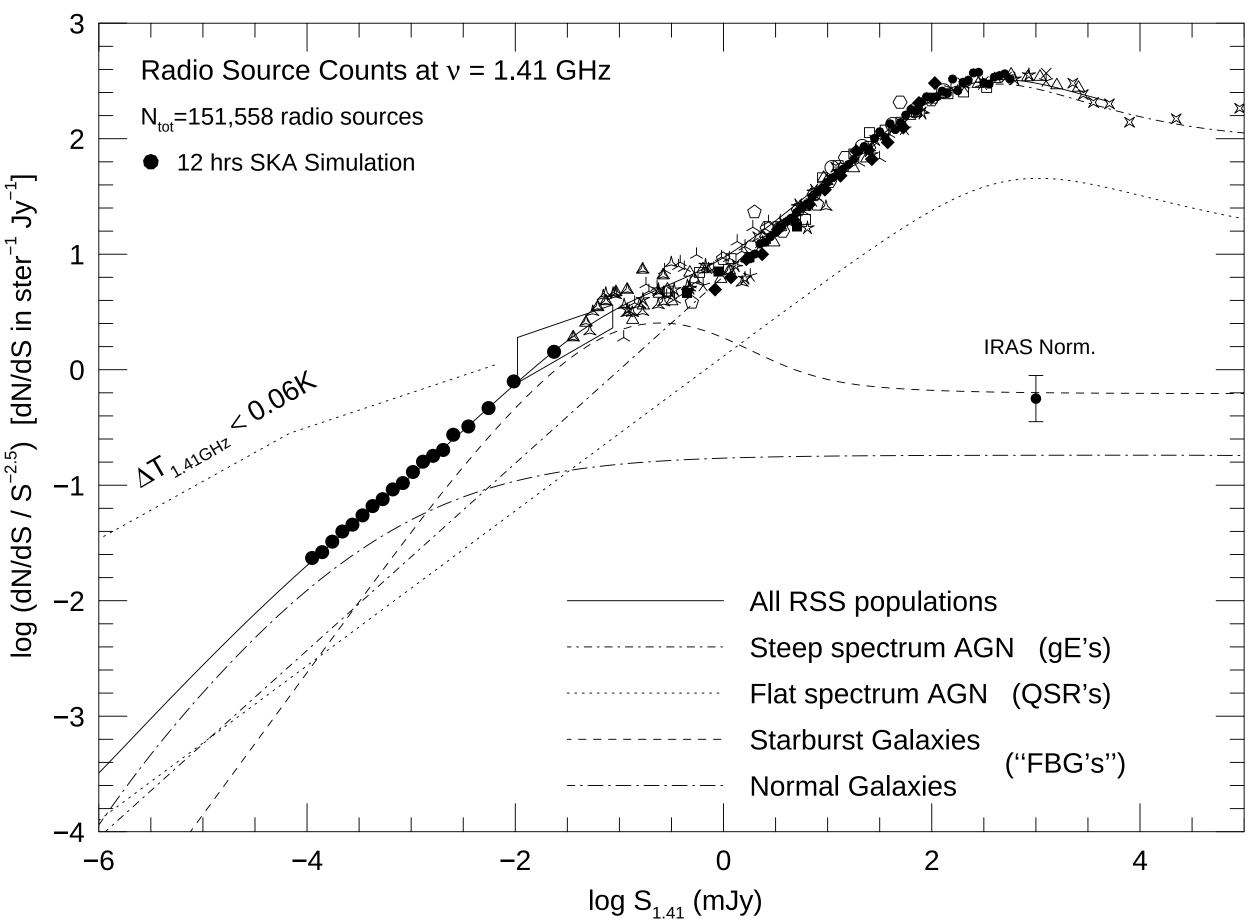
(Left): HST/PC of radio galaxy 53W002 at z=2.39 (Windhorst et al. 1998): rest-UV $r^{1/4}$-law + Lyα & Cont AGN-cloud.

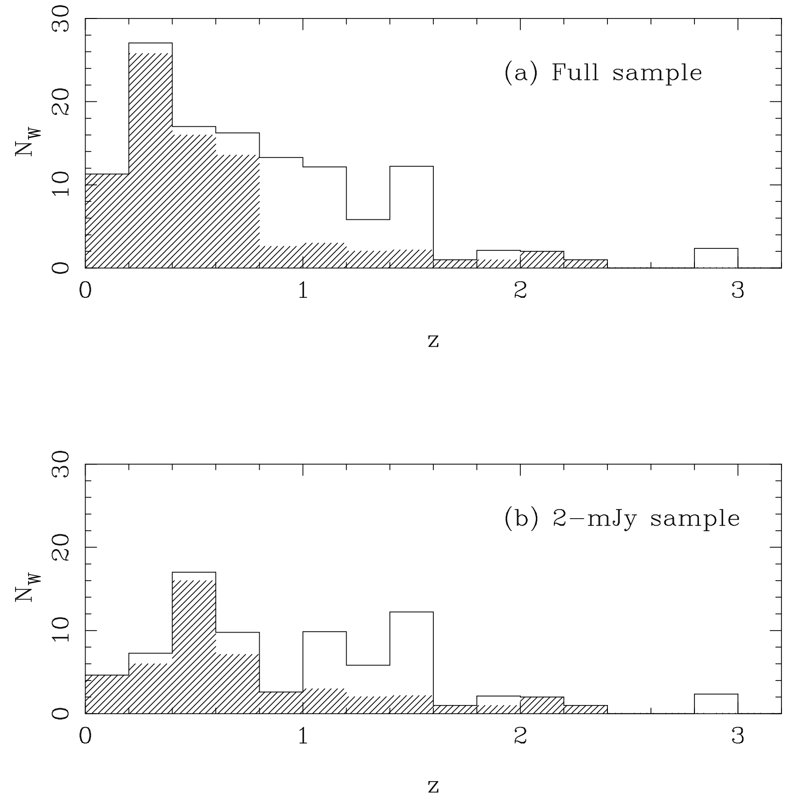




Coronagraph simulation of z=6 SDSS QSO host (using HST/NIC2+Corona). Can measure $>L^*$ AGN-host at z$\gtrsim$6.

- 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.

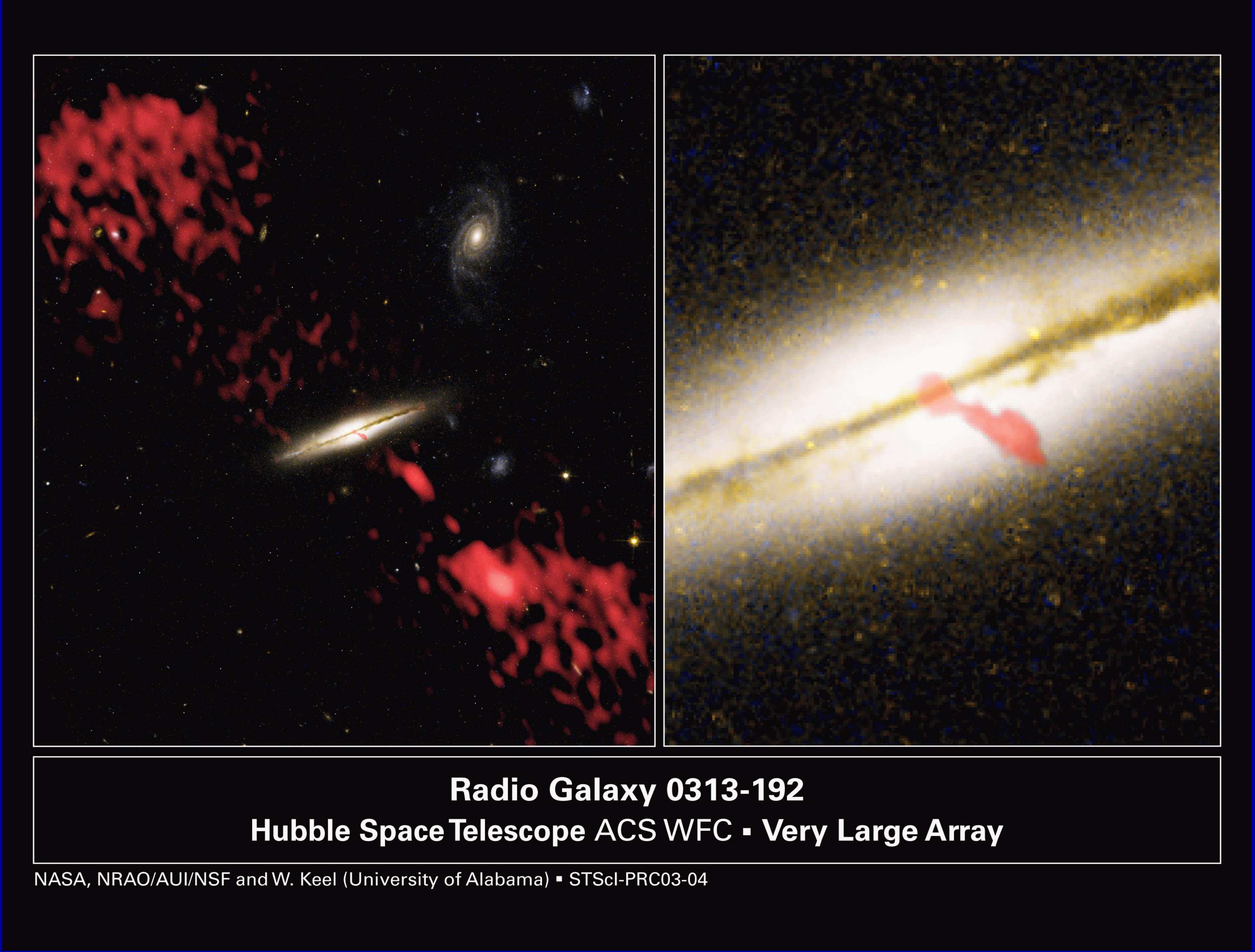




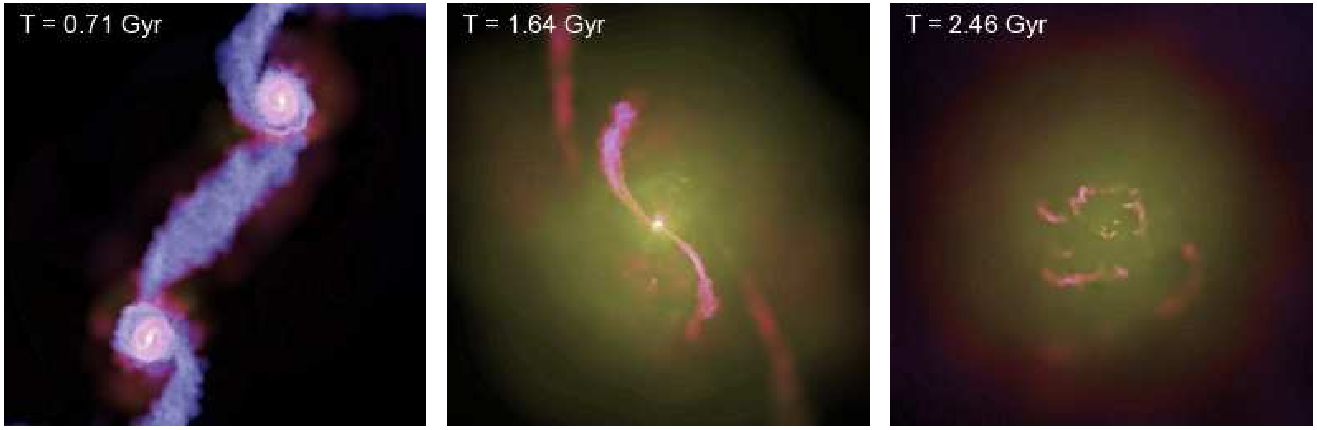
(LEFT) 1.41 GHz source counts (Windhorst et al. 1993, 2003; Hopkins et al. 2000) from 100 Jy to 100 nJy: AGN (monsters) dominate $\gtrsim$1 mJy, starbursts below 1 mJy [12-hr SKA simulation below 10 μJy].

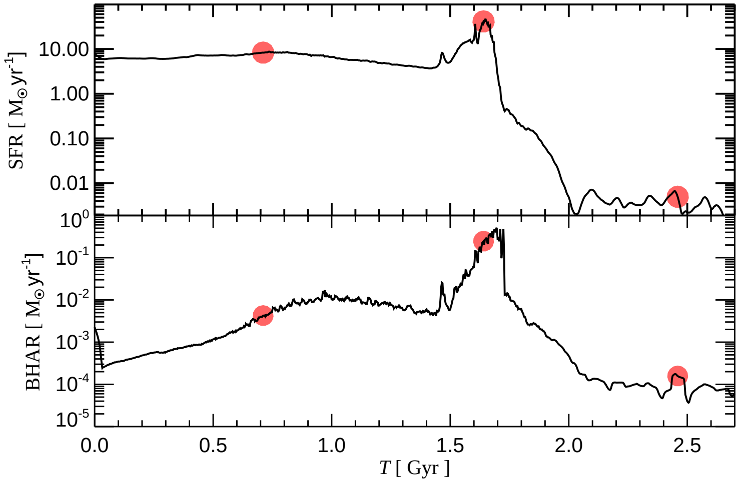
(RIGHT) Redshift distribution of mJy radio sources (Waddington^{+} 2001):

- 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!



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



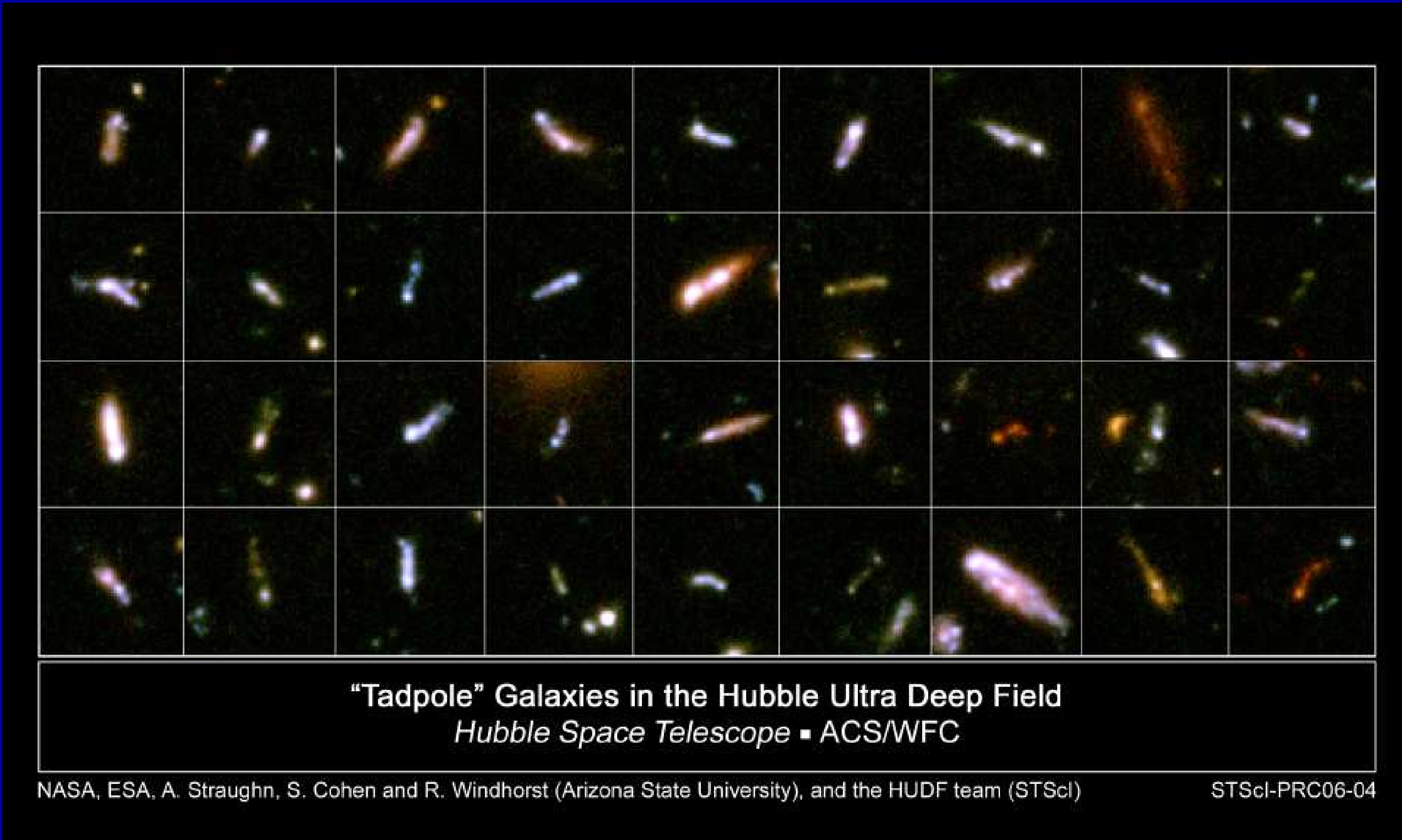


• [LEFT] Simulated merger of two disk galaxies at three different times, including the effects of SMBH growth and AGN feedback by Springel, di Matteo, Hernquist (2005, ApJ, 620, 79). Shown is the gas distribution with color indicating temperature, and brightness indicating gas density.

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

⇔ 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.

