# Galaxy Assembly and AGN Growth with the Hubble Wide Field Camera 3 and the James Webb Space Telescope

**Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist**

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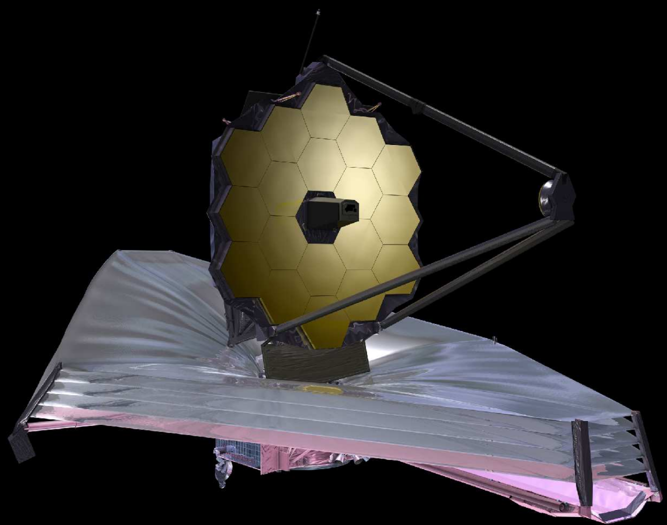
*& (Ex) ASU Grad Students: N. Hathi, H. Kim, R. Ryan, M. Rutkowski, A. Straughn, & K. Tamura*



*Kavli Workshop on "Cosmology in the Era of Extremely Large Telescopes"*

*— First Annual GMT Community Science Meeting*

*Gleacher Center, University of Chicago, IL, Wednesday June 12, 2013*

# Outline

- (1) Results on Galaxy Assembly with the HST/WFC3,
and what JWST can do.

- (2) New Results on AGN-growth with the HST/WFC3,
and what JWST can do.

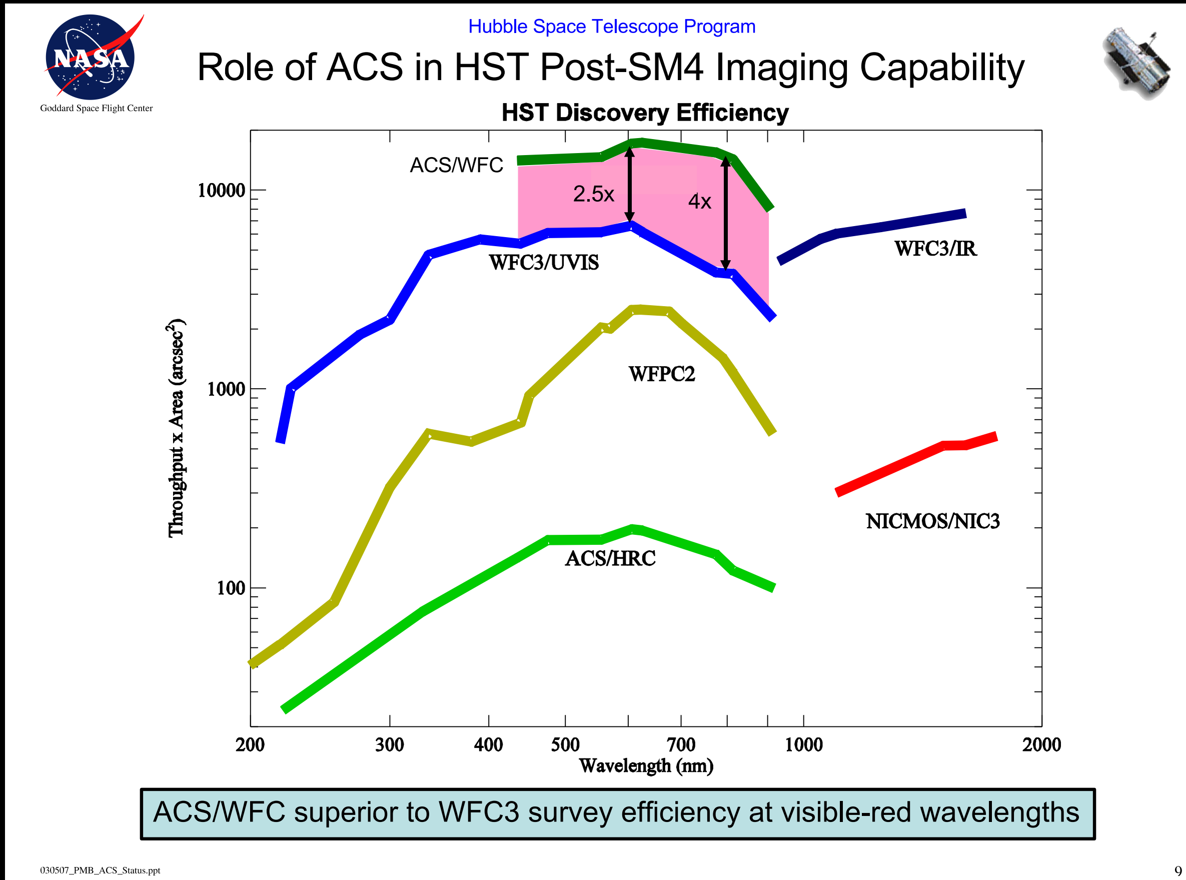
- (3) SED ages of radio and X-ray host galaxies vs. epoch:
May trace AGN-growth vs. Galaxy Assembly directly.

