Observing AGN growth in radio, X-rays, with HST & JWST:

When during galaxy assembly did AGN growth take place?

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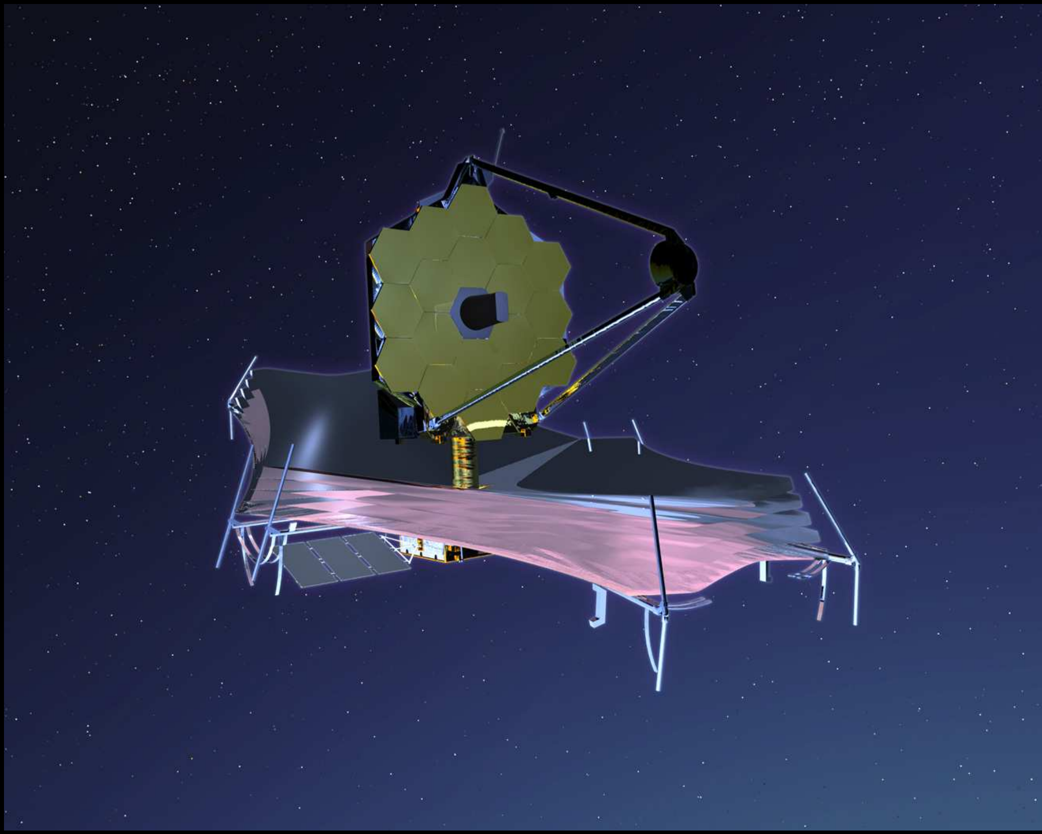

LOFAR Seminar, ASU, Tempe, Arizona, Monday March 18, 2013

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

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

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

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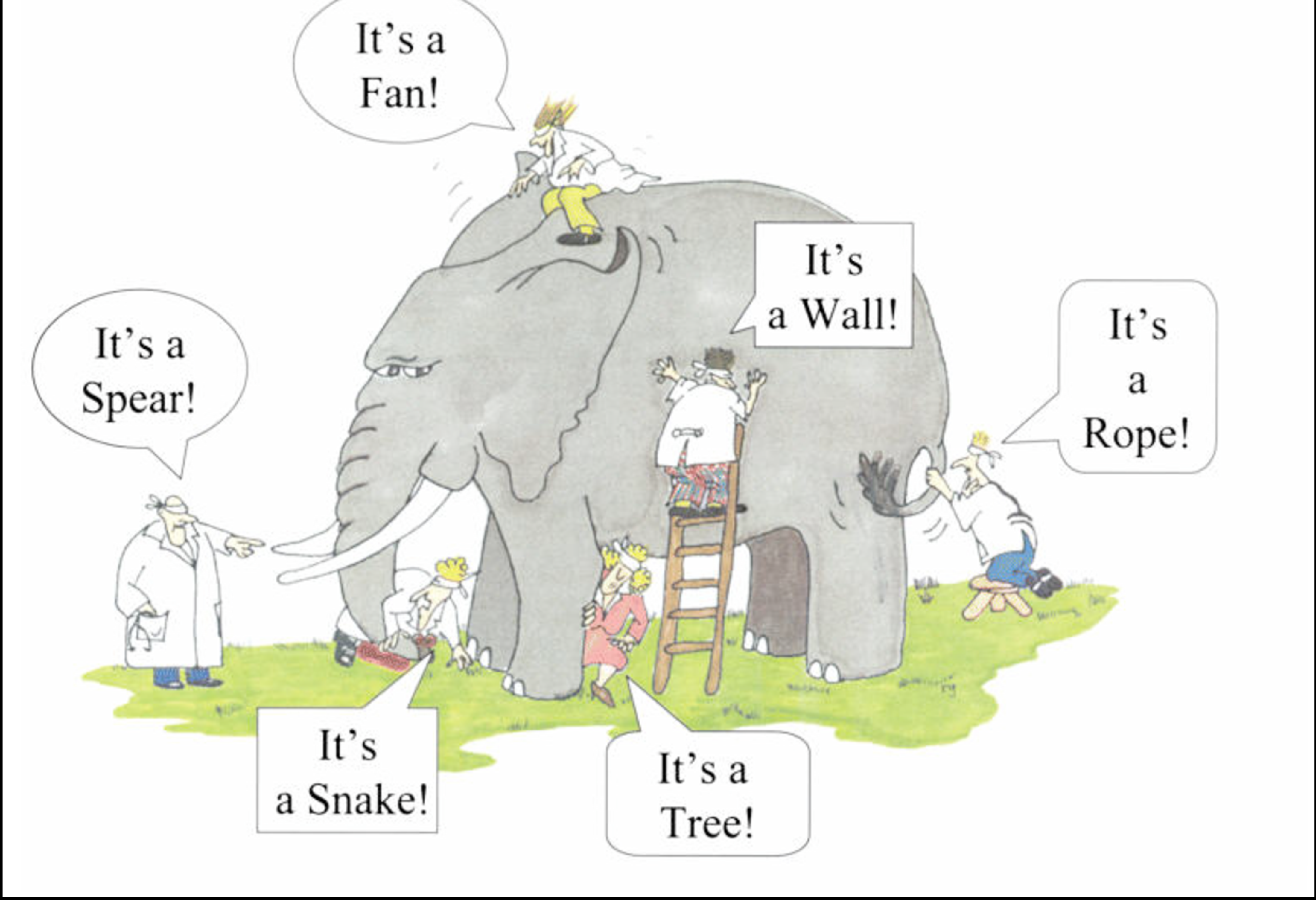
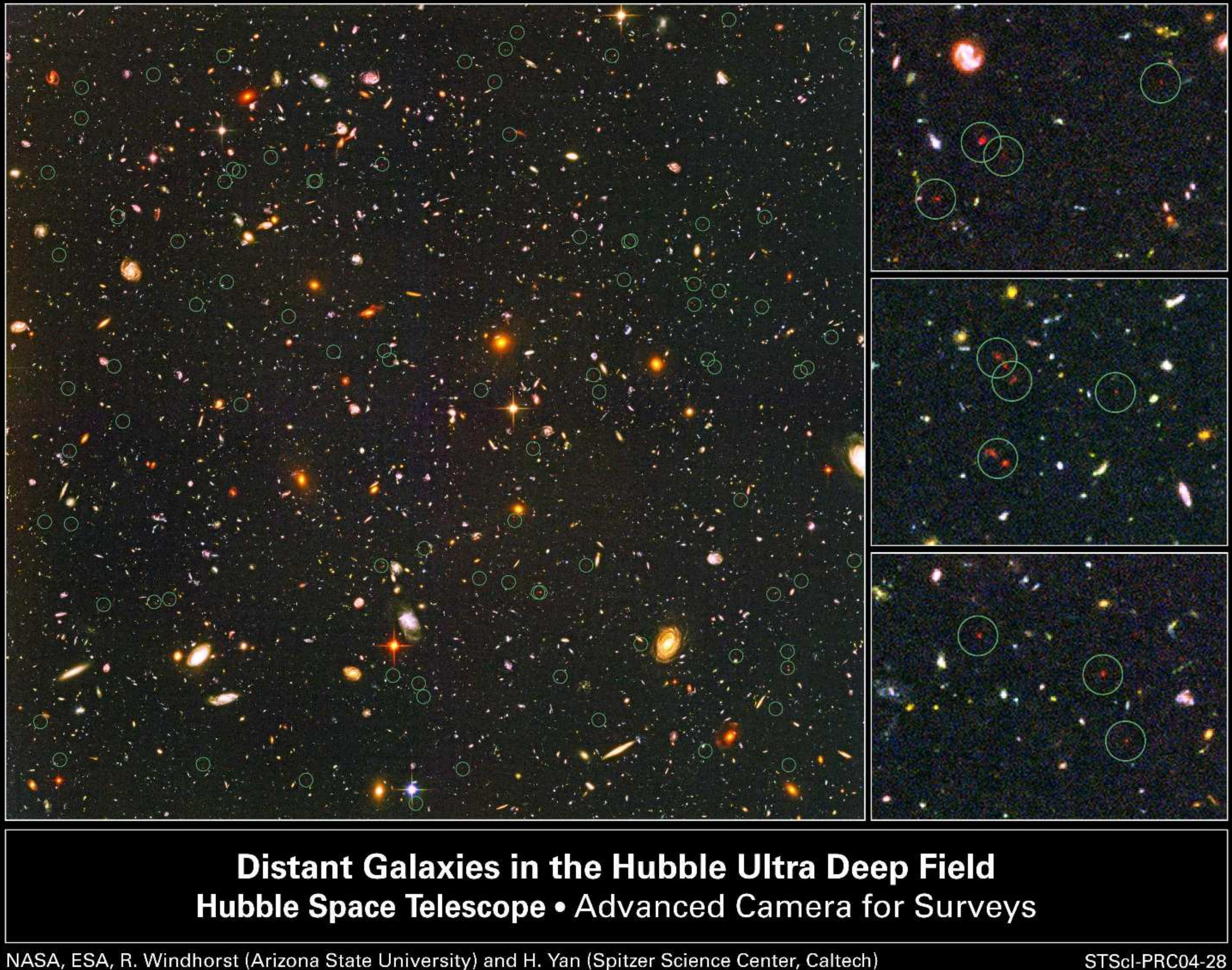


AGN are the cosmic elephants that surprise both observers and theorists ... !

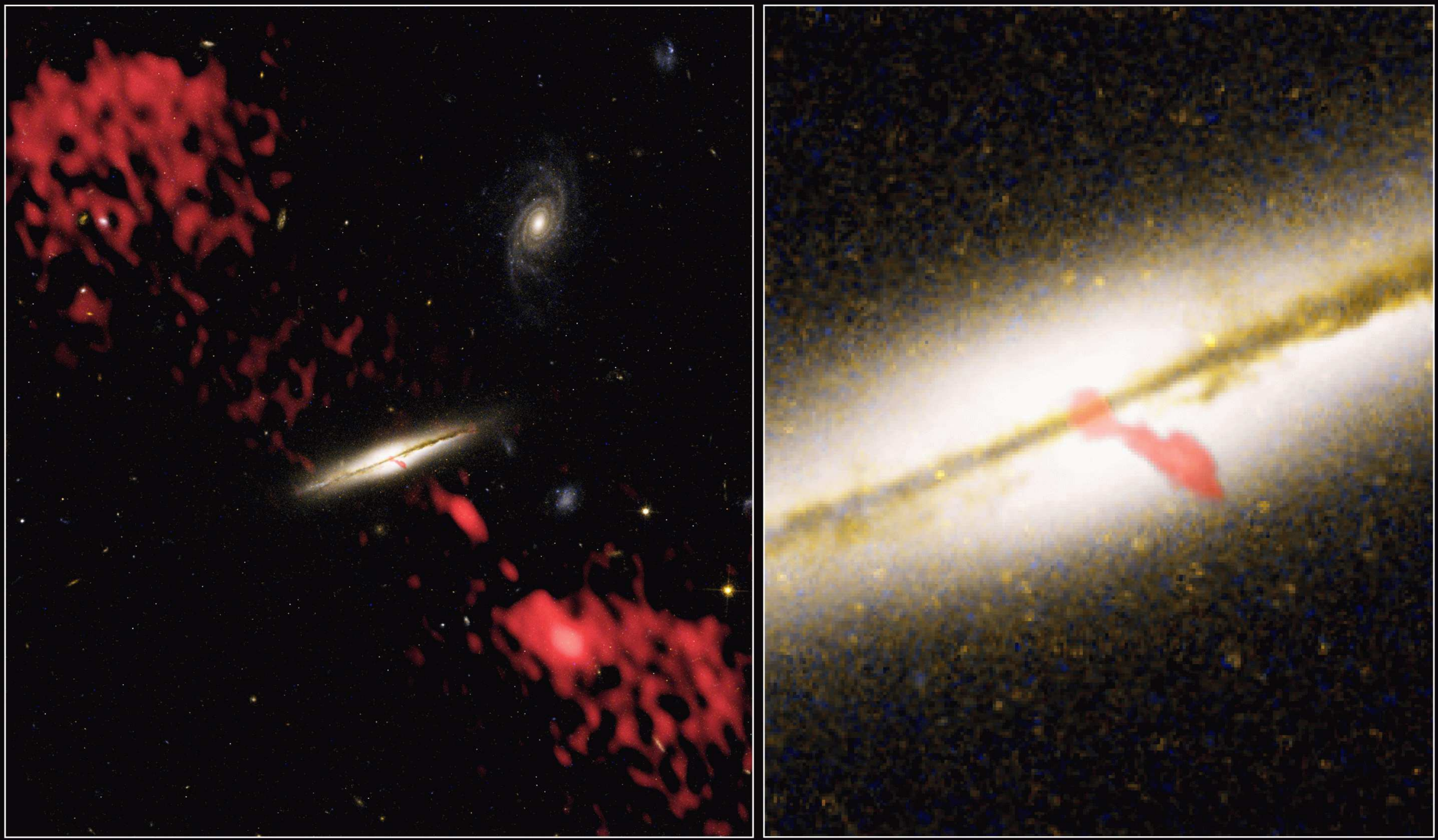


In an HUDF^3 volume at z$\simeq$2–6:

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

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

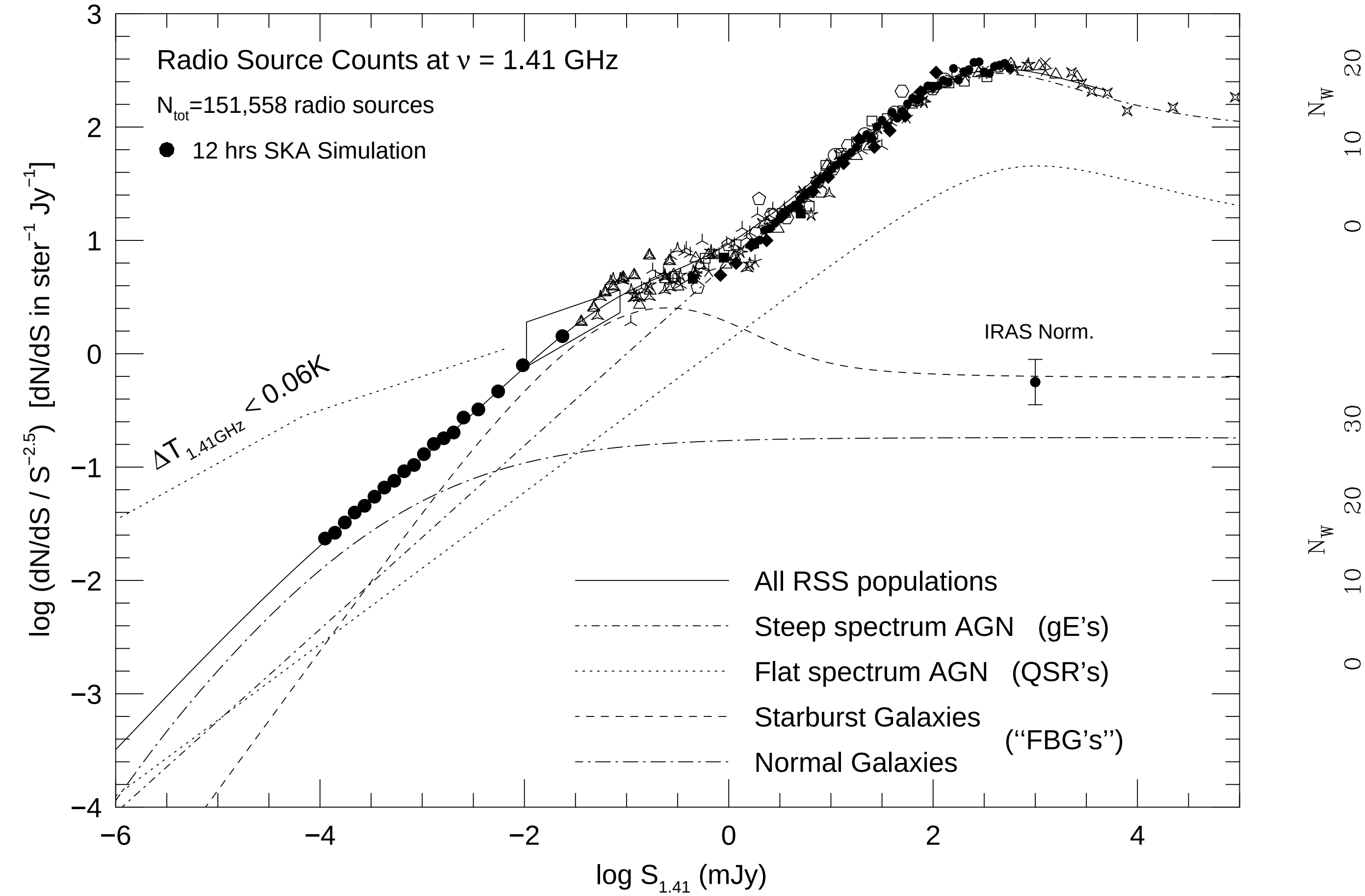
(0) How can HST & JWST measure Galaxy Assembly & SMBH/AGN Growth?

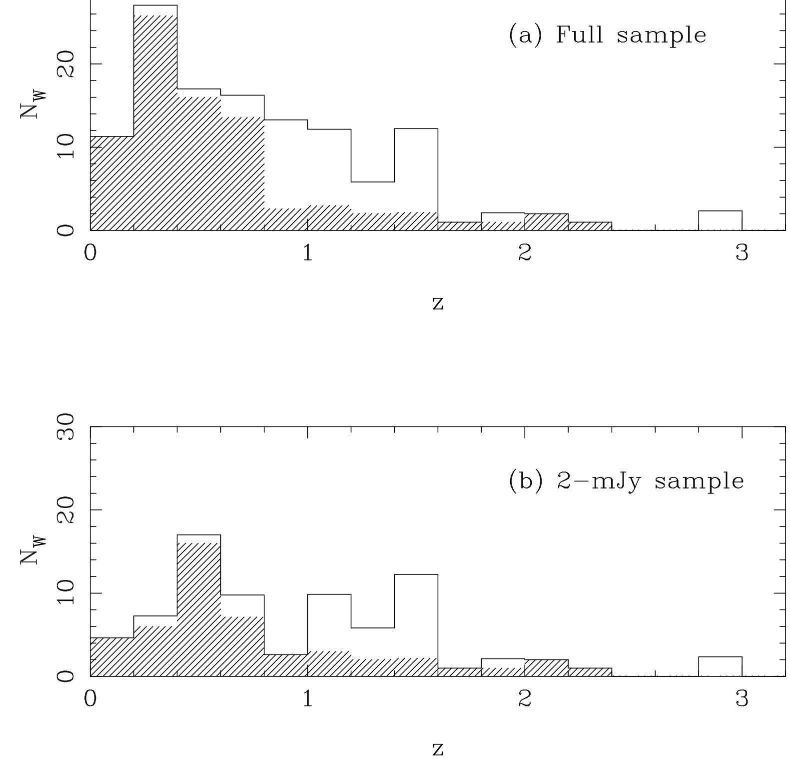


Radio Galaxy 0313-192
Hubble Space Telescope ACS WFC ▪ **Very Large Array**

NASA, NRAO/AUI/NSF and W. Keel (University of Alabama) ▪ STScI-PRC03-04

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

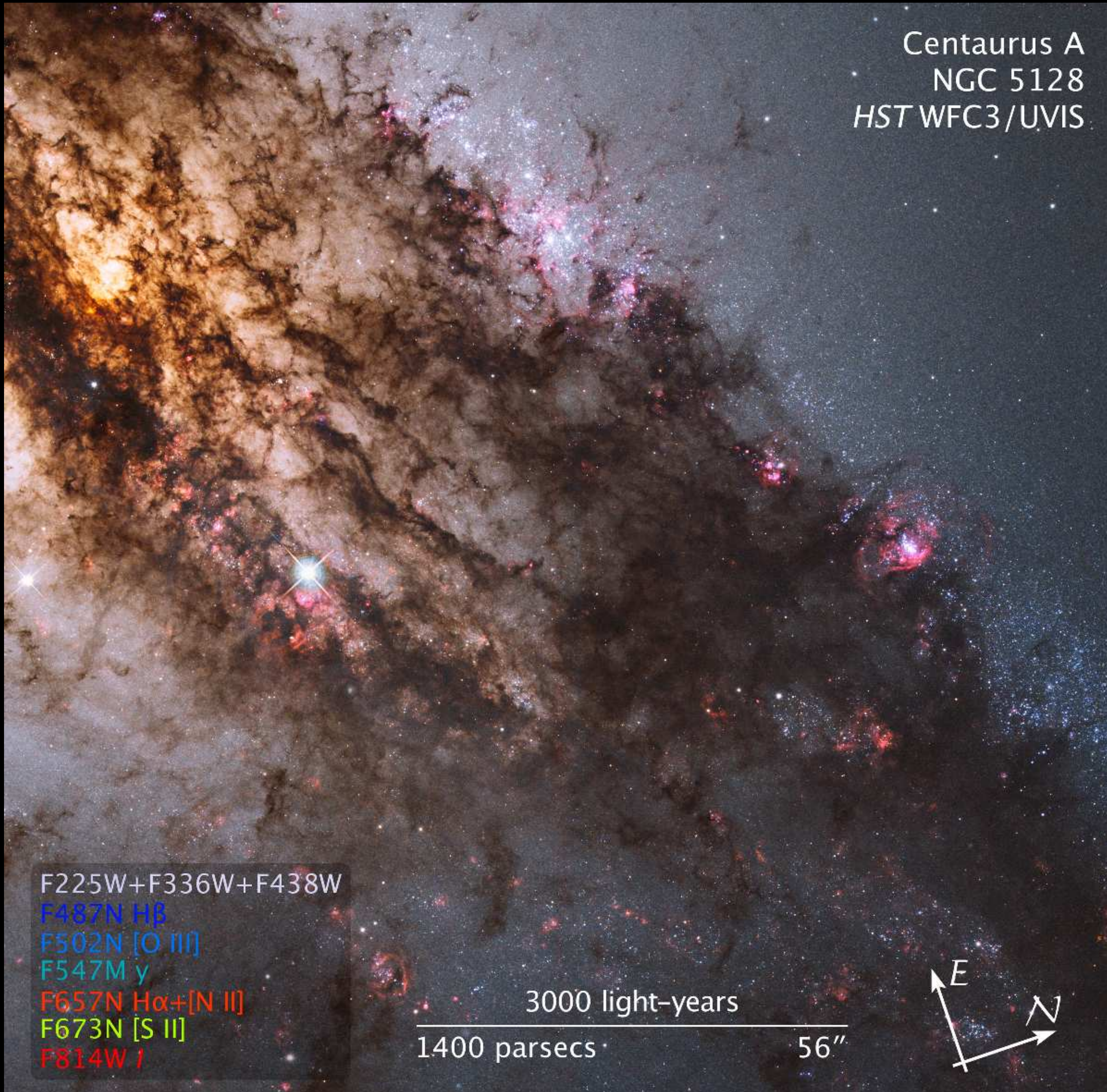


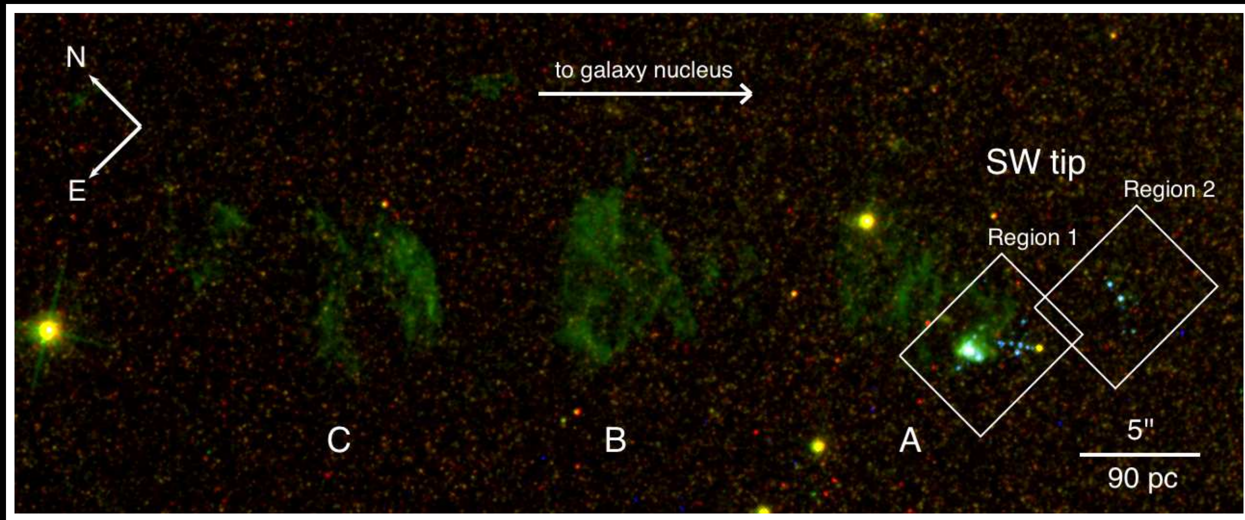


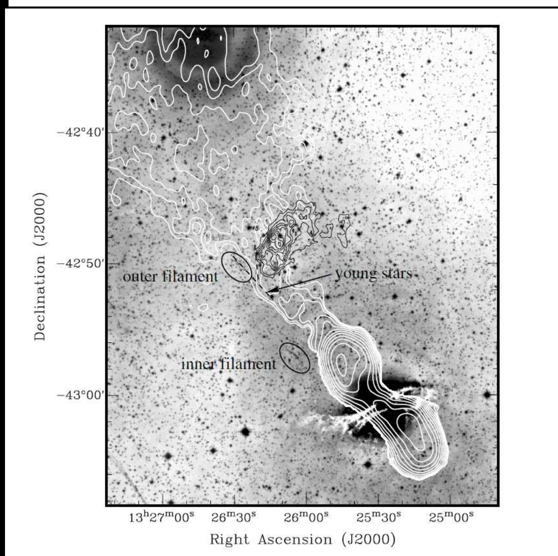
(LEFT) 1.41 GHz source counts (Windhorst et al. 1993, 2003; Hopkins et al. 2000) from 100 Jy to 100 nJy: AGN (monsters) dominate $\gtrsim$1 mJy, starbursts below 1 mJy [12-hr SKA simulation below 10 μJy].

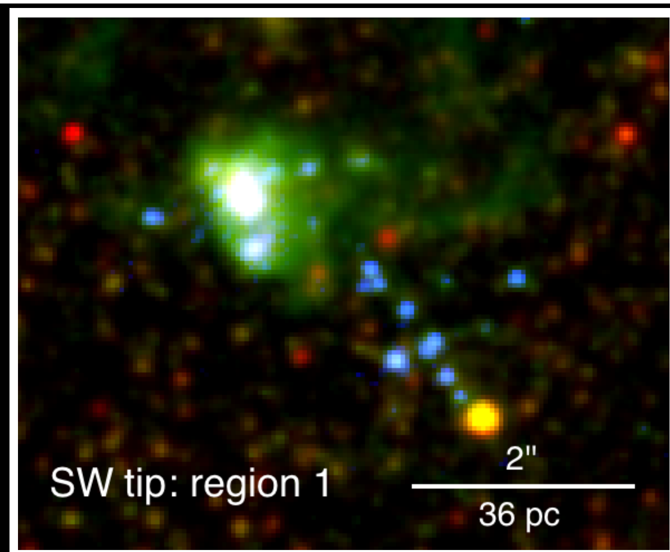
(RIGHT) Redshift distribution of mJy radio sources (Waddington$^+$ 2001):

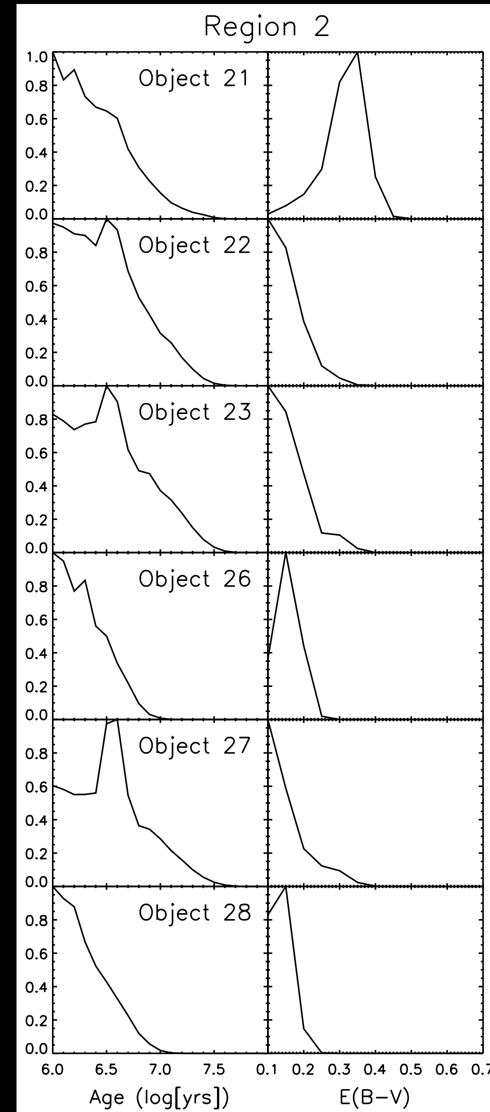
- Median redshift $z_{med} \lesssim$1 at all flux levels, due to radio K-correction.
- Same in X-rays $\Longrightarrow$ Radio and X-ray fairly poor high-z AGN tracers!