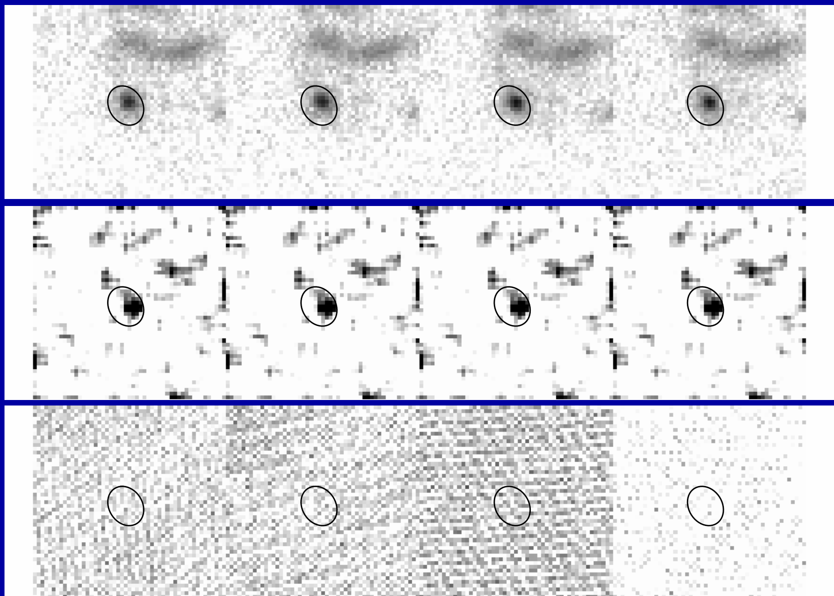
(2) A study of Early-Stage Mergers in the HUDF

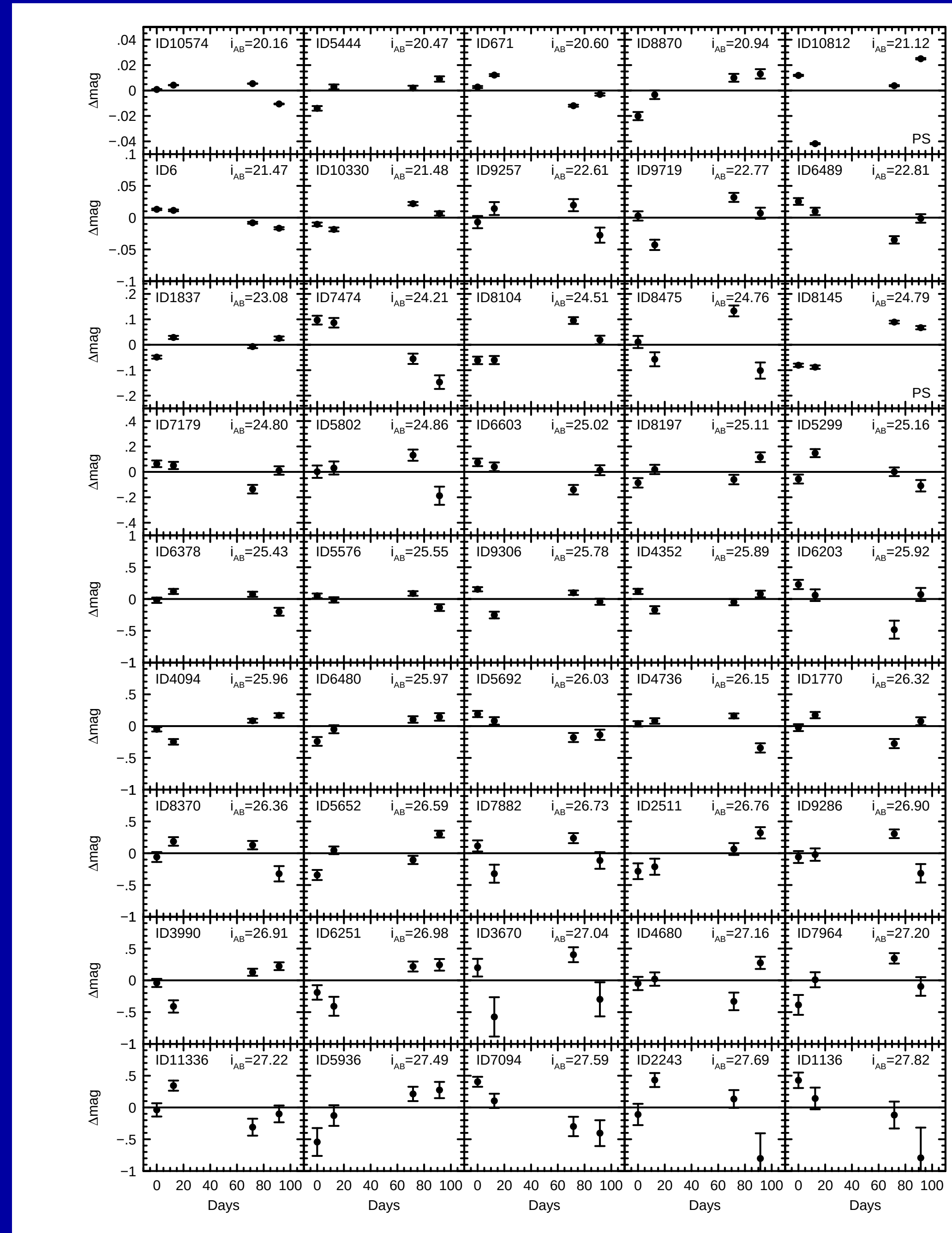


Tadpole galaxies in HUDF: www.hubblesite.org/newscenter/archive/2006/04/

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

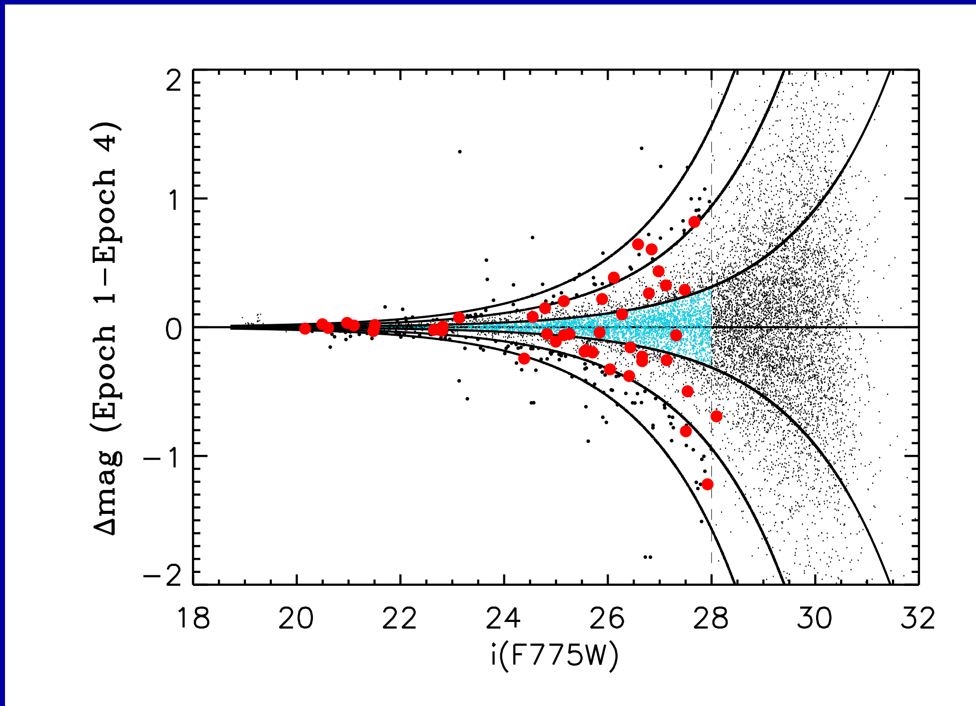
(3) Variable Objects in the HUDF

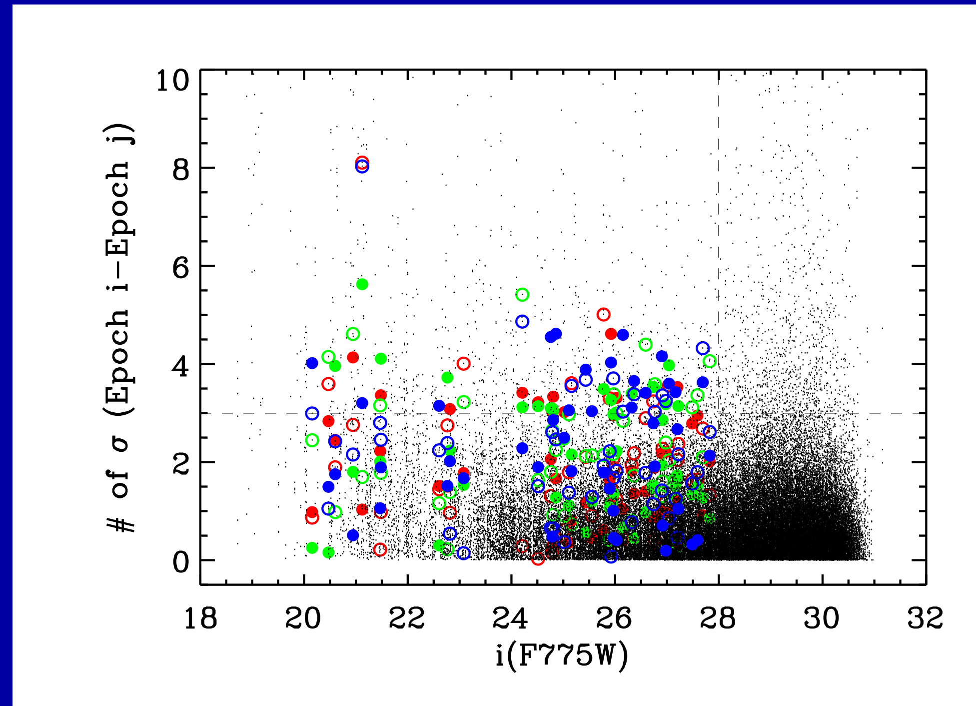




Top: 4 epochs; Middle: Variance map; Bottom: 4 Weight-maps. (Cohen, S., et al. 2006, ApJ, 639, 731; astro-ph/0511414)

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





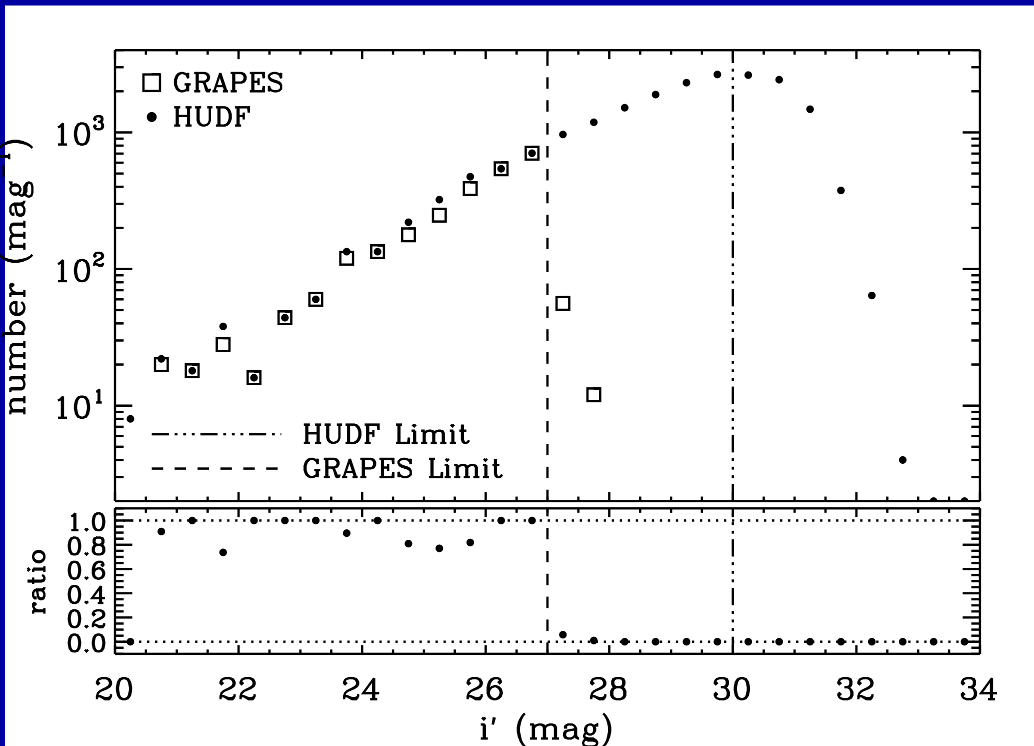
Flux ratio of all objects between two HUDF epochs ($\Delta t \simeq$few weeks–months) vs. total i-band flux. Lines are at $\pm 1.0\sigma$ (blue), $\pm 3.0\sigma$, $\pm 5.0\sigma$.

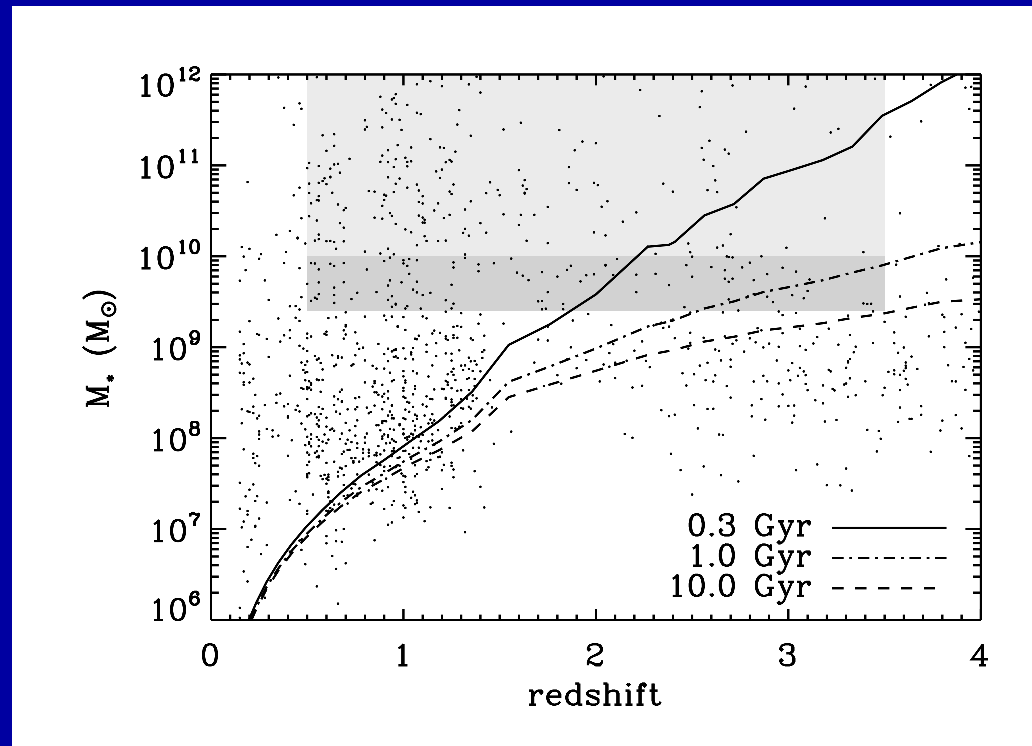
- Objects with |Delta mag|$\geq 3.0\sigma$ in $\geq$2 epoch-pairs are variable.
- 3 out of 16 Chandra sources are faint point-like objects variable at $\gtrsim 3.0\sigma$. Other Chandra sources are brighter (early-type) galaxies.

$\Rightarrow$ 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.

(4) Epoch dependent major merger rate to AB$\lesssim$27 mag.





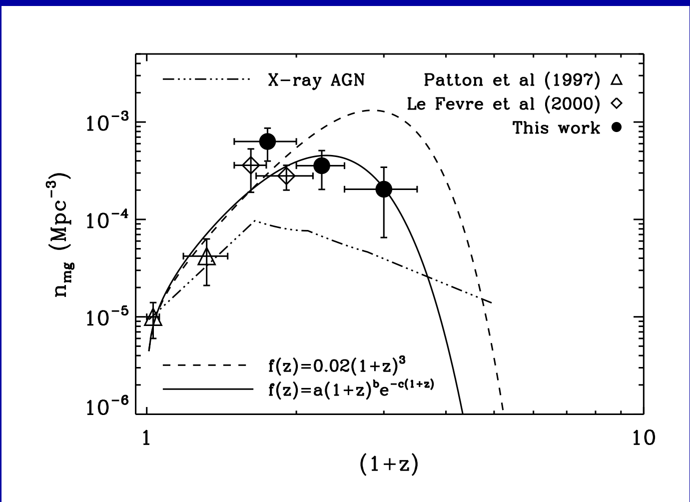
Ryan et al. (2007): HST/ACS grism pair-fraction(z) — sample selection:

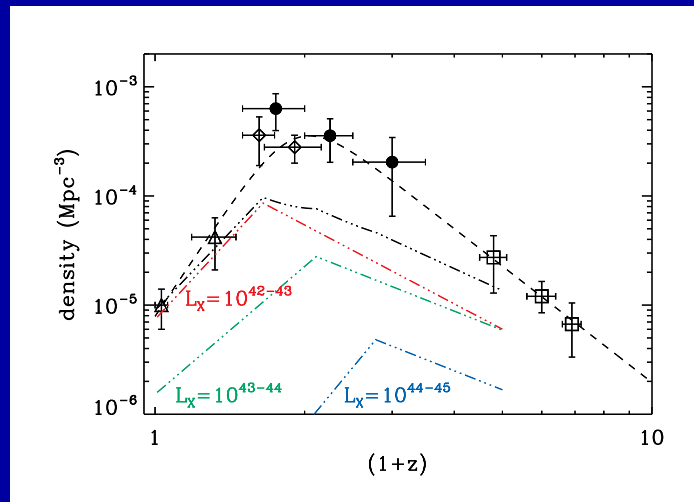
- HUDF broad-band point source completeness at i_{AB} $\lesssim$30.0 mag.
- HUDF ACS grism point source completeness at i_{AB} $\lesssim$27.0 mag.

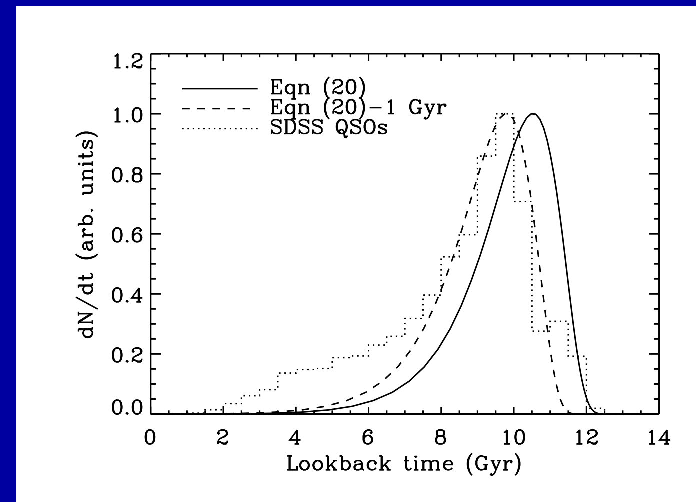
Mass completeness limit for z$\lesssim$2 from flux limits/SED fitting:

- M$\gtrsim$10$^{10.0}$ $M_\odot$ for primary galaxy mass in pair.
- M$\gtrsim$10$^{9.4}$ $M_\odot$ for secondary galaxy mass in pair (0.25$\leq$M$_2$/M$_1$$\leq$1).