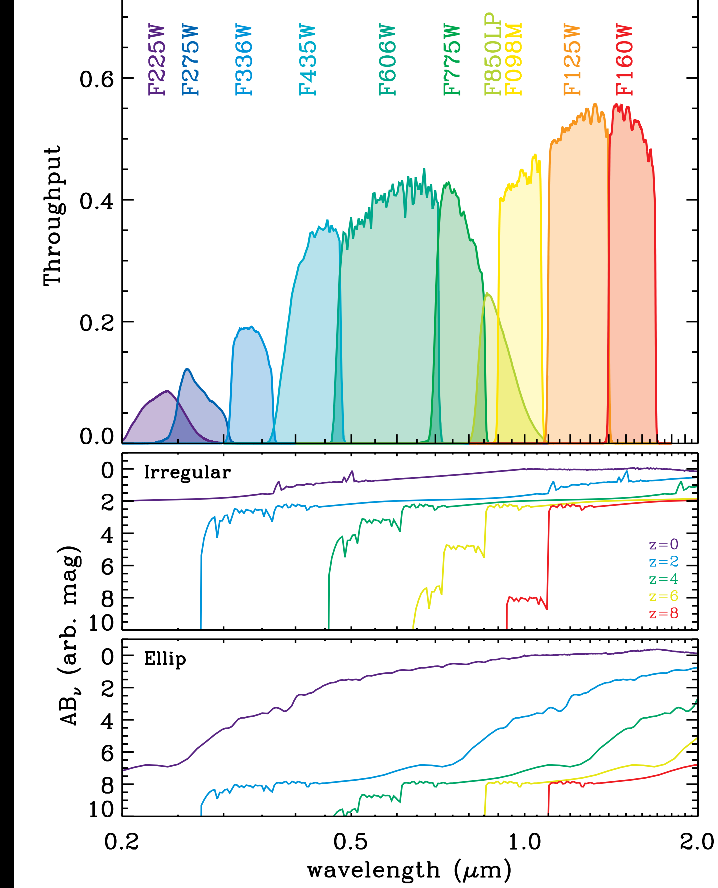
- (4) Synergy between the 20–30 meter class telescopes and JWST:
When $1 + 1 > 2$.

- (5) Summary and Conclusions

Sponsored by NASA/JWST.

Arizona State University




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:

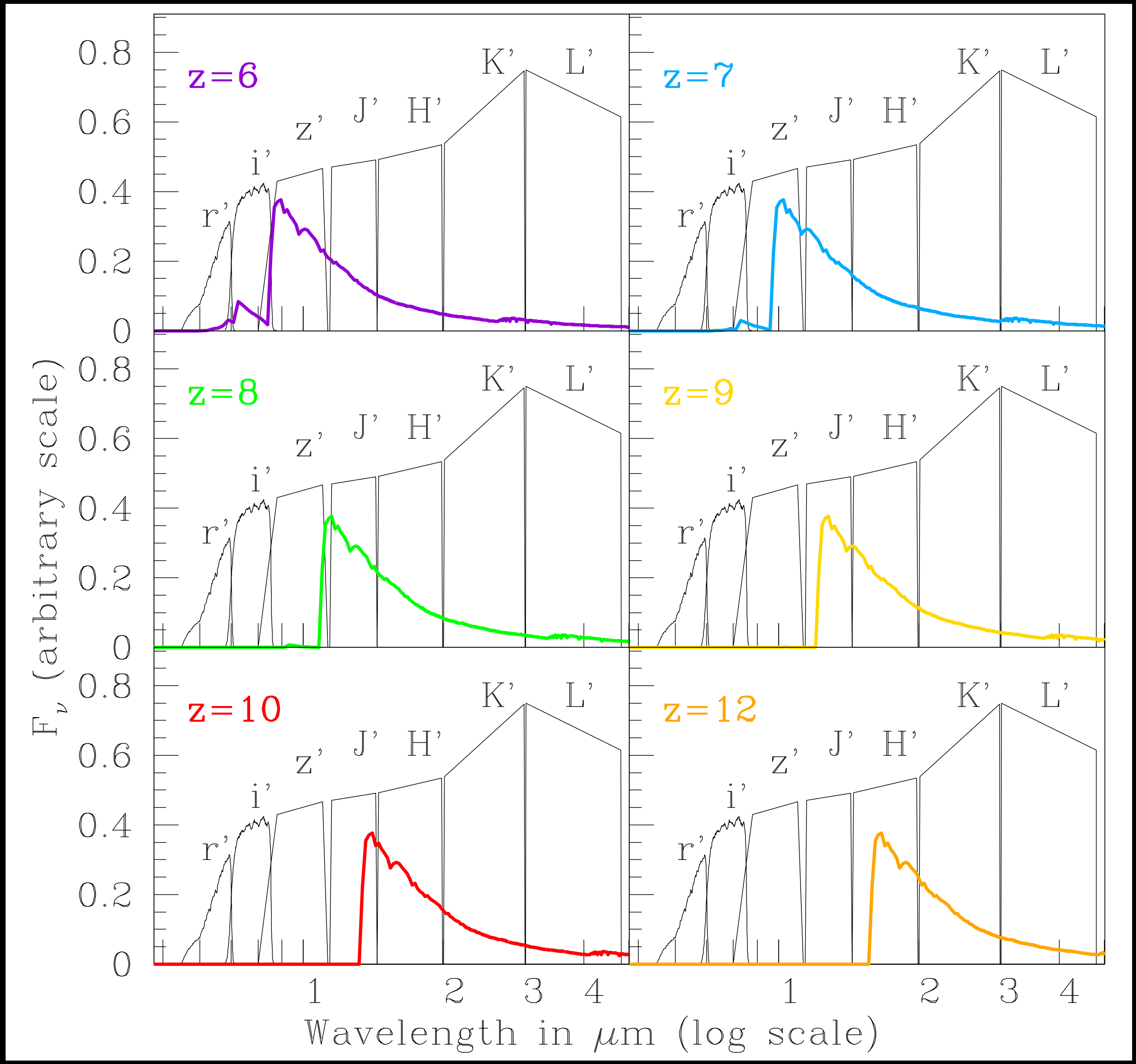
- QE$\gtrsim$70%, 1k$\times$1k array, $0''.13$ pixels, FOV $\simeq$ $2'.25 \times 2'.25$.

$\Rightarrow$ 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.