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





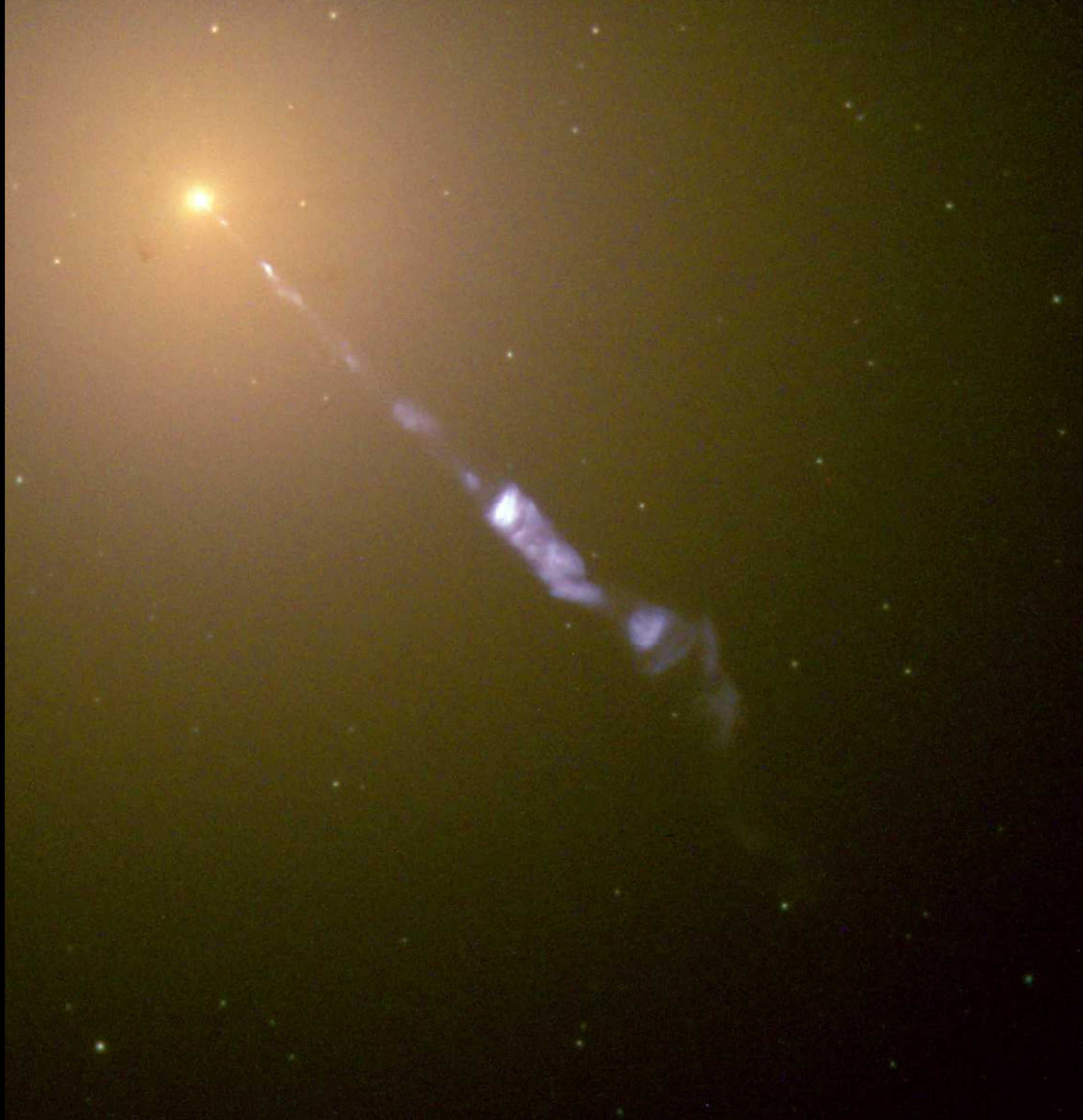




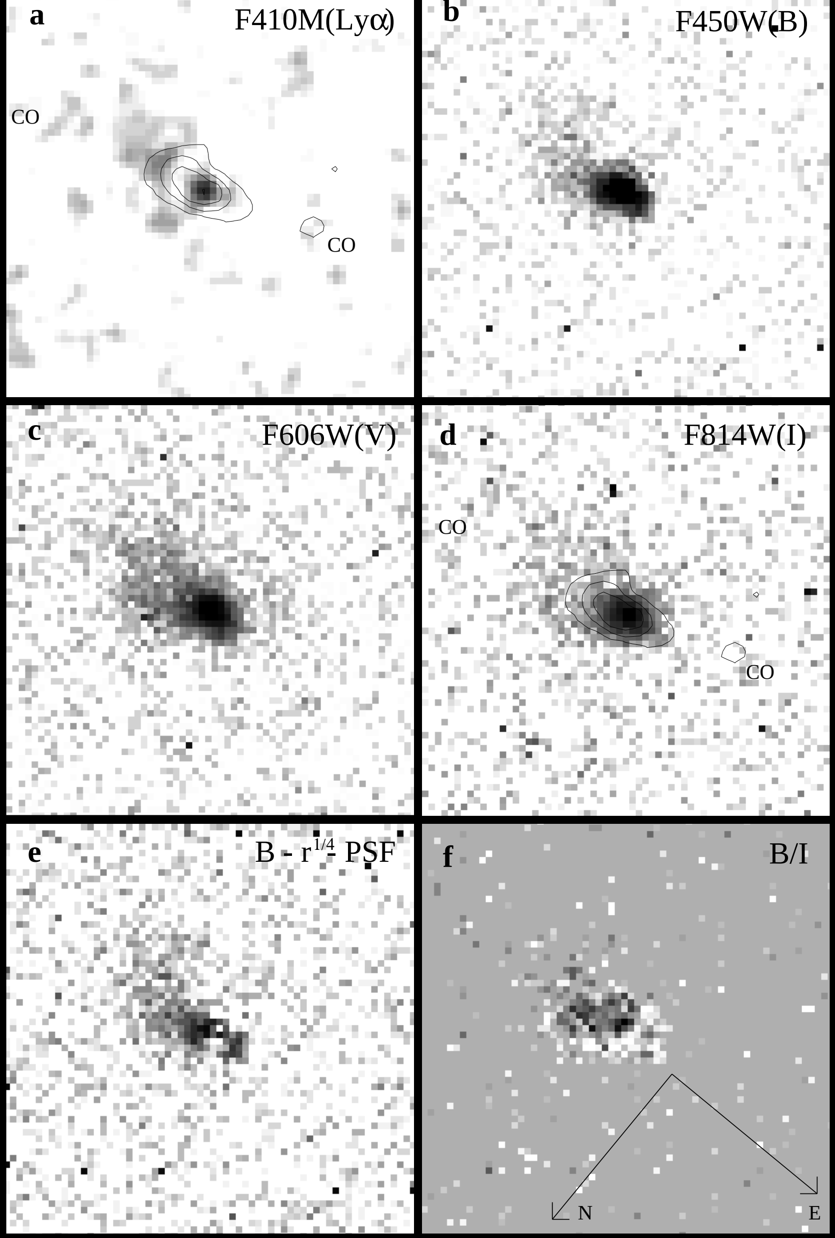
Well determined ages for young (∼2 Myr) stars in Centaurus A jet with star-formation in jet's wake (Crockett et al. 2012, MNRAS, 421, 1602).

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

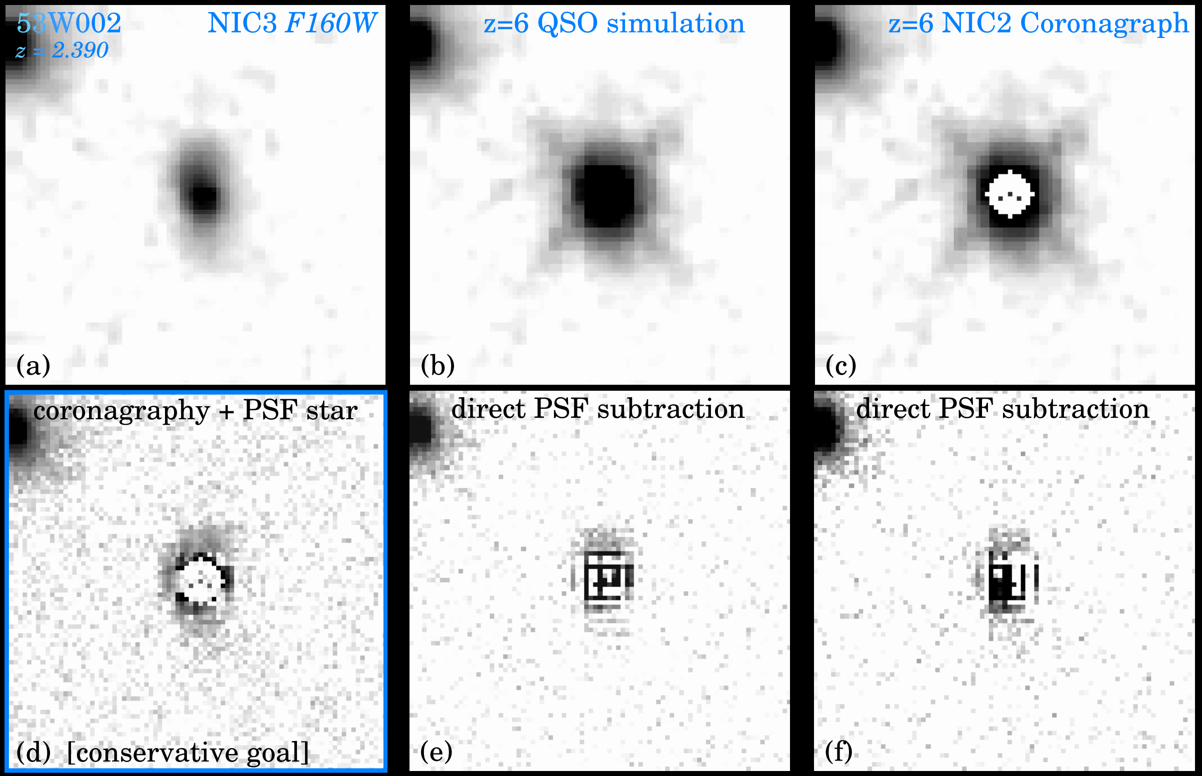
- We must do all we can with HST in UV–blue before JWST flies.



Elliptical galaxy M87 with Active Galactic Nucleus (AGN) and relativistic jet.



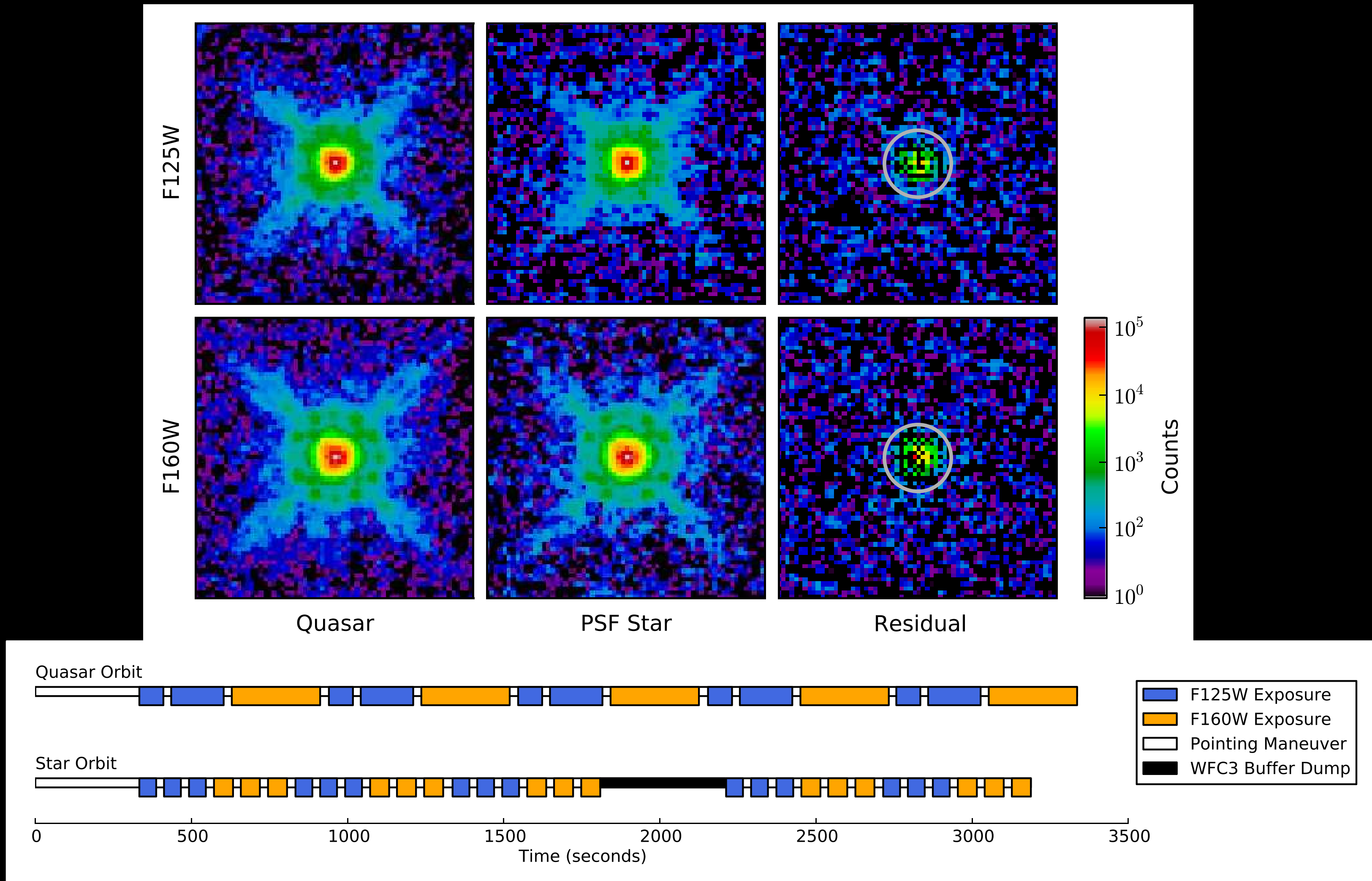
(Left): HST/PC of radio galaxy 53W002 at z=2.39 (Windhorst et al. 1998): rest-UV $r^{1/4}$-law + Lyα & Cont AGN-cloud.



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

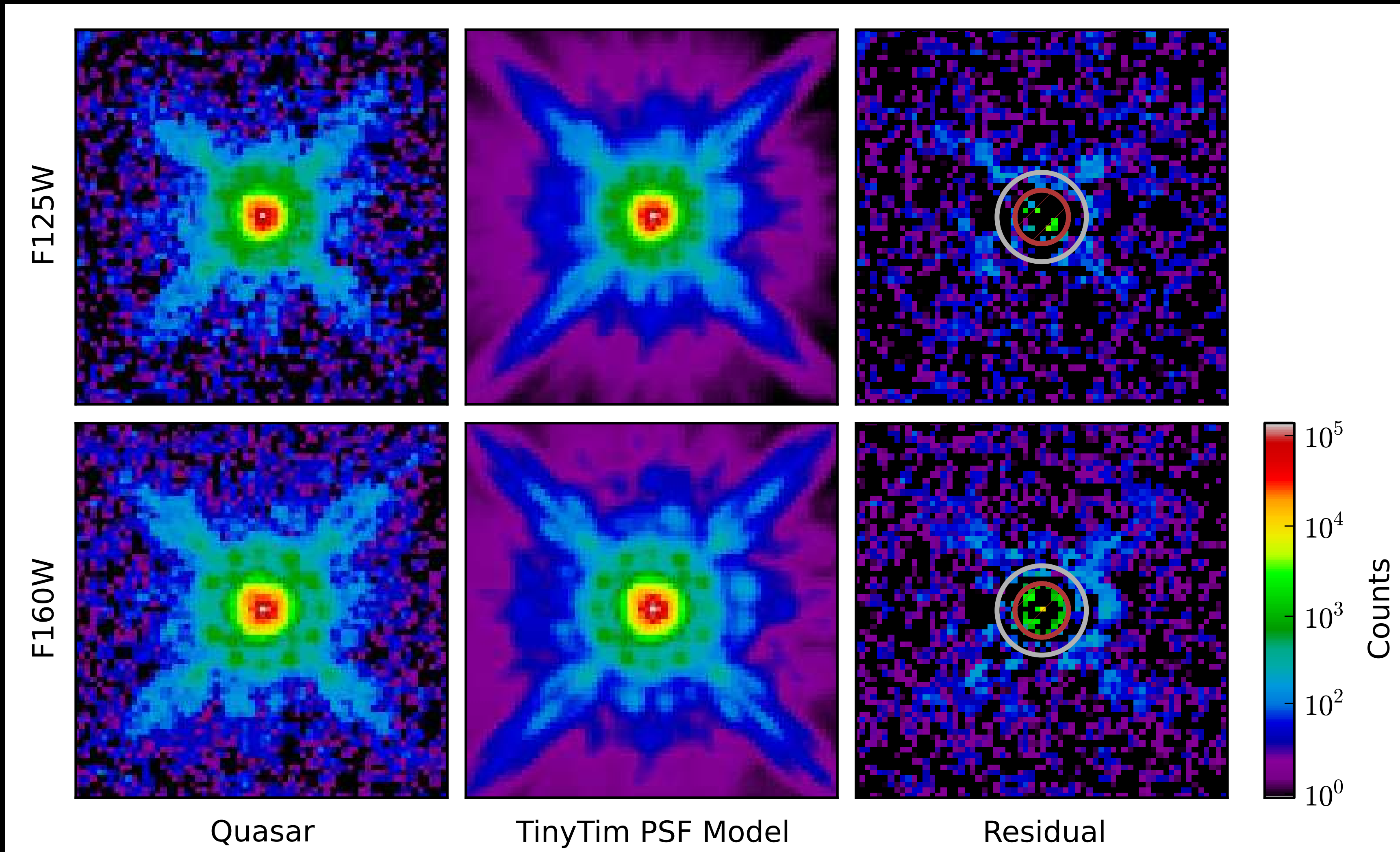
- JWST can measure AGN hosts 3 mag fainter in restframe UV-Opt to z$\lesssim$20.
- Such AGN are very rare. JWST must use other ways to trace AGN-growth.

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).

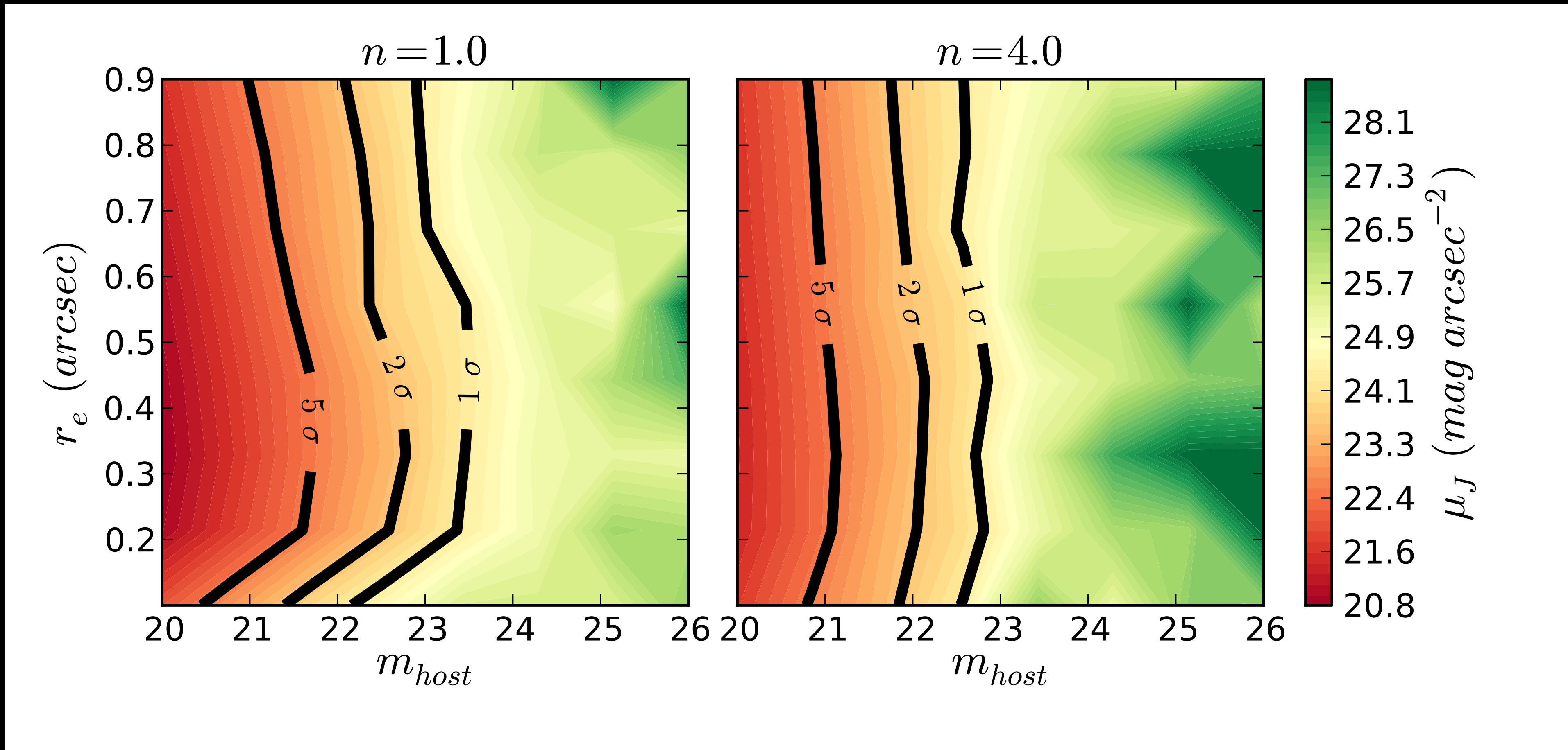
HST WFC3 observations of Quasar Host Galaxies at z≃6 (age≲1 Gyr)



• 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.

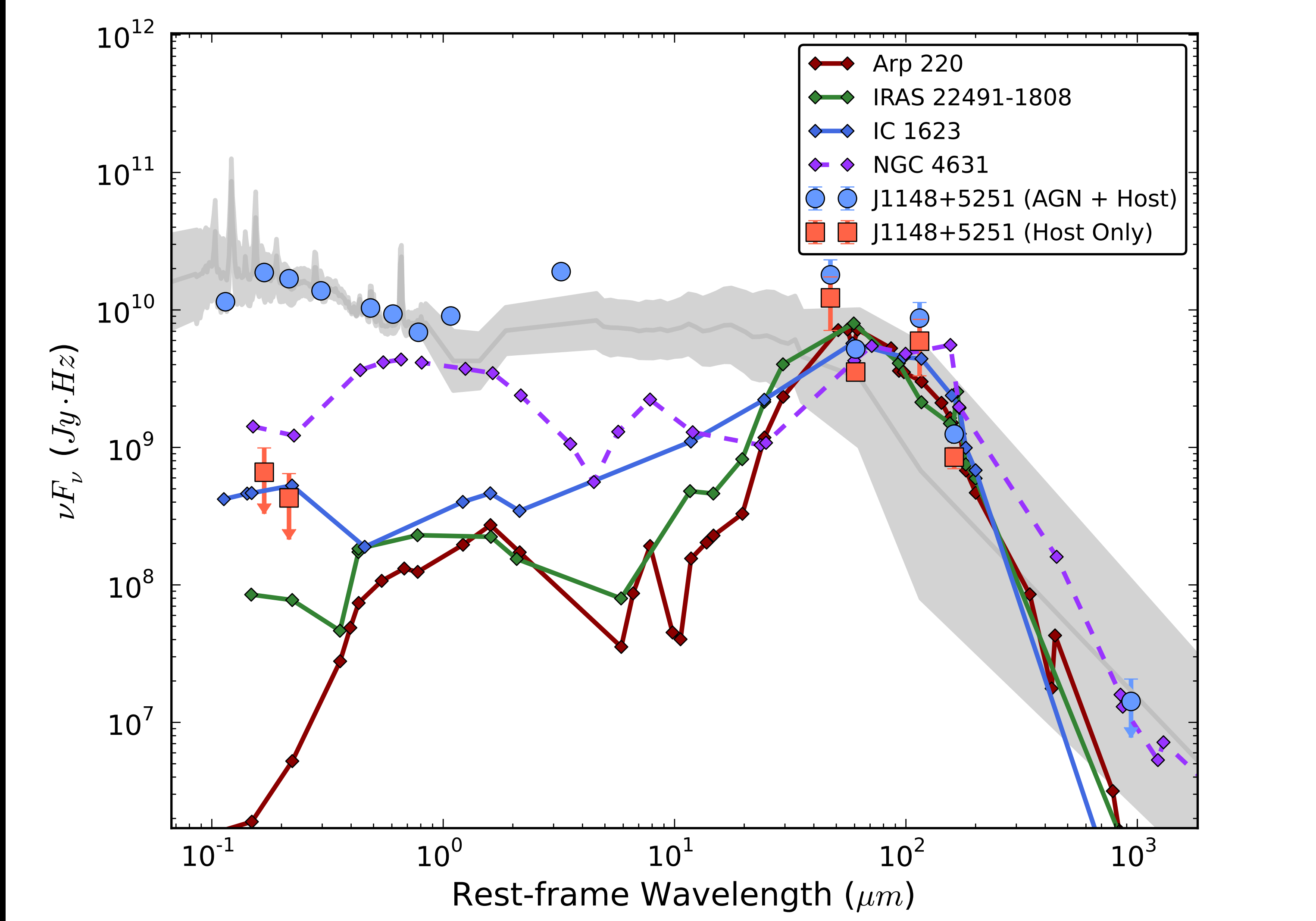
THE most luminous Quasars in the Universe: Are all their host galaxies faint (dusty)? ⇒ Major implications for Galaxy Assembly–SMBH Growth.

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



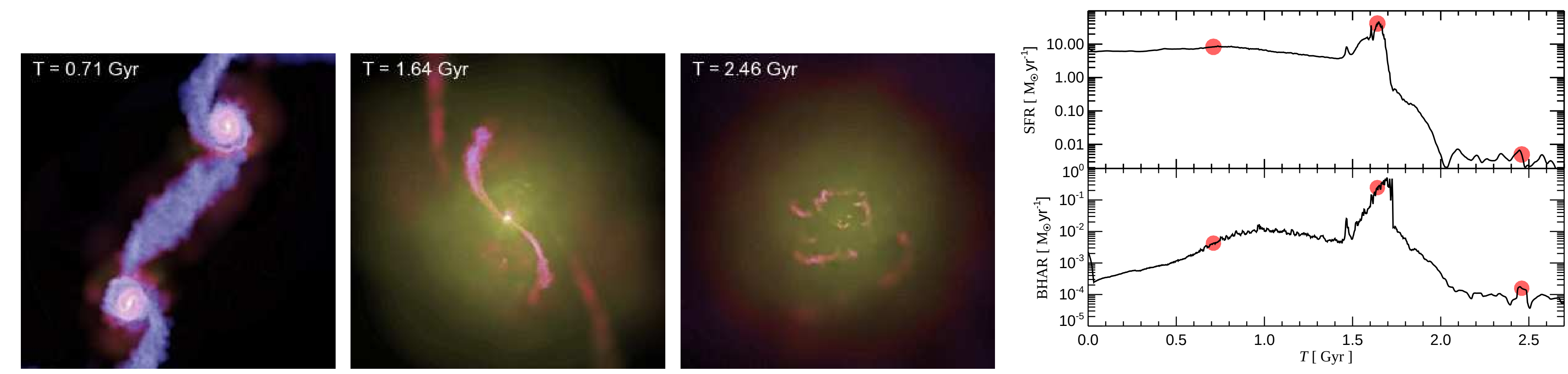
- TinyTim fit of PSF-star + GalFit models of galaxy light-profile, nearly to the noise limit: NO host galaxy at AB≳23.0 mag with $r_e \simeq 0\farcs5$ (Mechtley et al. 2012, ApJL, 756, L23; astro-ph/1207.3283)

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

(0) How to trace SMBH/AGN-growth after Galaxy Merger &/or Starburst?

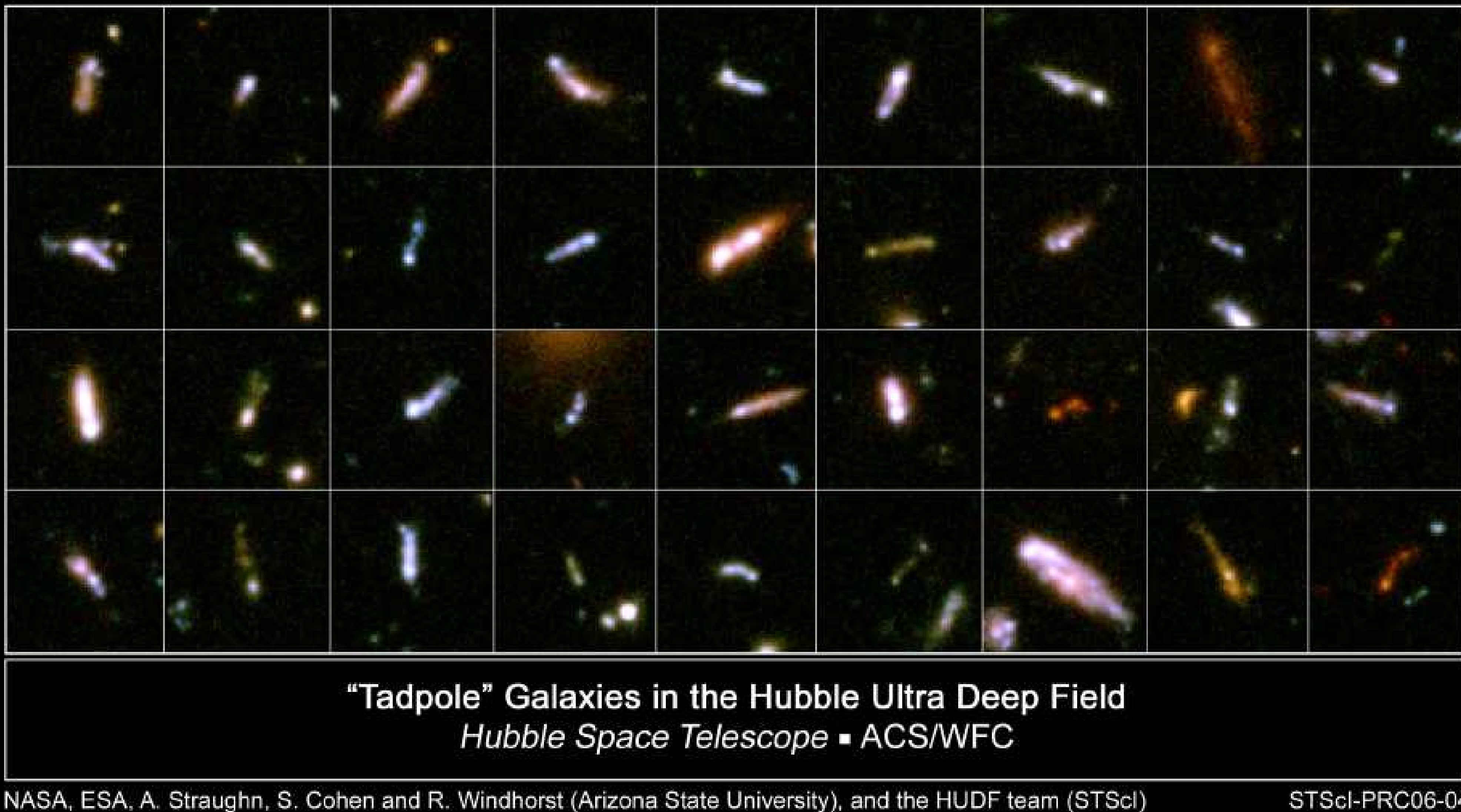


- [LEFT] Simulated merger of two disk galaxies at three different times, including the effects of SMBH growth and AGN feedback by Springel, di Matteo, Hernquist (2005, ApJ, 620, 79). Shown is the gas distribution with color indicating temperature, and brightness indicating gas density.

- [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.

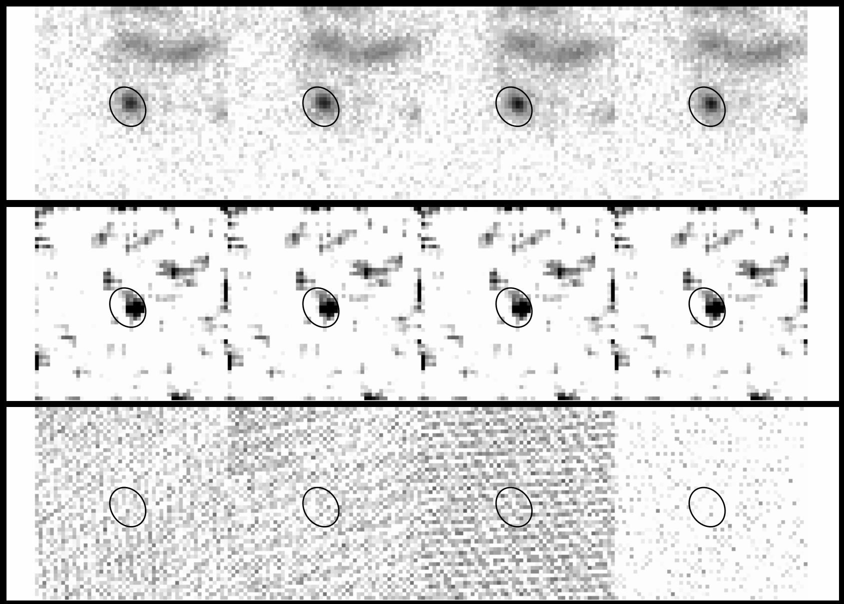
(2) A study of Early-Stage Mergers in the HUDF: Any AGN?