(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??

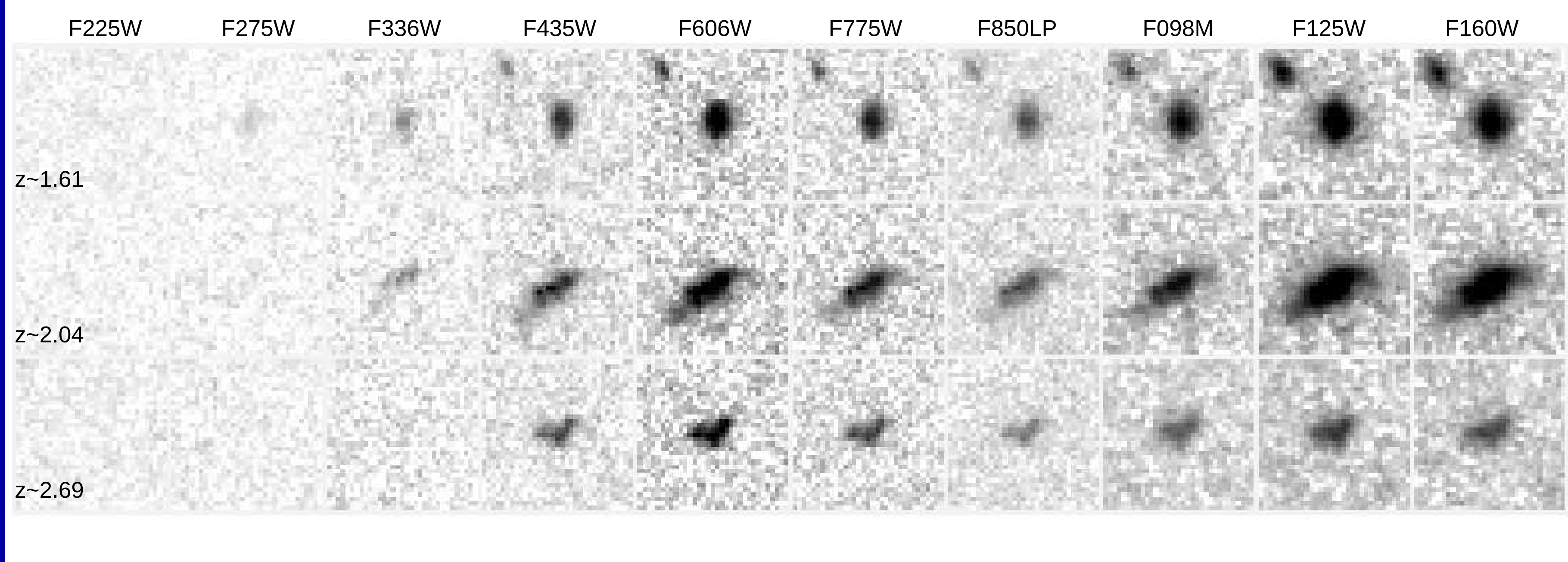
$\Rightarrow$ May support the hierarchical models: There could be a $\sim$1 Gyr delay between major mergers and visible SMBH feeding — weak AGN.

• 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.

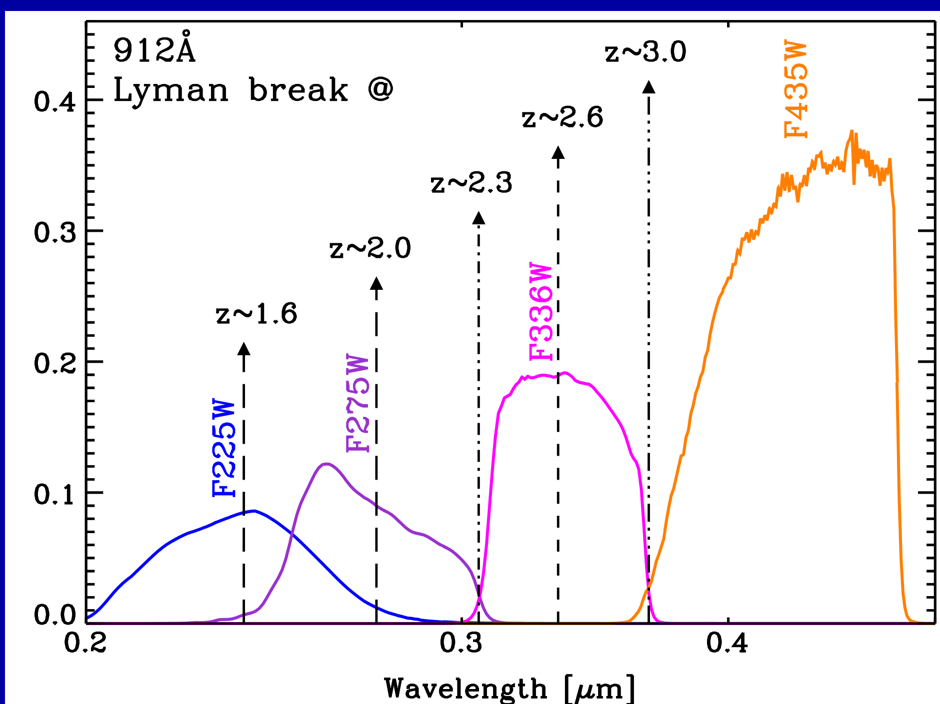
• (5) How to directly trace weak AGN growth with WFC3 and JWST

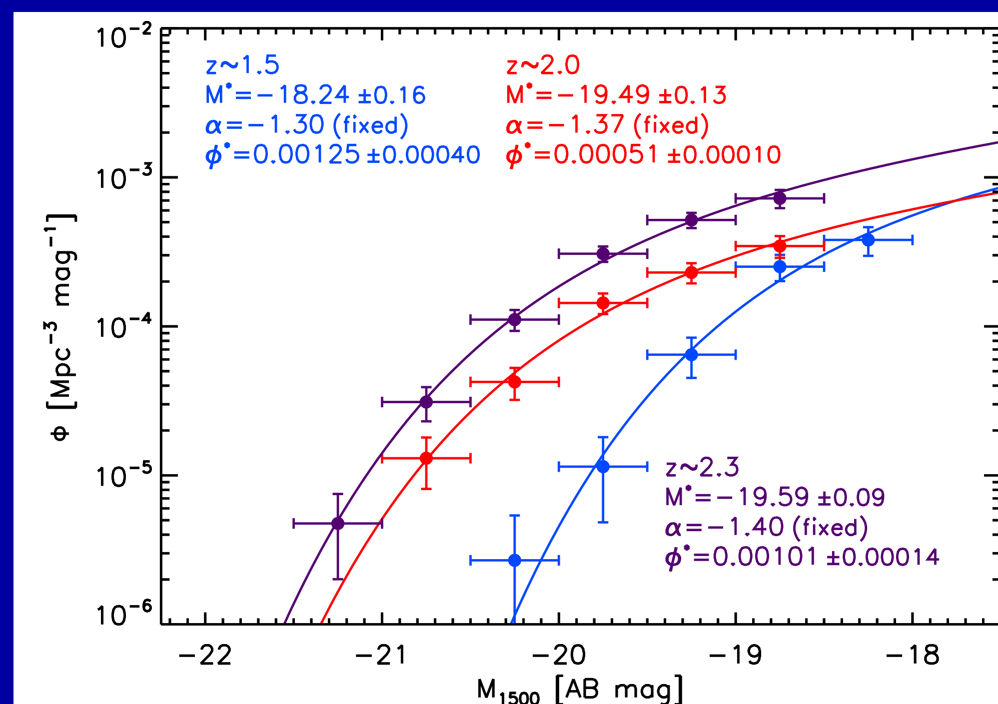
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

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.

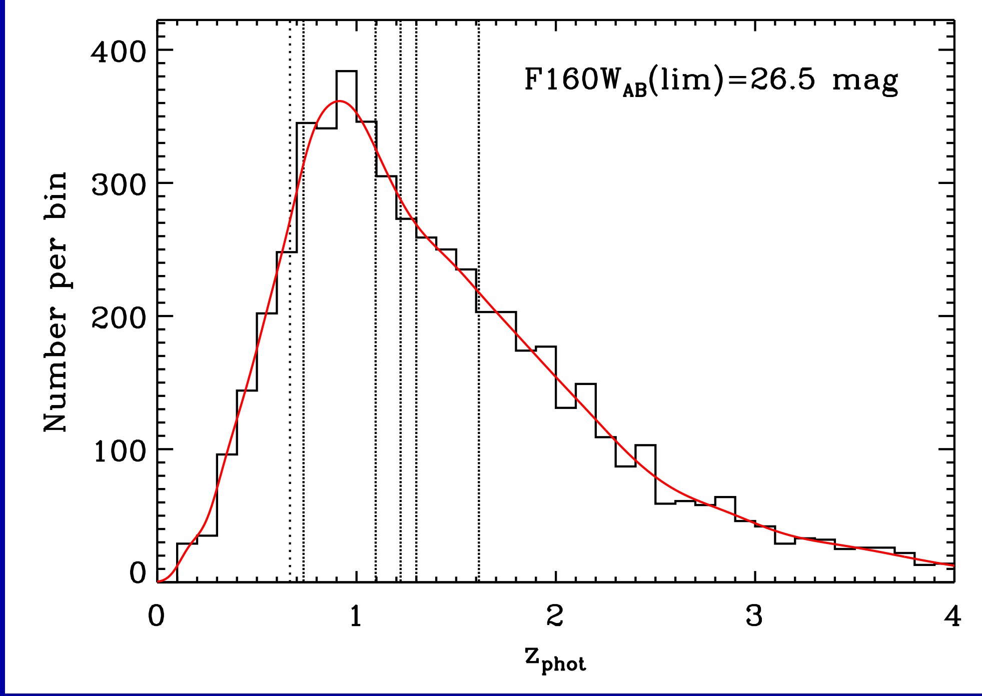


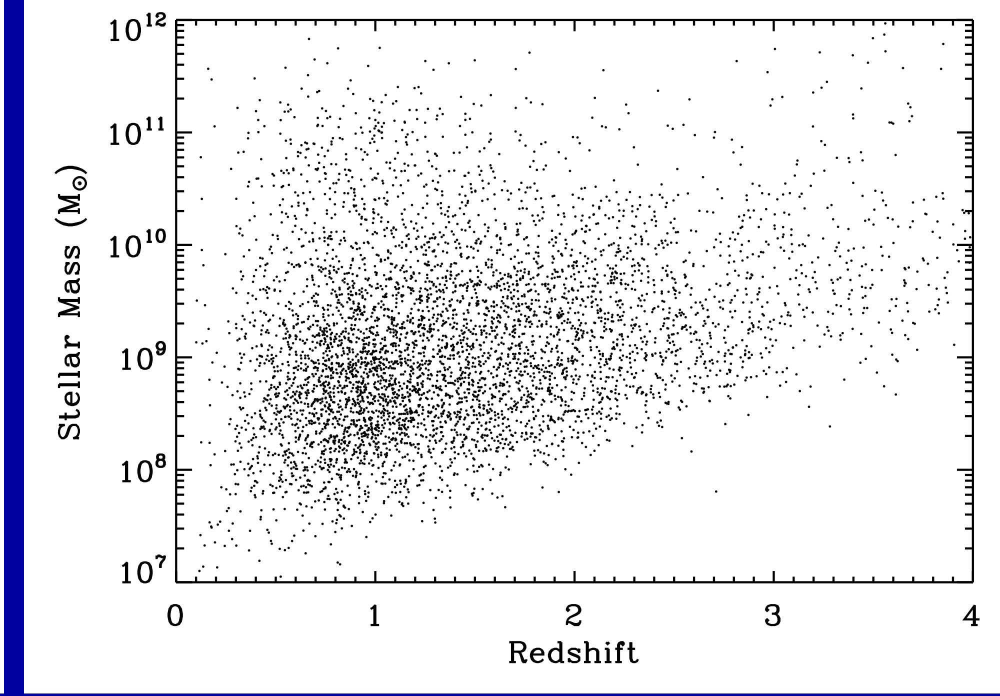
WFC3 Lyman break galaxies at the peak of cosmic SF (z≃1-3; Hathi[+] 2010)





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





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.

- The HUDF (Illingworth's talk) shows WFC3's capabilities at z≃7–9.

⇒ WFC3 is an essential pathfinder at z≲8 for JWST (0.7–29 μm) at z≳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 $S_\nu \propto \nu^\alpha$ 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 τ 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: A_V = [0, 4.0] in 0.2 mag steps (n=21).
- α=[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.

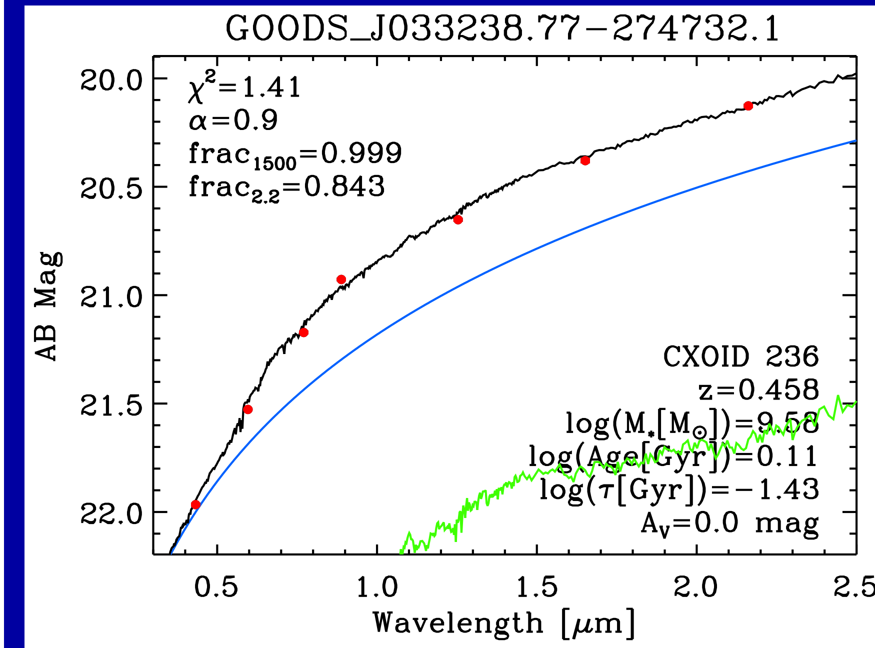
[5] Work in progress on other potential caveats:

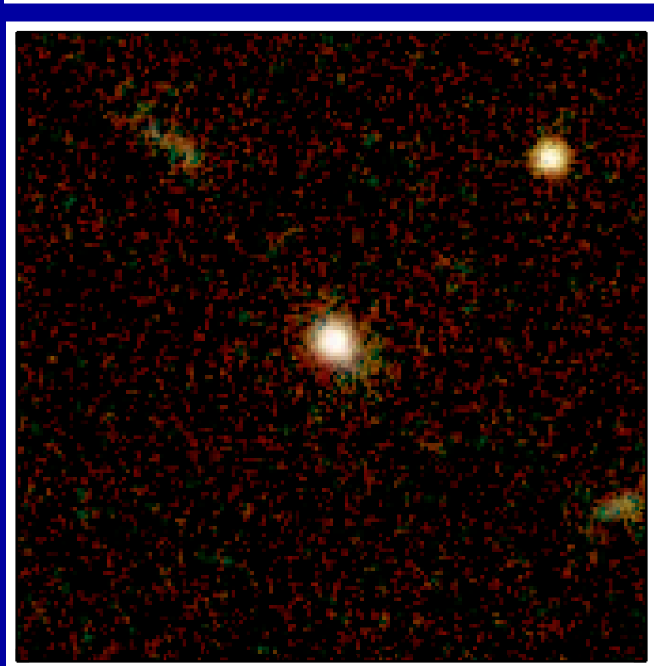
- Young stellar populations have power-law UV spectra (Hathi et al. 2008), and may overestimate UV AGN power-law.

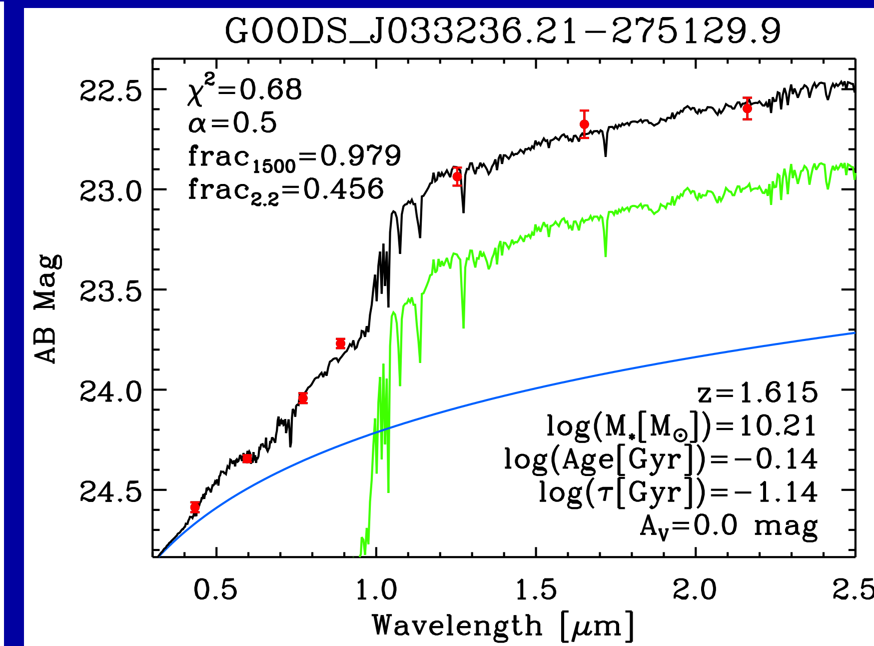
- Include IRAC data and incorporate 1–2 Gyr red AGB population.