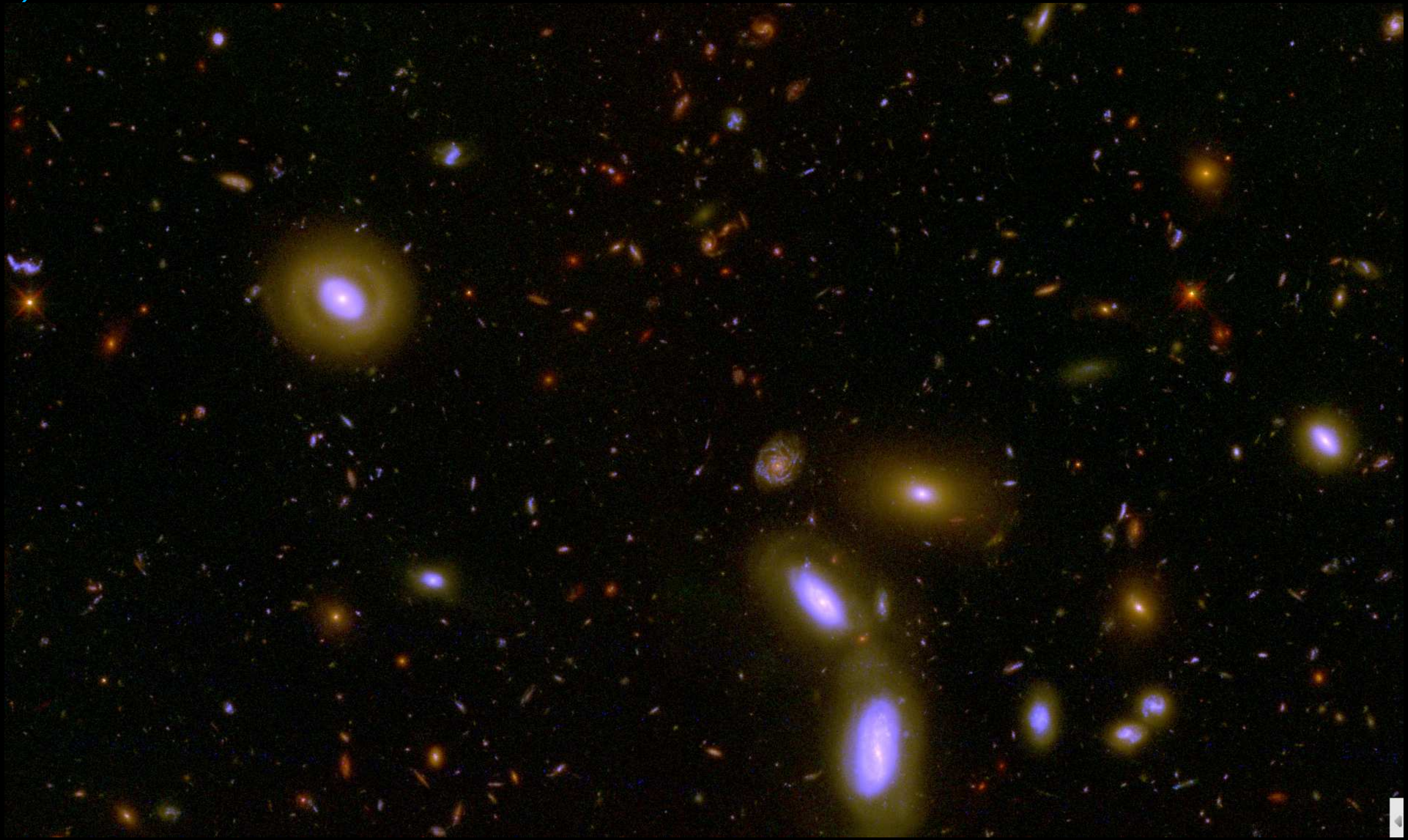
# (1) How can HST & JWST measure Galaxy Assembly & SMBH/AGN Growth?




Can't beat redshift: to see First Light, must observe near–mid IR (J. Gardner's talk).

⇒ This is why JWST needs NIRCam at 0.8–5 $\mu$m *and* MIRI at 5–29 $\mu$m.

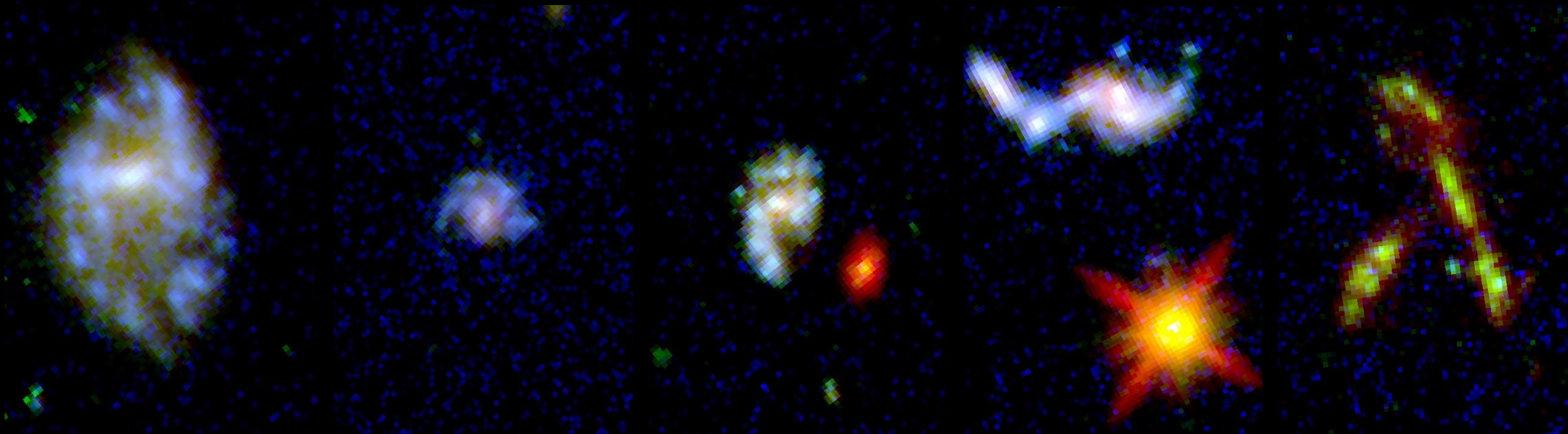
# (1) Measuring Galaxy Assembly & weak AGN growth with WFC3 & JWST