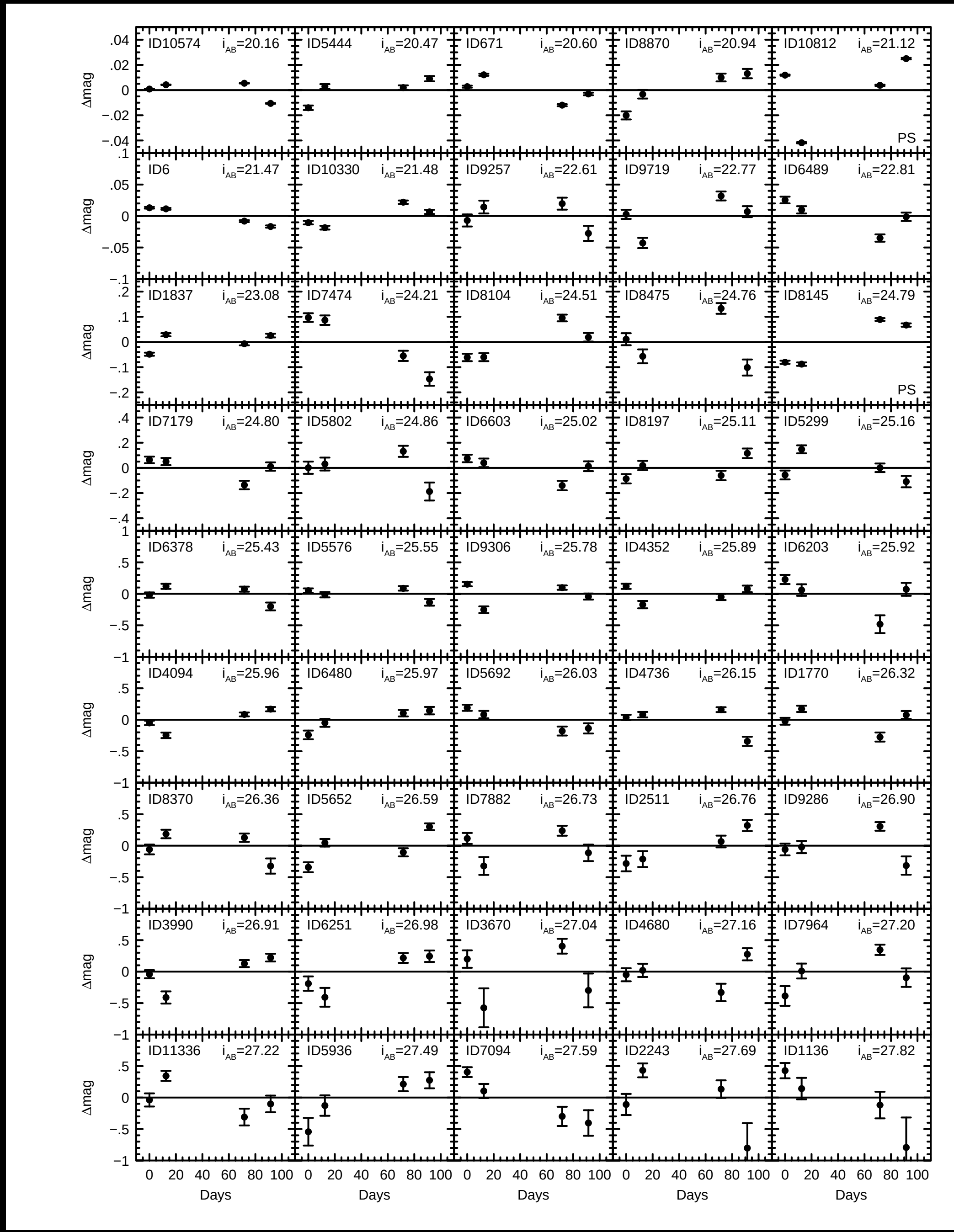
Tadpole galaxies in HUDF: www.hubblesite.org/newscenter/archive/2006/04/

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

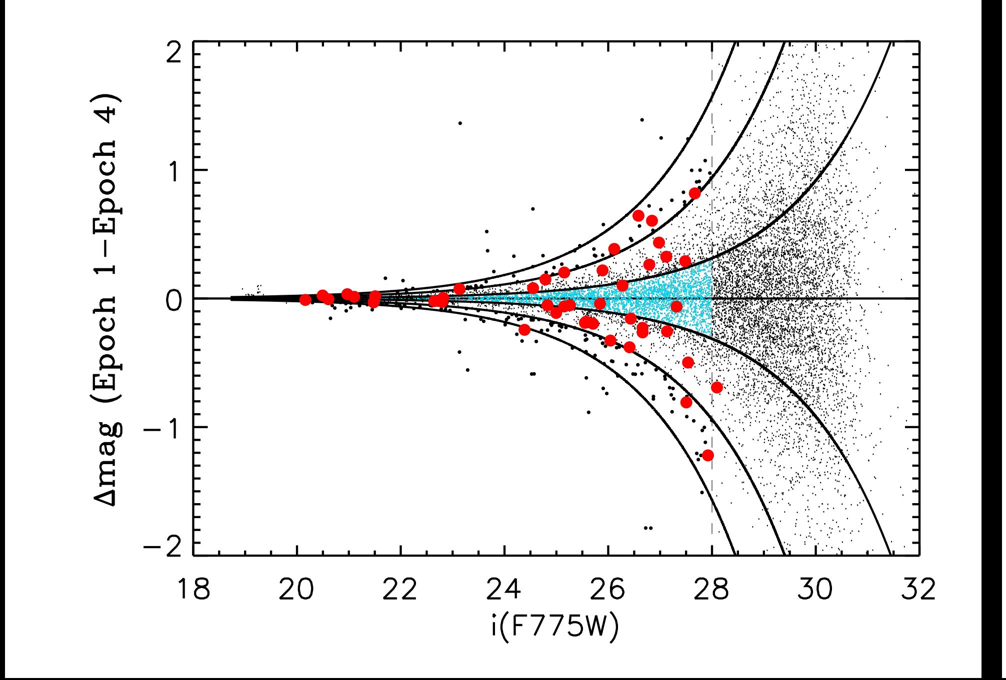
(3) Variable Objects in the HUDF

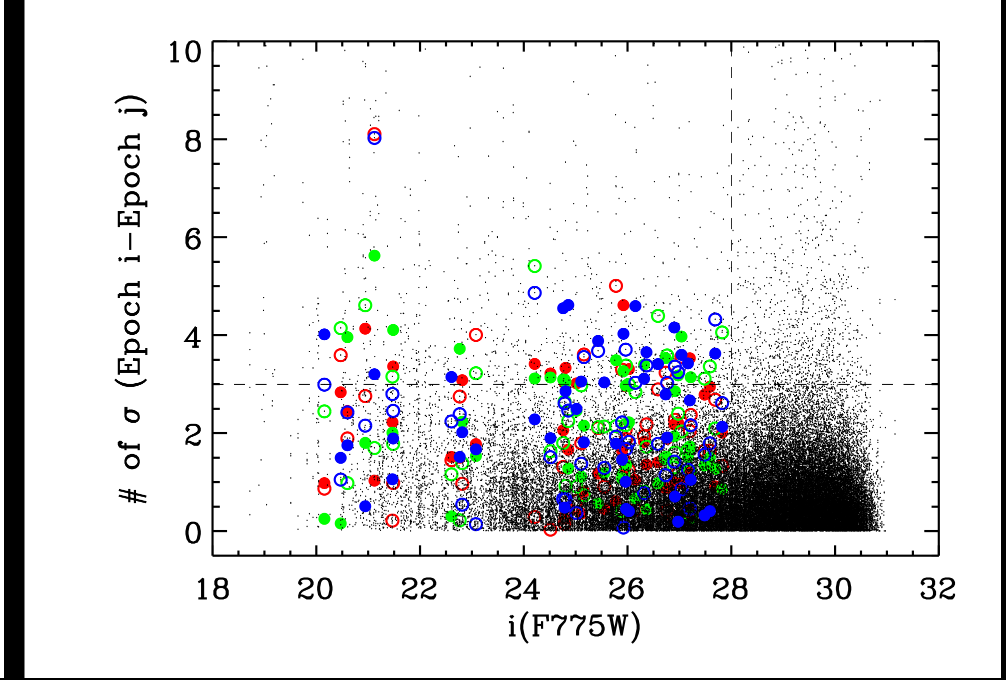


Top: 4 epochs; Middle: Variance map; Bottom: 4 Weight-maps. (Cohen, S., et al. 2006, ApJ, 639, 731; astro-ph/0511414)



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





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

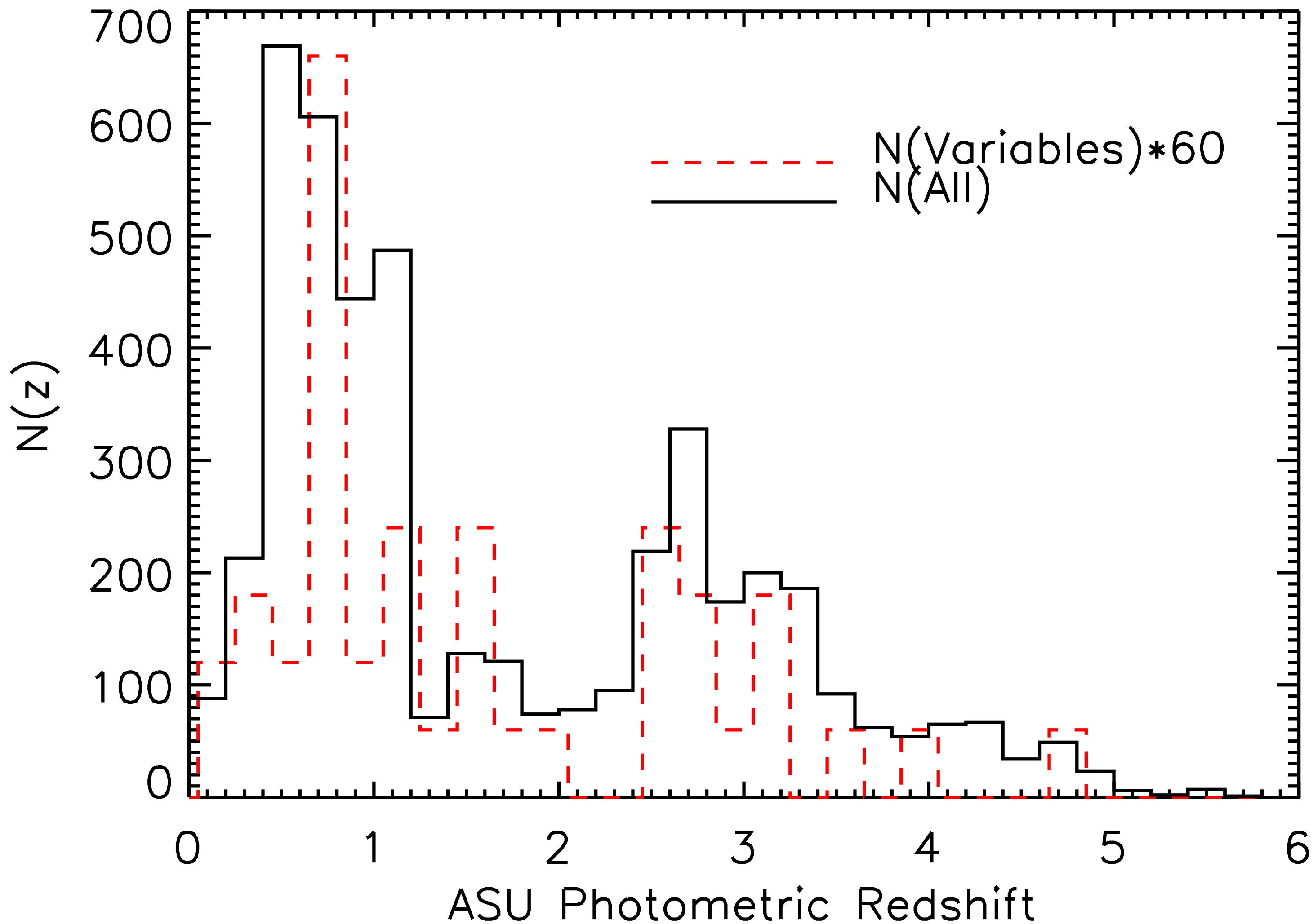
- Objects with |Delta mag|$\geq 3.0\sigma$ in $\geq$2 epoch-pairs are variable.

- 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. This AGN sample is not complete — we miss all non-variable and obscured AGN.

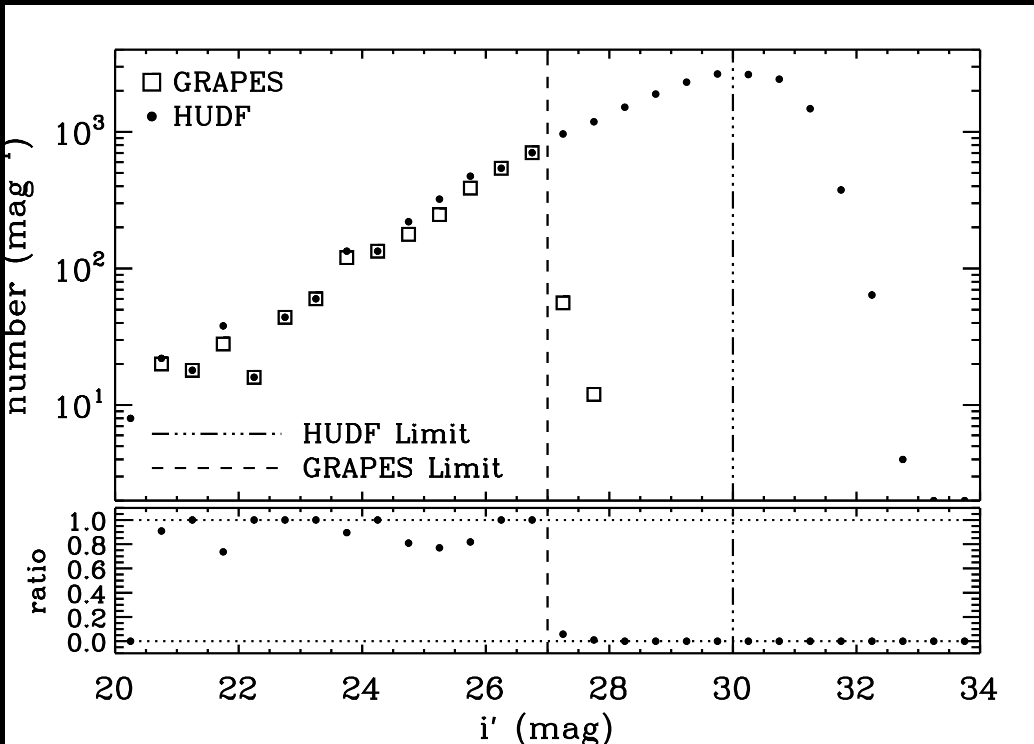


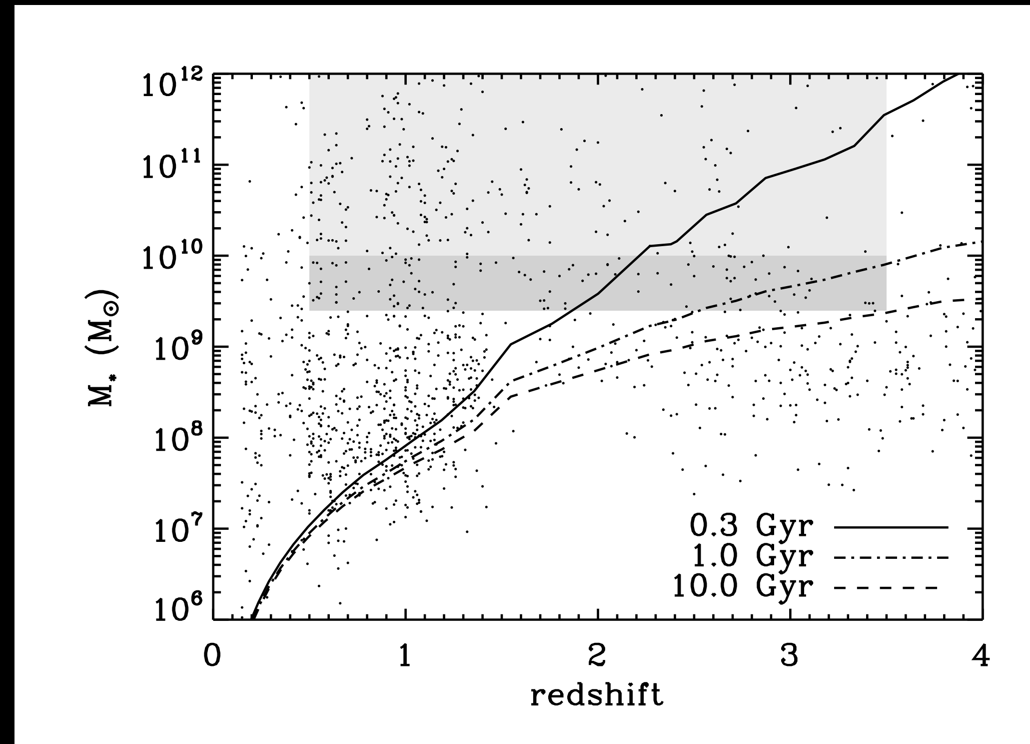
BViz(JH) Photo-z distribution of HUDF field gxys and variable objects:

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

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

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





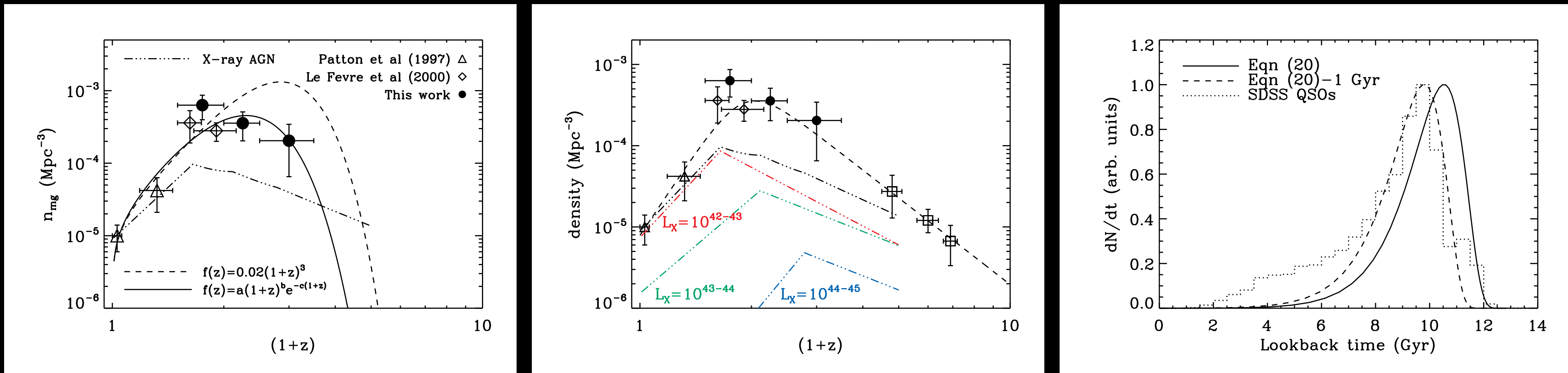
Ryan et al. (2007): HST/ACS grism pair-fraction(z) — sample selection:

- 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)

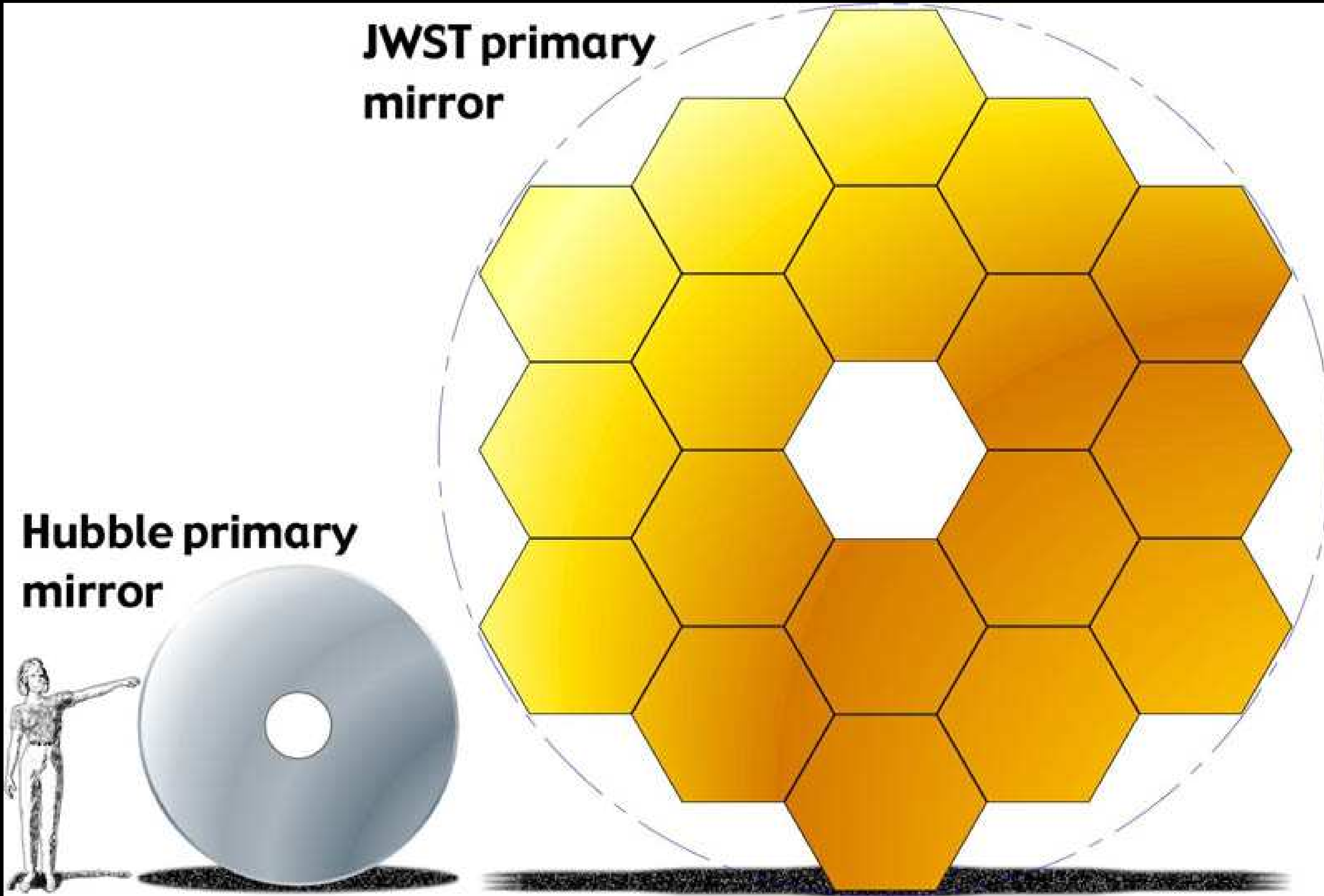


Ryan et al. (2007, 2008): HST/ACS grism epoch-dependent galaxy pair-fraction for AB$\lesssim$27, z$\lesssim$6: spectro-photo-z's for both objects in pair. Merger samples are very complex to select (Lotz et al. 2009).

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??

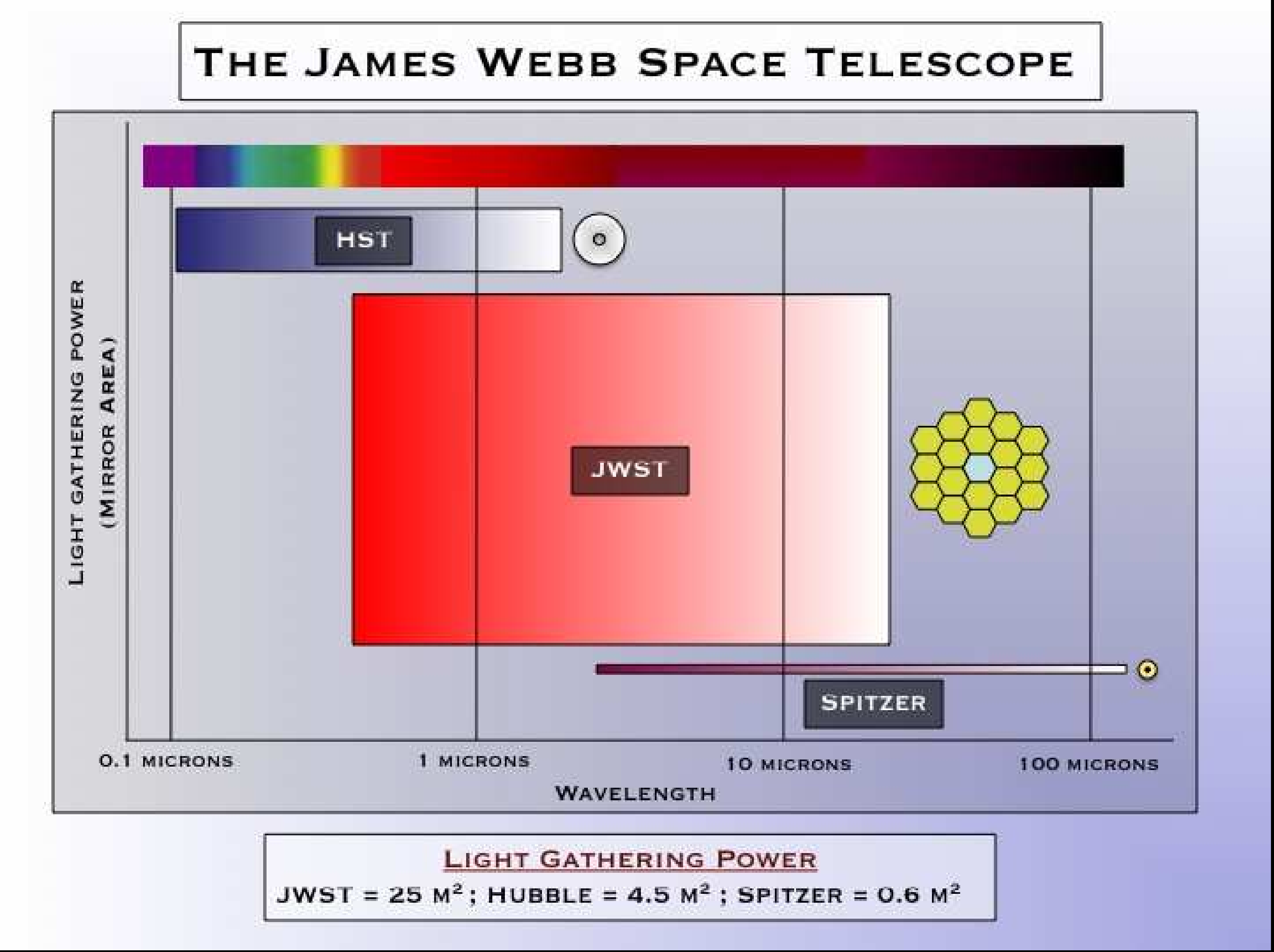
$\Rightarrow$ Circumstantial support for hierarchical models: a $\sim$1 Gyr delay between major mergers & visible SMBH feeding — weak AGN?

• 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.



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

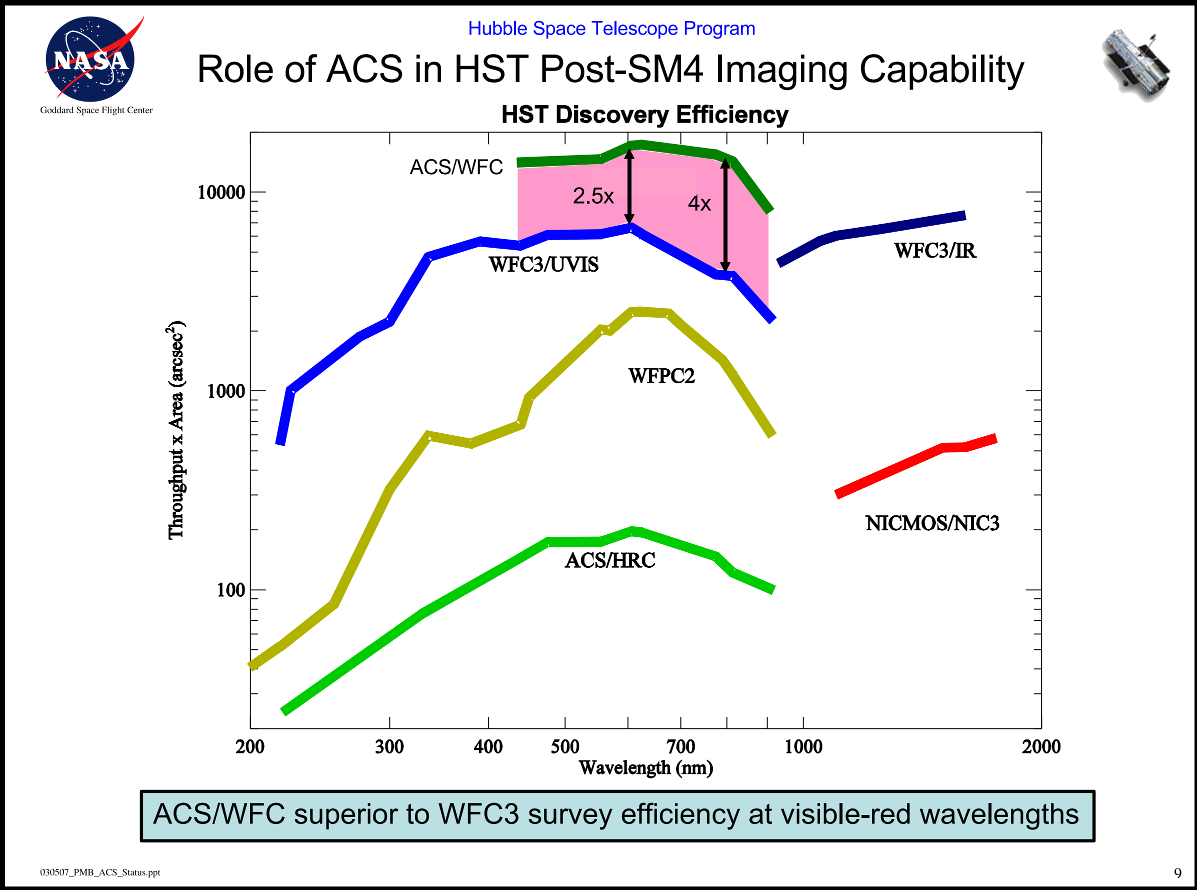
JWST has the same resolution in the near-IR as Hubble in the optical.

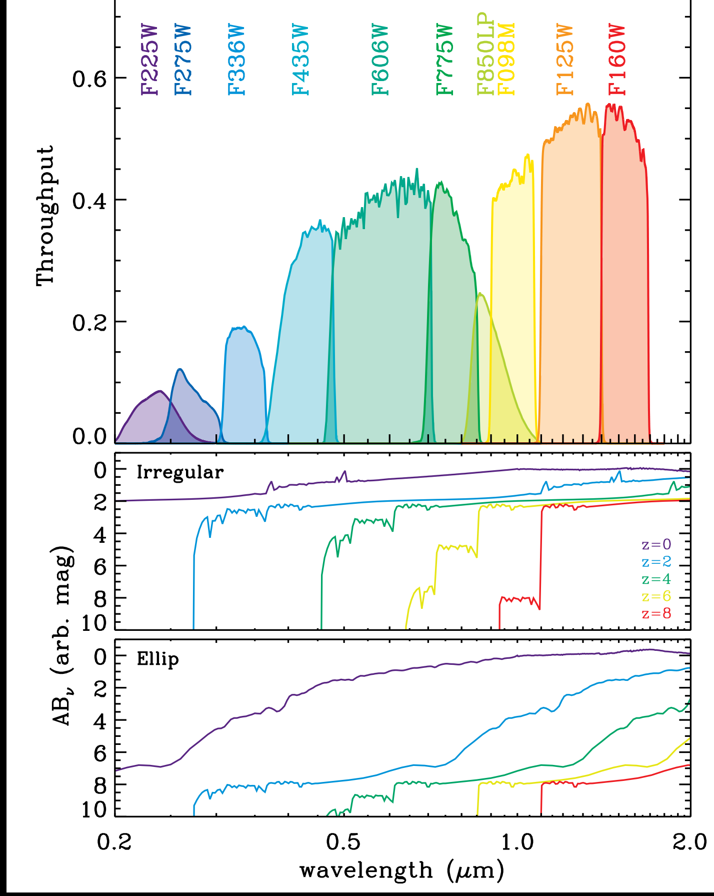


2000 Decadal: JWST is the near–mid-IR sequel to HST and Spitzer:

- 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:

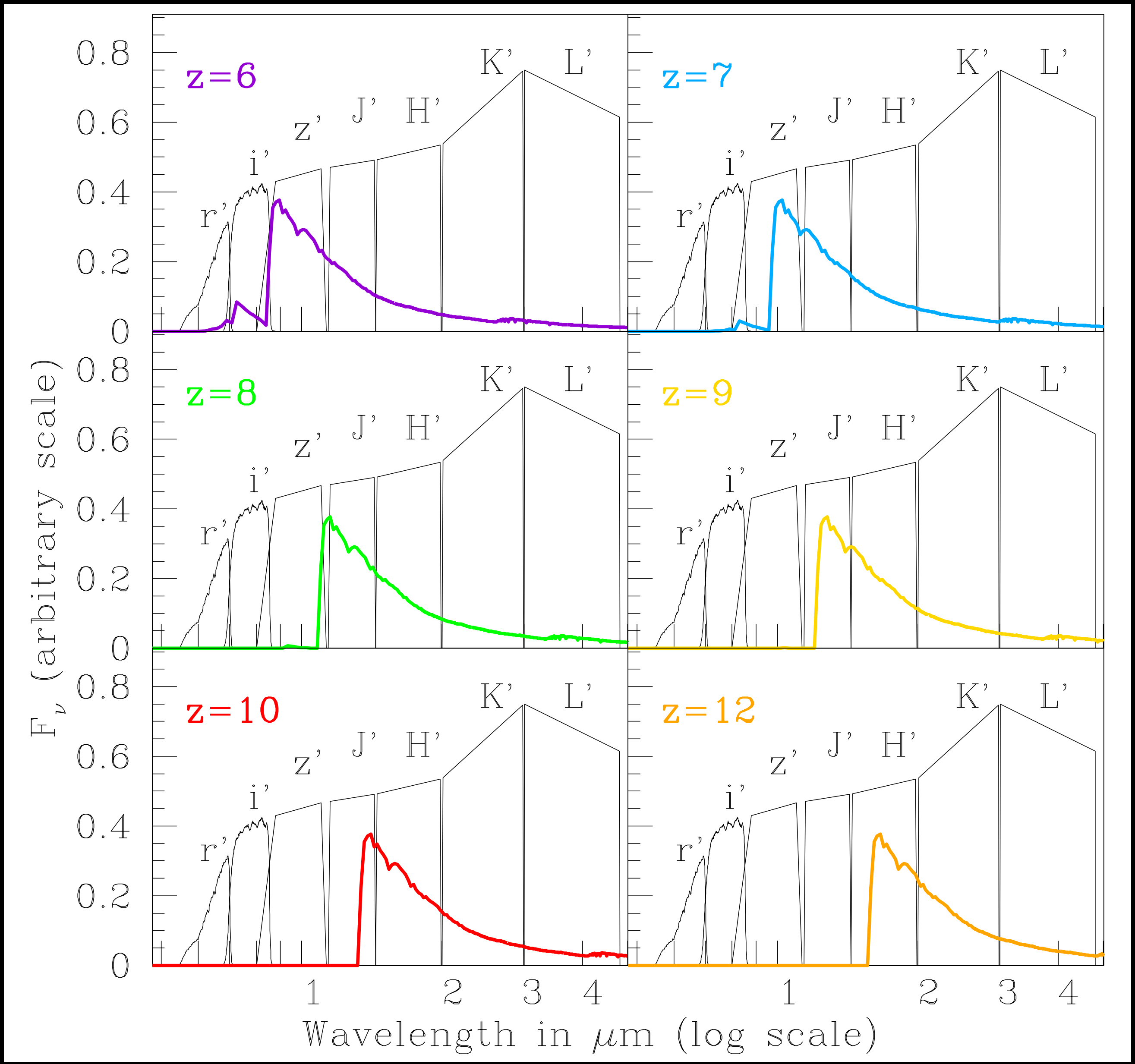
- QE$\gtrsim$70%, 1k$\times$1k array, 0.″13 pixels, FOV $\simeq$ 2.′25 $\times$2.′25.

$\Rightarrow$ 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.