- 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.

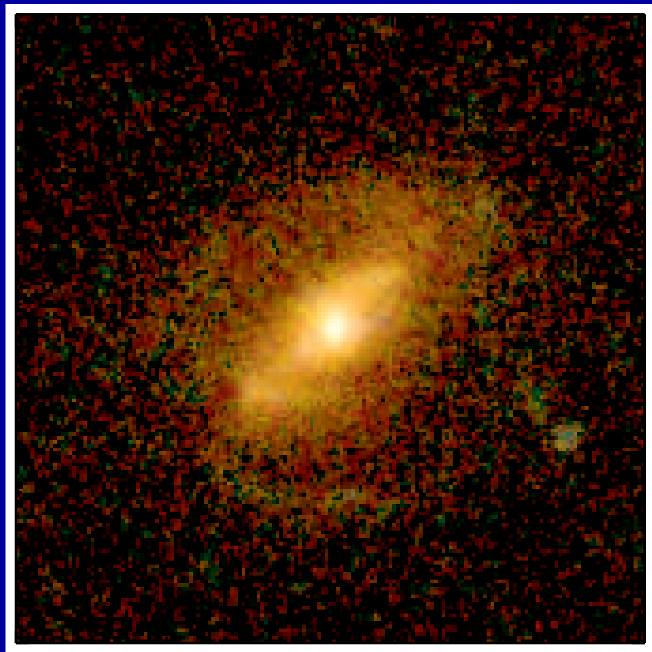


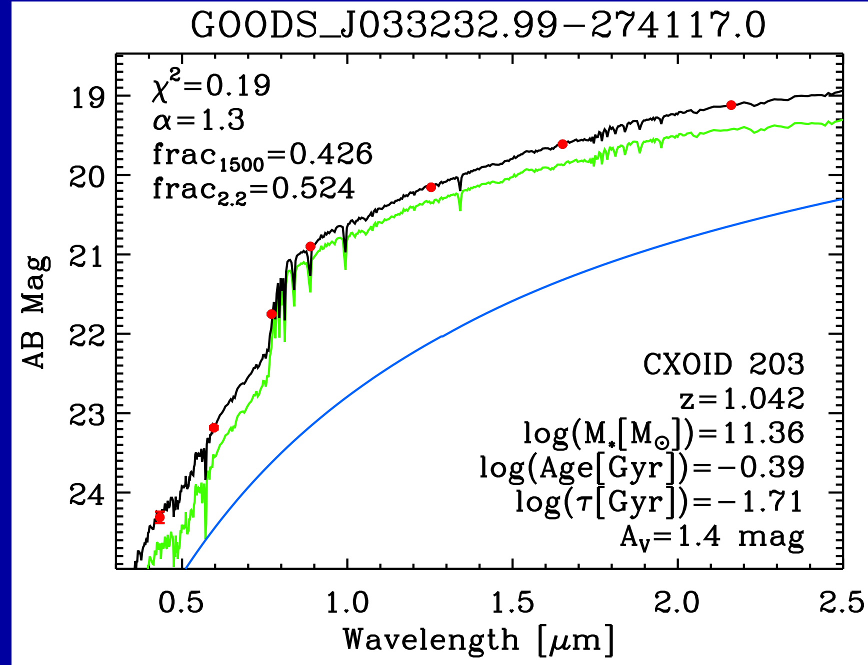


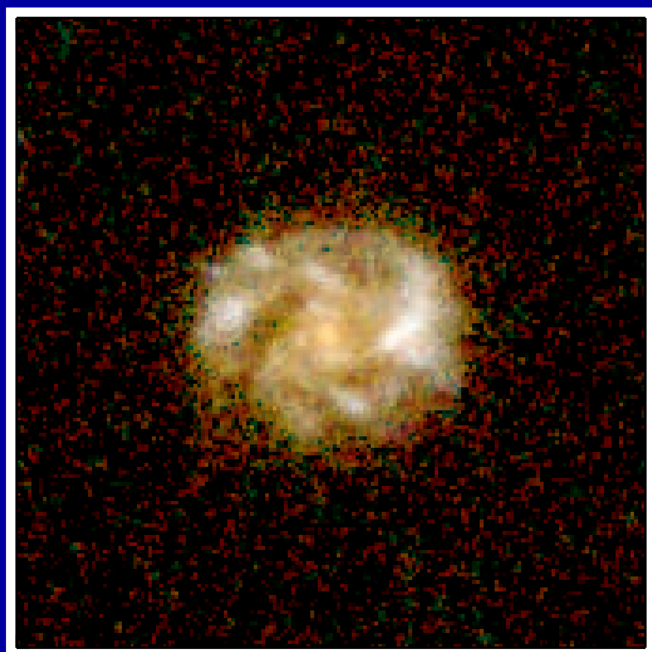


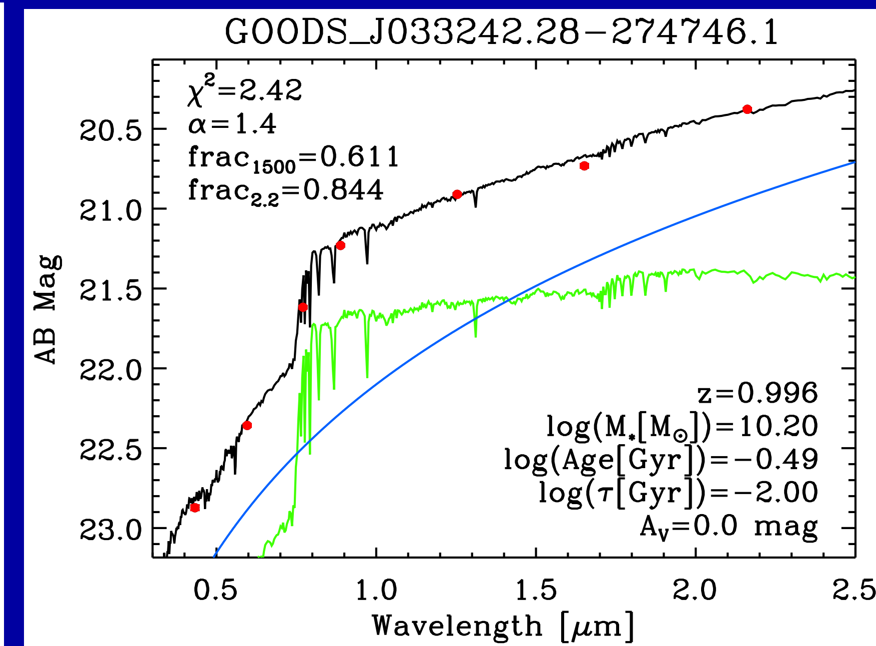
Cohen et al. (2010): GOODS/VLT BVizJHK images

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









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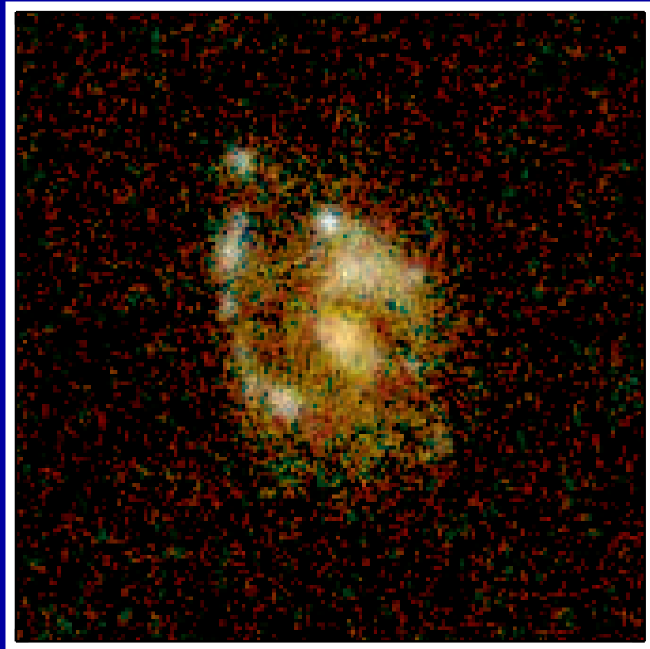

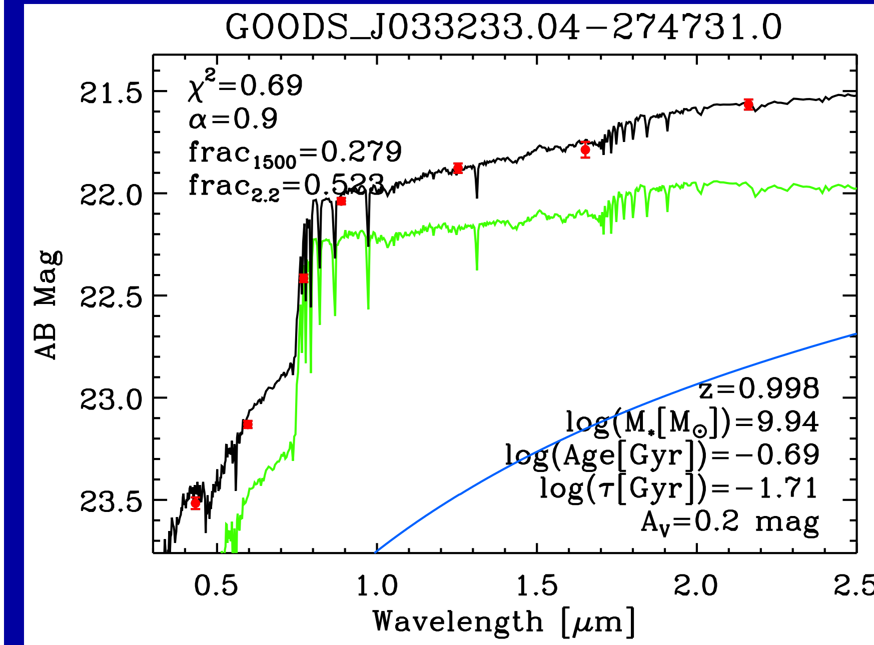

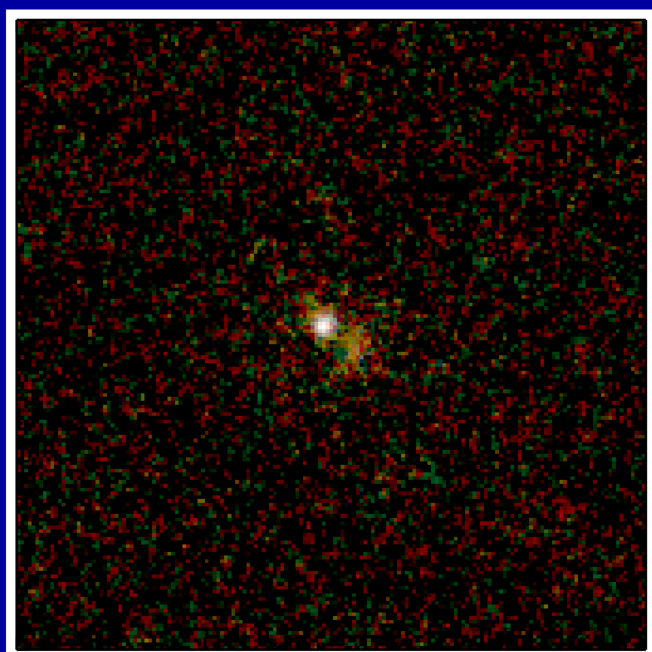

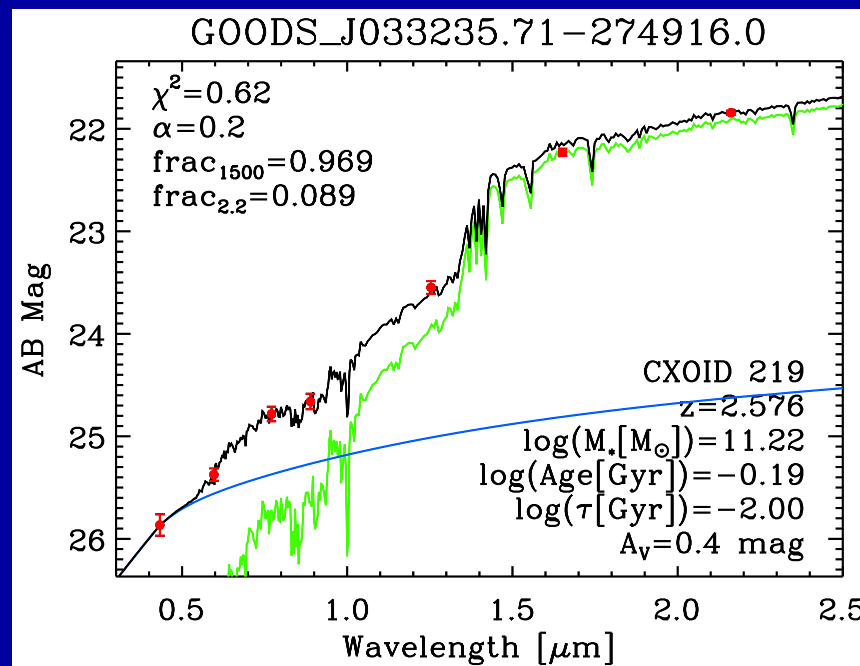

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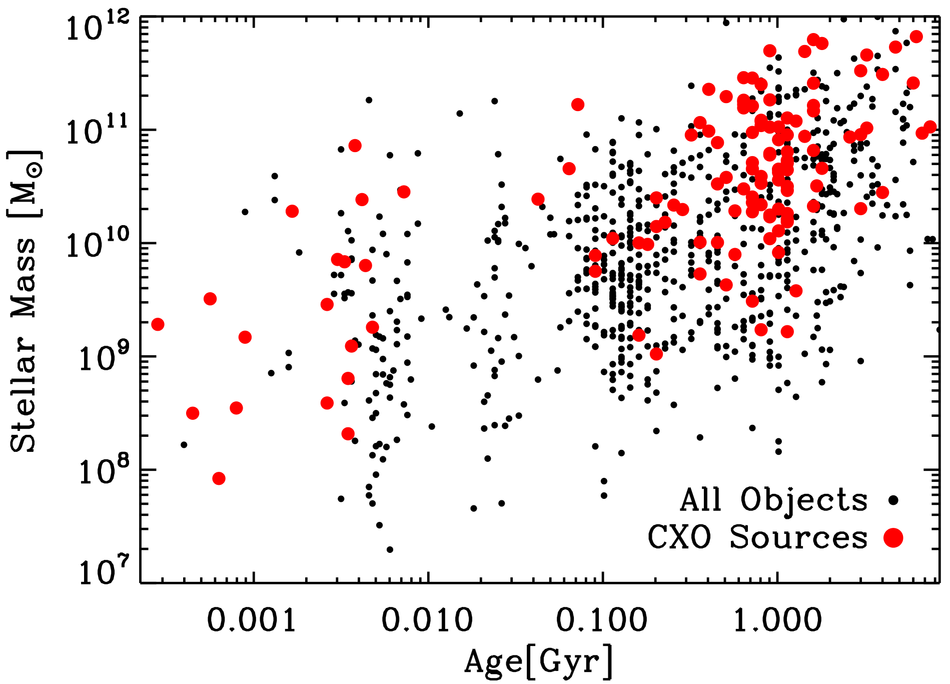
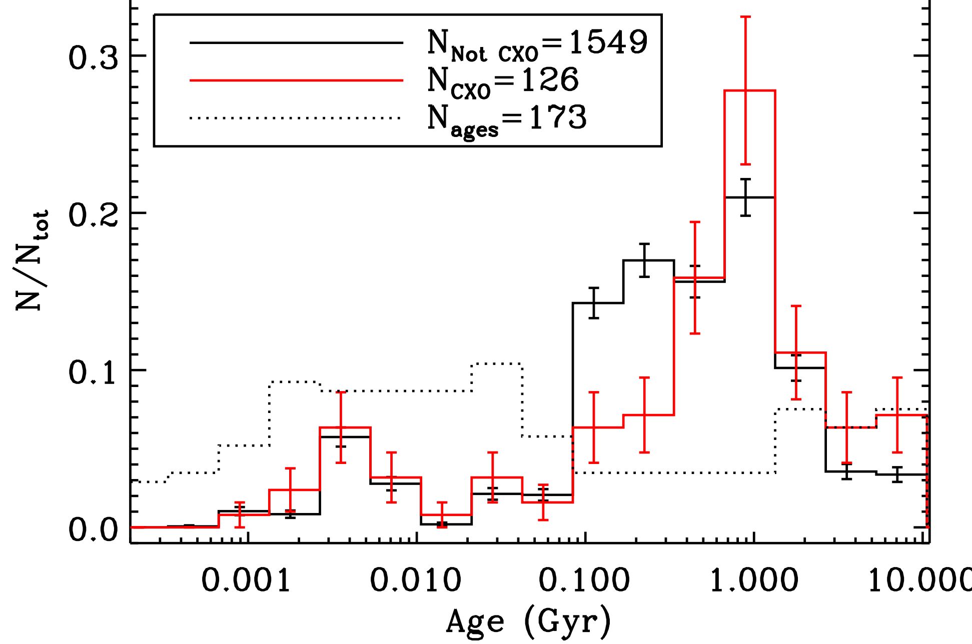




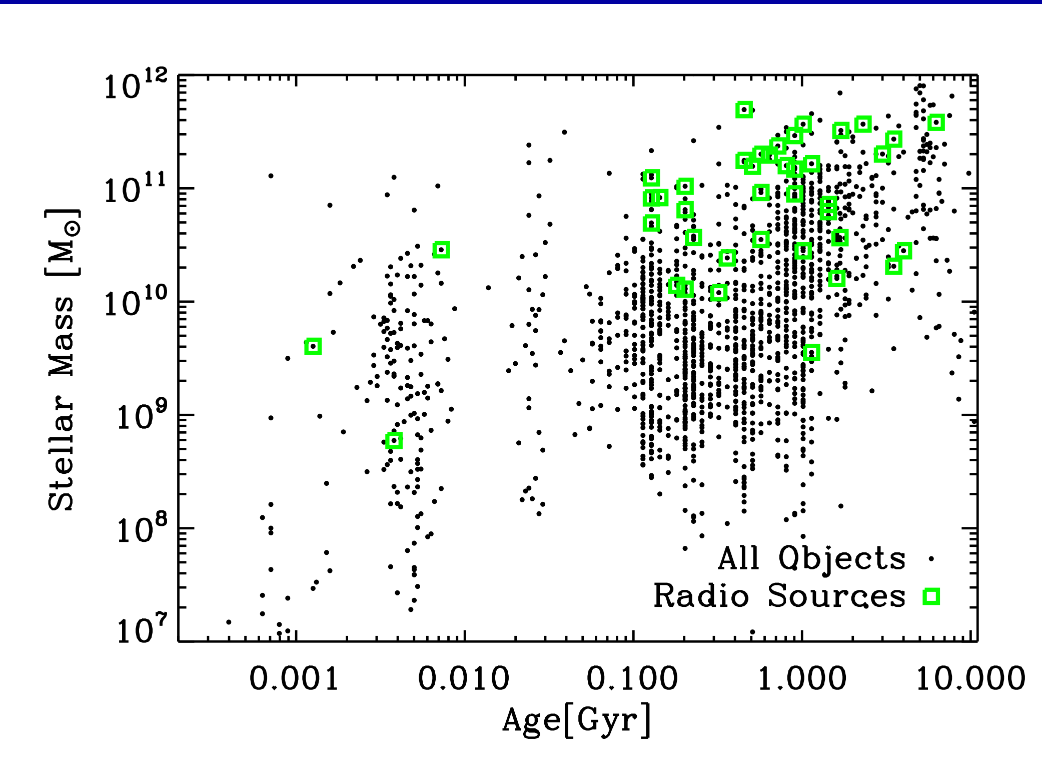
Cohen et al. (2010): Best fit Stellar Mass vs. Age: X-ray and field galaxies.