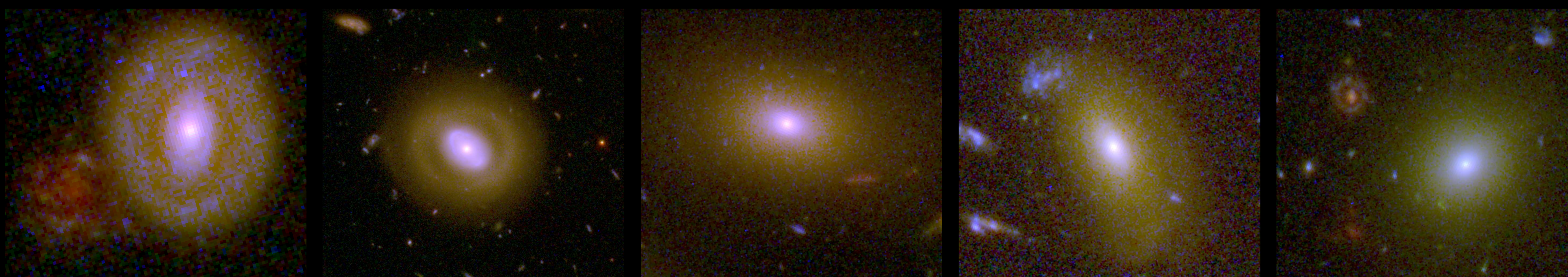
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-$\sigma$) over 40 arcmin$^2$ at 0.07–0.15" FWHM from 0.2–1.7$\mu$m (UVUBVizYJH).

JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5$\mu$m, and 0.2–1.2" FWHM at 5–29$\mu$m, tracing young+old SEDs & dust.

# (1) Science results of the Wide Field Camera 3 Early Release Science data:



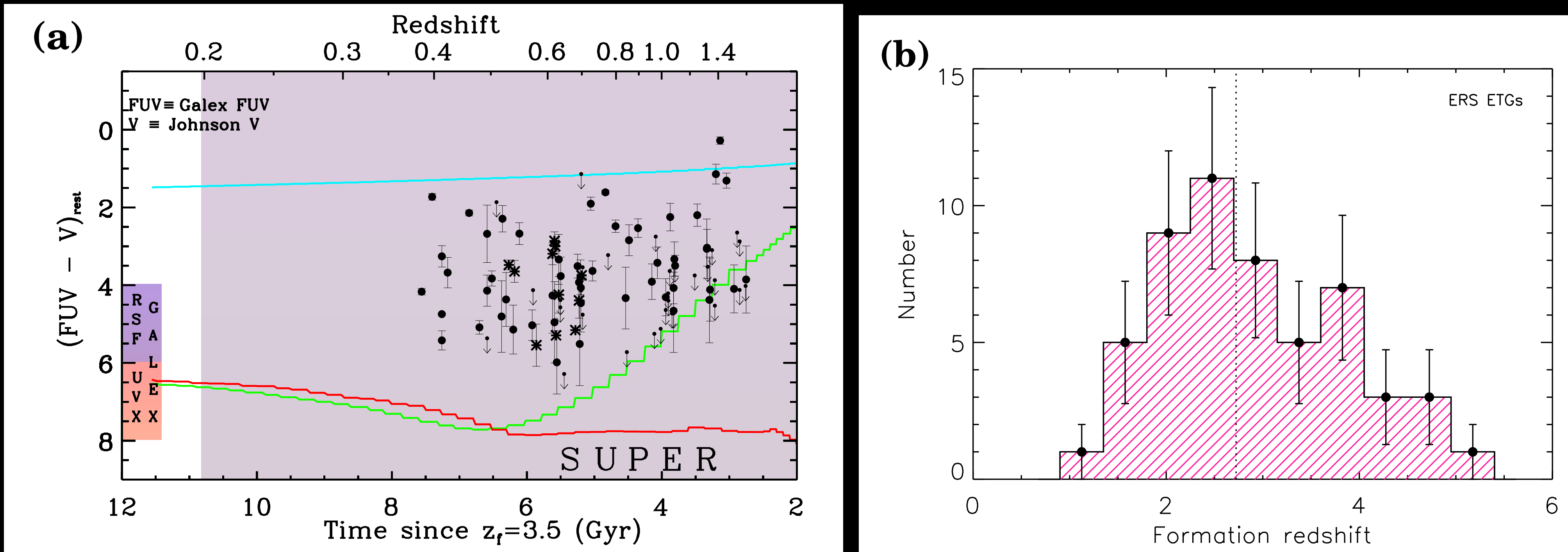
Galaxy structure at the peak of the merging epoch ($z \simeq 1$–2) is very rich: some resemble the cosmological parameters $\boldsymbol{H_0}$ , $\boldsymbol{\Omega}$, $\boldsymbol{\rho_o}$, $\boldsymbol{w}$, and $\boldsymbol{\Lambda}$, resp.



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 $\boldsymbol{\mu}$m wavelength.