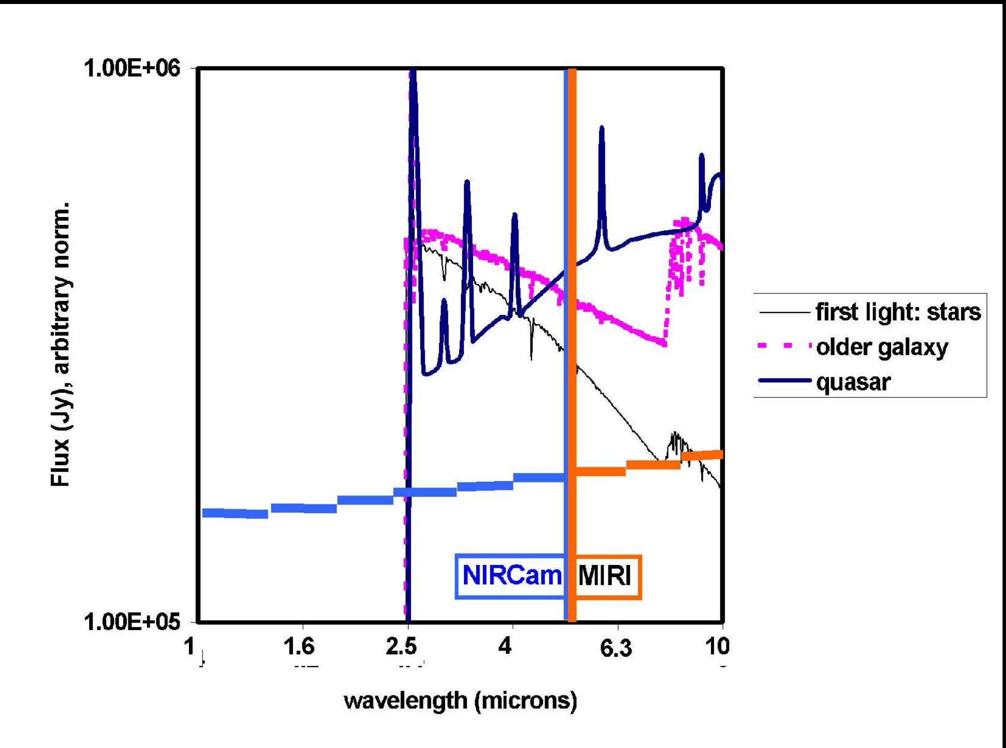
How can HST & JWST measure Galaxy Assembly & SMBH/AGN Growth?

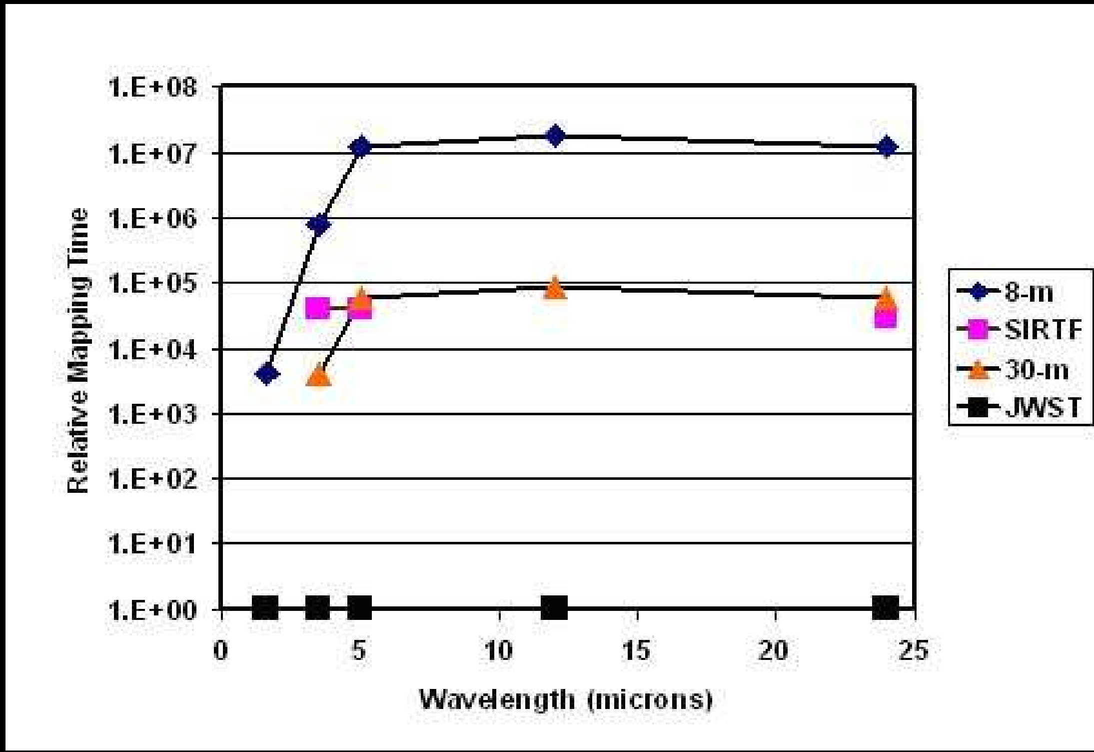


- Can't beat redshift: to see First Light, must observe near–mid IR.

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

• (1b) What sensitivity will JWST have?



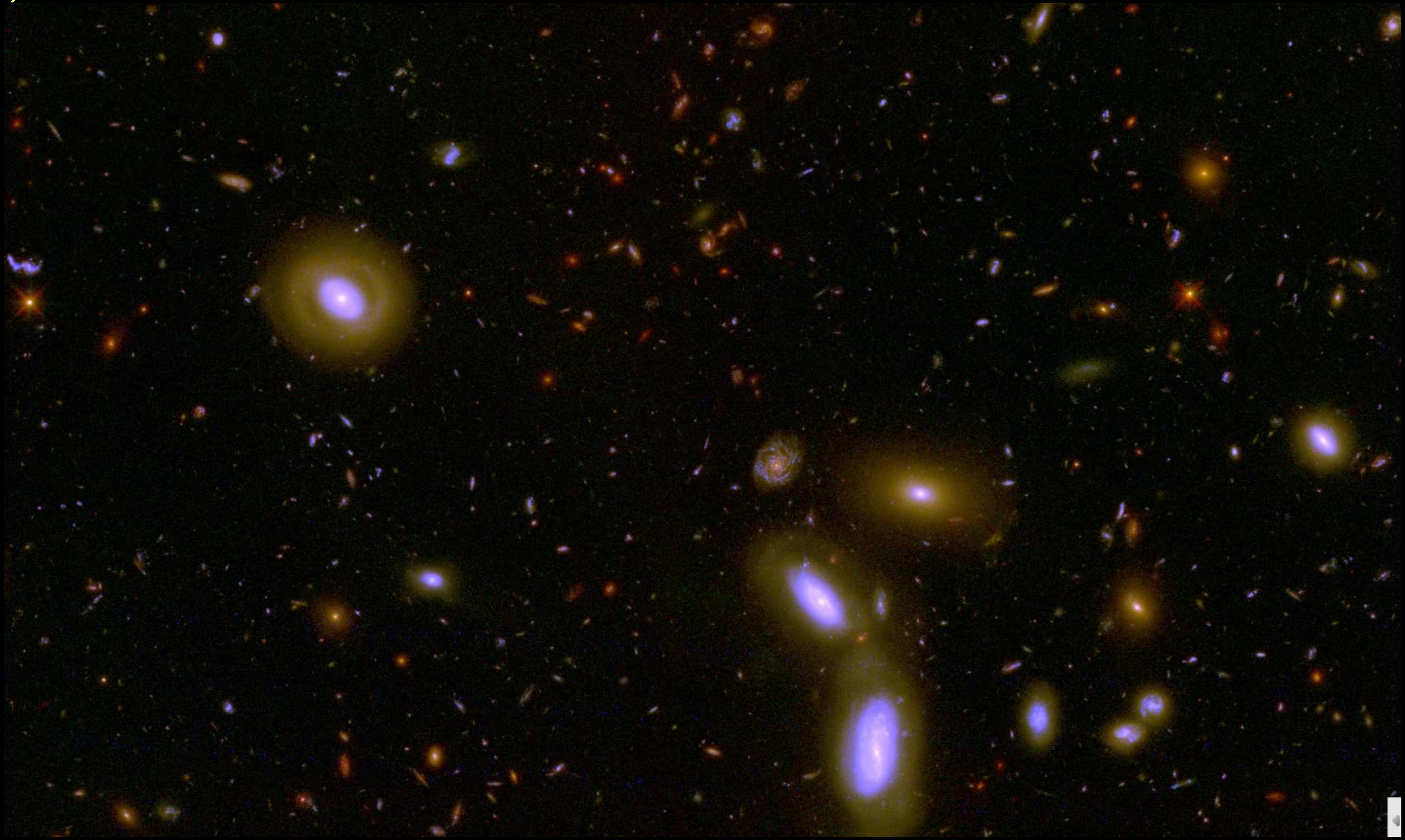


NIRCam and MIRI sensitivity complement each other, straddling $\lambda \simeq 5\ \mu$m. Together, they allow objects to be found to z=15–20 in $\sim 10^5$ sec (28 hrs).

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.

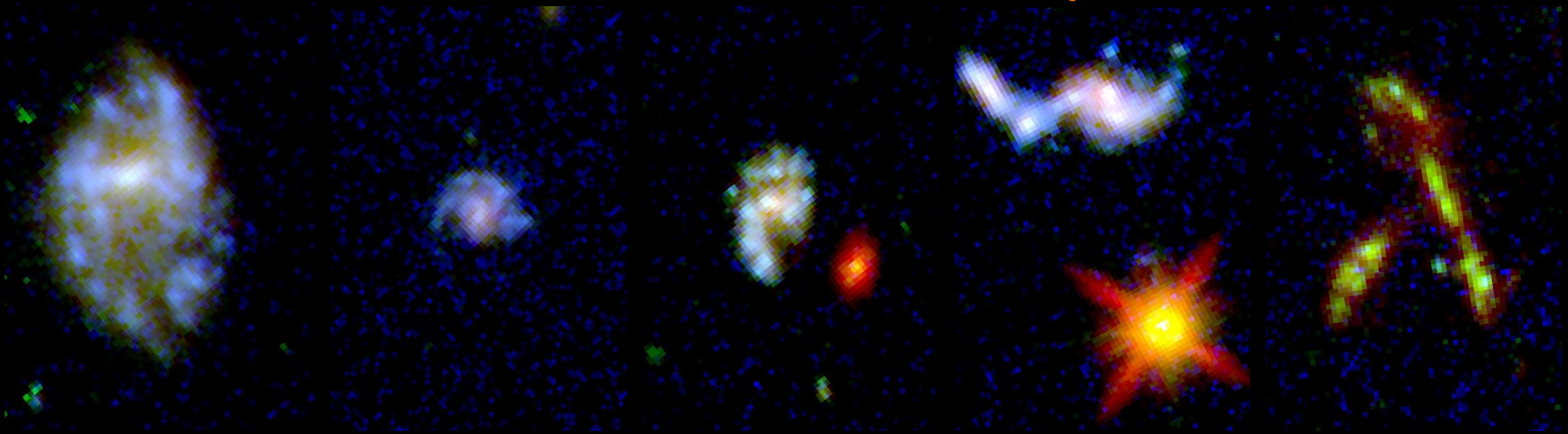
• (5) Can we DIRECTLY trace weak AGN growth with WFC3 and JWST?



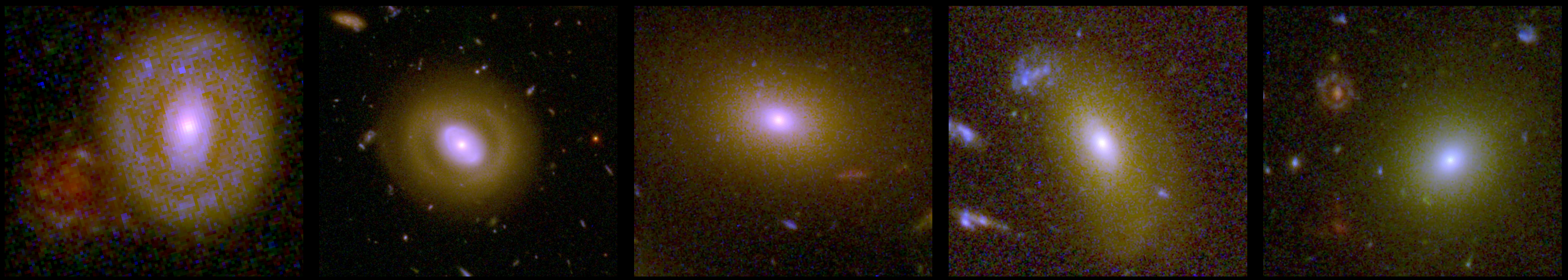
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

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.

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.

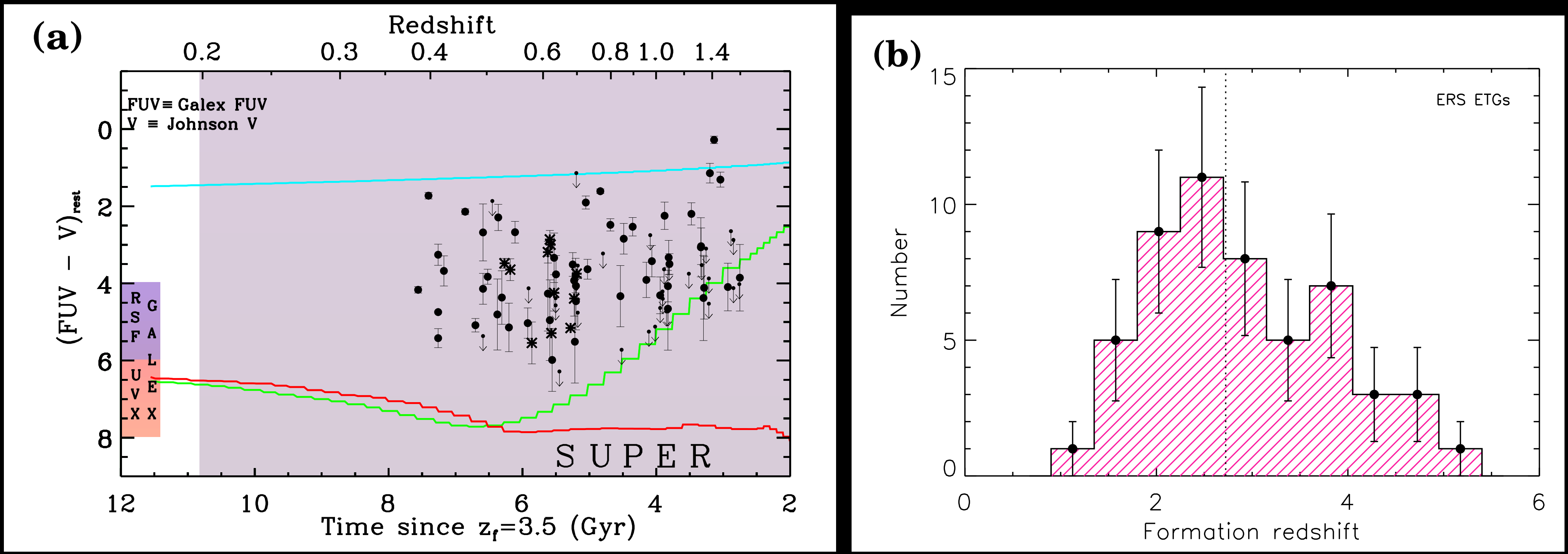


Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

(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 $z \lesssim 1.5$.

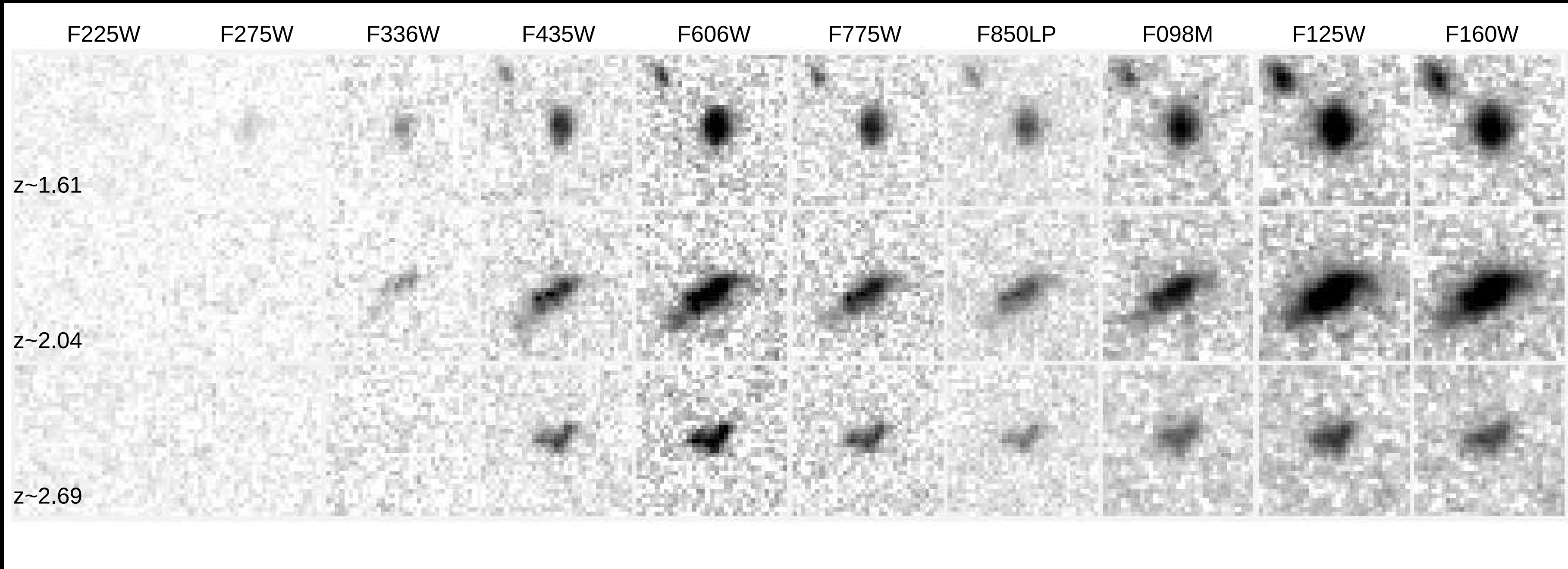


- 10-band WFC3 ERS data measured rest-frame UV-light in nearly all early-type galaxies at $0.3 \lesssim z \lesssim 1.5$ (Rutkowski et al. 2012, ApJS, 199, 4).

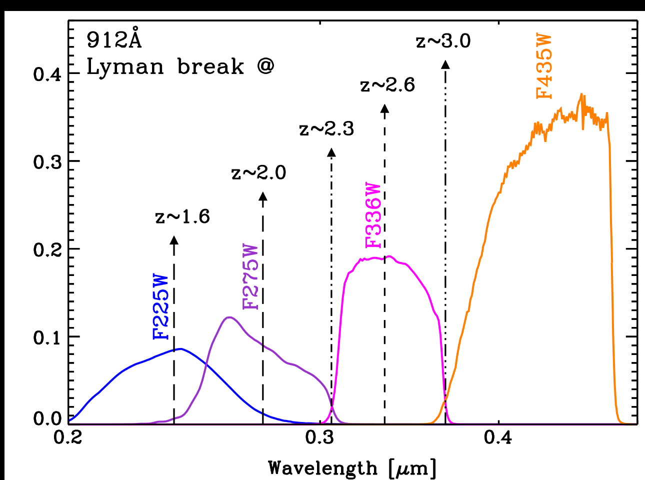
$\Longrightarrow$ Most ETGs have continued residual star-formation after they form.

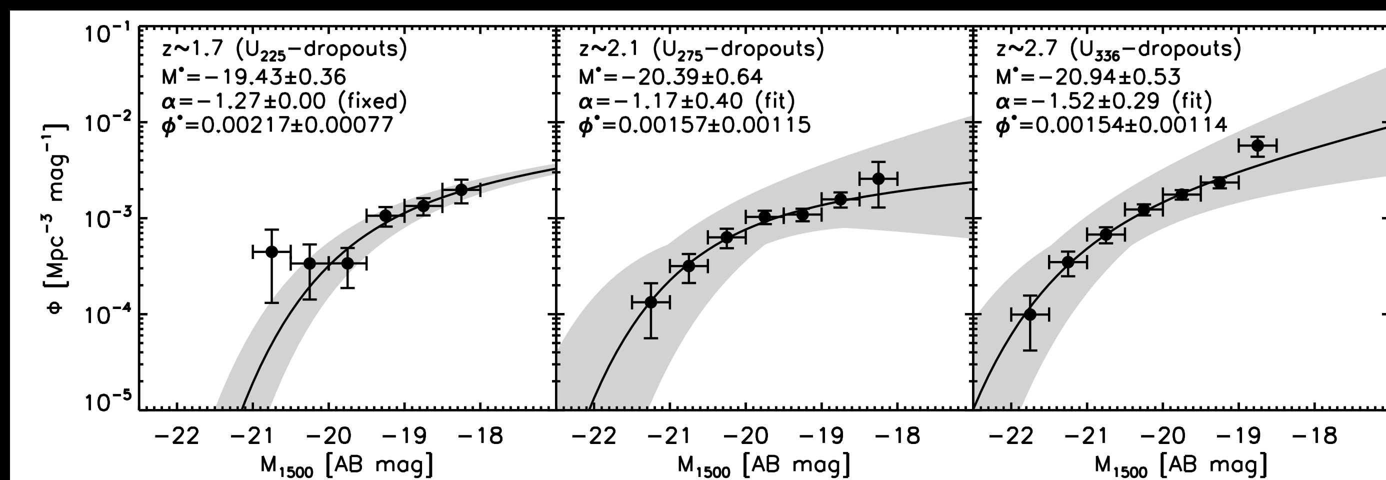
- Can determine their $N(z_{form})$, which resembles the cosmic SFH diagram (*e.g.*, Madau et al. 1996). This can directly constrain the process of galaxy assembly and down-sizing (Kaviraj, Rutkowski et al. 2012, MNRAS).

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



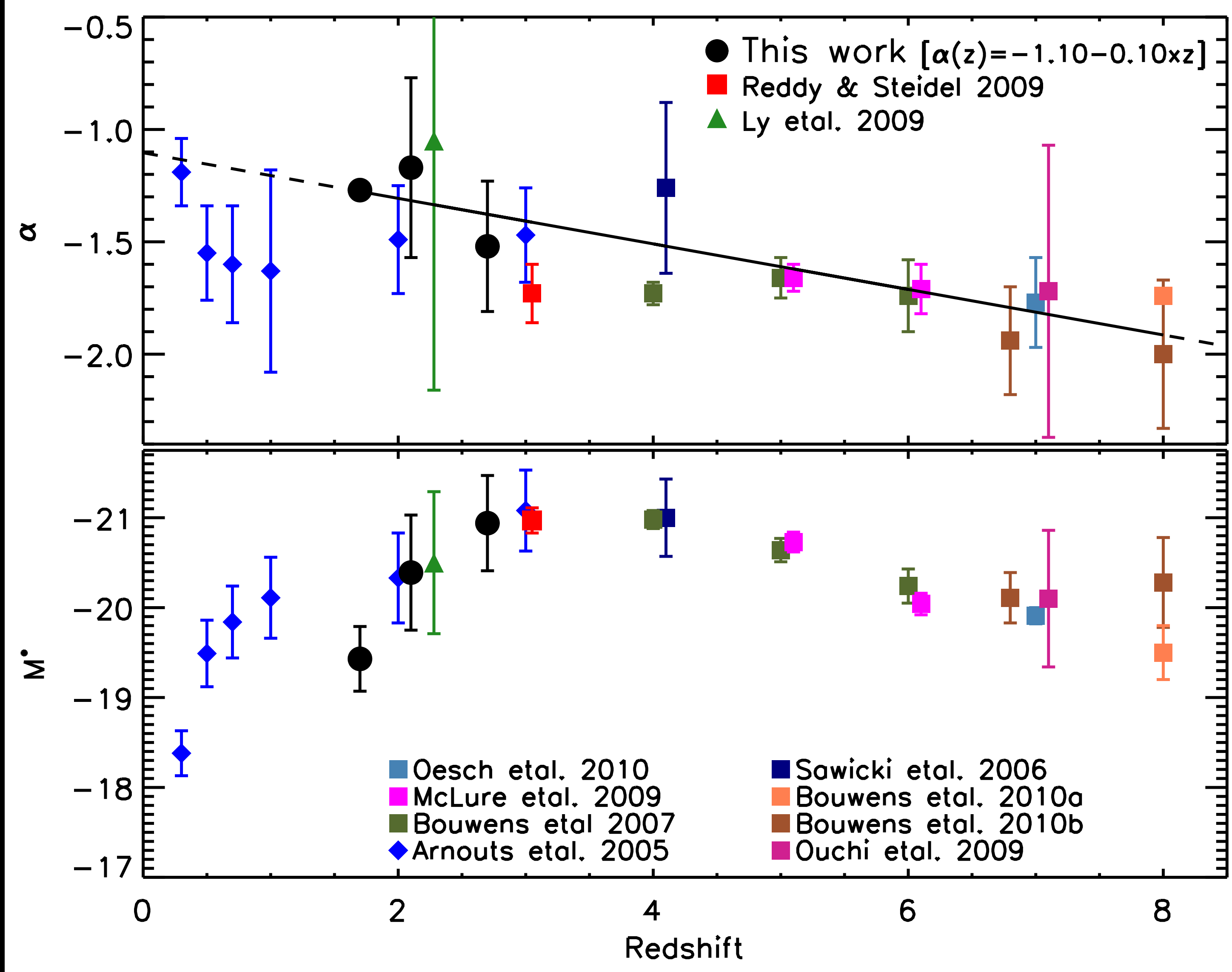
Lyman break galaxies at the peak of cosmic SF (z≃1-3; Hathi ea. 2010)





- 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).

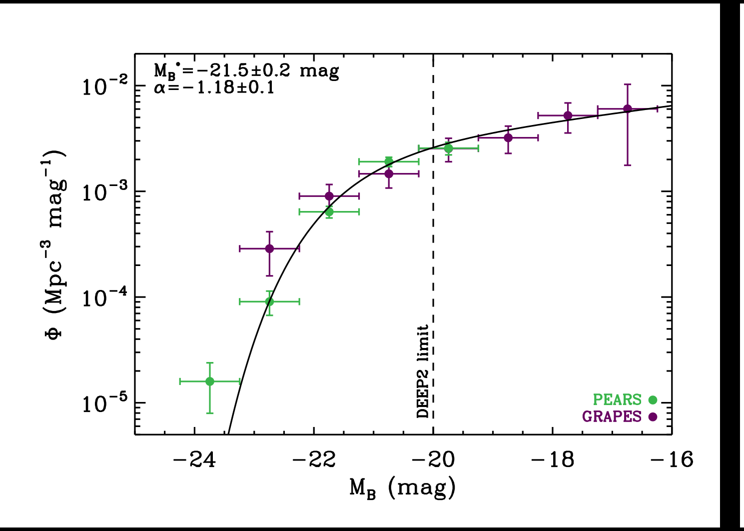


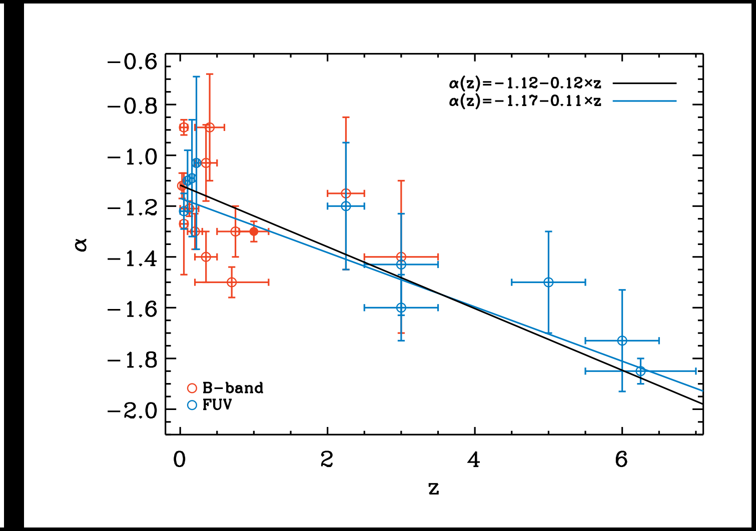
Measured faint-end LF slope evolution (top) and characteristic luminosity evolution (bottom) from Hathi et al. 2010 (ApJ, 720, 1708).

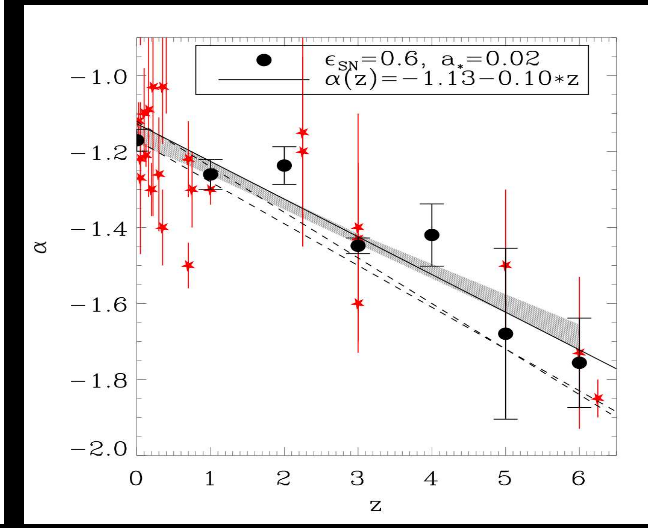
- In the JWST regime at z$\gtrsim$8, expect faint-end LF slope $\alpha \simeq$2.0.
- In the JWST regime at z$\gtrsim$8, expect characteristic luminosity M^* $\gtrsim$–19.

$\Rightarrow$ Could have critical consequences for gravitational lensing bias at z$\gtrsim$10.

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

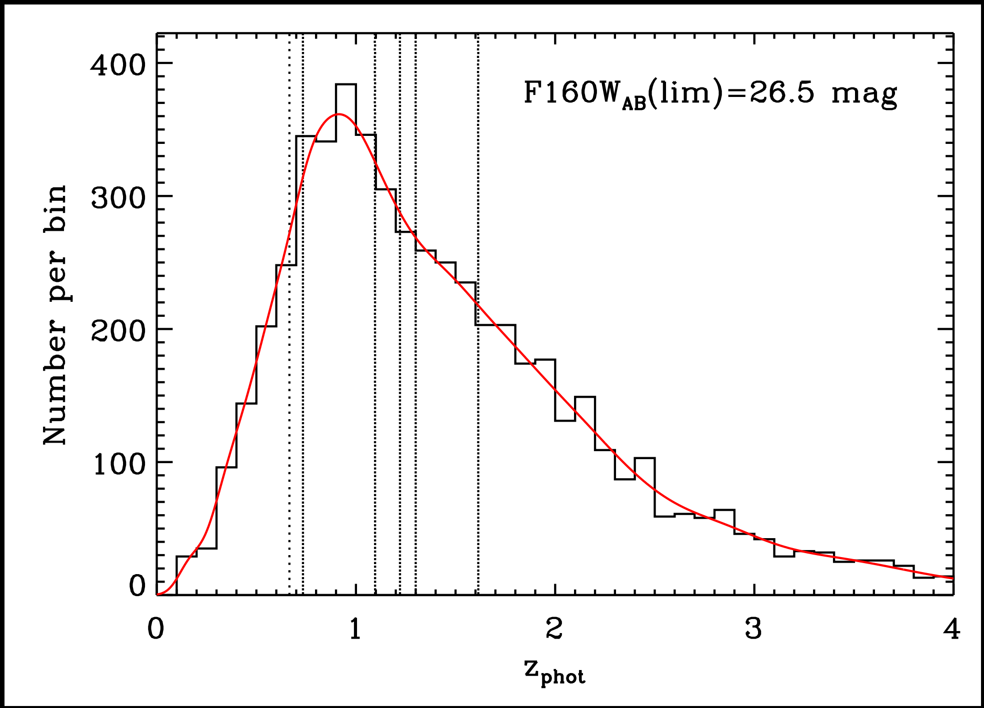


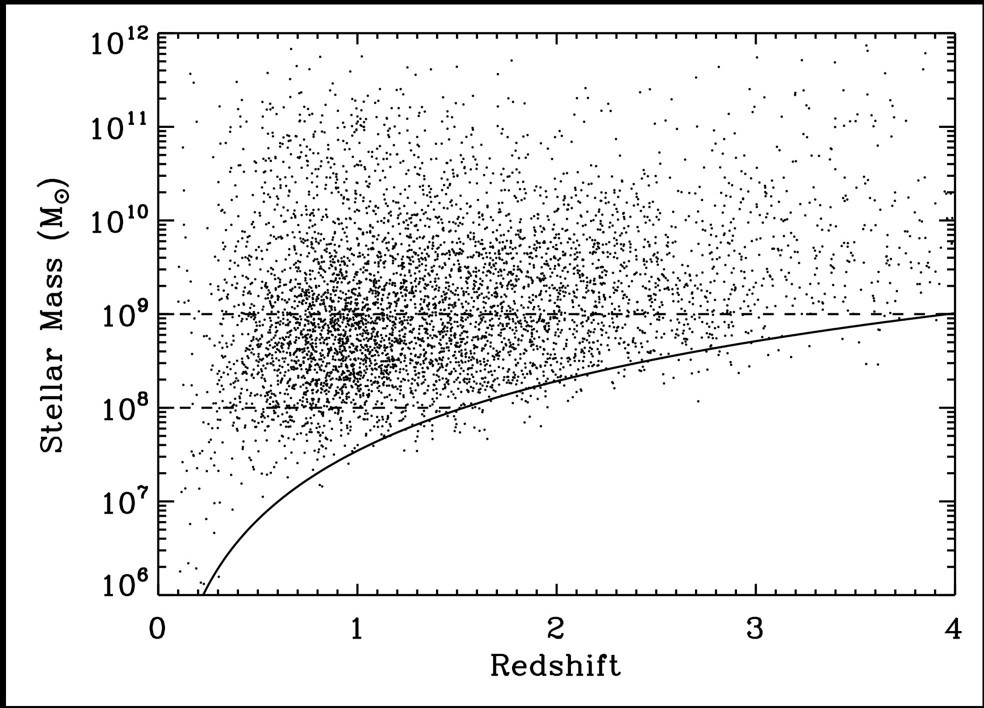




Faint-end LF-slope at z$\gtrsim$1 with accurate ACS grism z's to AB$\lesssim$27 (Cohen et al.; Ryan et al. 2007, ApJ, 668, 839) constrains hierarchical formation:

- 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 $\lesssim$4% with small systematic errors (Hathi et al. 2010, 2012), resulting in a reliable N(z).