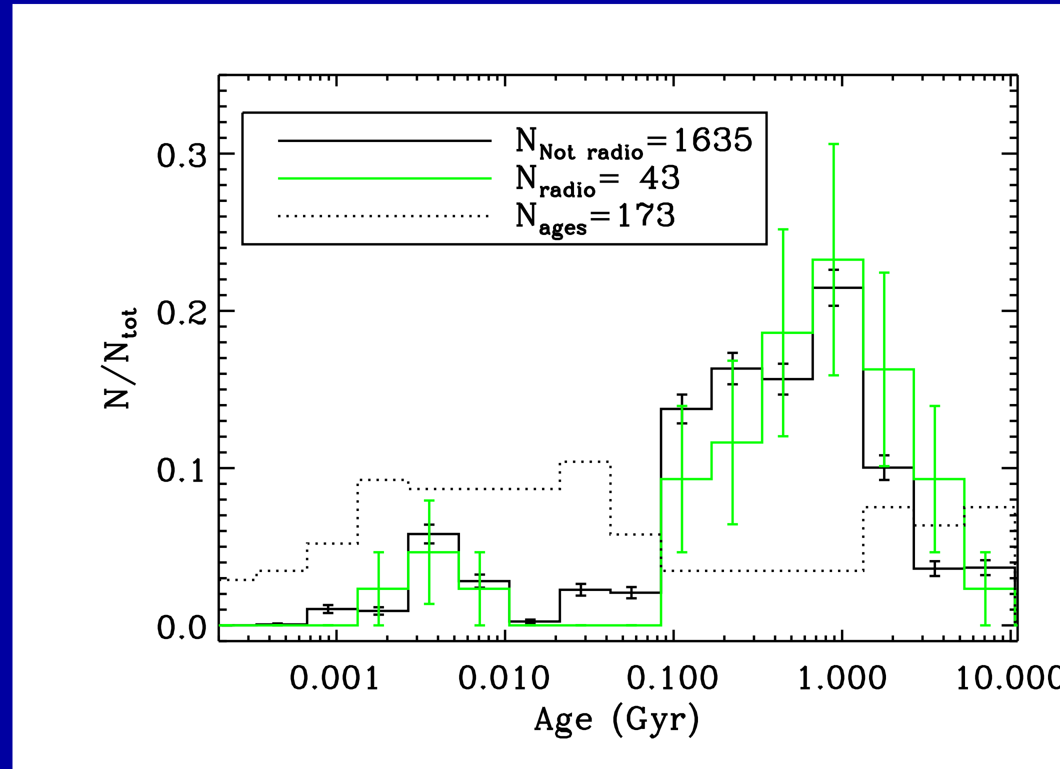
Field galaxies have: Blue cloud of ∼100-200 Myr, Red cloud of ≳1–2 Gyr.

- X-ray sources reside in galaxies that are a bit older than the general field population, but by no more than ≲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≲10.

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





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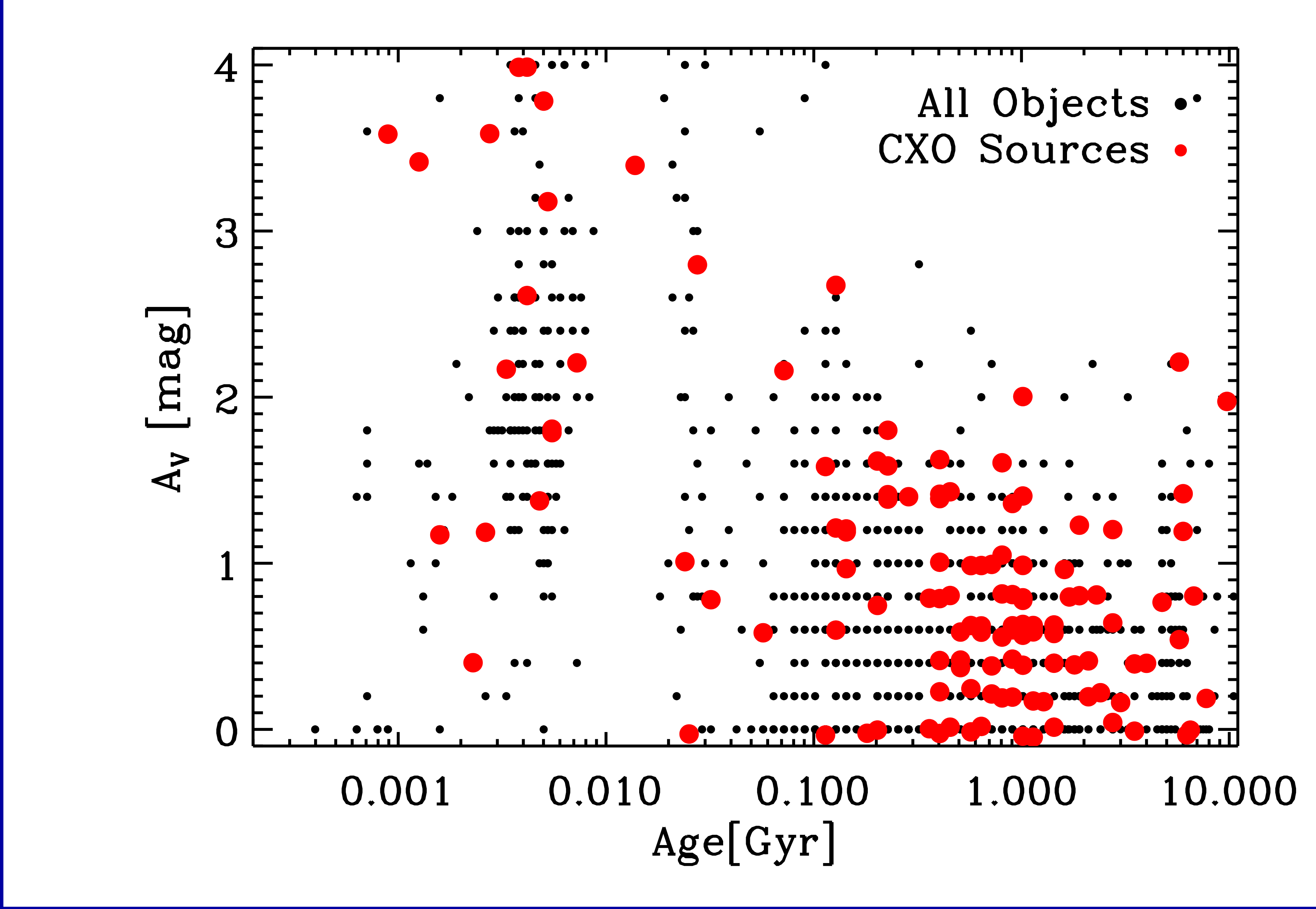
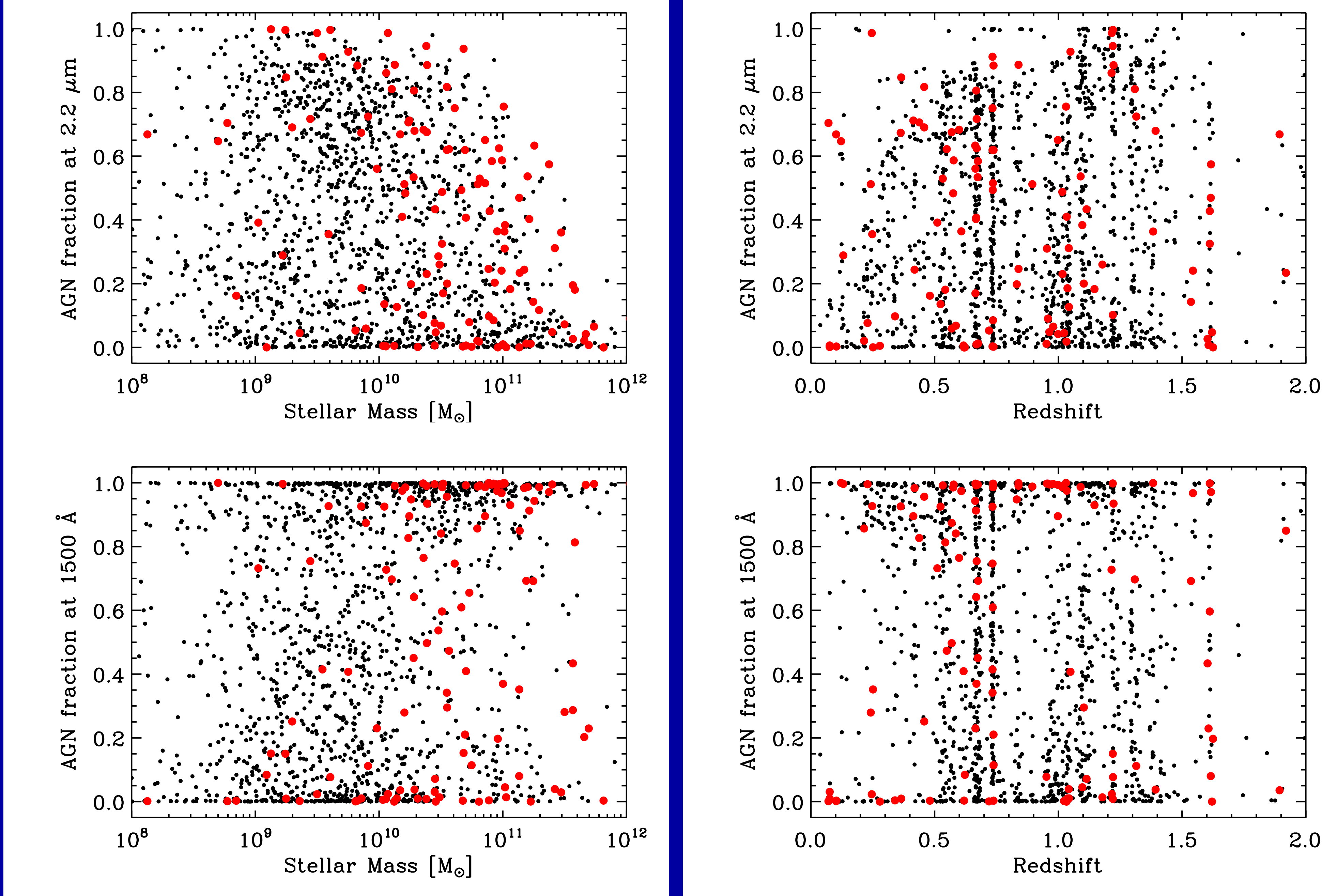


Cohen et al. (2010): Best fit extinction A_V distribution: X-ray and field.

- 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.

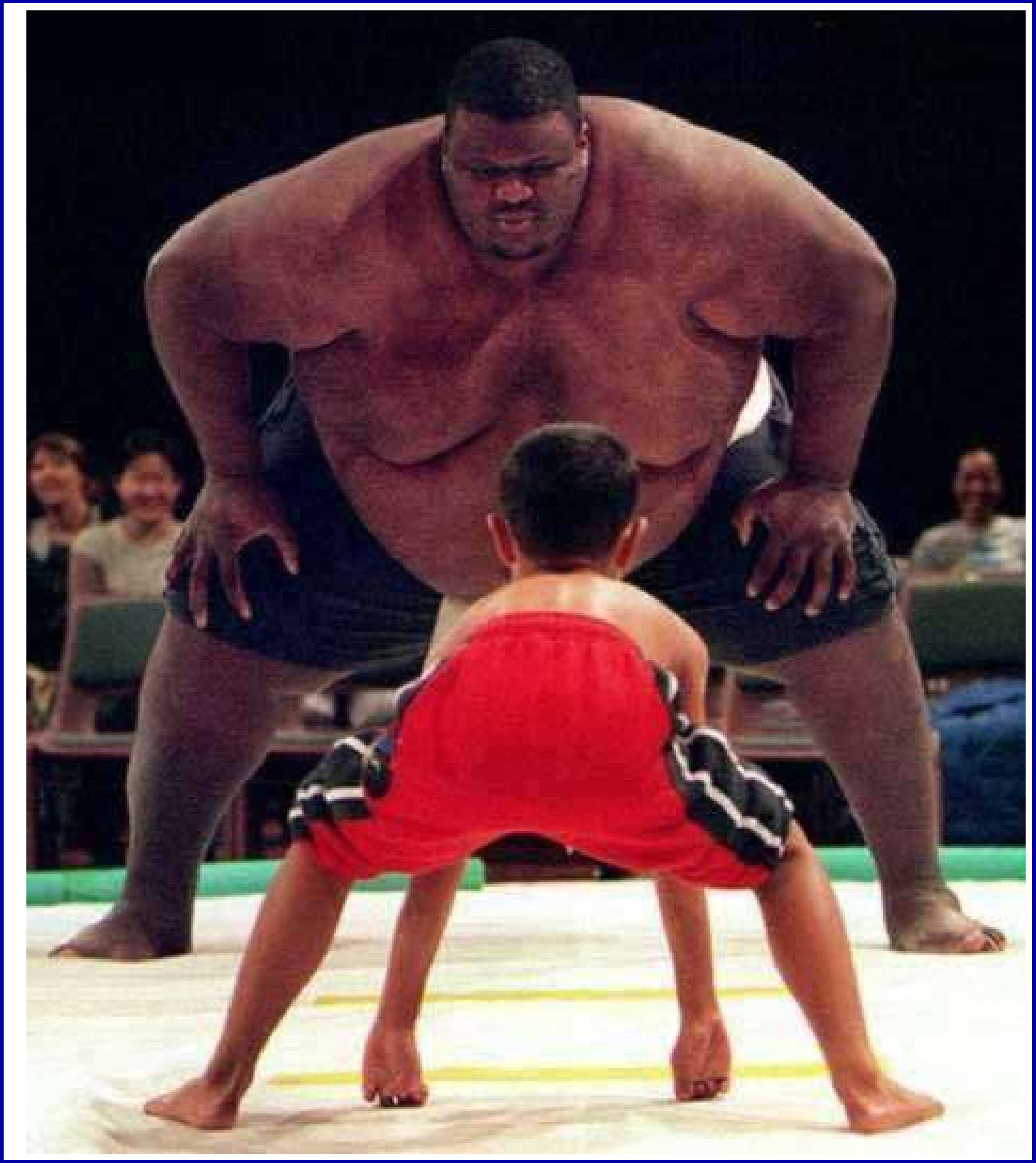
(3) Epoch dependent density of major mergers may precede peak in X-ray selected AGN $\rho(z)$, but by no more than 1–2 Gyr.

(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.