# (1) HST WFC3: Rest-frame UV-evolution of Early Type Galaxies since z≲1.5.

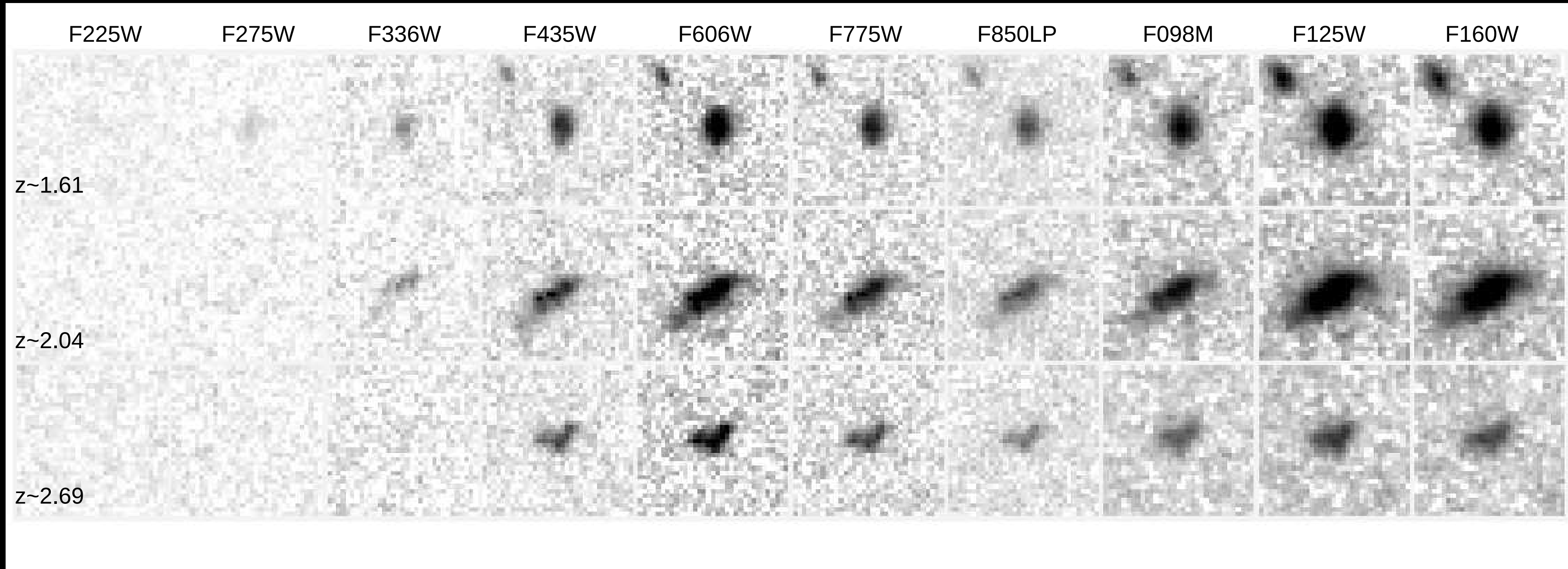



- 10-band WFC3 ERS data measured rest-frame UV-light in nearly all early-type galaxies at 0.3≲z≲1.5 (Rutkowski et al. 2012, ApJS, 199, 4).

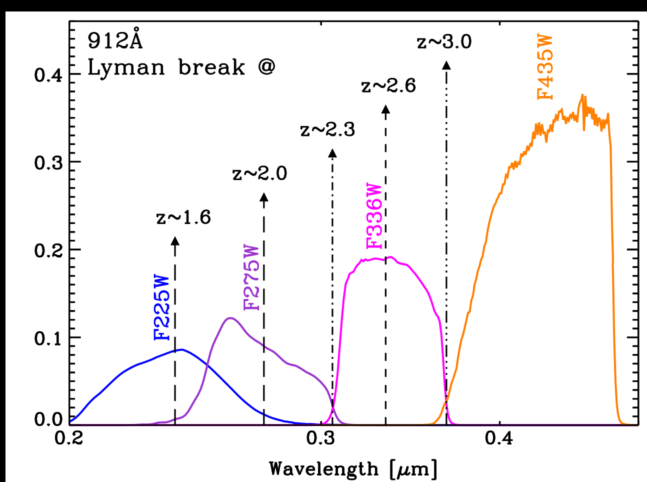
⟹ Most ETGs have continued residual star-formation after they form.

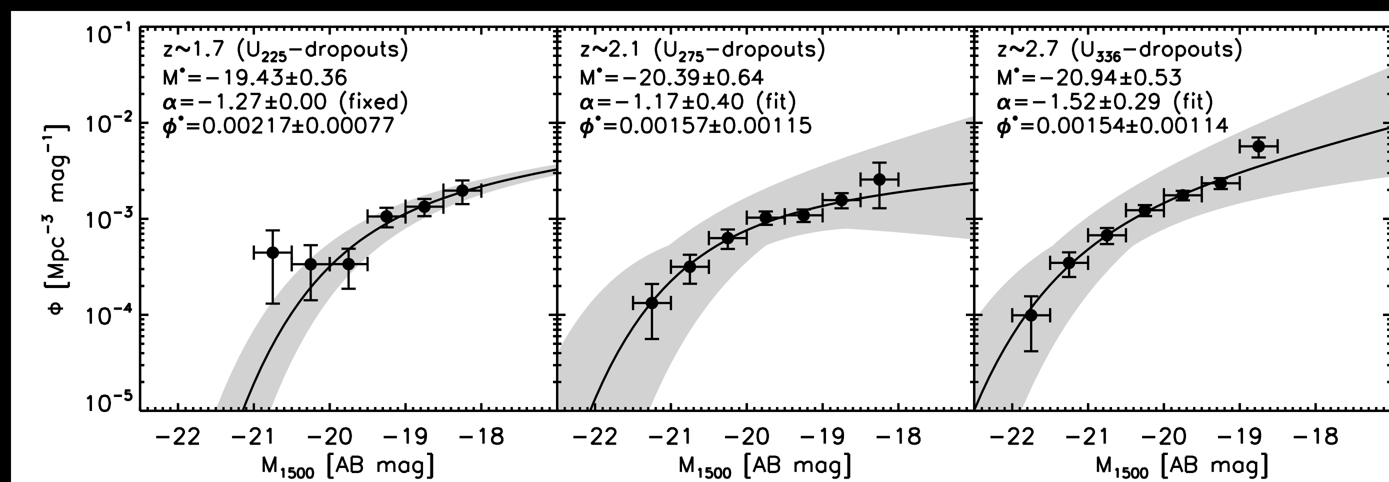
- Can determine their N($z_{form}$), which resembles the cosmic SFH diagram (*e.g.*, Madau et al. 1996). This can directly constrain the process of galaxy assembly and down-sizing (Kaviraj, Rutkowski et al. 2012, MNRAS).

- JWST will extend Balmer+4000Å-break ages to z≲11.