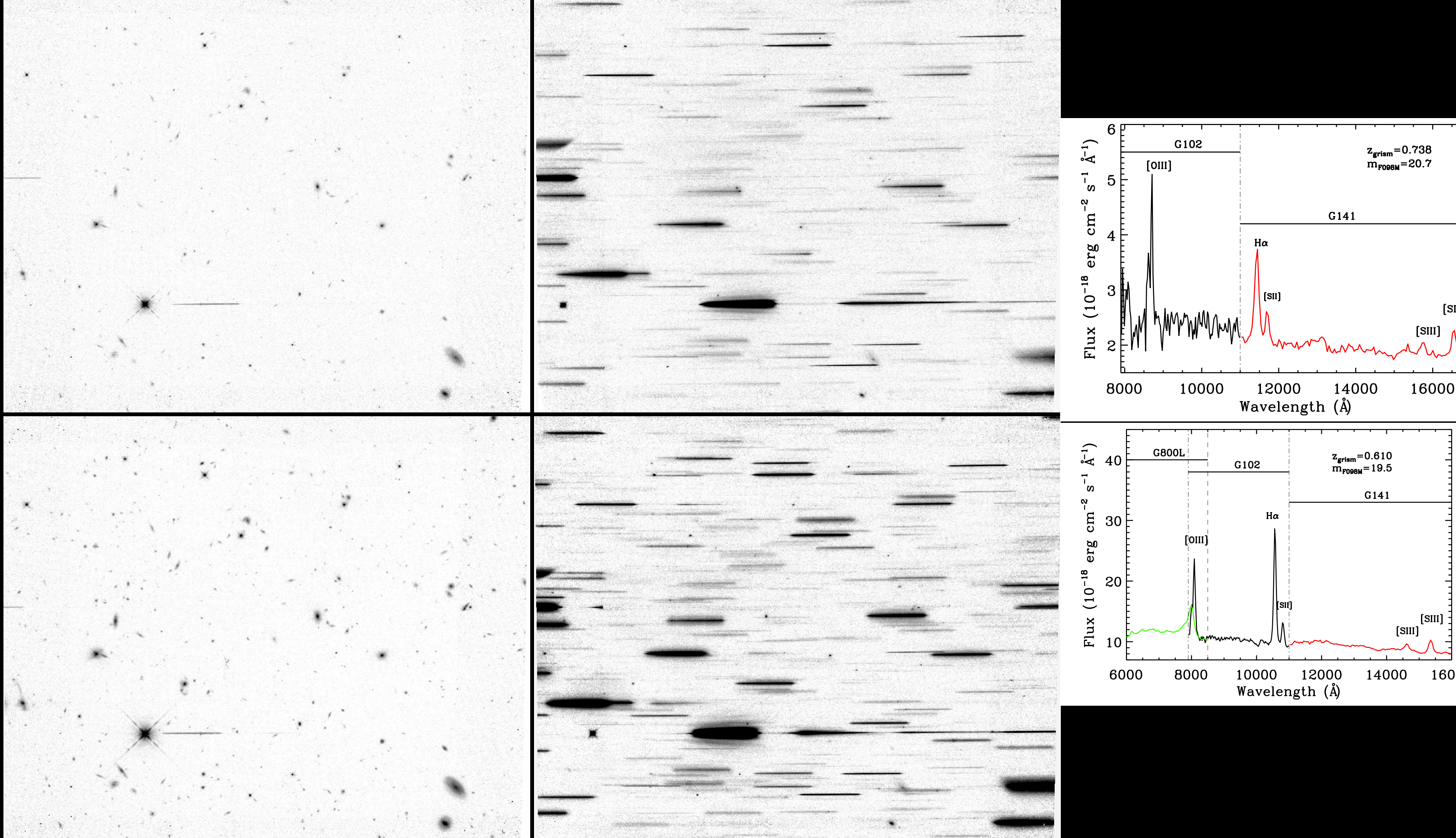
• Measure masses of faint galaxies to AB=26.5 mag, tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?).

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.



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.

(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.

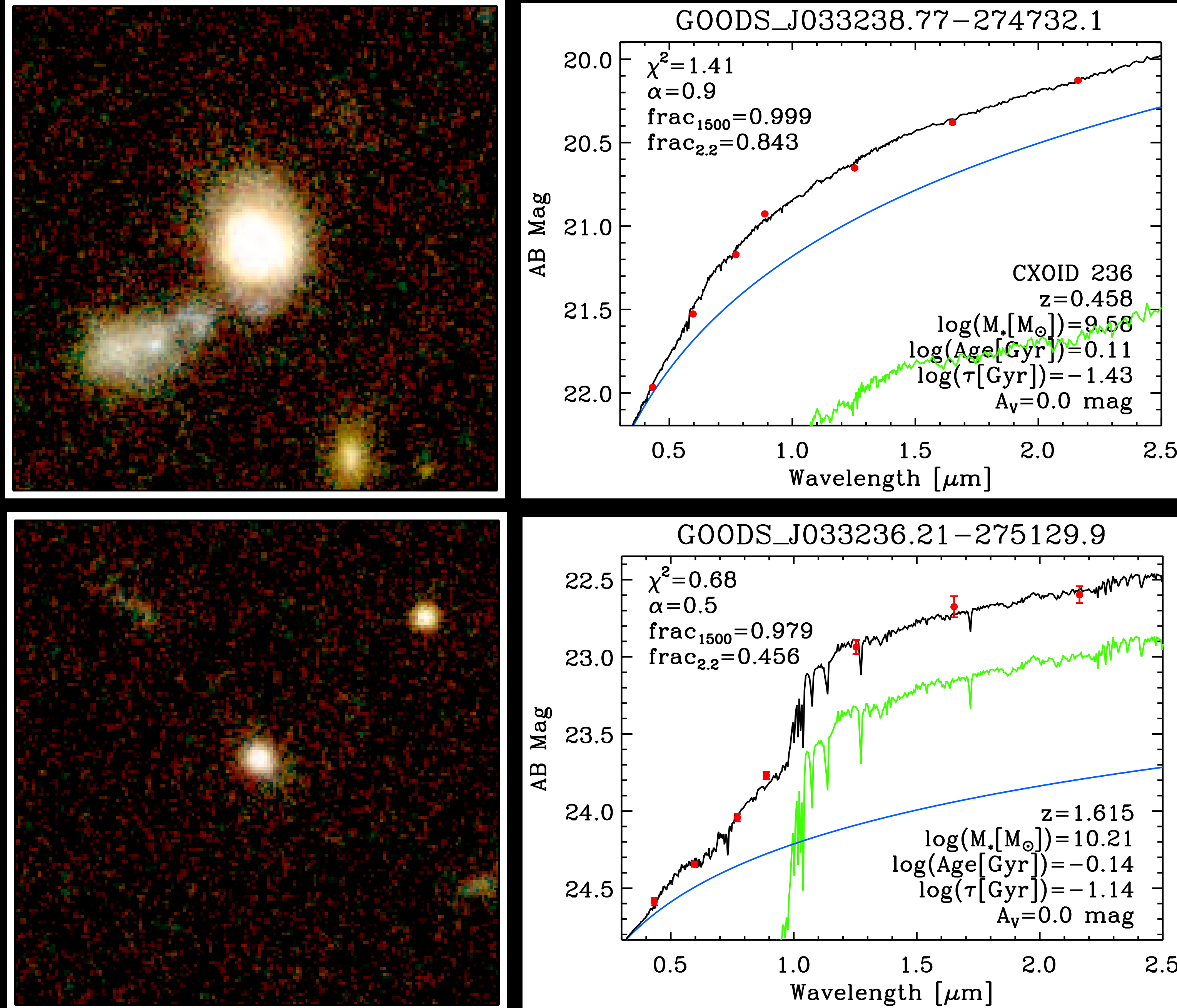
[5] Work in progress on other potential caveats:

- 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.

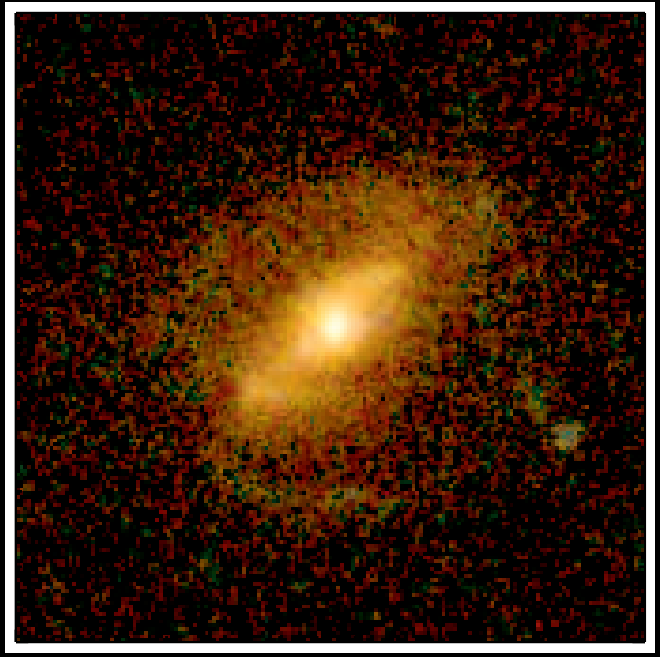
[6] Repeat [1]–[5] for 7000 ERS objects with 10-band spz's to AB=27 mag.

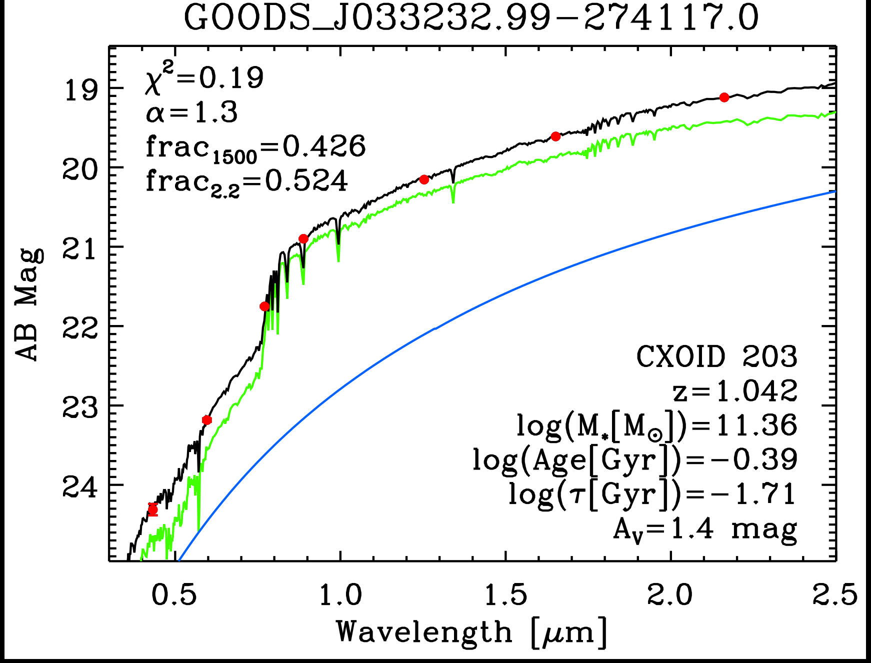
- Fit the BC03 stellar SED only to objects where χ^2 doesn't require both.

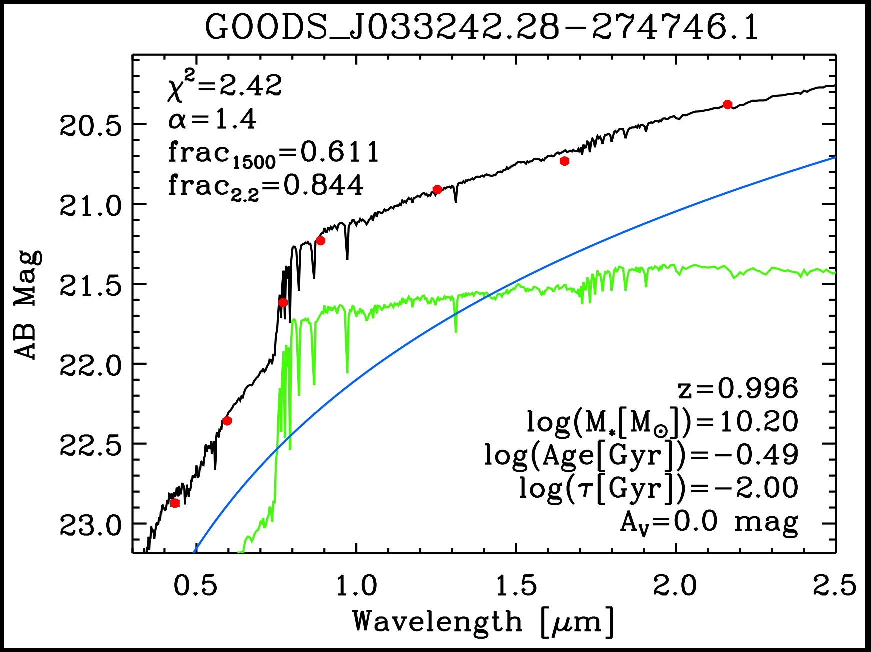


Cohen et al. (2010): GOODS/VLT BVizJHK images

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







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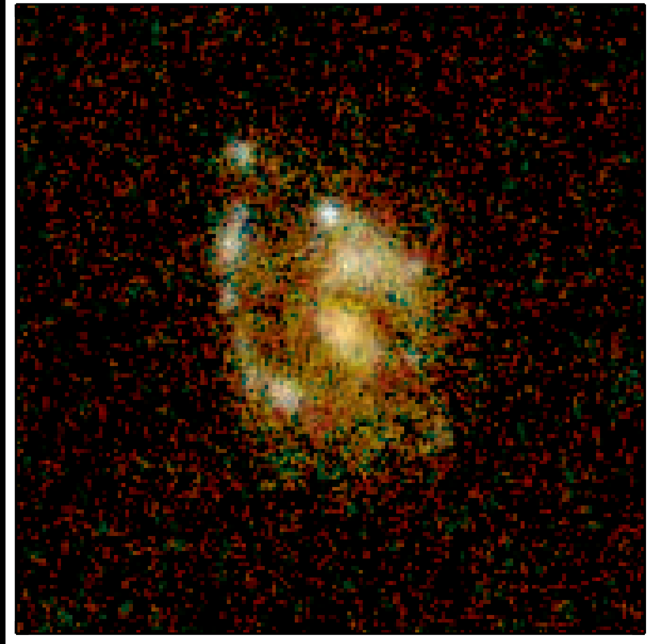

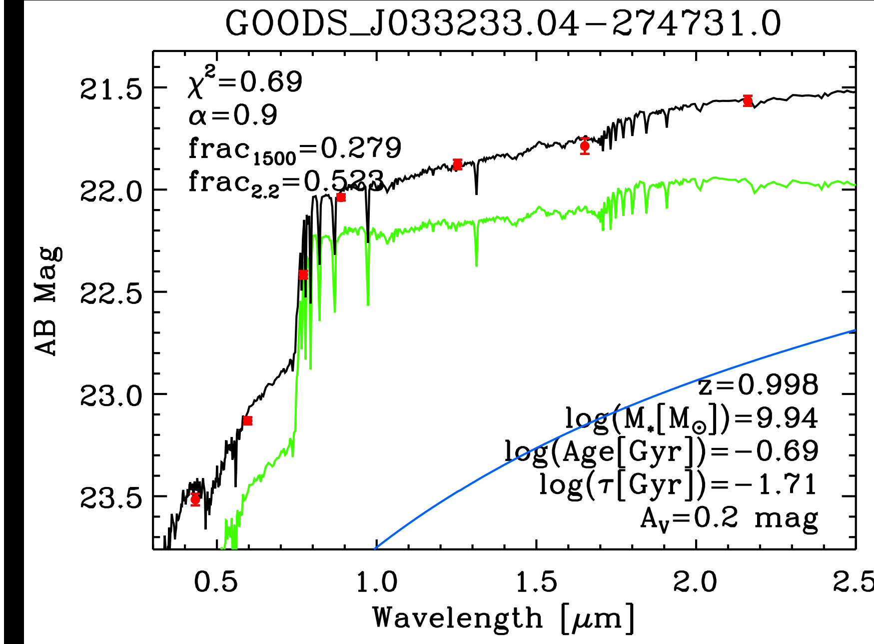

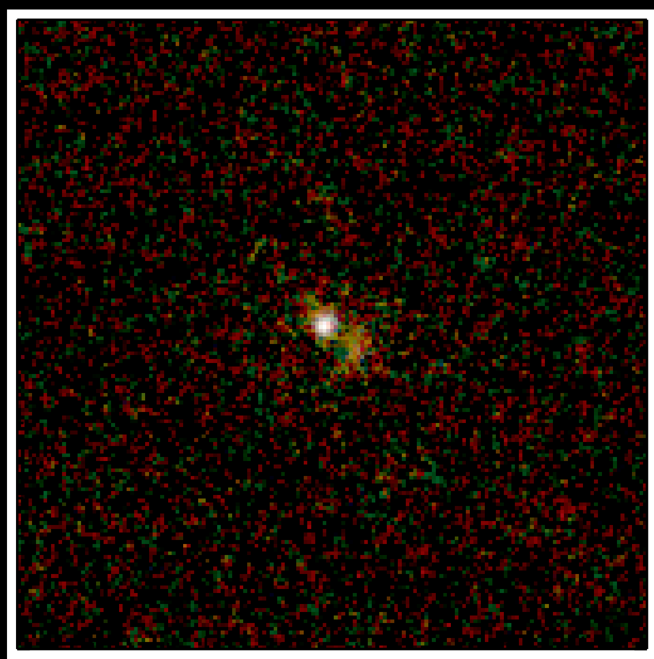

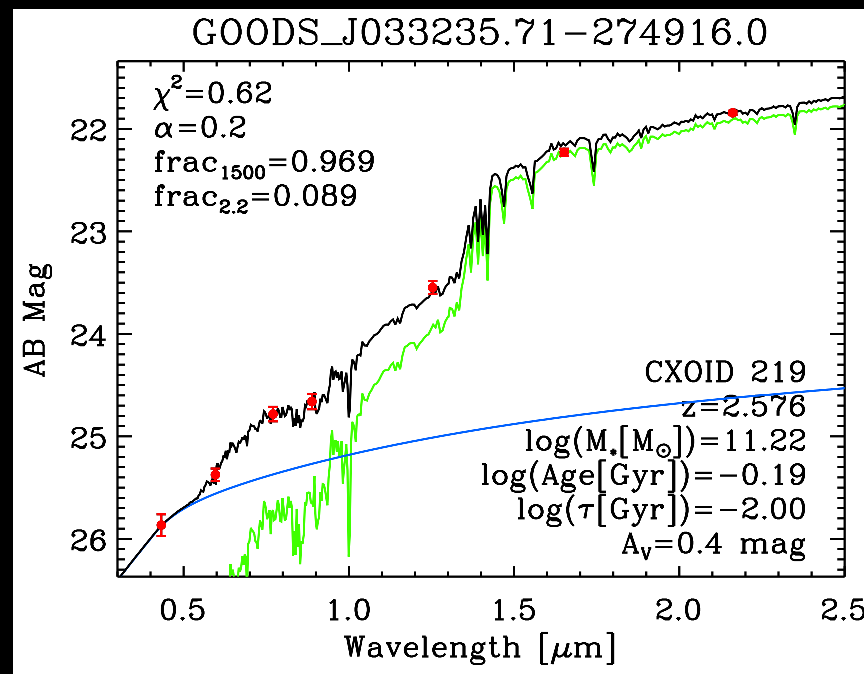

Cohen et al. (2010): GOODS/VLT BVizJHK images

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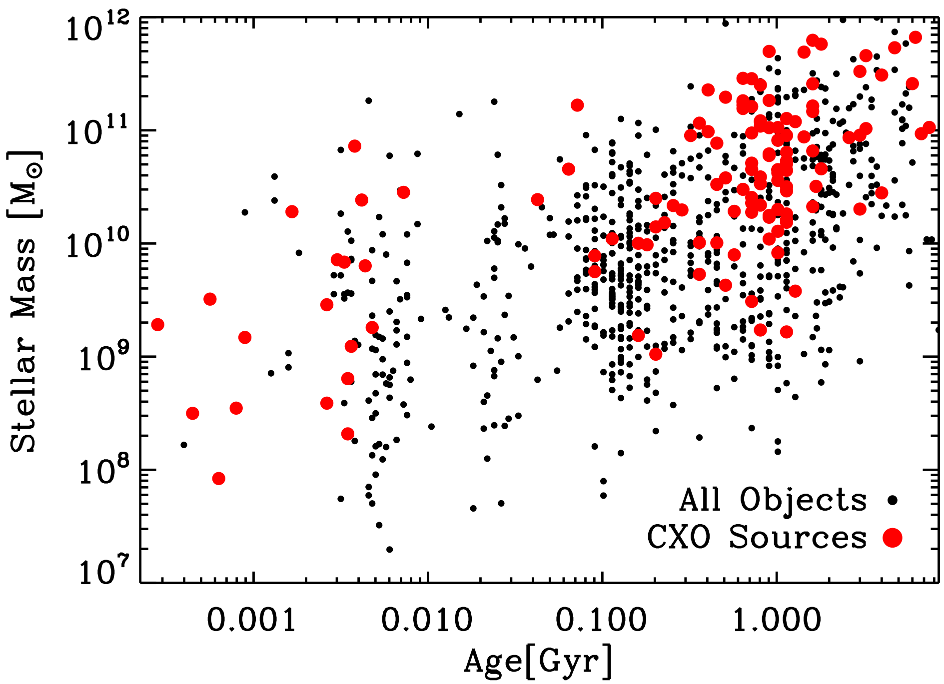
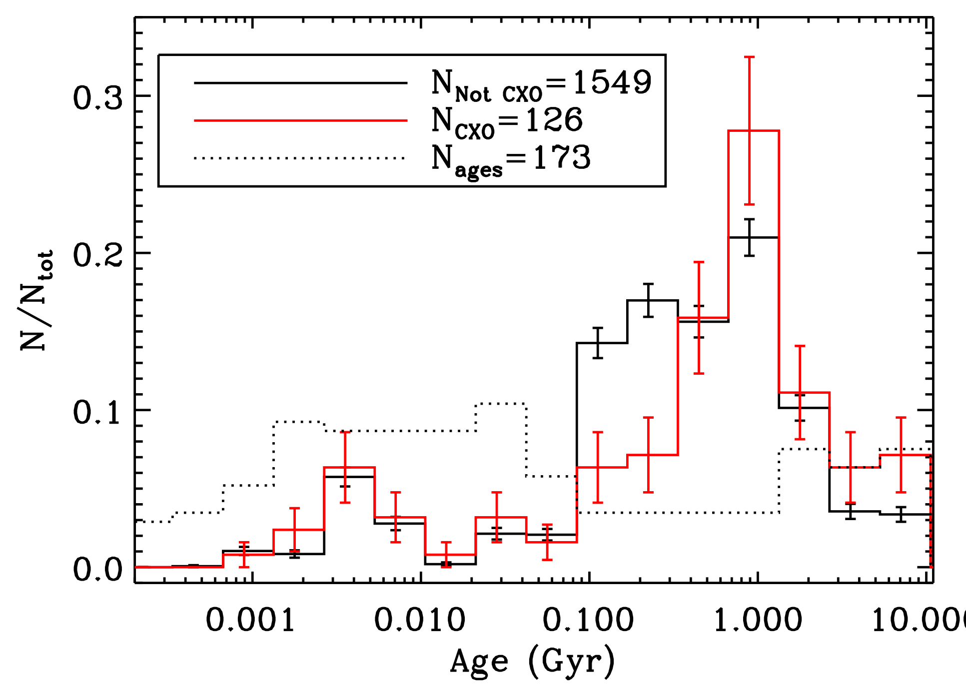




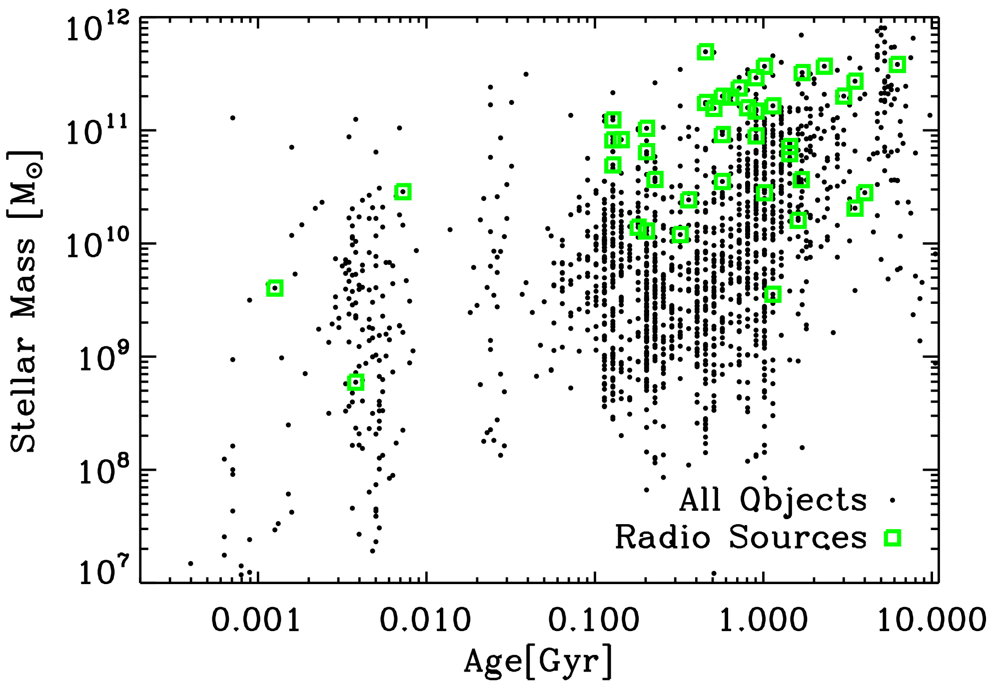
Cohen et al. (2010): Best fit Stellar Mass vs. Age: X-ray and field galaxies.

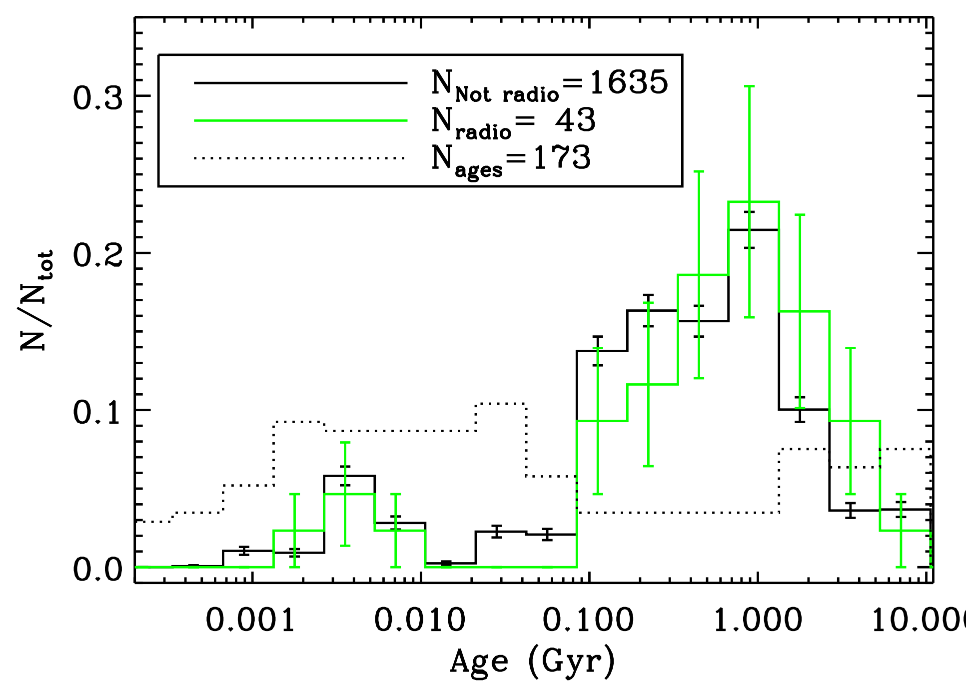
Field galaxies have: Blue cloud of ∼100-200 Myr, Red cloud of $\gtrsim$1–2 Gyr.

- 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.





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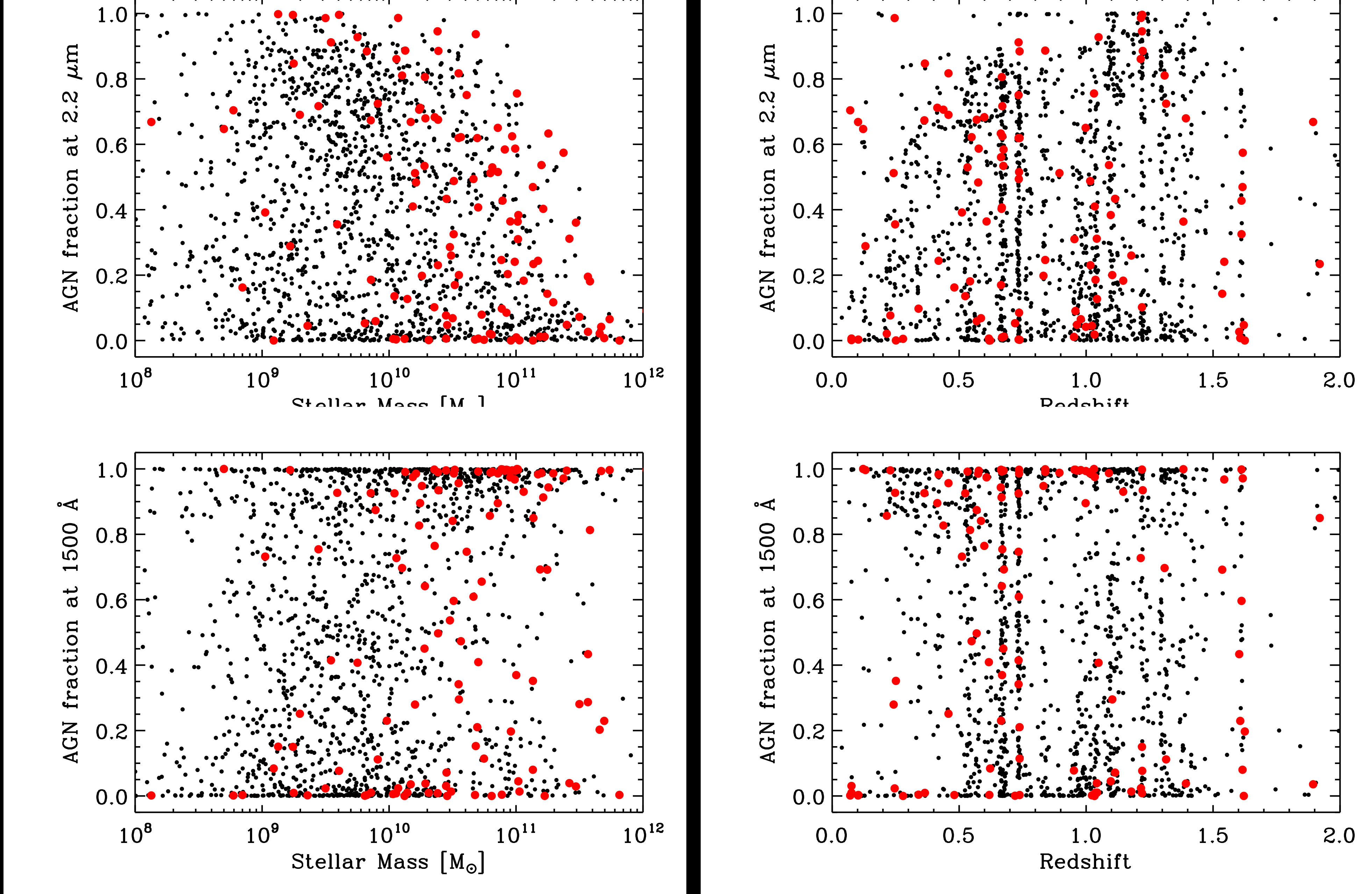
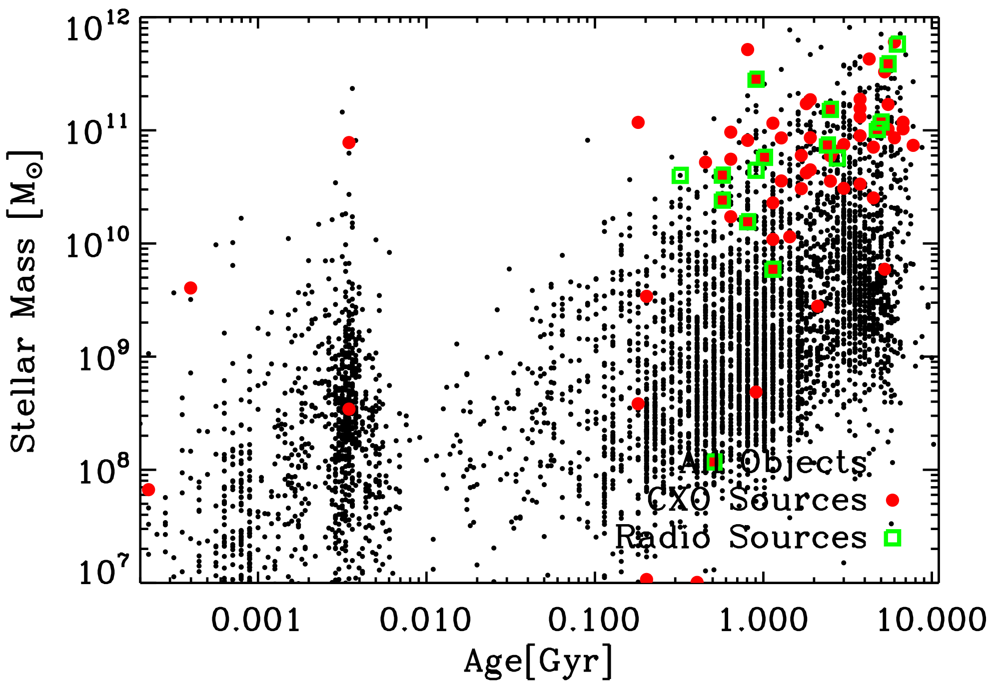
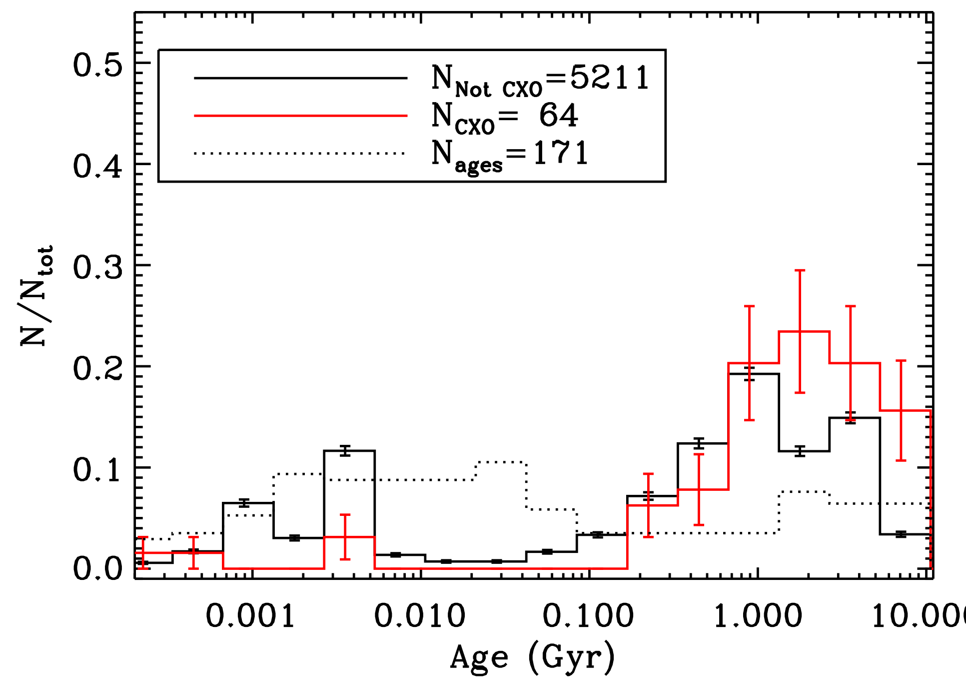


Cohen$^+$ (2010): AGN fraction vs. Stellar Mass & z: X-ray and field gxys.