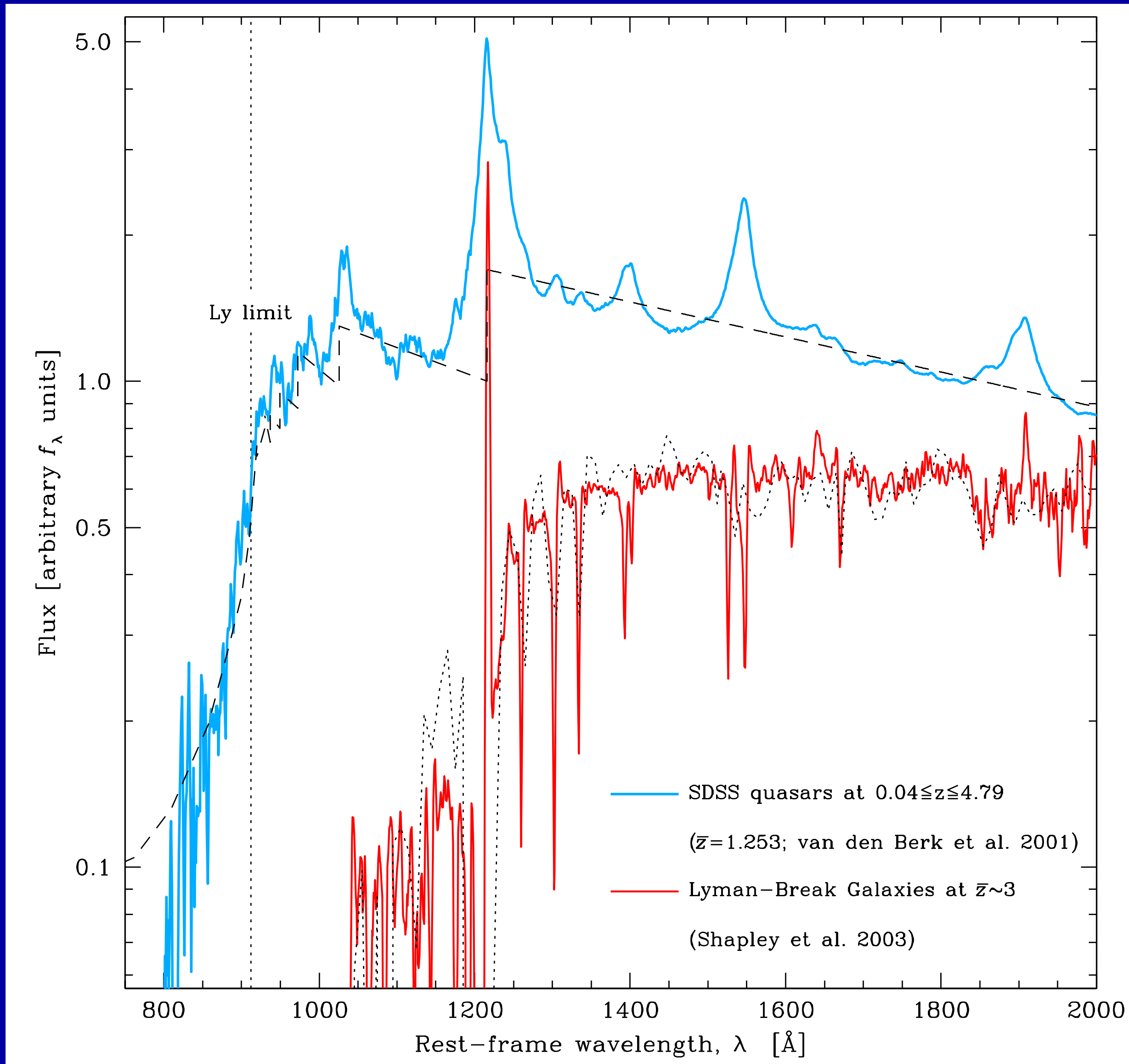
SPARE CHARTS



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

What comes around, goes around ...

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.

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

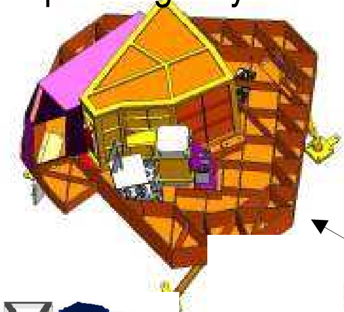
Instrument Overview

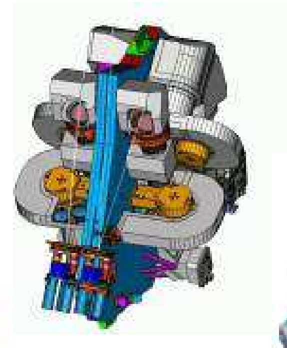
Fine Guidance Sensor (FGS)

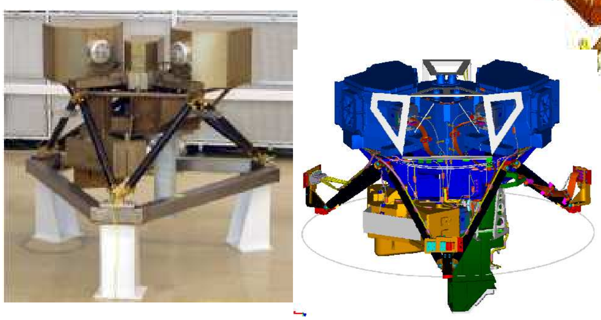
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

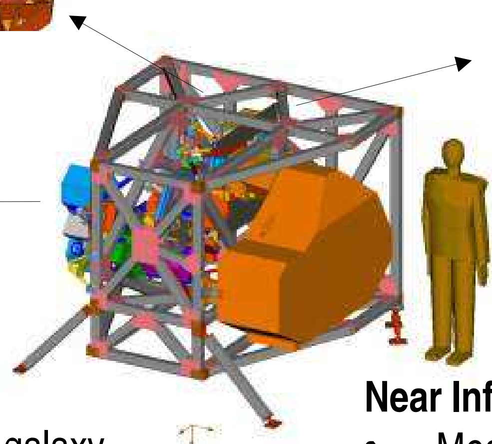
Near Infra-Red Camera (NIRCam)

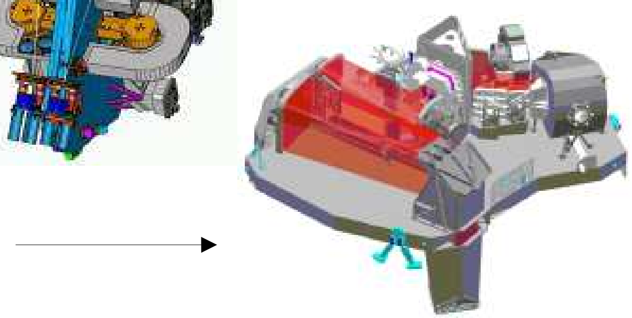
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC











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

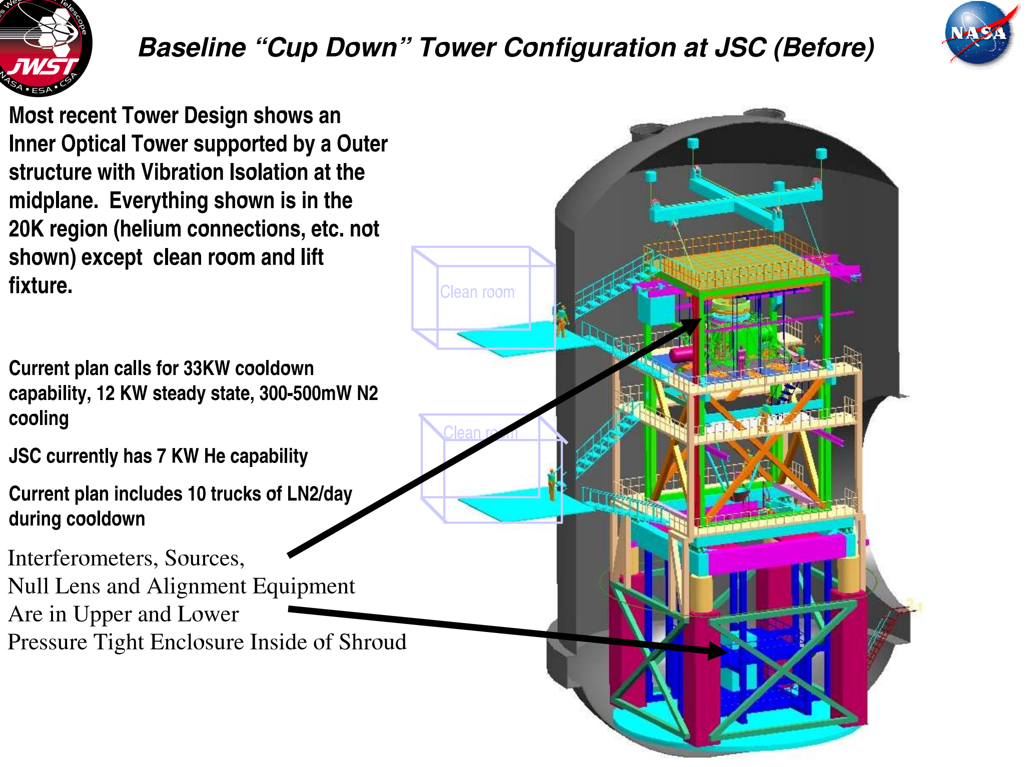
Near Infra-Red Spectrograph (NIRSpec)

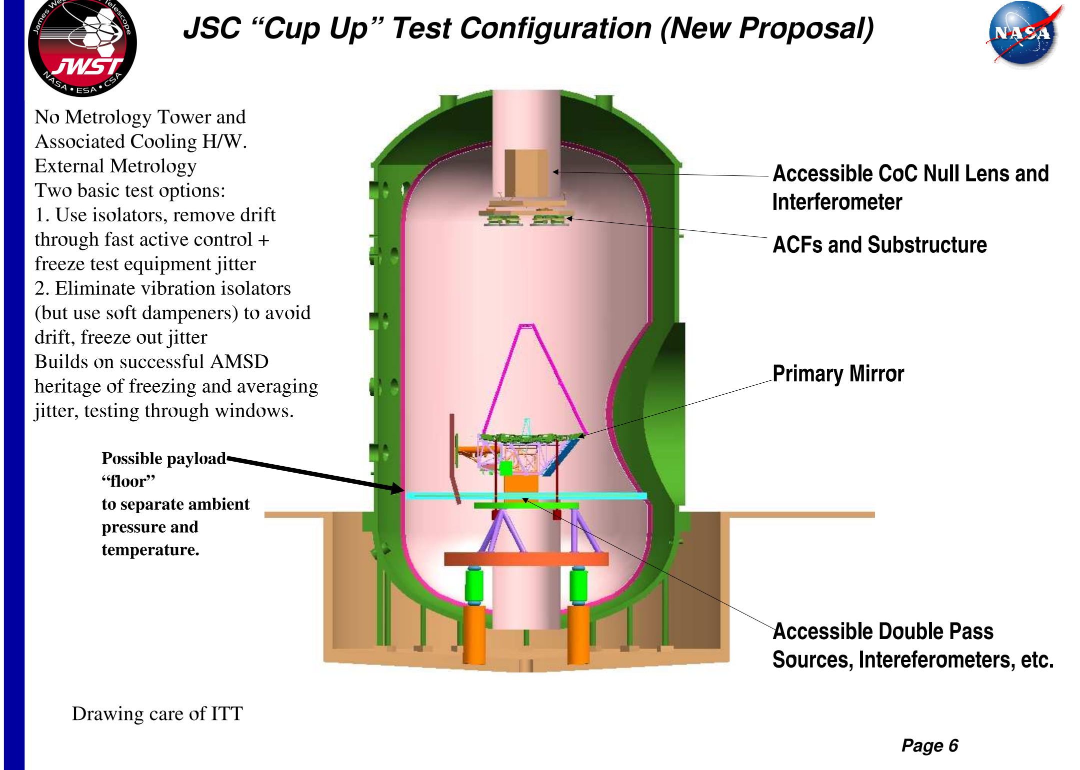
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/GSFC Detector & Microshutter Subsystems

Northrop Grumman Expertise in Space Deployable Systems

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

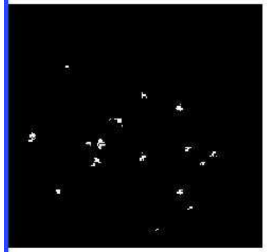
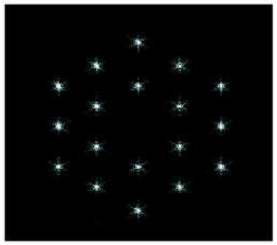
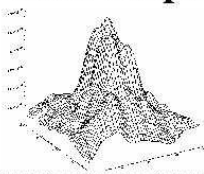






JWST underwent several significant replans and risk-reduction schemes:

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

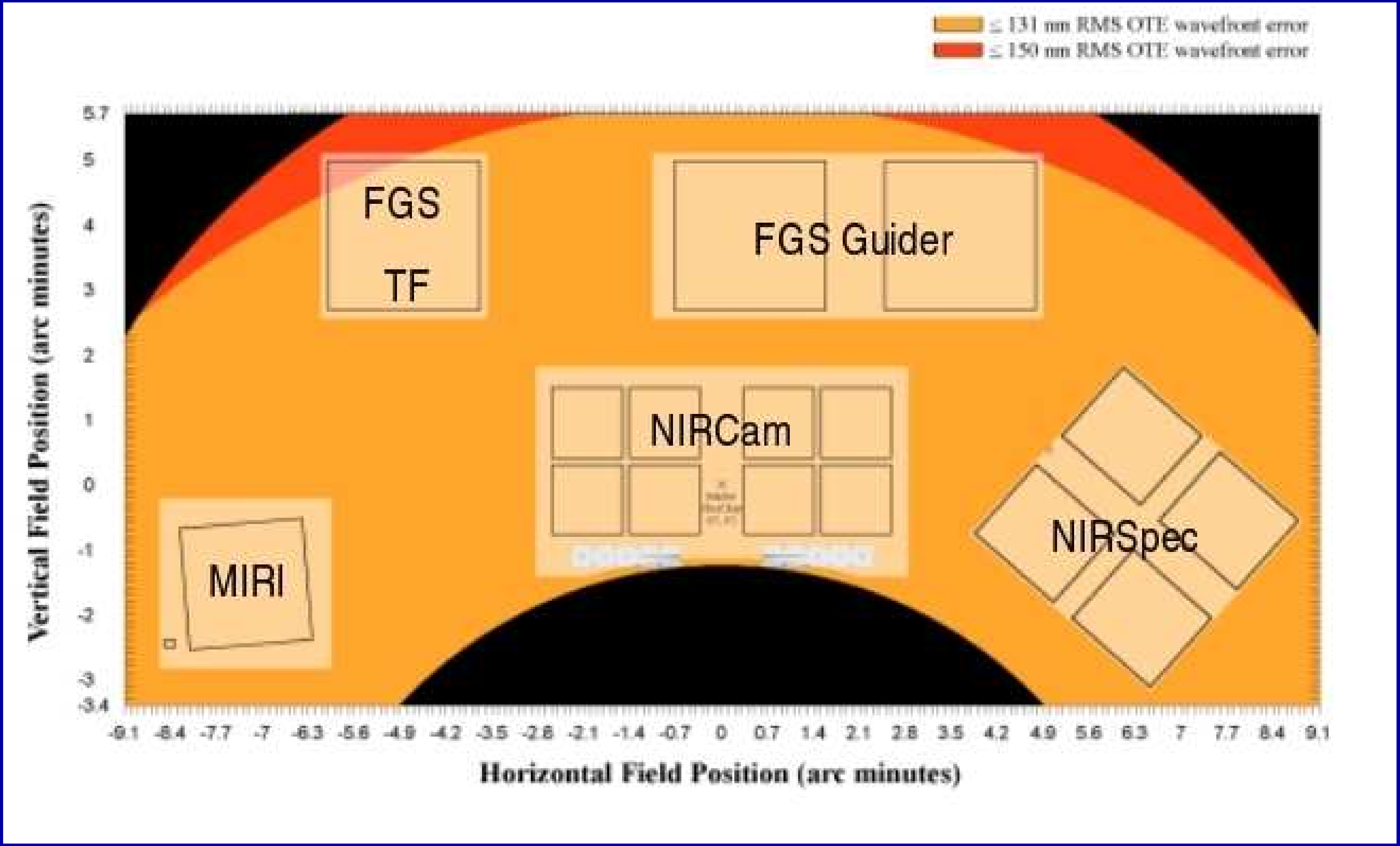
Step		Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	After Step 1 	18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 μm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
2. Coarse Alignment 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.

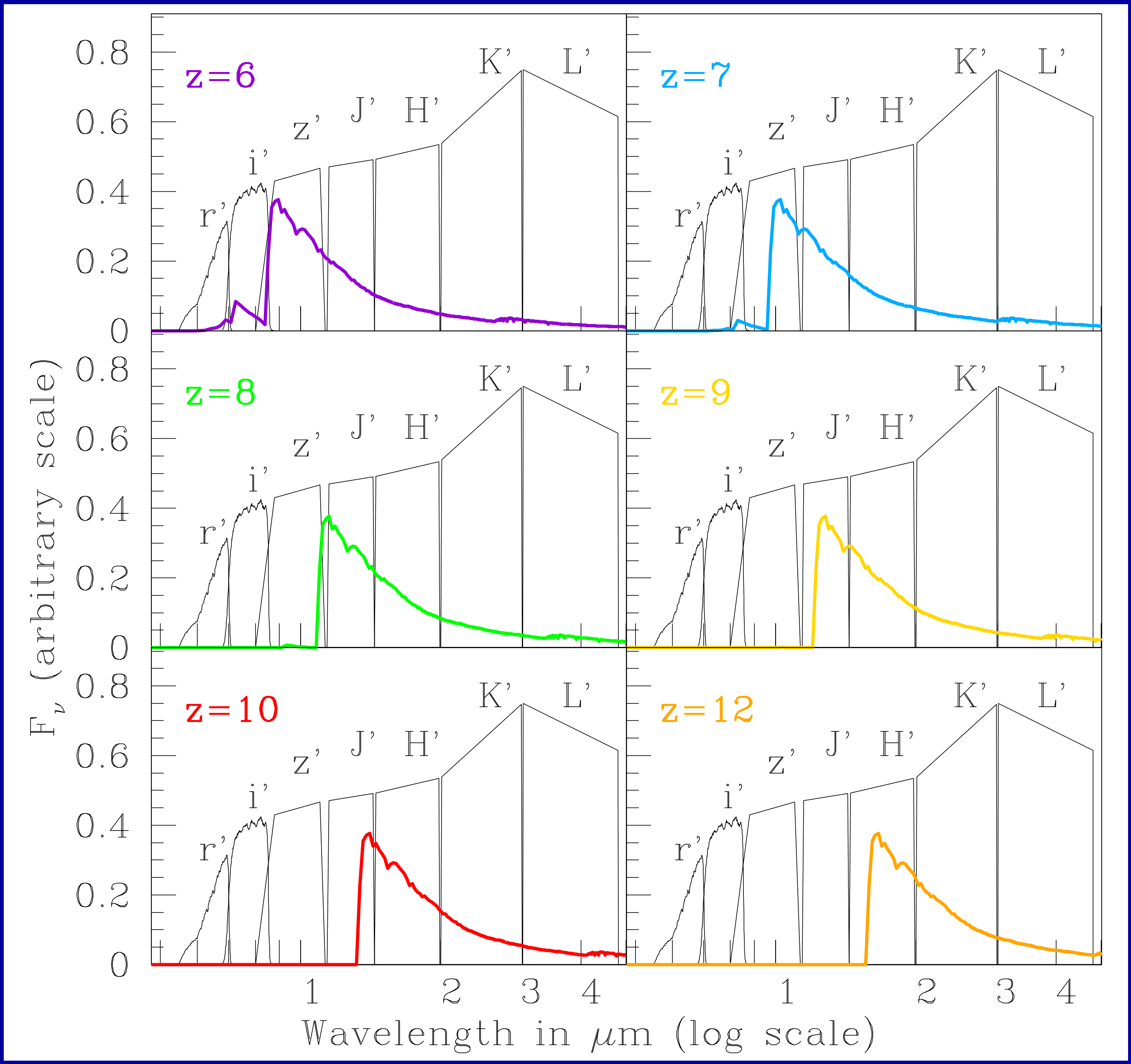
• (2) What instruments will JWST have?