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

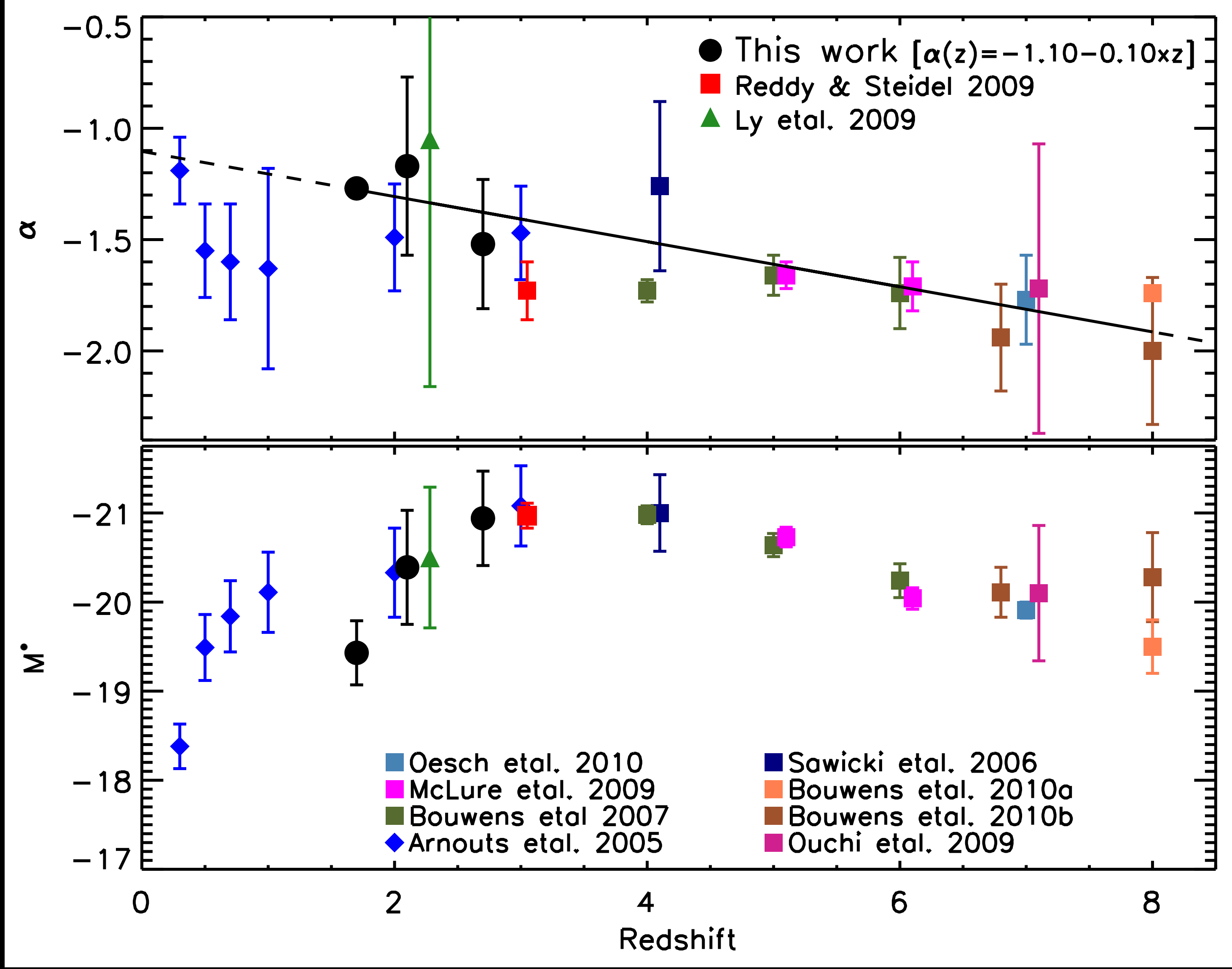



- JWST will similarly measure faint-end LF-slope evolution for 1≲z≲12.

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

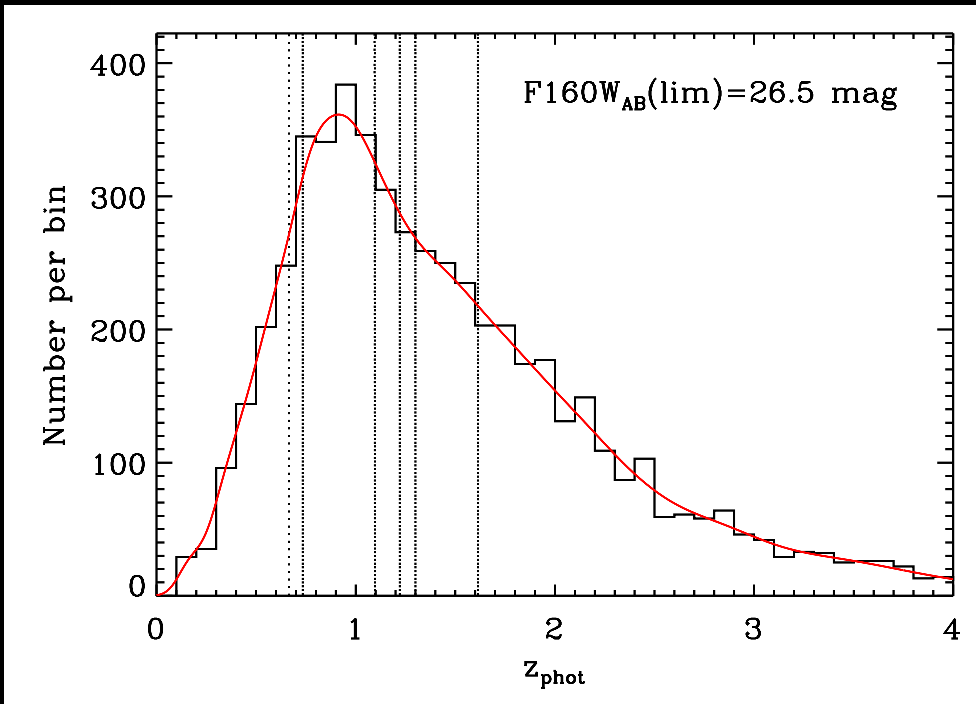
See also talks this conference (e.g., A. Dressler, H. Ferguson, many others).