⇒ 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.

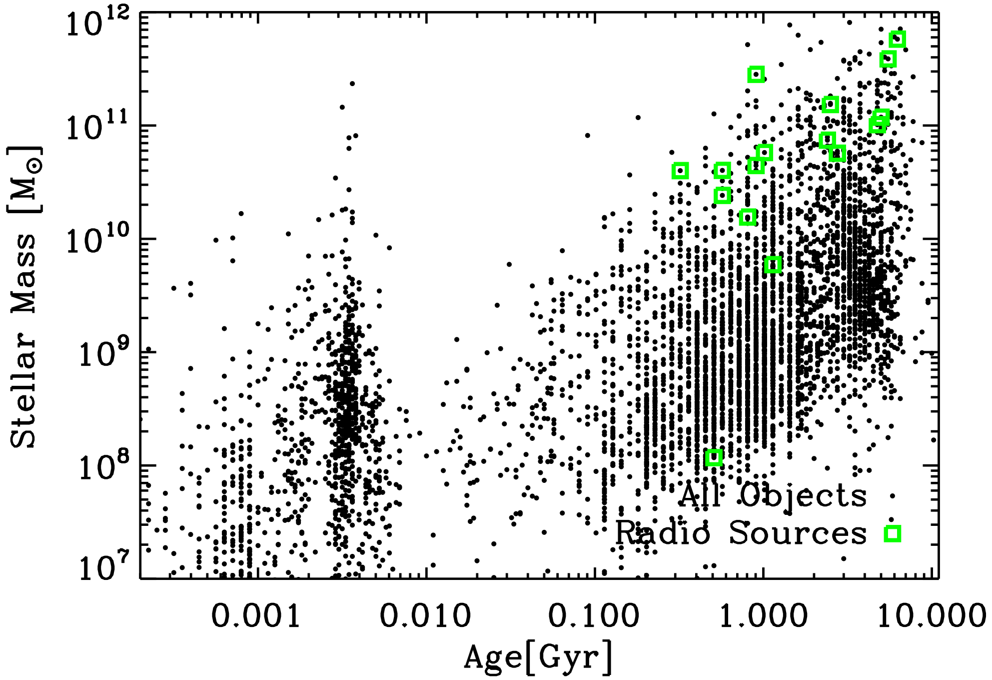


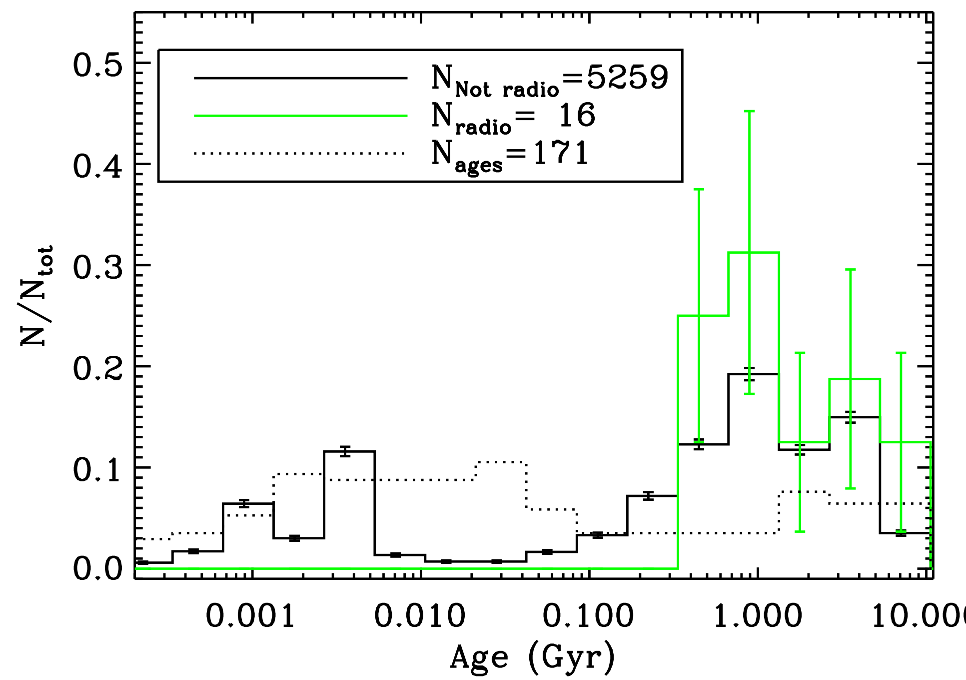


Cohen et al. (2010): Best fit Stellar Mass vs. Age: X-ray and field galaxies.

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

- X-ray sources reside in galaxies with M$\gtrsim 10^{10}$ $M_\odot$, and are older than the field population by $\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.





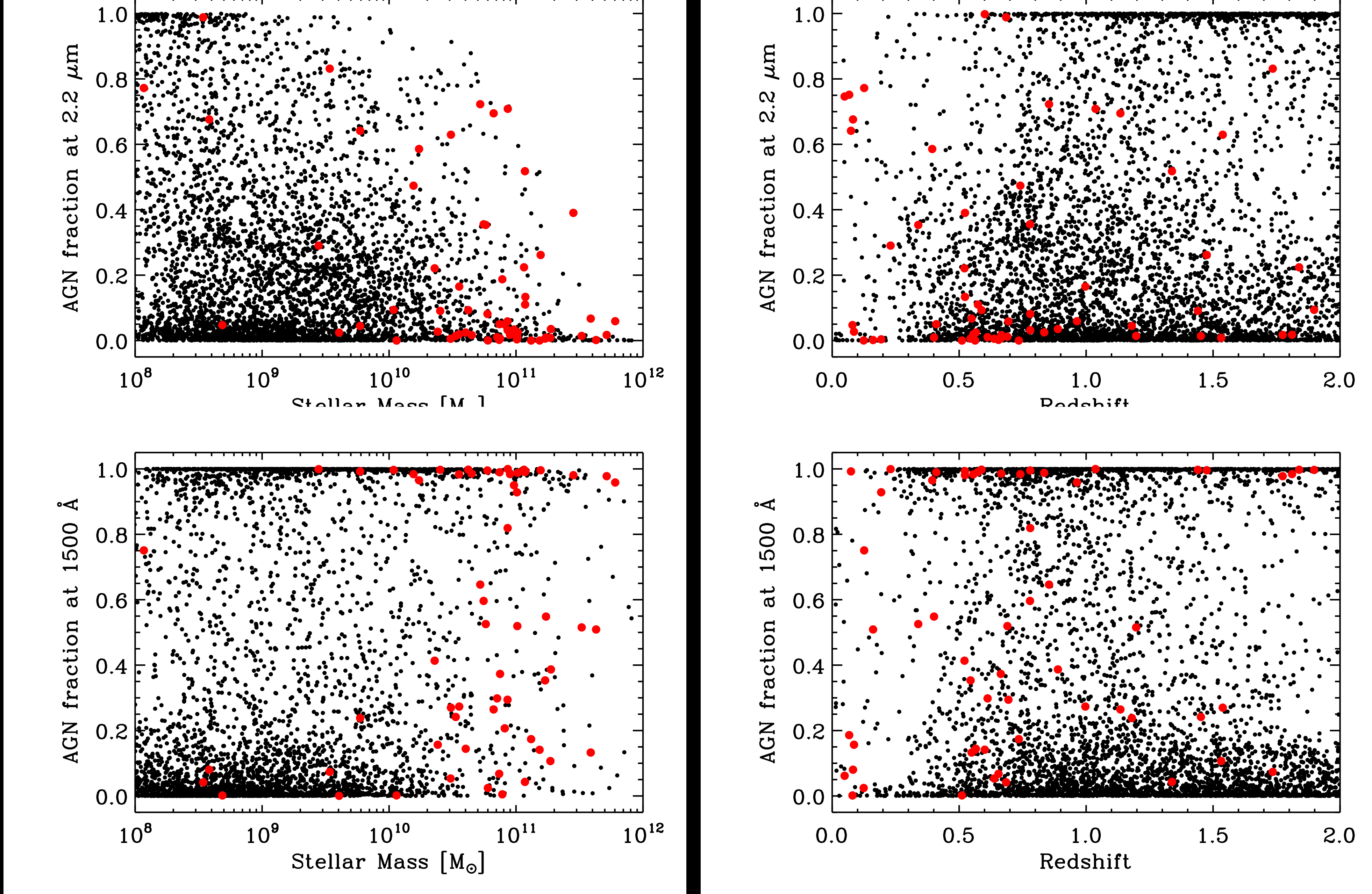
Cohen et al. (2010): Best fit Stellar Mass vs. Age: Radio and field galaxies.

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

- Radio sources reside in galaxies with M$\gtrsim 10^{10}\ M_{\odot}$. Not enough statistics yet to say if radio hosts in ERS older than field galaxies.

- 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$\sim$10.



Cohen$^+$ (2010): AGN frac vs. Stellar Mass & *spz*: X-ray & field gxys.

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

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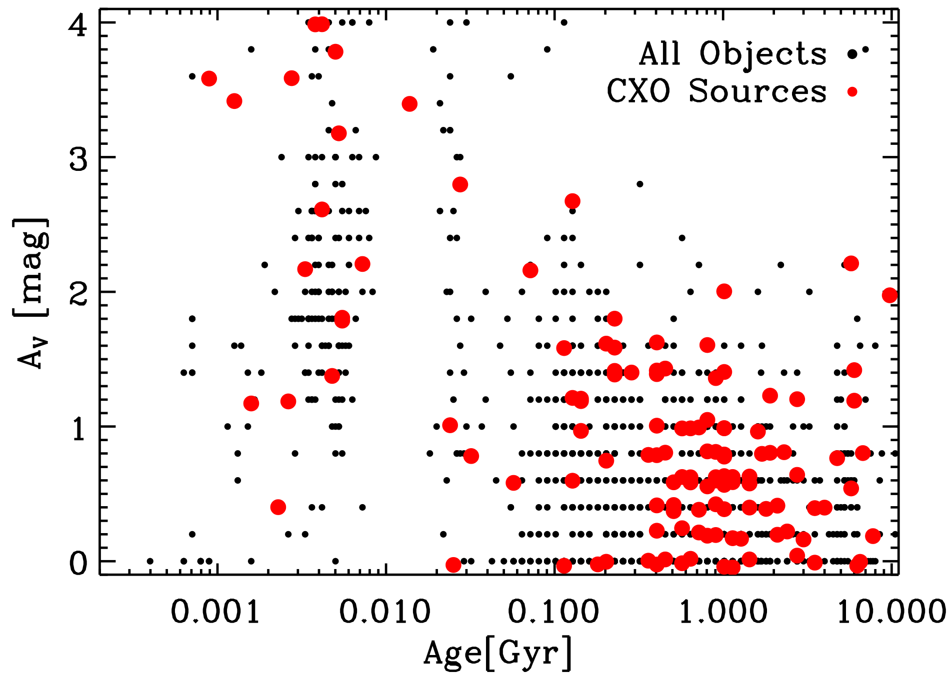
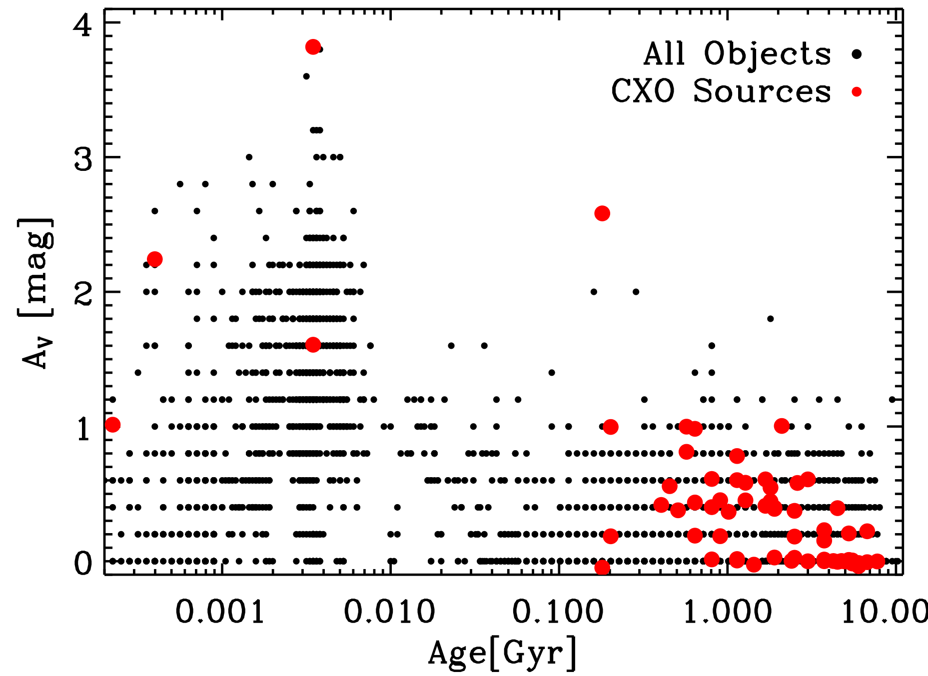




LEFT: 1549 CDF-S objects with z's. RIGHT: 7000 CDF-S ERS with spz's.

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 the age-metallicity relation may complicate this.

(6) Summary and Conclusions

(1) (Major) Mergers have a redshift distribution similar to that of HUDF field galaxies, but no AGN seen amongst them.

(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.

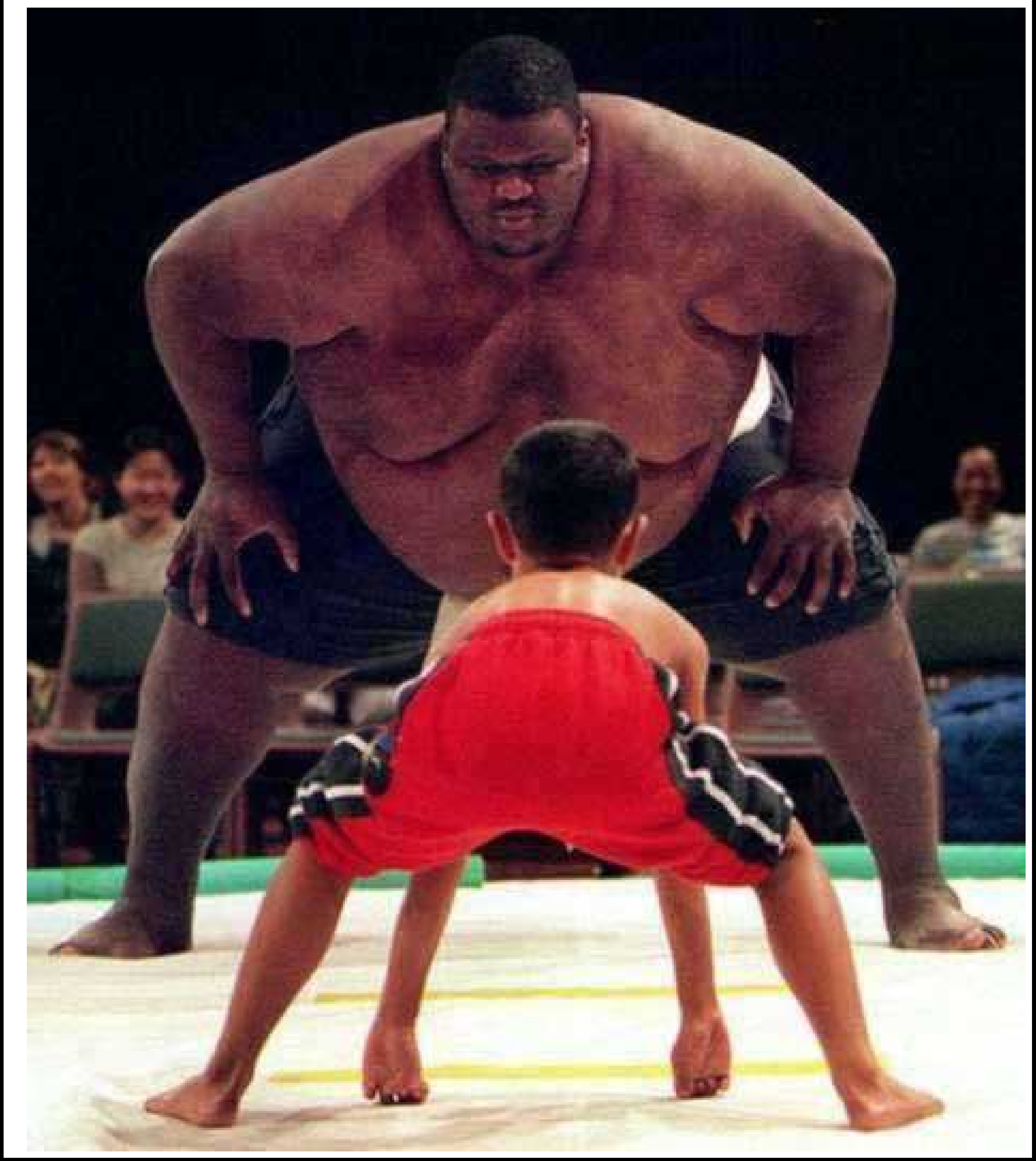
(3) Epoch dependent density of major mergers may precede peak in X-ray selected AGN ρ(z), but by no more than 1–2 Gyr (circumstantial).

(4) Radio and X-ray selected galaxies are — at z$\simeq$0.5–2 — on average 0.5–1 Gyr older than the typical FBG or LBG age of 0.1–0.2 Gyr.

(5) AGN growth likely stays in pace with Galaxy Assembly, but Radio &/or X-ray source 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.

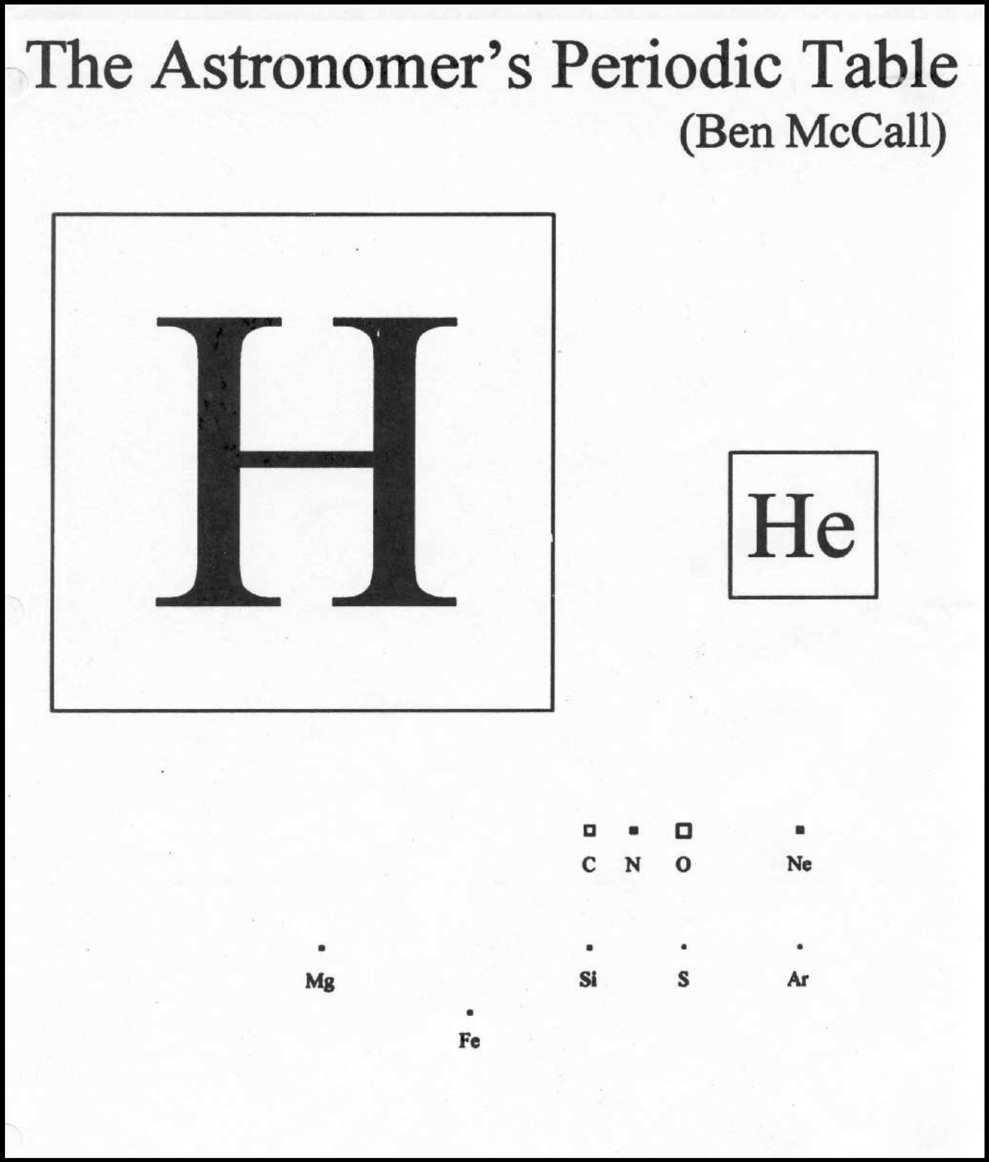
SPARE CHARTS



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

What comes around, goes around ...

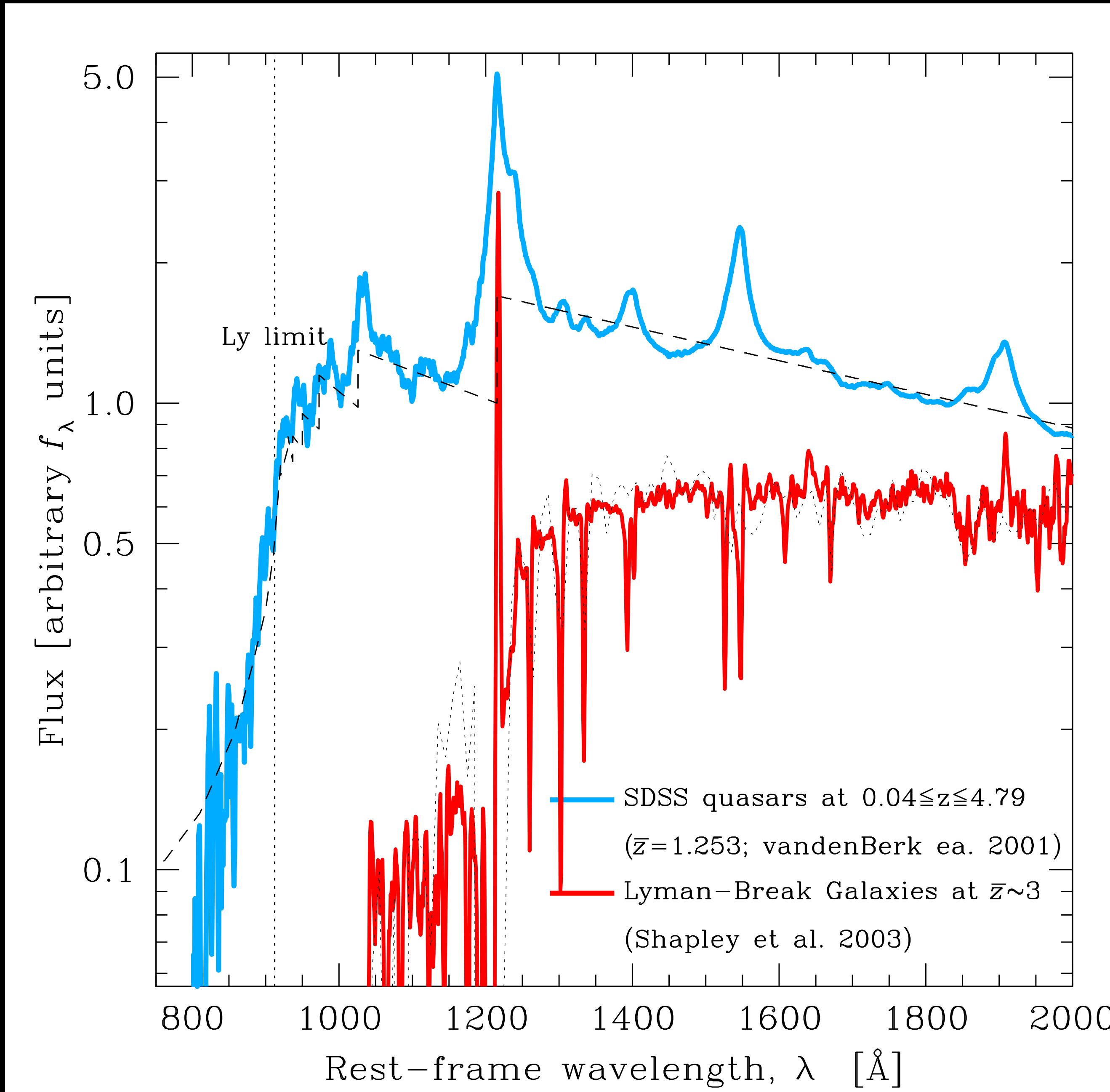
The Universe was reionized (at least) twice:



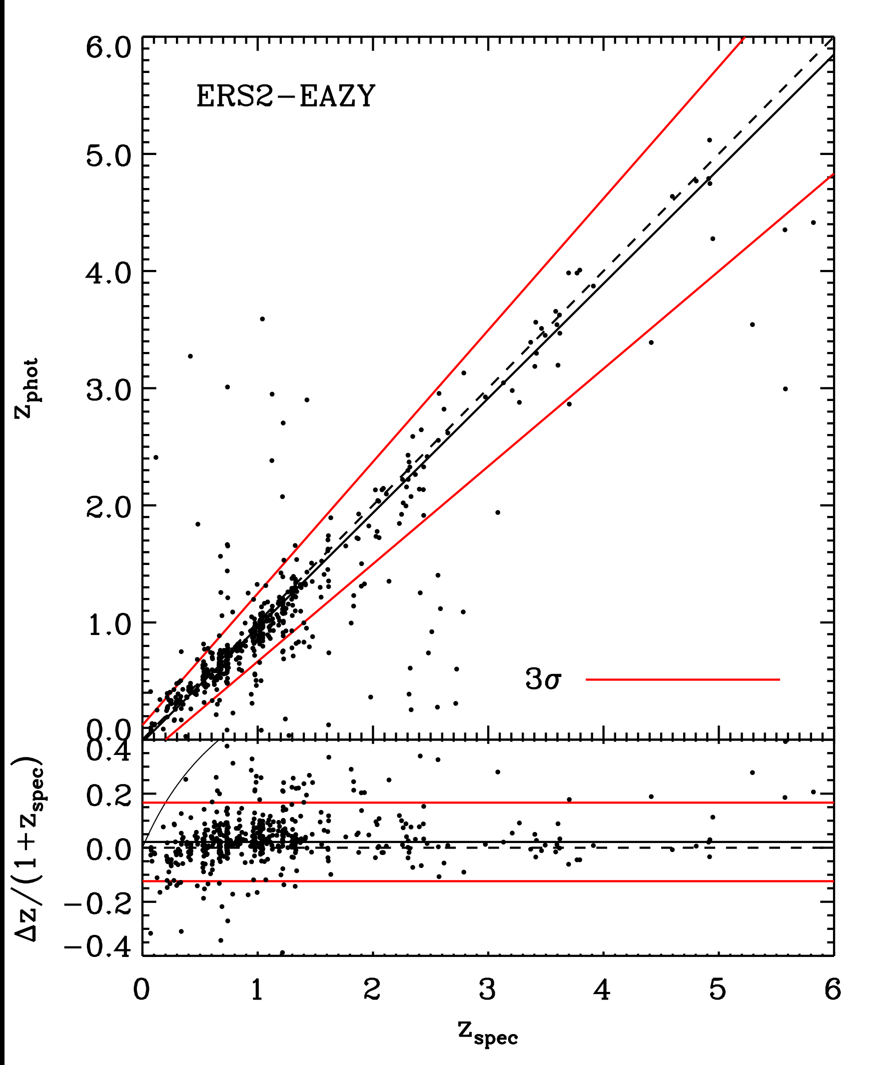
[Astronomers periodic table — with cosmic abundances included:]

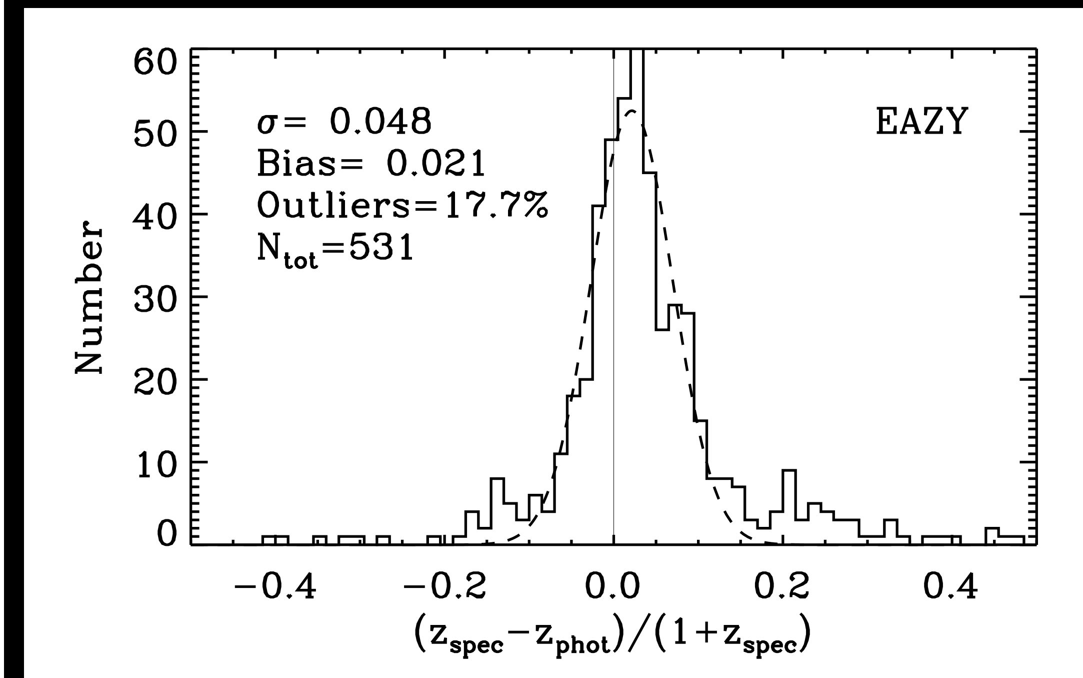
- SF in dwarfs galaxies likely caused H-reionization at z≃12 ⟶ z≃7.
- Hard-UV of QSO's and weak AGN likely caused He-reionization at z≃3.