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

- Currently only being implemented for parallel *calibrations.*

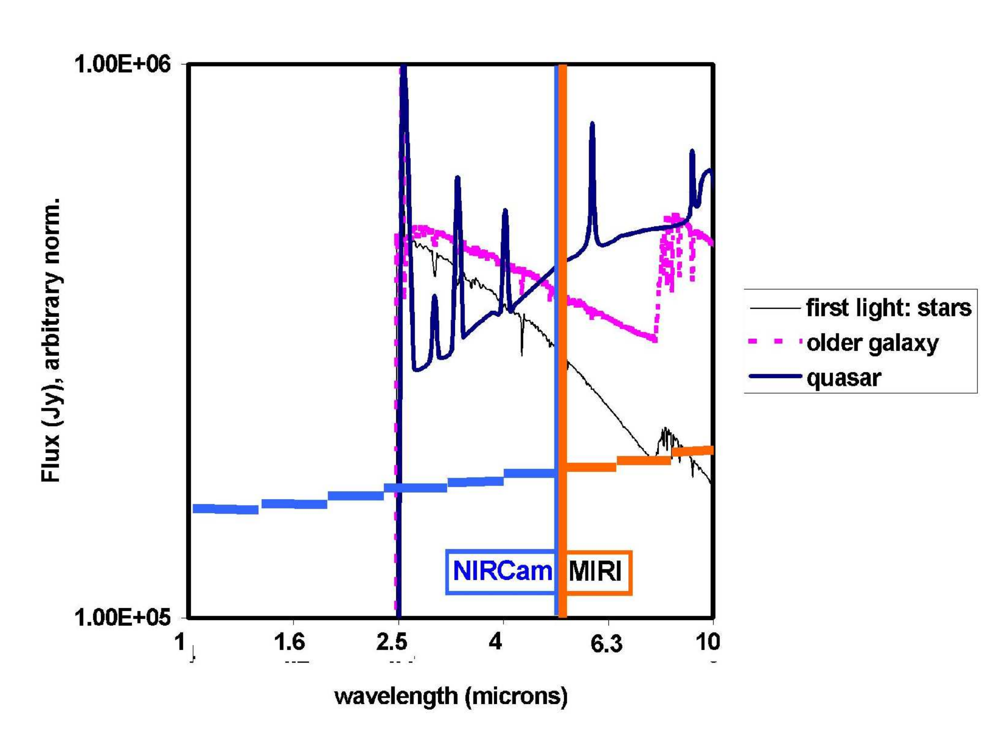
• (3) How can JWST measure First Light and Reionization?

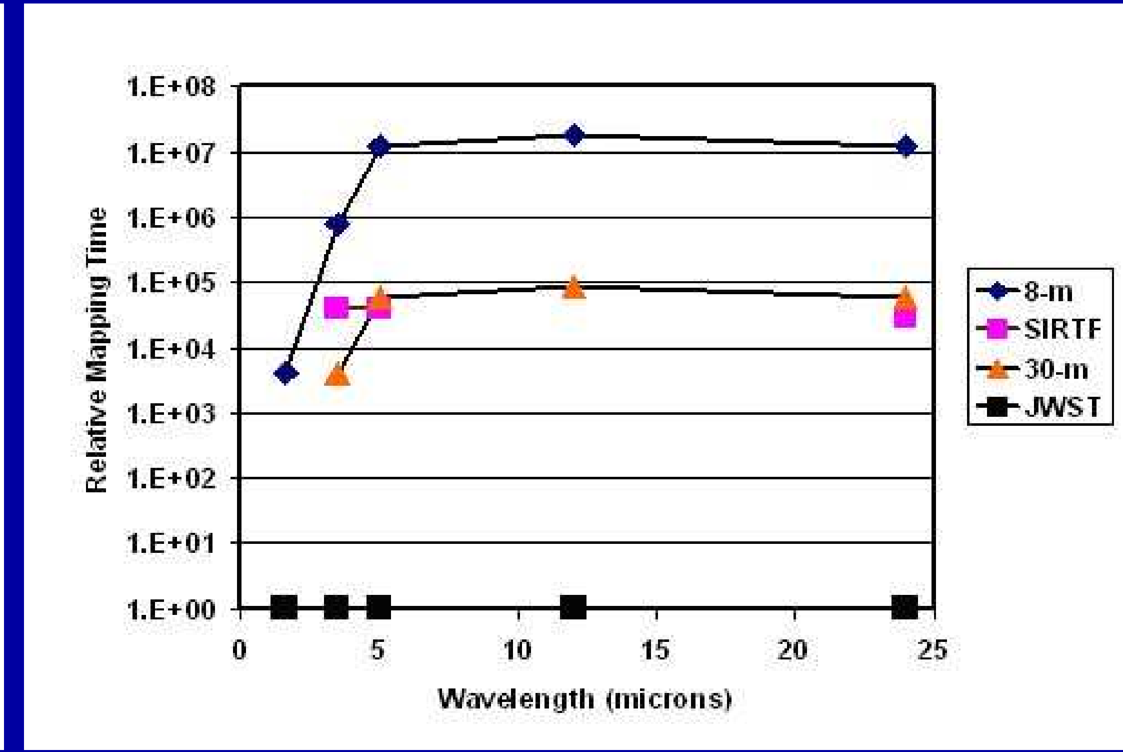


• Can't beat redshift: to see First Light, must observe near–mid IR.

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

• (2) What sensitivity will JWST have?





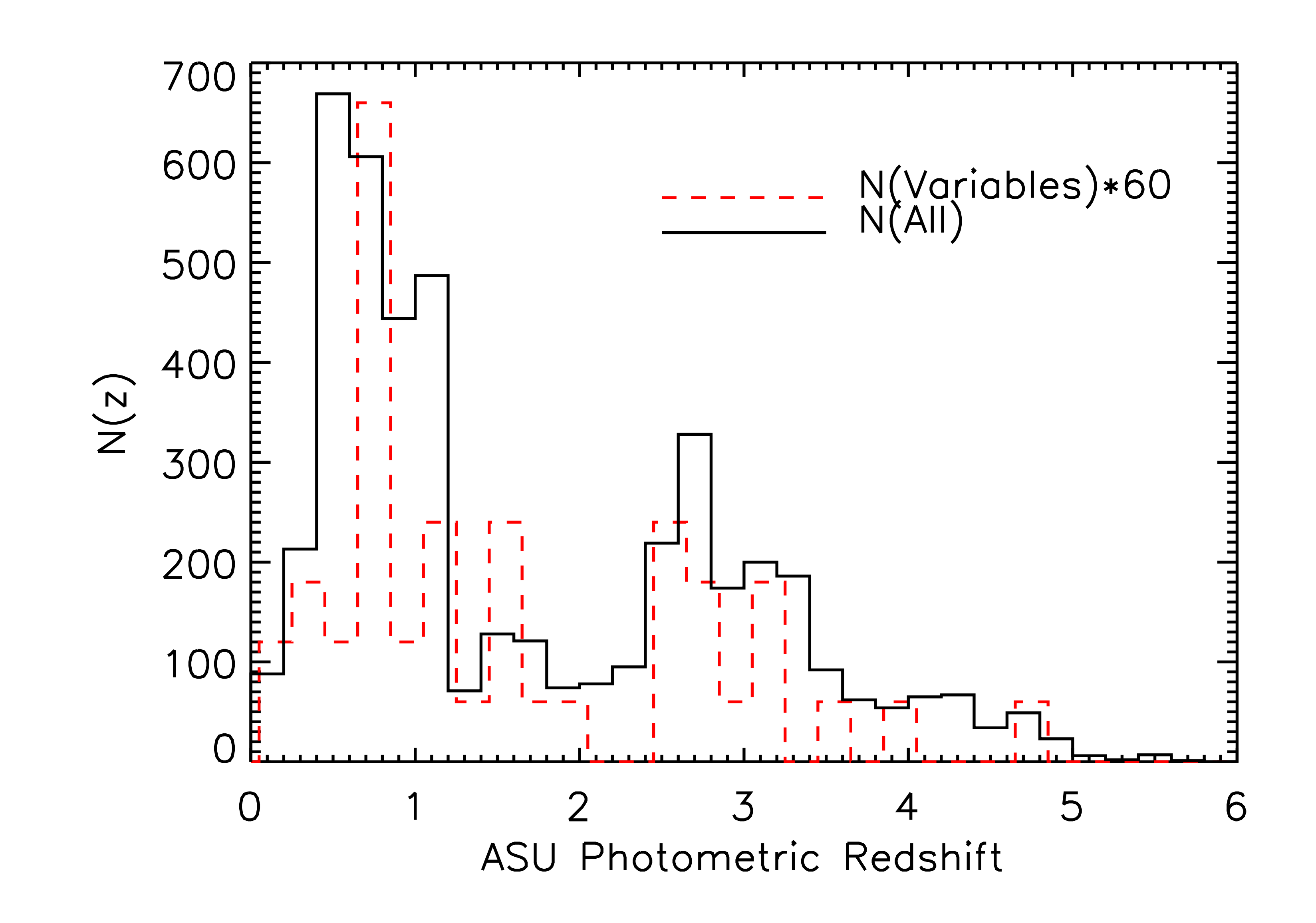
NIRCam and MIRI sensitivity complement each other, straddling $\lambda \simeq 5$ μm.

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.

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

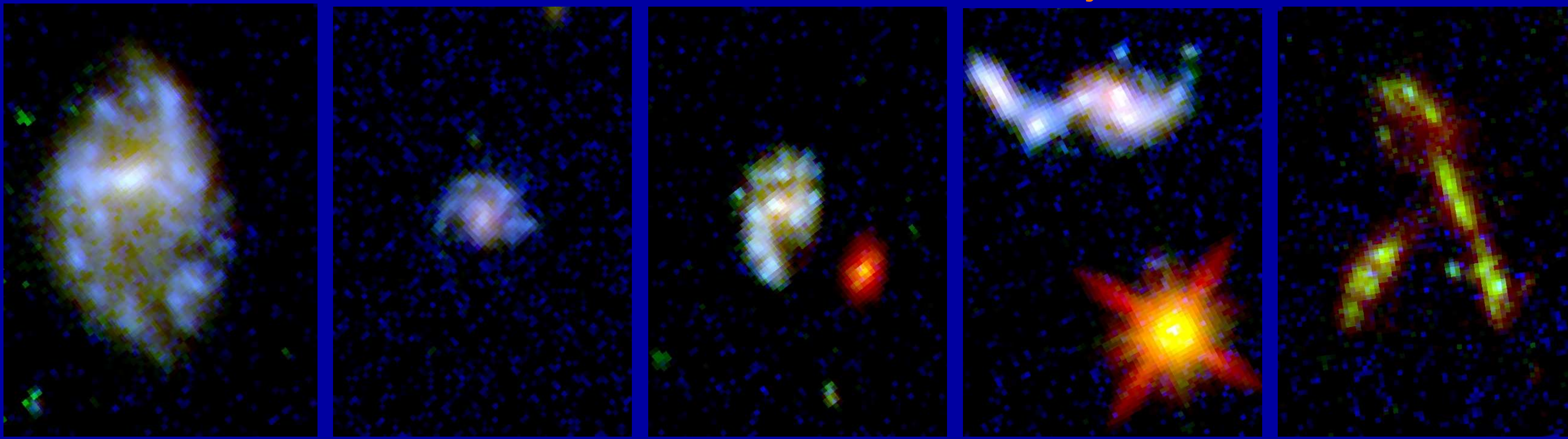


BViz(JH) Photo-z distribution of HUDF field gxys and variable objects:

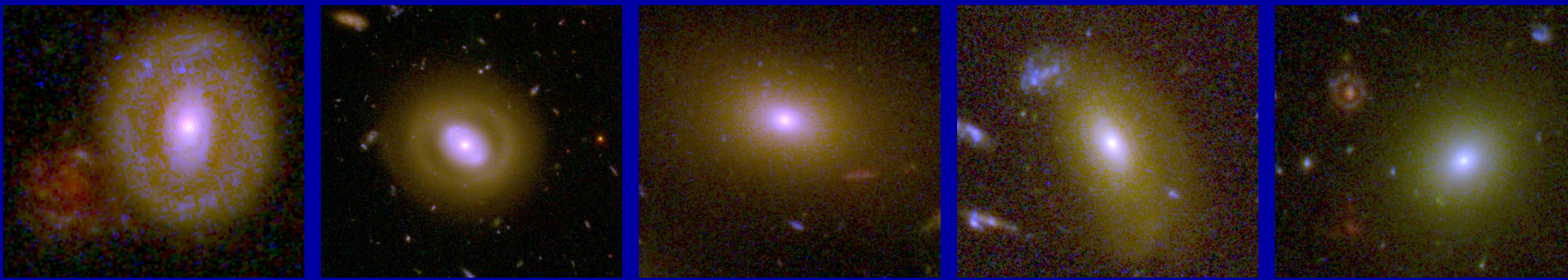
- Variable objects show a similar N(z) as field galaxies. About 1% of all field galaxies have variable weak AGN at all redshifts.

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

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

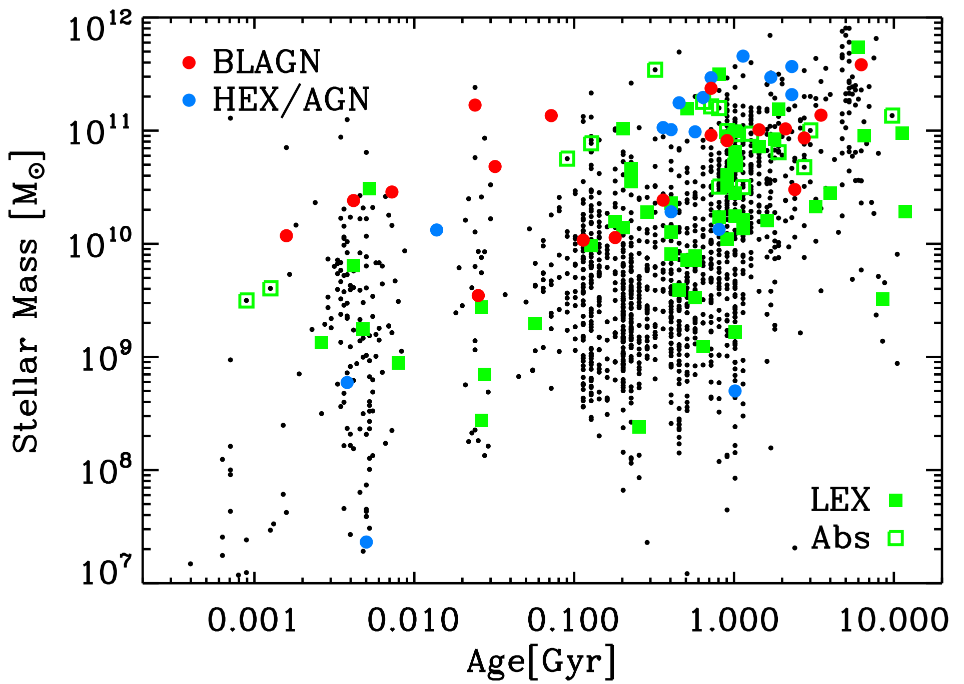


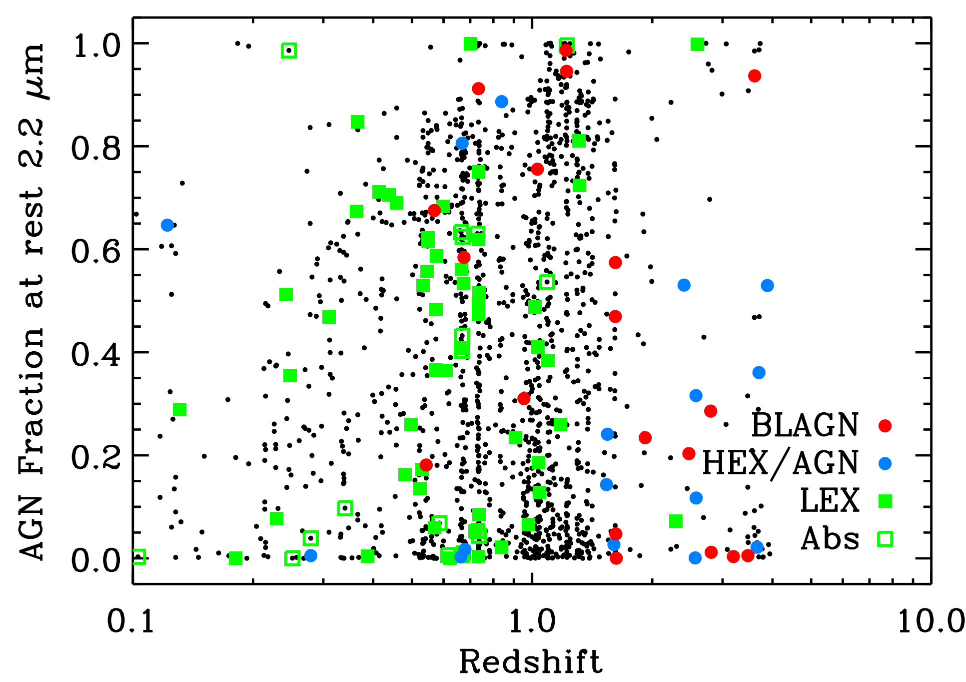
Galaxy structure at the peak of the merging epoch (z$\simeq$1–2) is very rich: some resemble the cosmological parameters $\boldsymbol{H_0}$, $\boldsymbol{\Omega}$, $\boldsymbol{\rho_o}$, $\boldsymbol{w}$, and $\boldsymbol{\Lambda}$, resp.