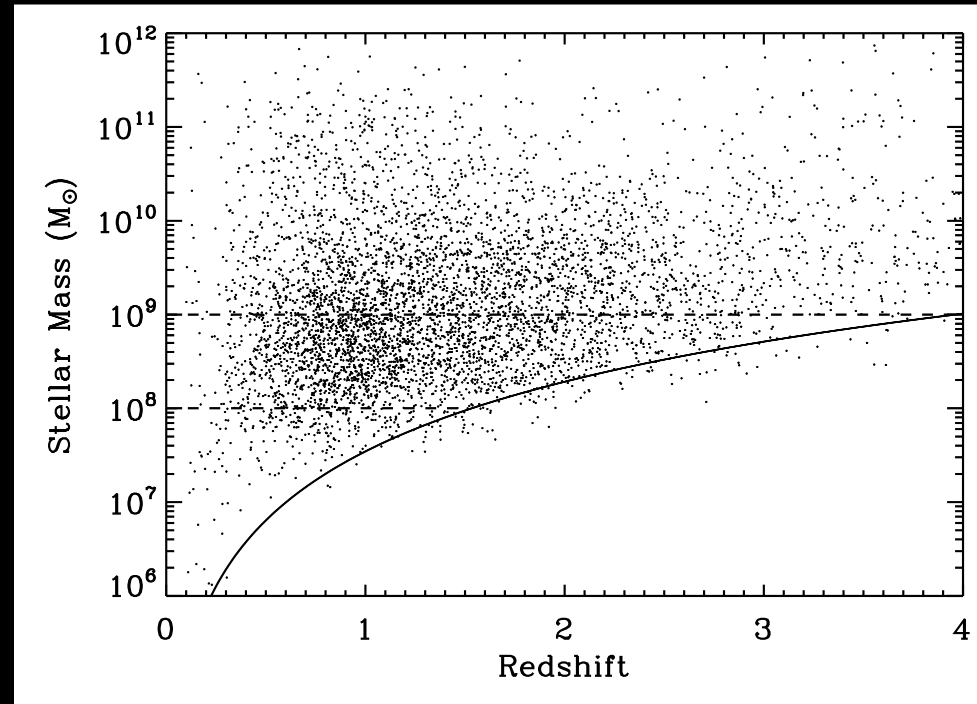



Measured faint-end LF slope evolution (top) and characteristic luminosity evolution (bottom) from Hathi et al. 2010 (ApJ, 720, 1708).

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

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




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

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

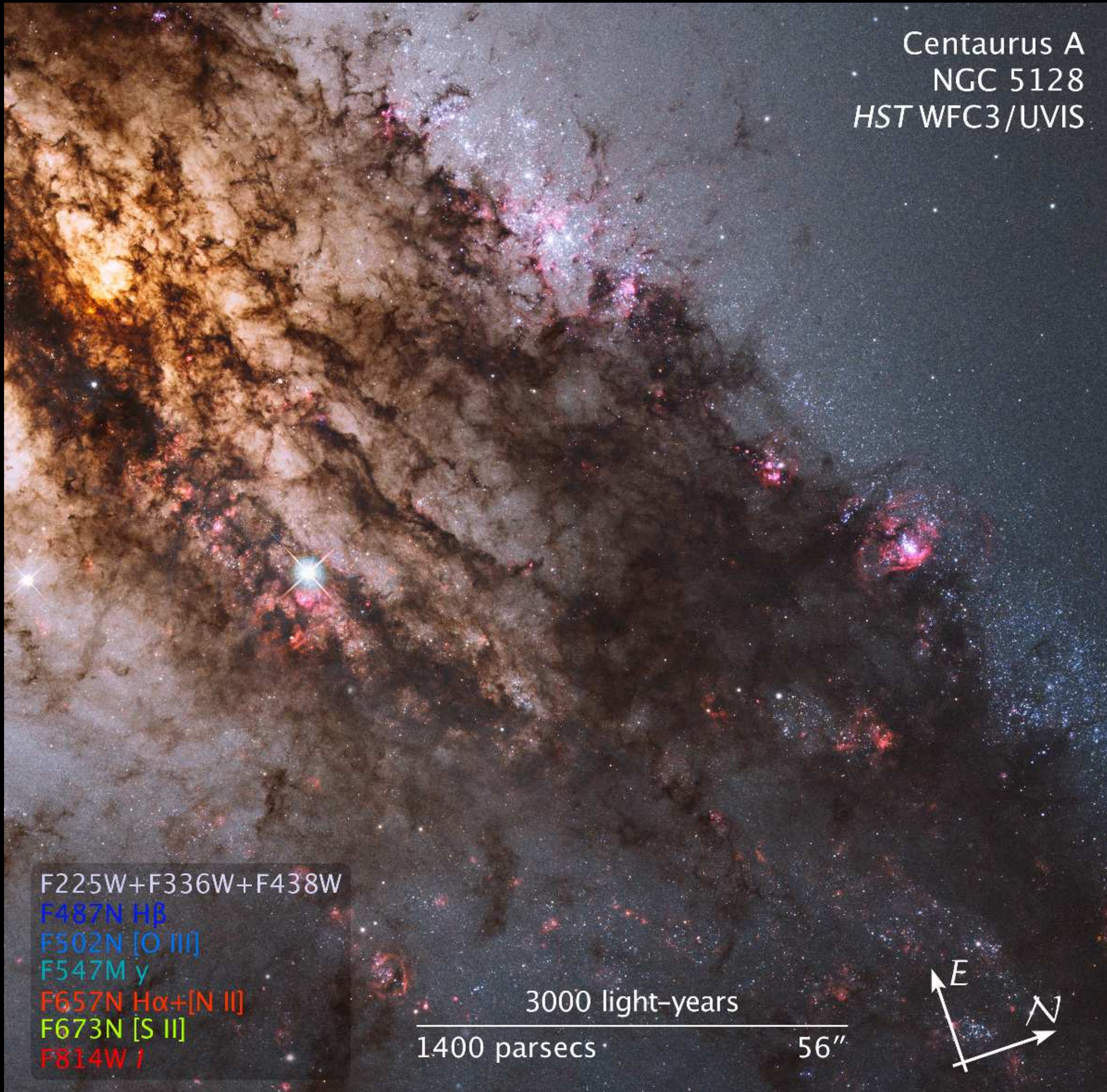
ERS shows WFC3's new panchromatic capabilities on galaxies at z$\simeq$0–7.