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



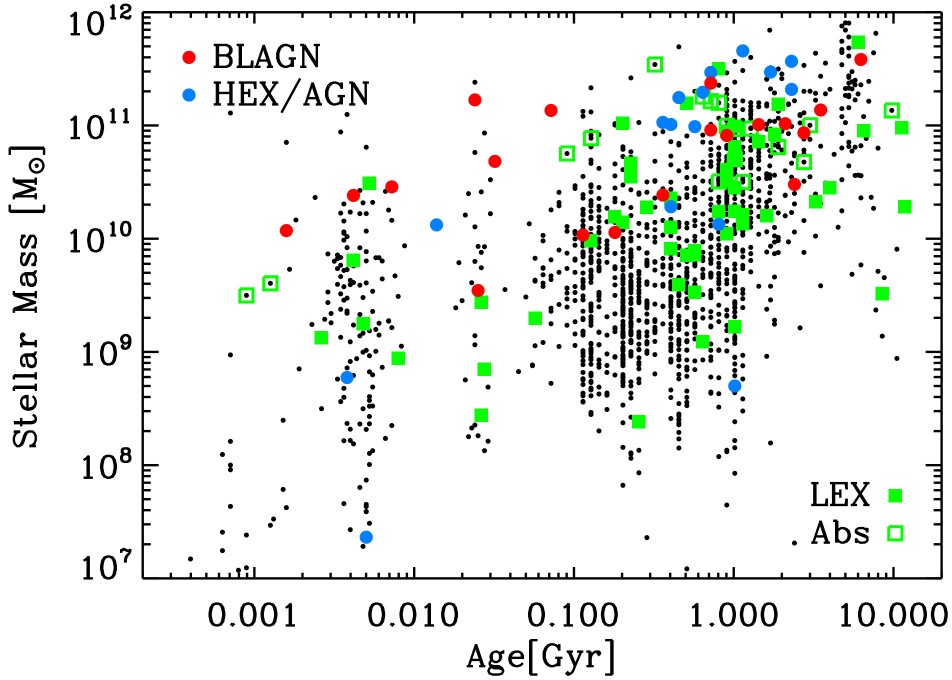
• In principle, the hard-UV of QSO's and weak AGN can outdo the young SED's of LBG's or dwarf galaxies, but likely by no more than $\gtrsim$1 dex.

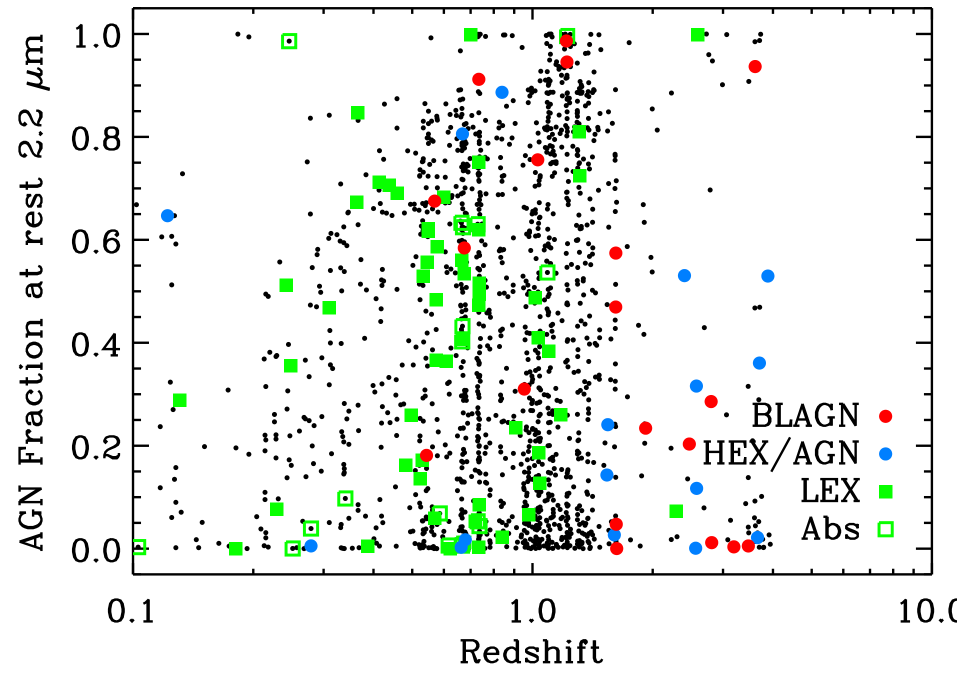




WFC3 ERS 10-band redshift estimates accurate for AB$\lesssim$27 mag to $\sim$4%, especially at 1$\lesssim$z$\lesssim$2, with small systematics (Cohen et al. 2010).

- JWST can get accurate photo-z's to AB$\lesssim$31 mag for at z$\simeq$0.5–15.





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.

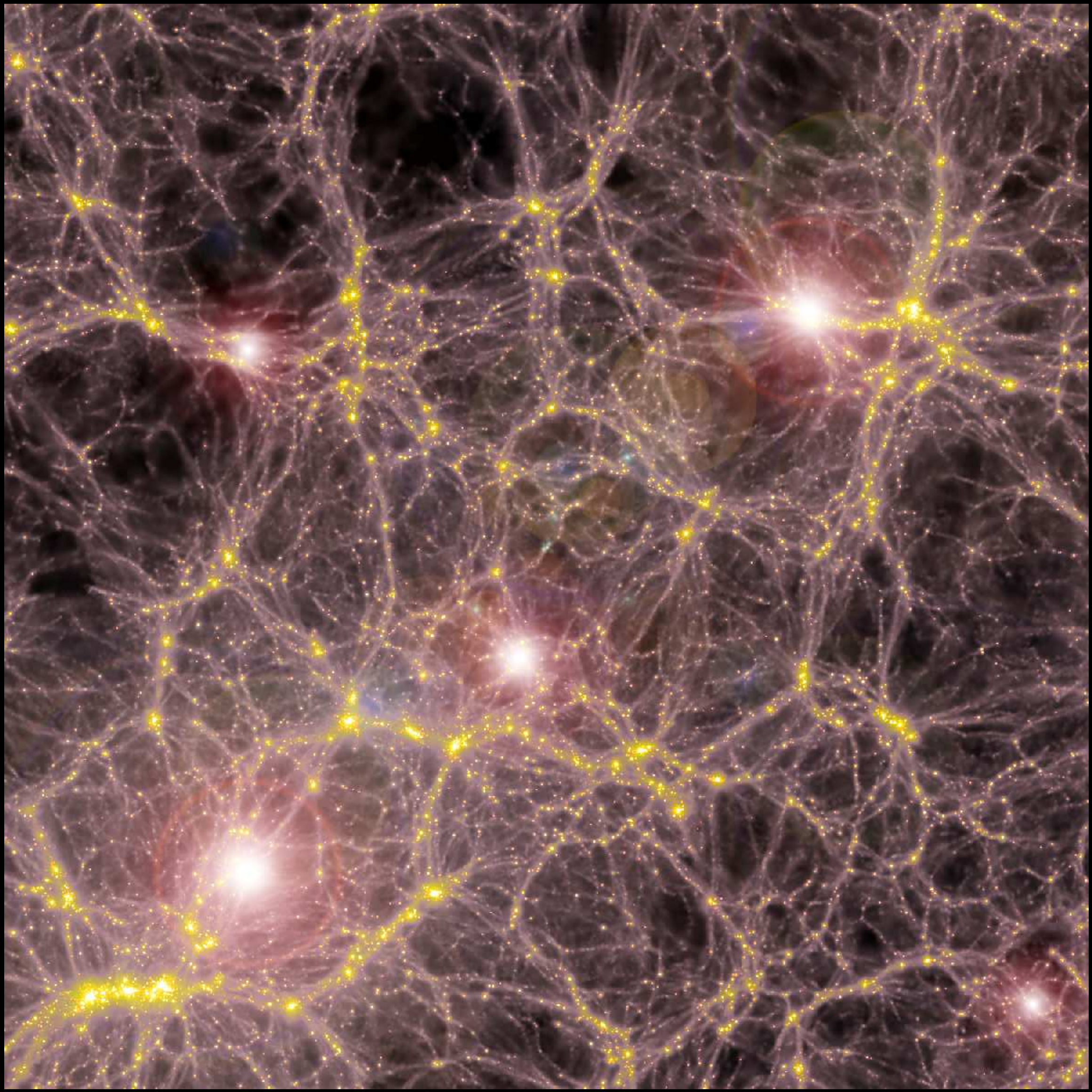
All optical AGN types: emission lines and absorption features.

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!

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



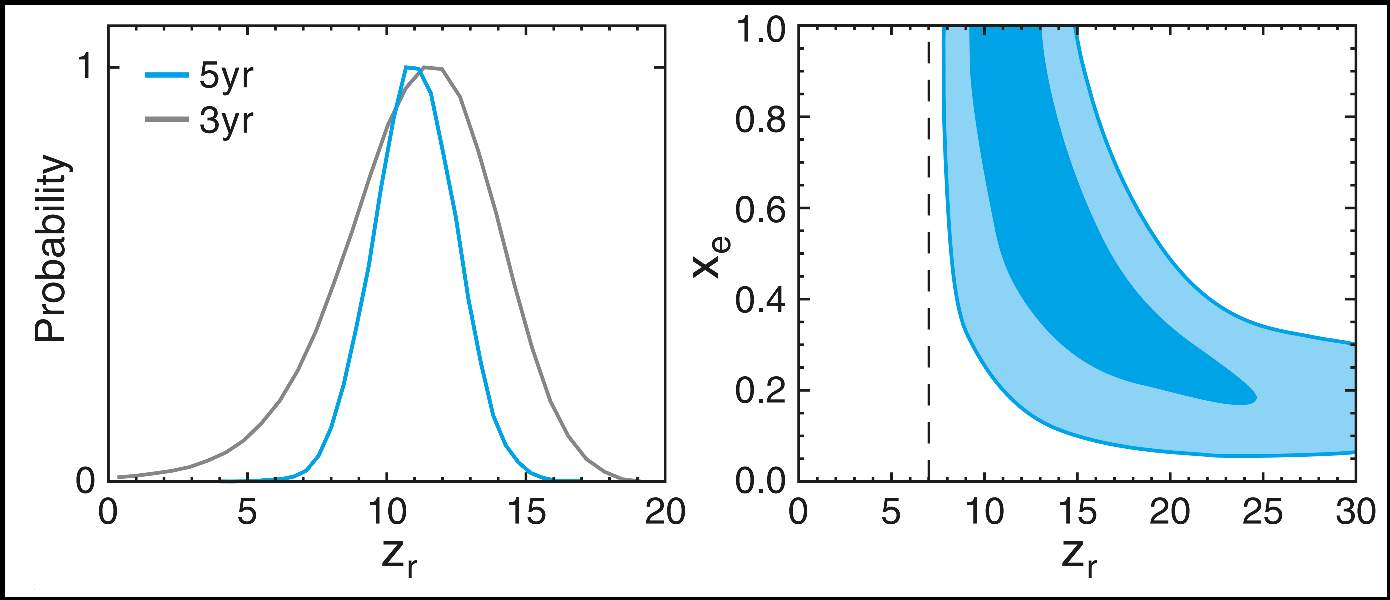
- Detailed Hydrodynamical models (e.g., V. Bromm) suggest that massive Pop III stars may have reionized universe at redshifts z$\lesssim$10–30 (First Light).

- 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 $\longleftarrow$ $\longrightarrow$ 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):

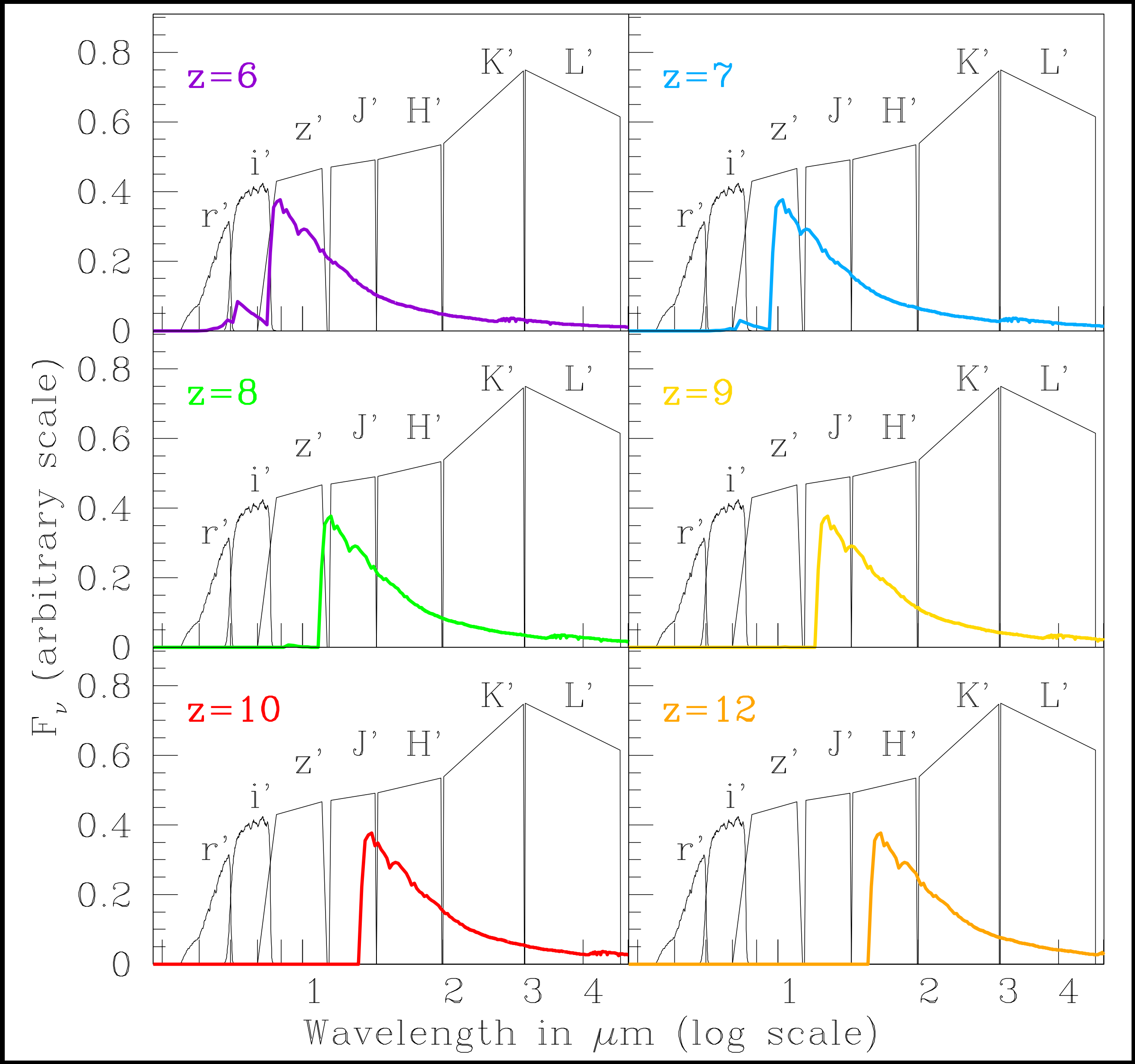
$\Longrightarrow$ First Light & Reionization occurred between these extremes:

- (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.

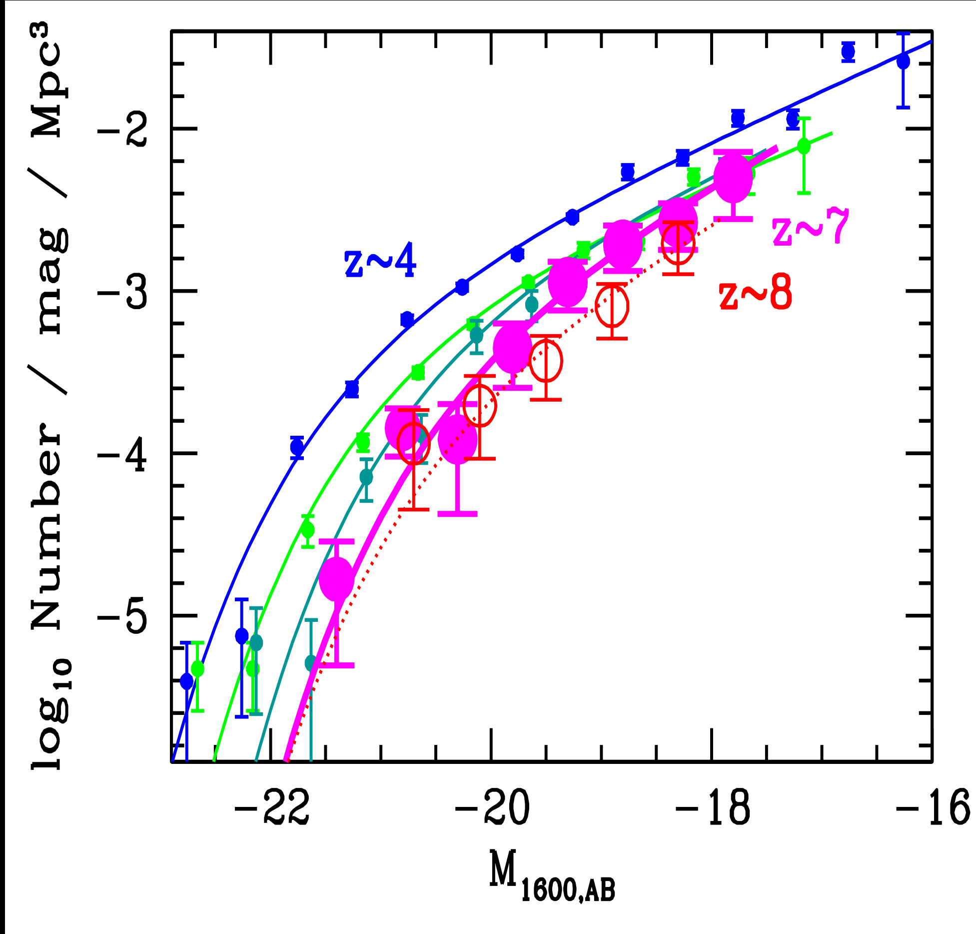
$\Rightarrow$ JWST must cover $\lambda = 0.7$–29 μm, with its diffraction limit at 2.0 μm.

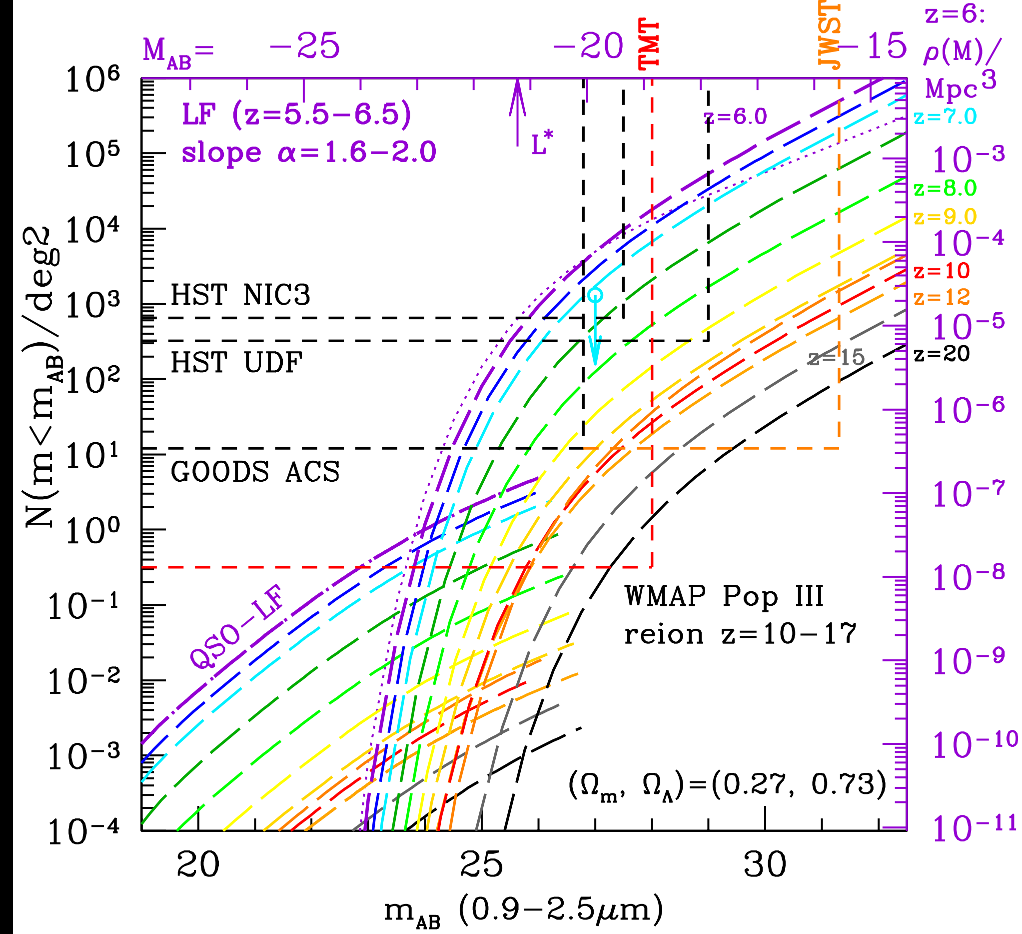
(4) How will JWST measure First Light & Reionization?



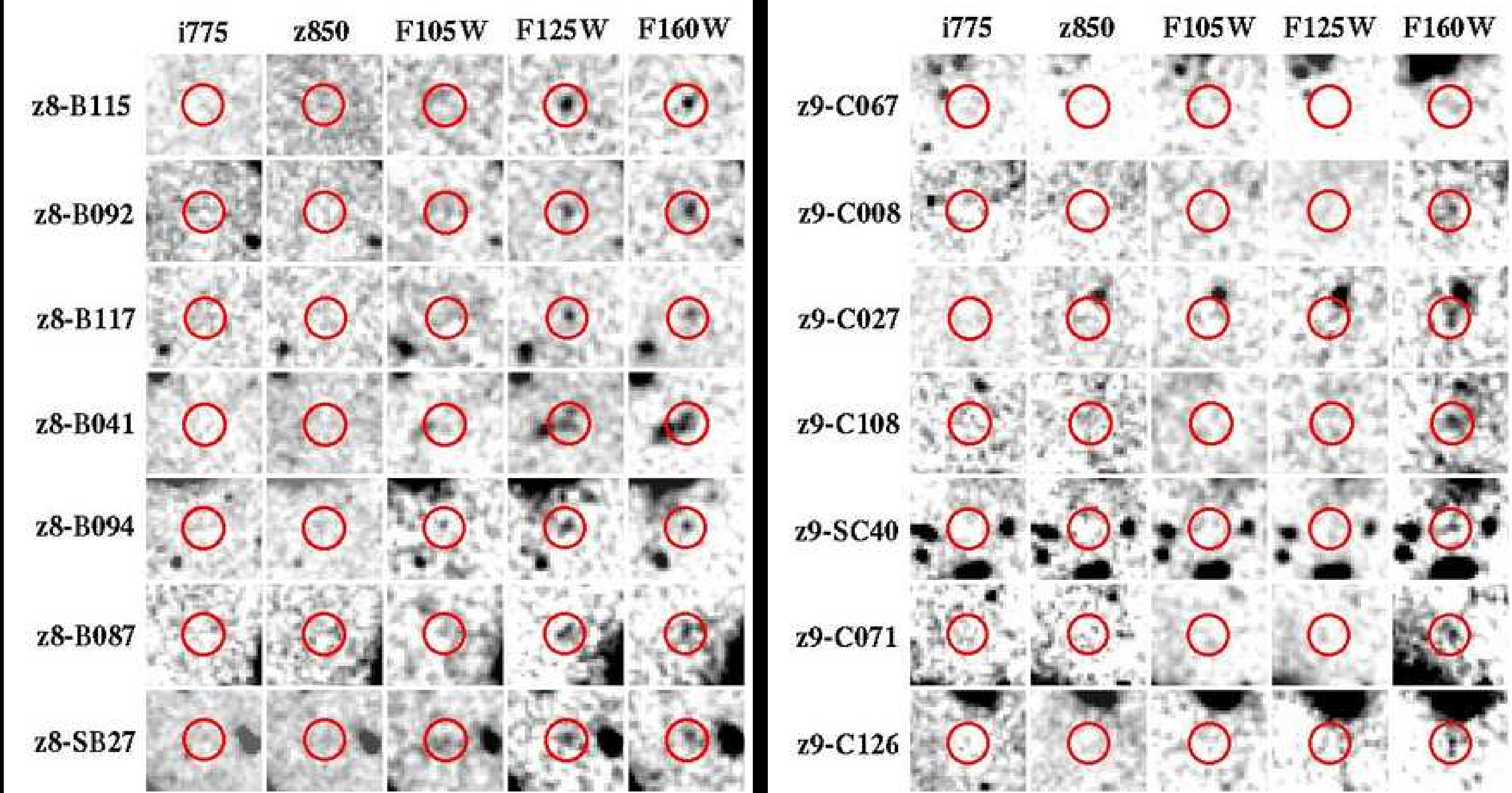
- Can't beat redshift: to see First Light, must observe near–mid IR.

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

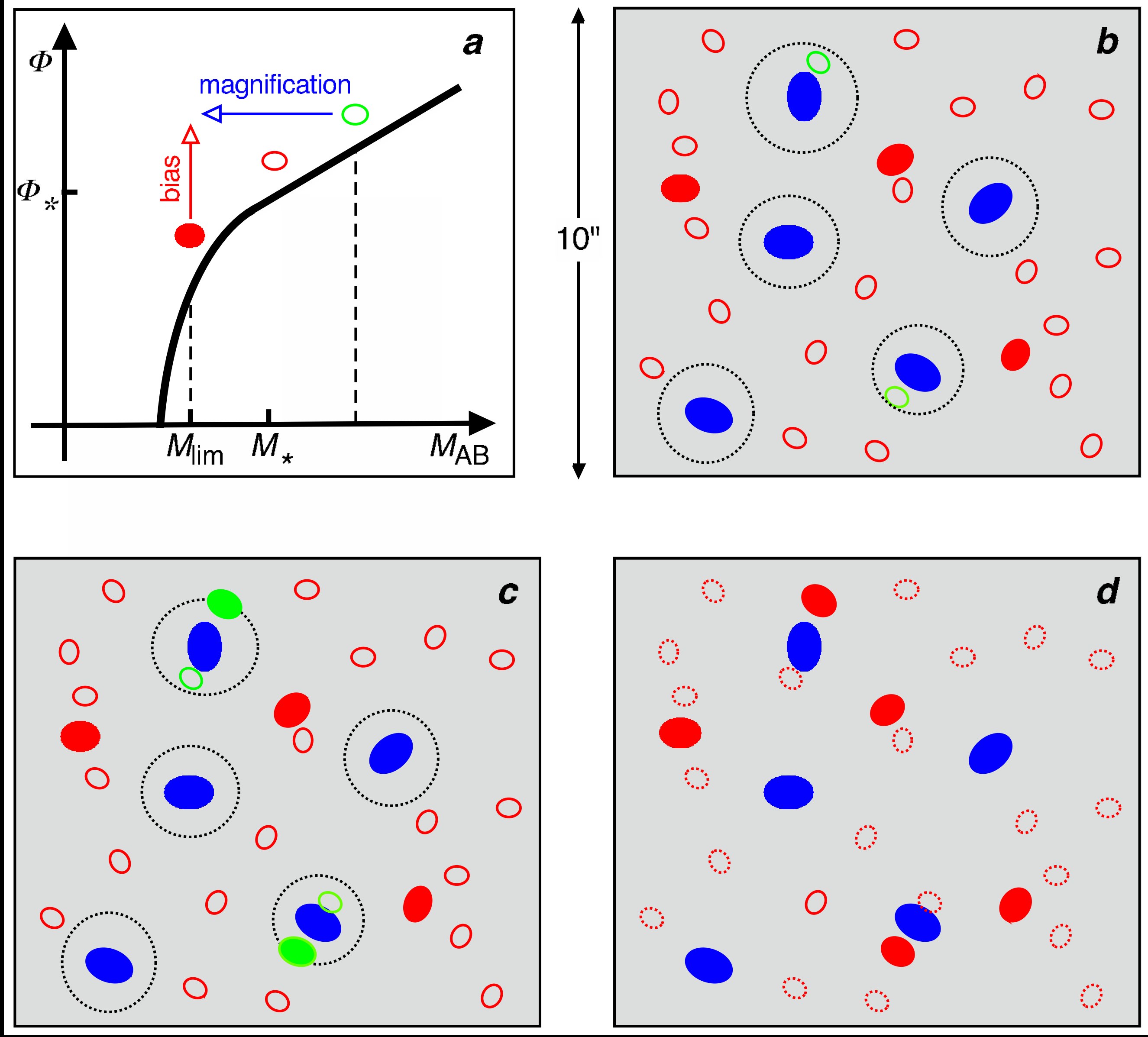




- Objects at z≳9 are rare (Bouwens+ 10; Trenti,+ 10; Yan+ 10), since volume elt is small, and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view ($\boldsymbol{\Omega}$), and $\boldsymbol{\lambda}$-range (0.7-29 μm).
- With proper survey strategy (area AND depth), 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≃1–2 (Wyithe et al. 2011, Nature, 469, 181).
- Need JWST to measure z≃9–15 LFs, and see if fundamentally different from z≲8. Does gravitational lensing bias boost LF bright-end?



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

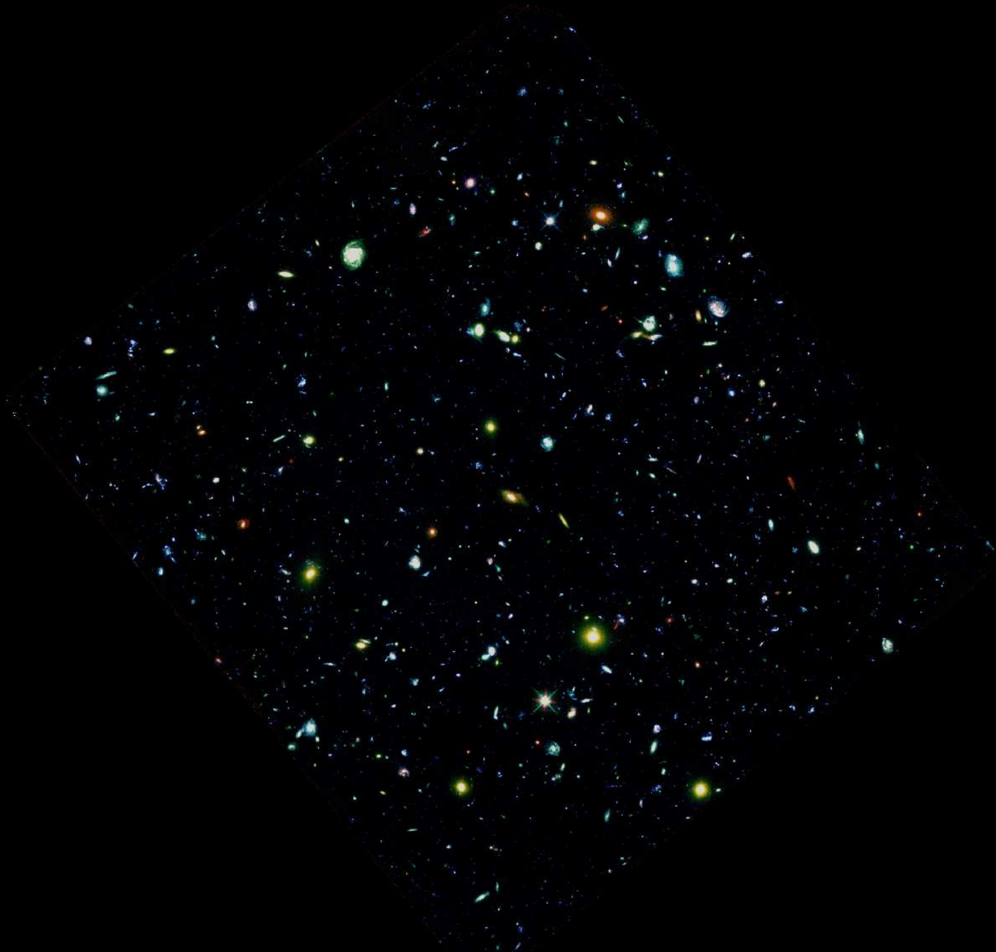
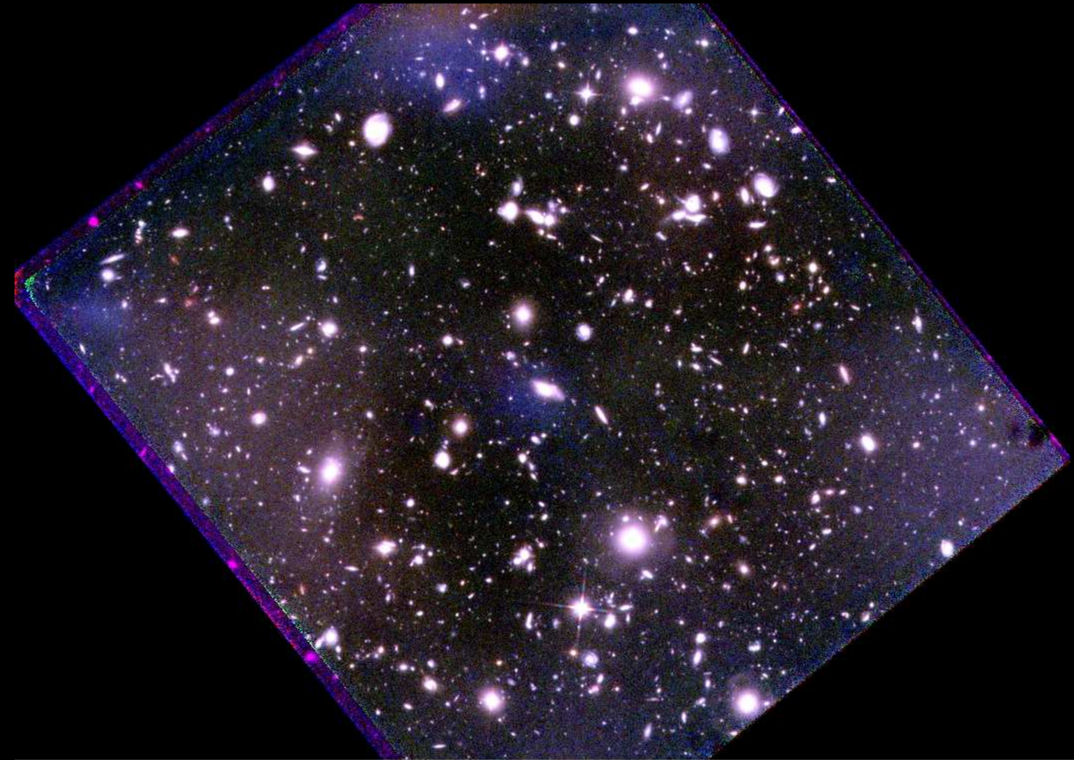
- Foreground galaxies (z≃1–2 or age≃3–6 Gyr) may gravitationally lens or amplify galaxies at z≳8–10 (cosmic age≲0.5 Gyr; Wyithe et al. 2011).
- This could change the landscape for JWST observing strategies.