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.





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.

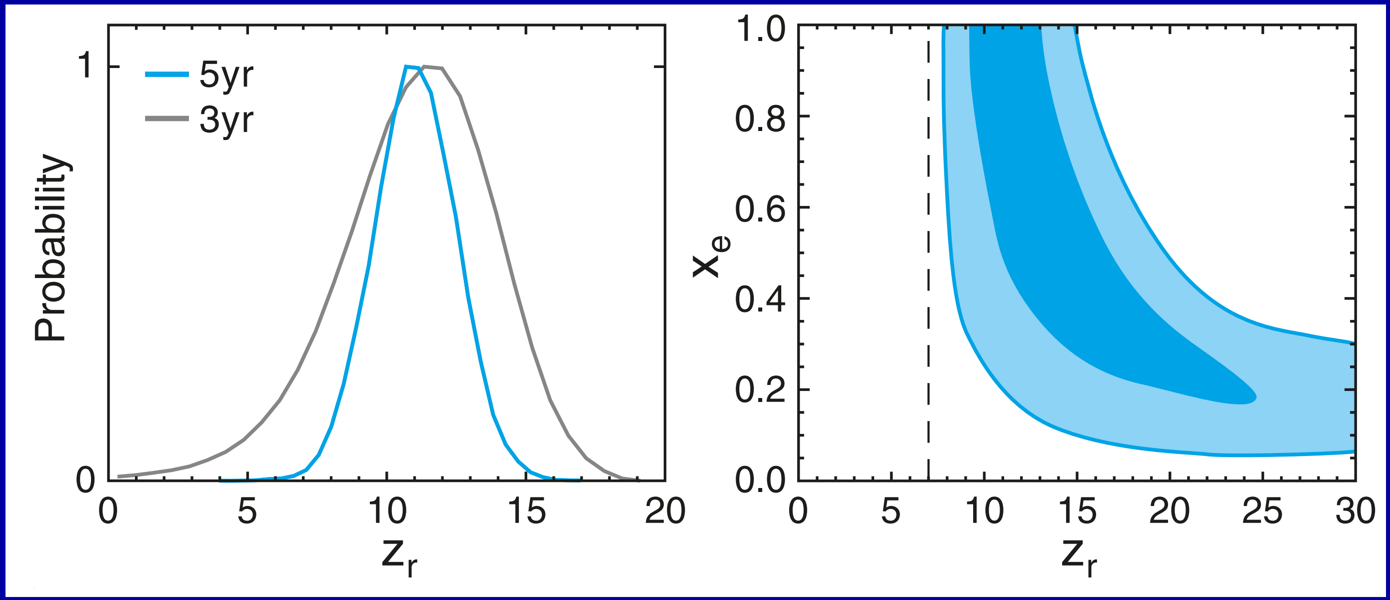
Most $\gtrsim$0.5–1 Gyr SEDs do not show AGN signatures in optical spectra.

- 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!

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

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



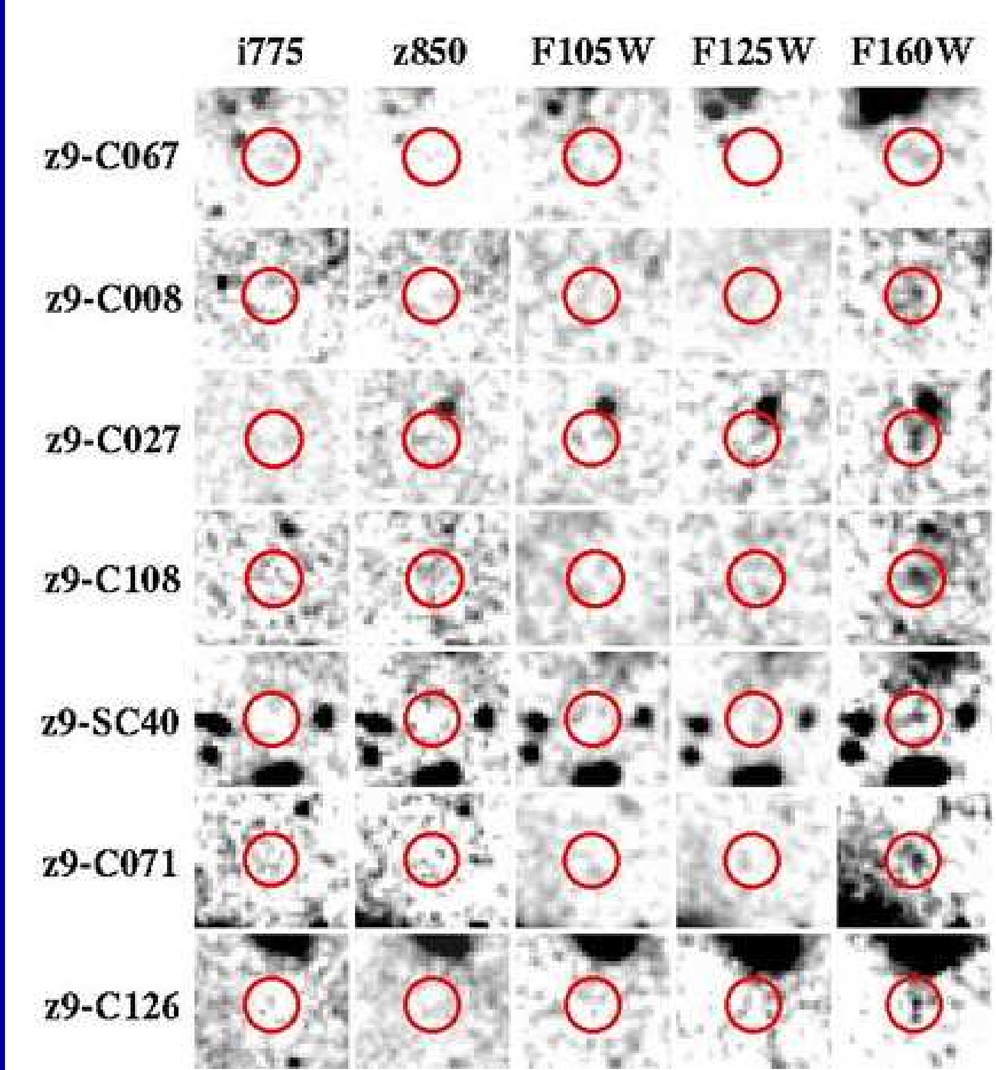
The year-7 WMAP data provided much better foreground removal (Dunkley et al. 2009; Komatsu et al. 2009, 2010; astro-ph/1001.4538)

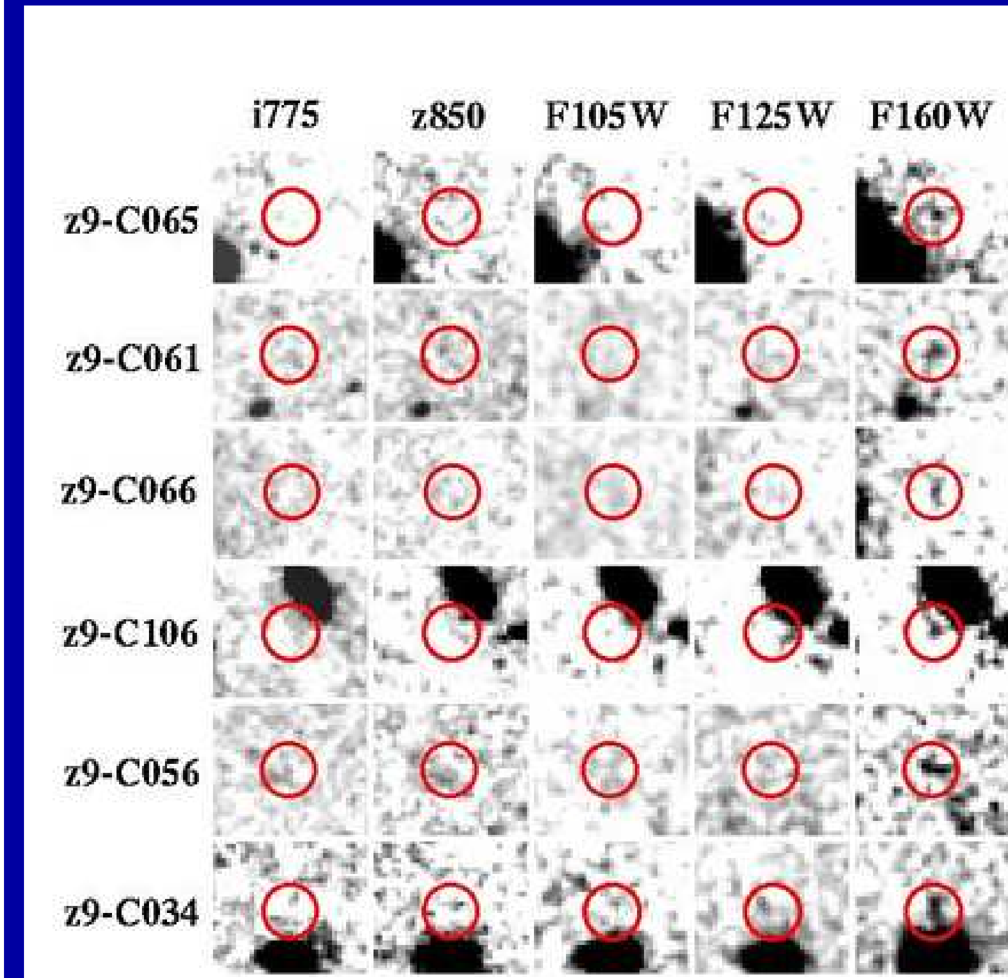
$\Longrightarrow$ First Light & Reionization occurred between these extremes:

- (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:

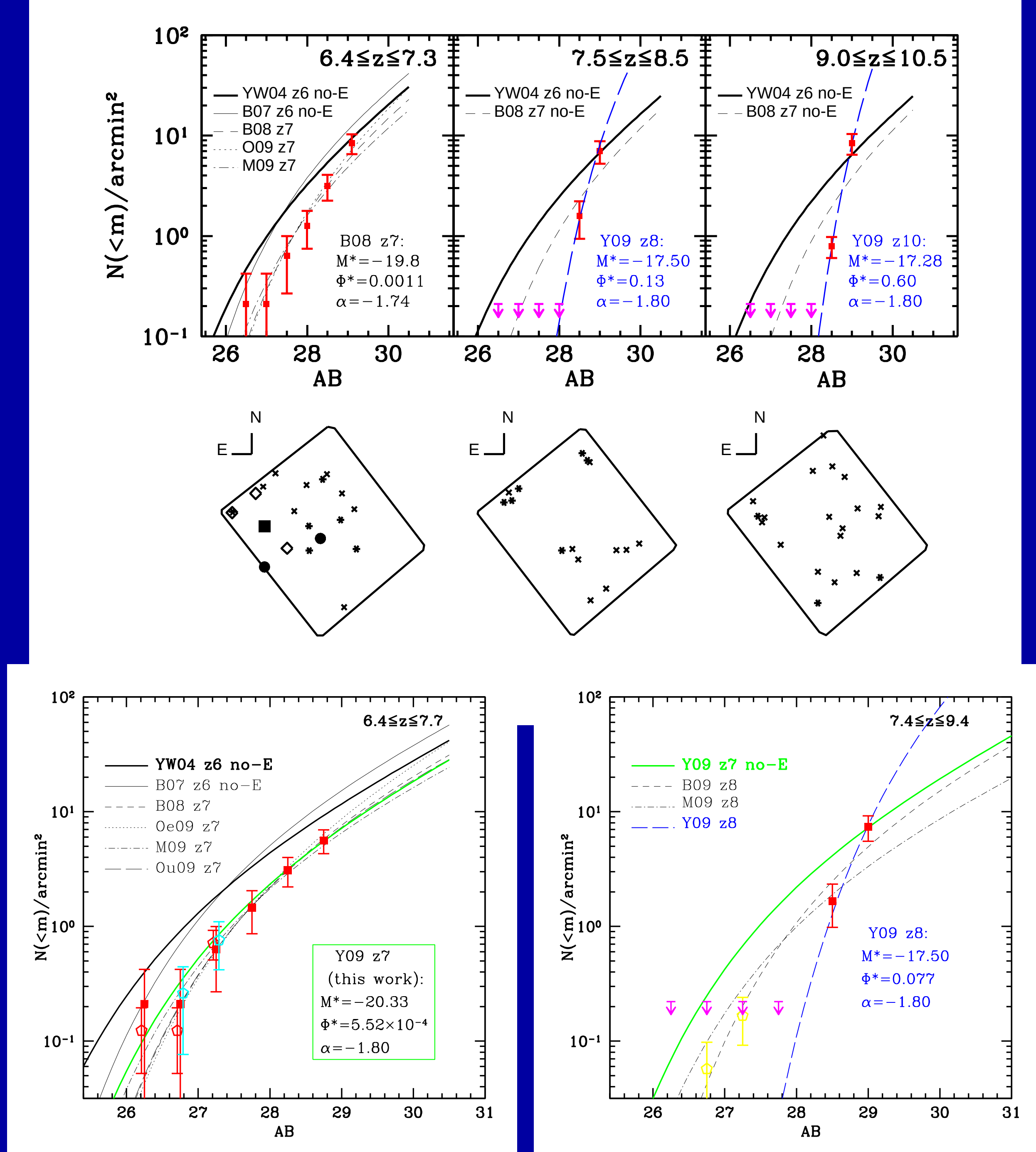
- HST/ACS has covered $z \lesssim 6$, and WFC3 is now covering $z \lesssim 7$–9.
- For First Light & Reionization, JWST must sample $z \simeq 8$ to $z \simeq 15$–20.

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



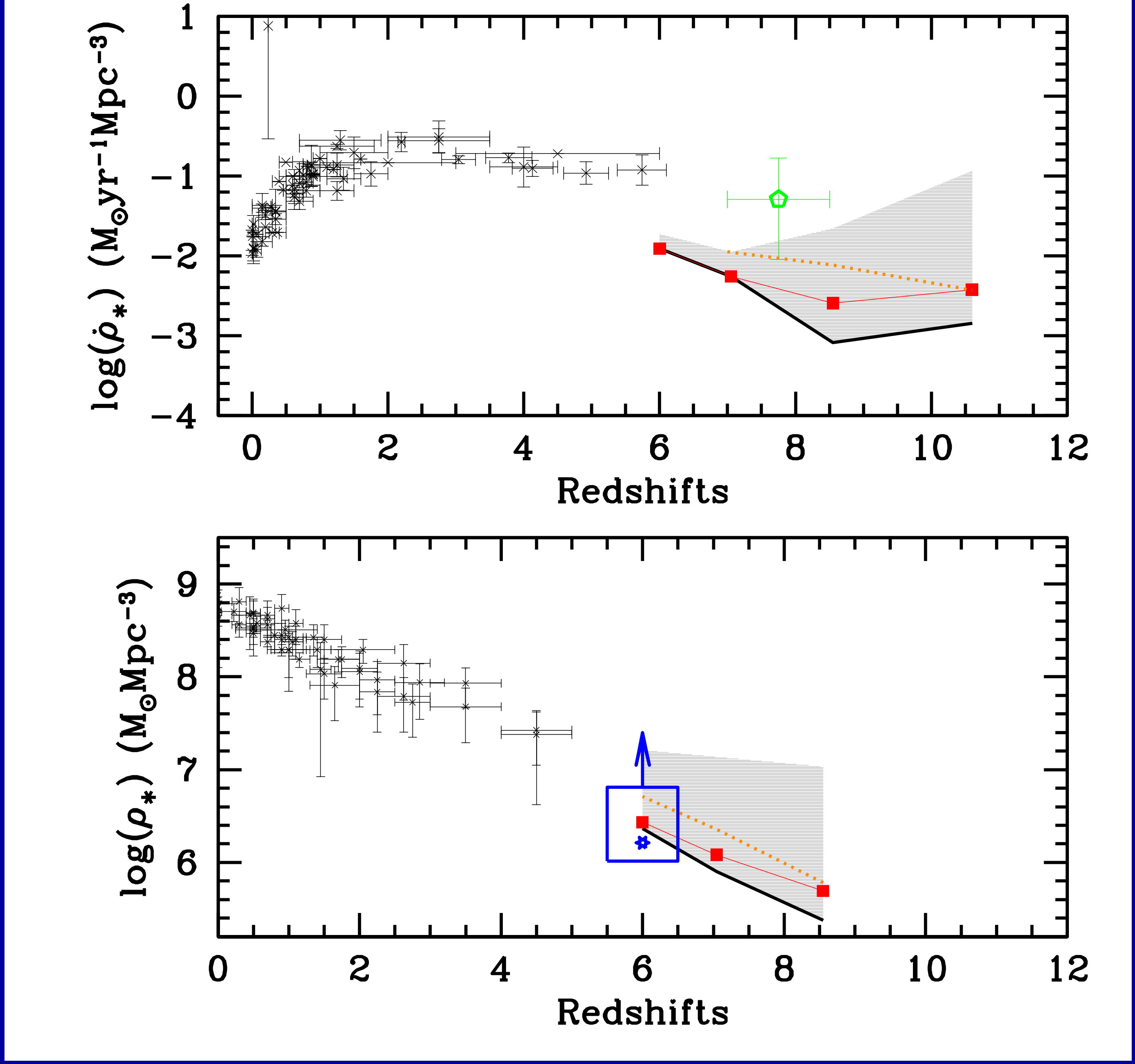


- Our simulations show that ∼50% of the J-drops close to bright galaxies are real (unlike Bouwens 2010), see Yan et al. 2010 (astro.0910.0077).
- Assume only 33% of J-drops are real *and* at z$\gtrsim$9. Together with the HUDF and ERS upper limits to AB$\lesssim$28 mag, the z∼9 LF is still steep!
- Need JWST to measure z$\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.

- 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://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"