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.

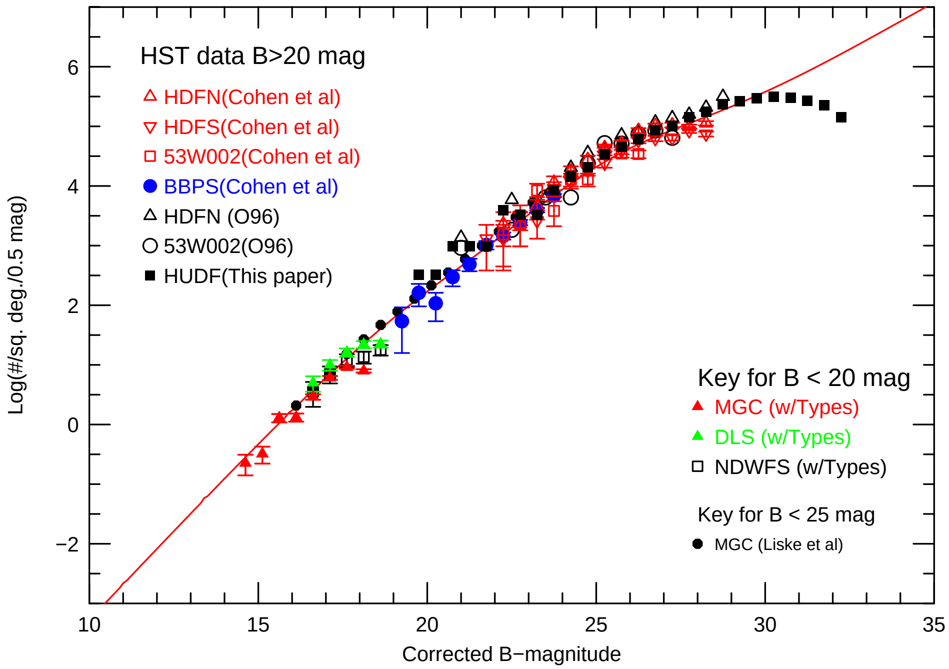
(Left) 128-hr HST/WFC3 IR-mosaic in HUDF at 1–1.6μm (YJH filters; Bouwens et al 2010, Yan et al. 2010; +85-hr by R. Ellis in 09/2012).

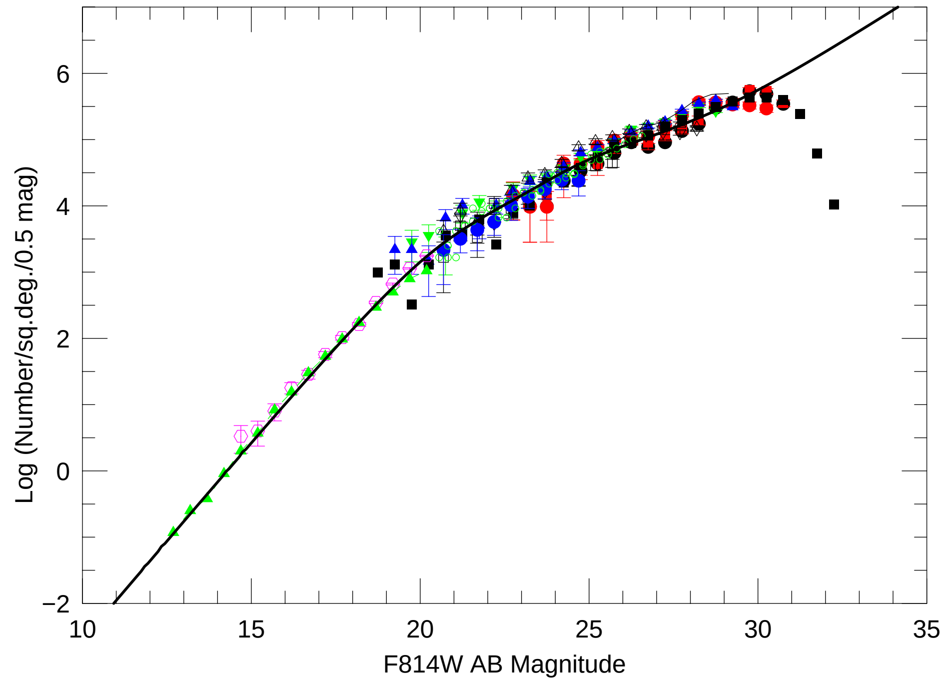
(Right) Same WFC3 IR-mosaic, but stretched to $\lesssim 10^{-3}$ of Zodical sky!

- 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.

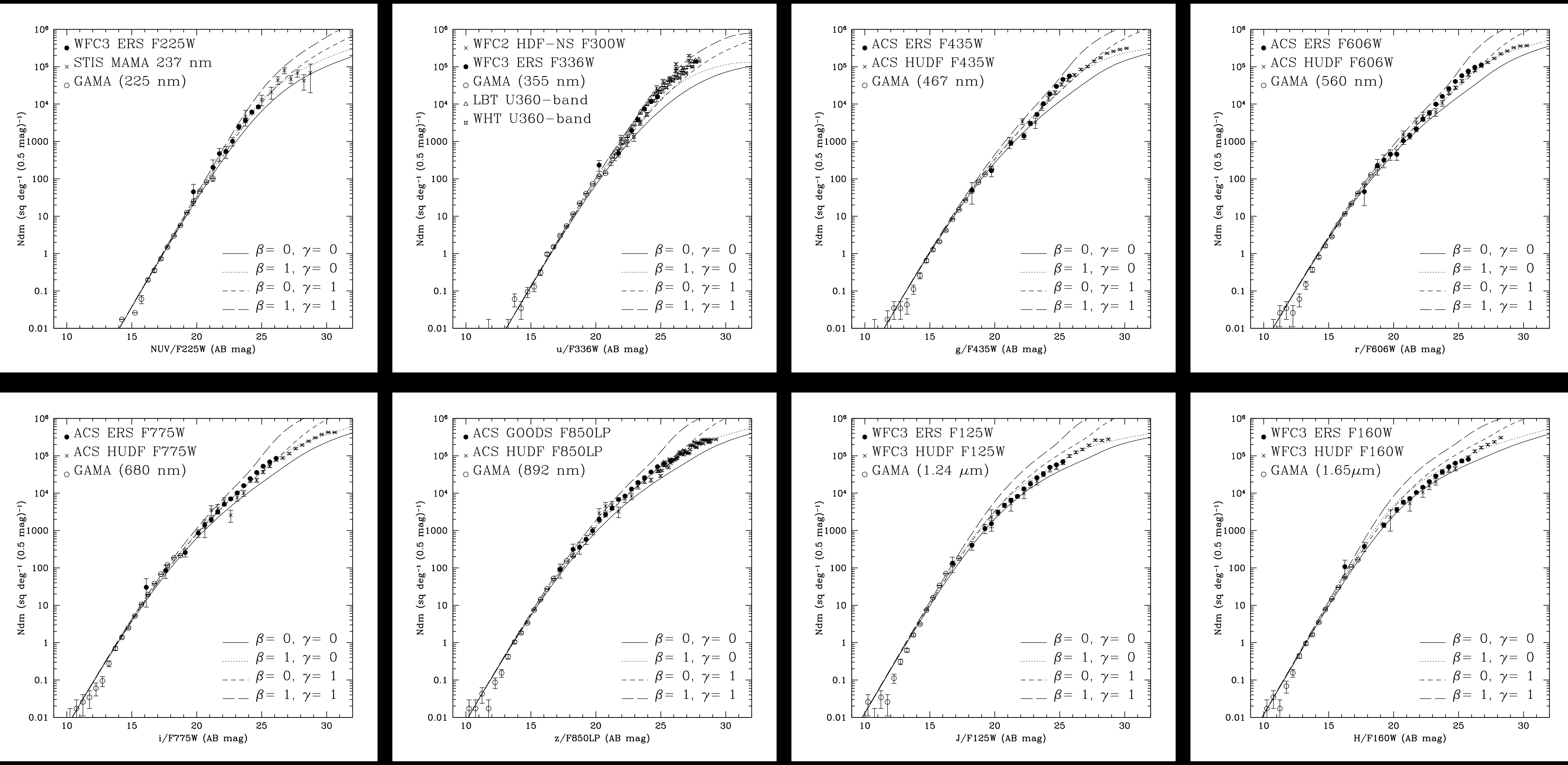
Appendix 1: will JWST (& SKA) reach the Natural Confusion Limit?





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

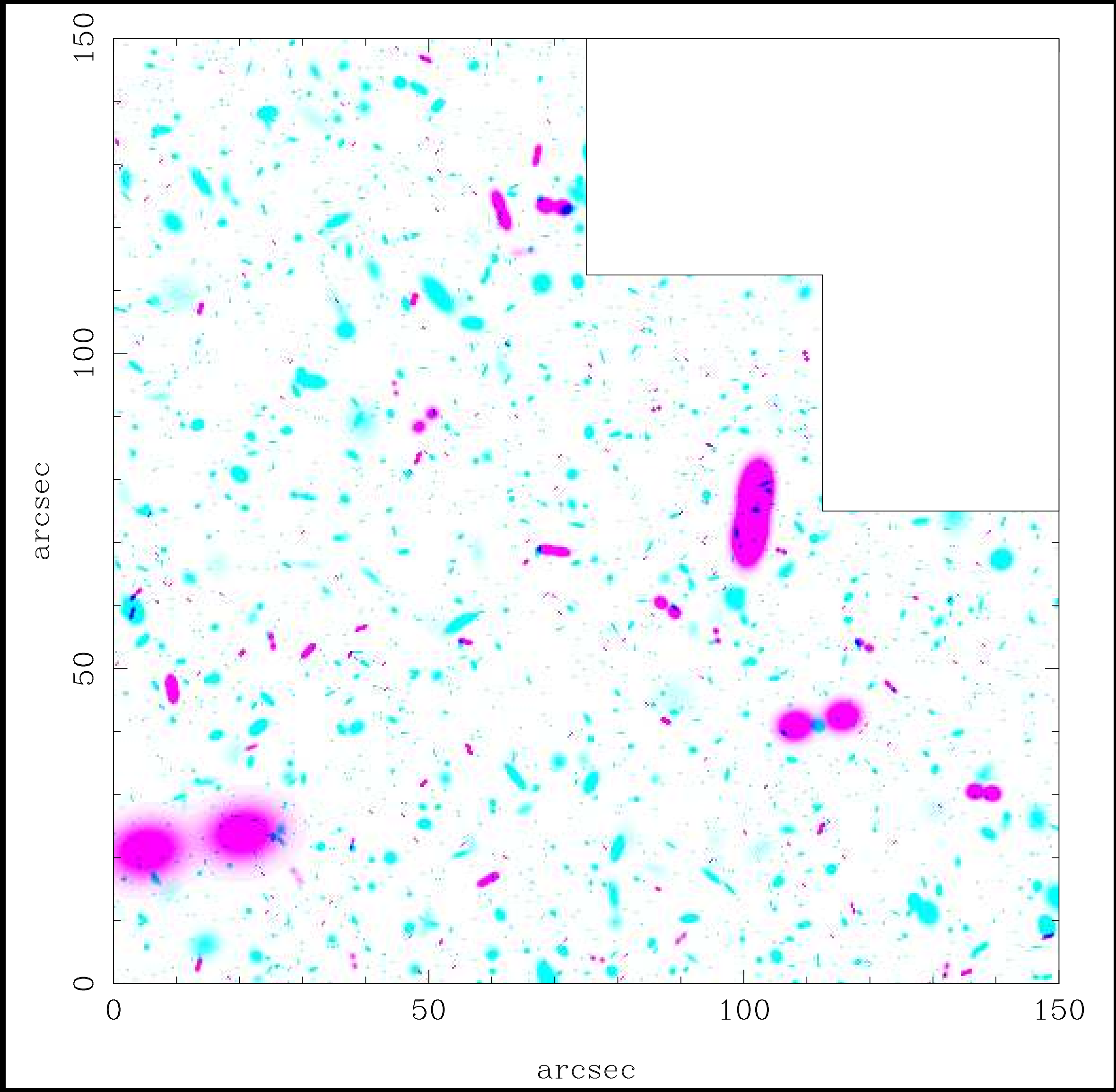
Panchromatic Galaxy Counts from $\lambda \simeq$0.2–2μm for AB$\simeq$10–30 mag



Data: GALEX, ground-based GAMA, HST ERS ACS+WFC3 + HUDF ACS+WFC3 (*e.g.*, Windhorst et al. 2011, ApJS 193, 27):

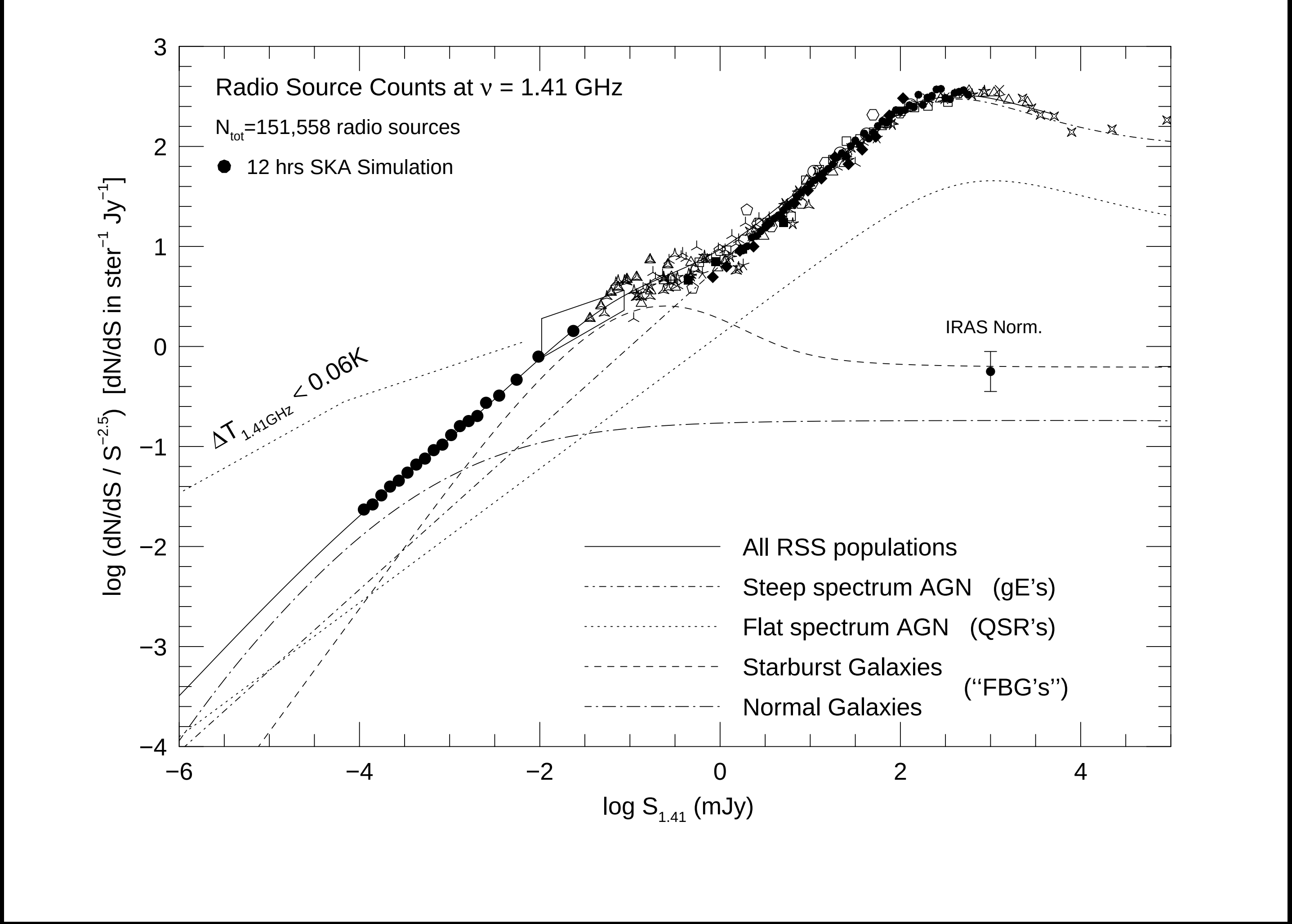
Filters: F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F098M/F105W, F125W, F160W.

- No single Lum.+Dens evol model fits over 1 dex in λ and 8 dex in flux.



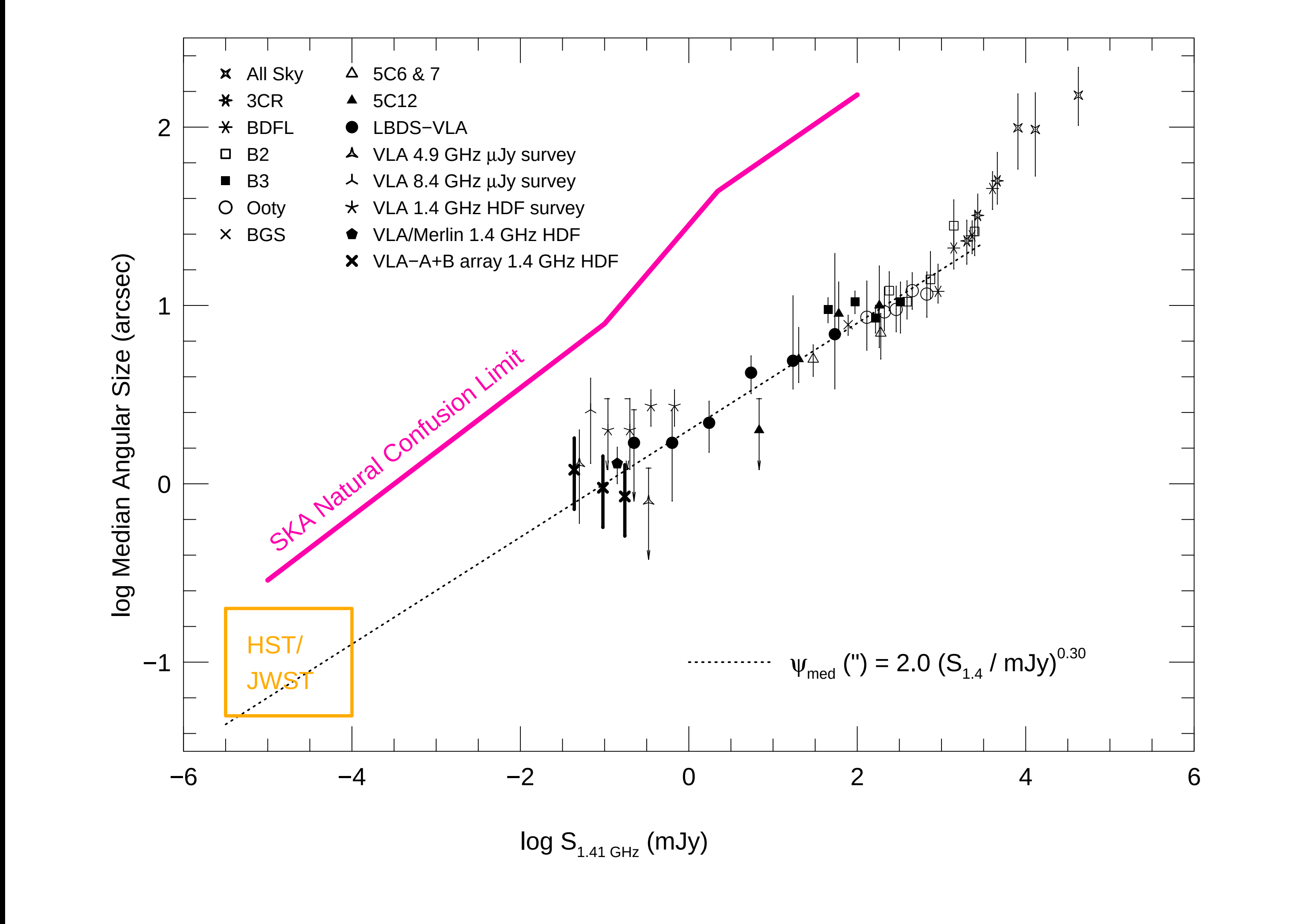
Simulated 12-hr SKA 1.4 GHz image: FWHM$\simeq$0$''$.1 and flux limit $\mathbf{0.1}$ $\boldsymbol{\mu}$Jy (5-$\boldsymbol{\sigma}$). Of the 1 deg$^{\mathbf{2}}$ FOV, only an HST/HDF area is shown (2$'$.5$\times$2$'$.5).

Red extended radio sources are AGN in early-type galaxies. Blue mostly point-like or disk-shaped sources reside in star-forming galaxies, which dominate the counts below 1 mJy. Normal spiral will dominate below 100 nJy.



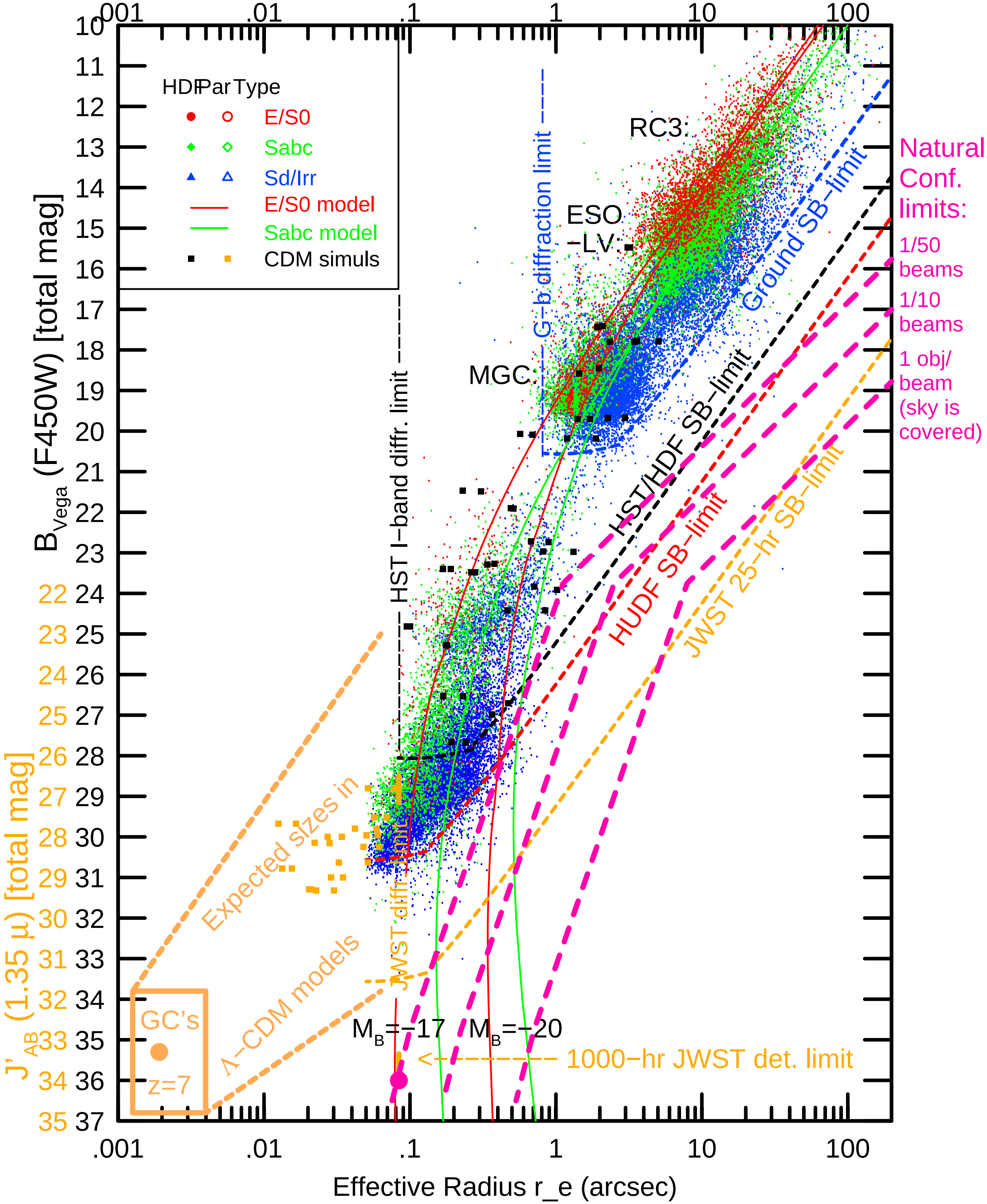
Normalized differential 1.41 GHz source counts (Windhorst et al. 1993, 2003; Hopkins et al. 2000) from 100 Jy down to 100 nJy. Filled circles below 10μJy show the 12-hr SKA simulation of Hopkins et al. (2006).

Models: giant ellipticals (dot-dash) and quasars dominate the counts to 1 mJy, starbursts (dashed) below 1 mJy. Normal spirals at cosmological distances (dot-long dash) will dominate the SKA counts below 100 nJy.



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

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


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"

- 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

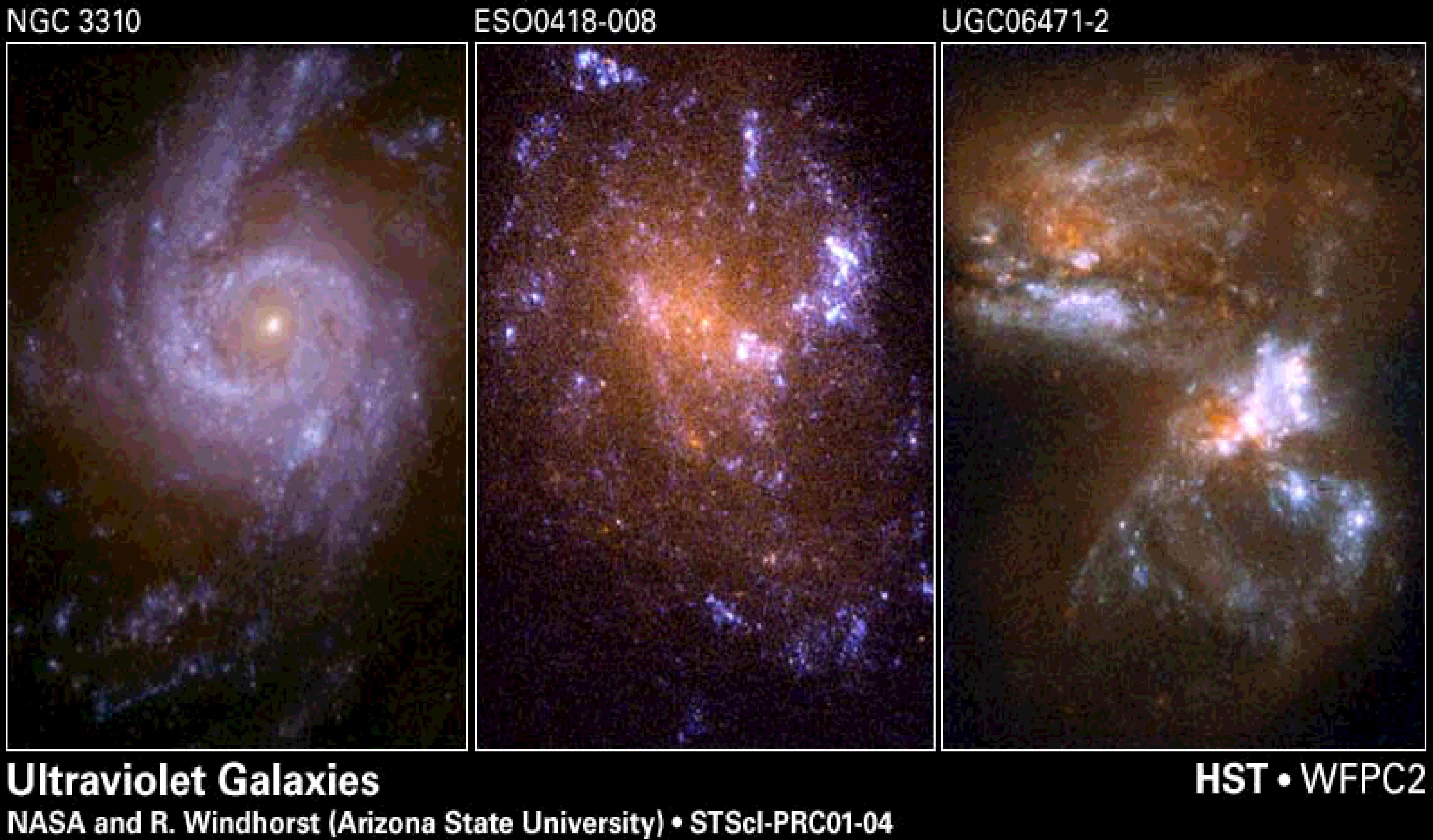
Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

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≃1–15

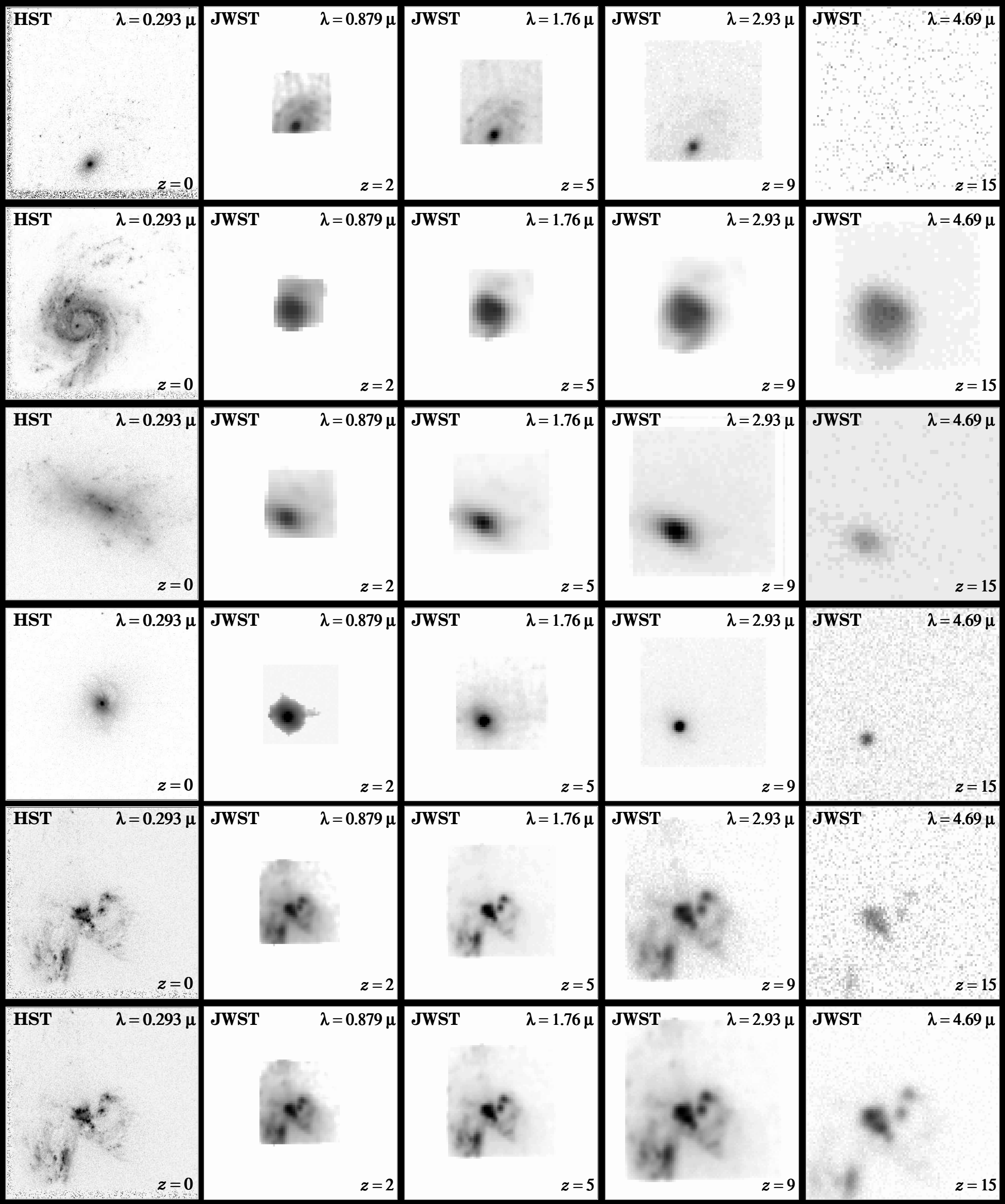


- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).

- 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.