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

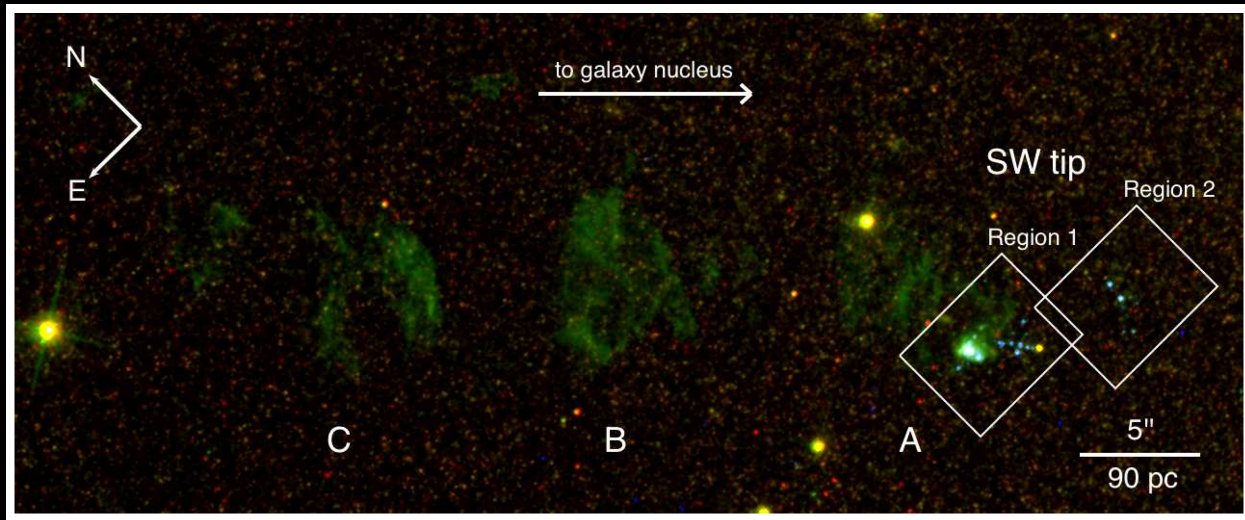
# (2) New Results on AGN-growth with HST/WFC3, and what JWST can do.

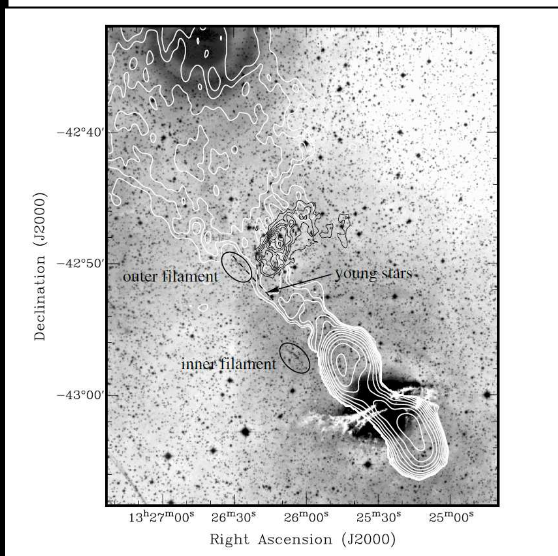
*"For God's sake, Edwards. Put the laser pointer away."*

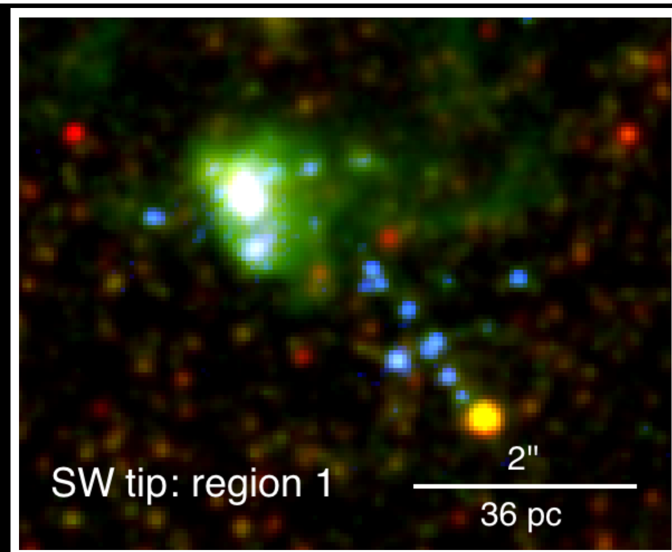
The danger of having Quasar-like devices too close to home ...

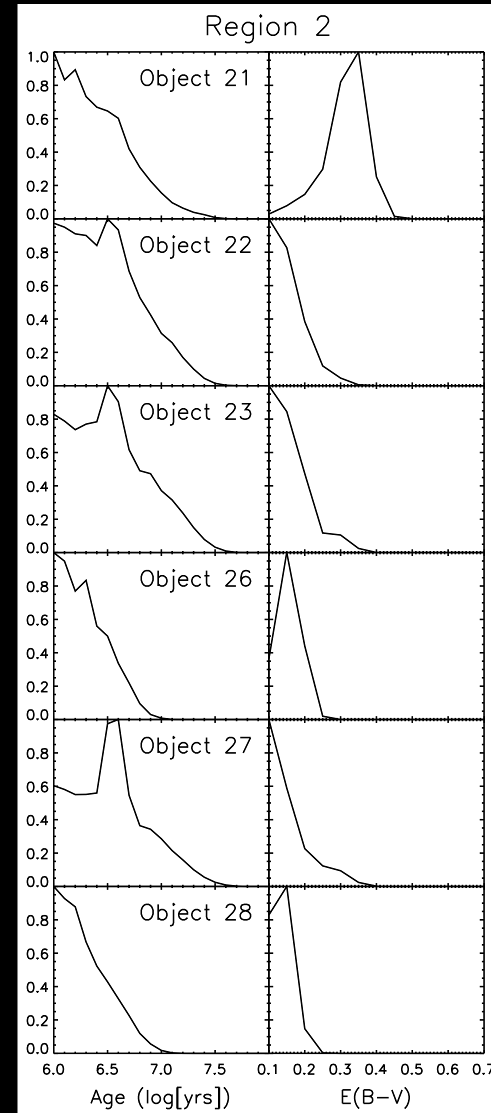


Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W I
3000 light-years
1400 parsecs
56″
E
N



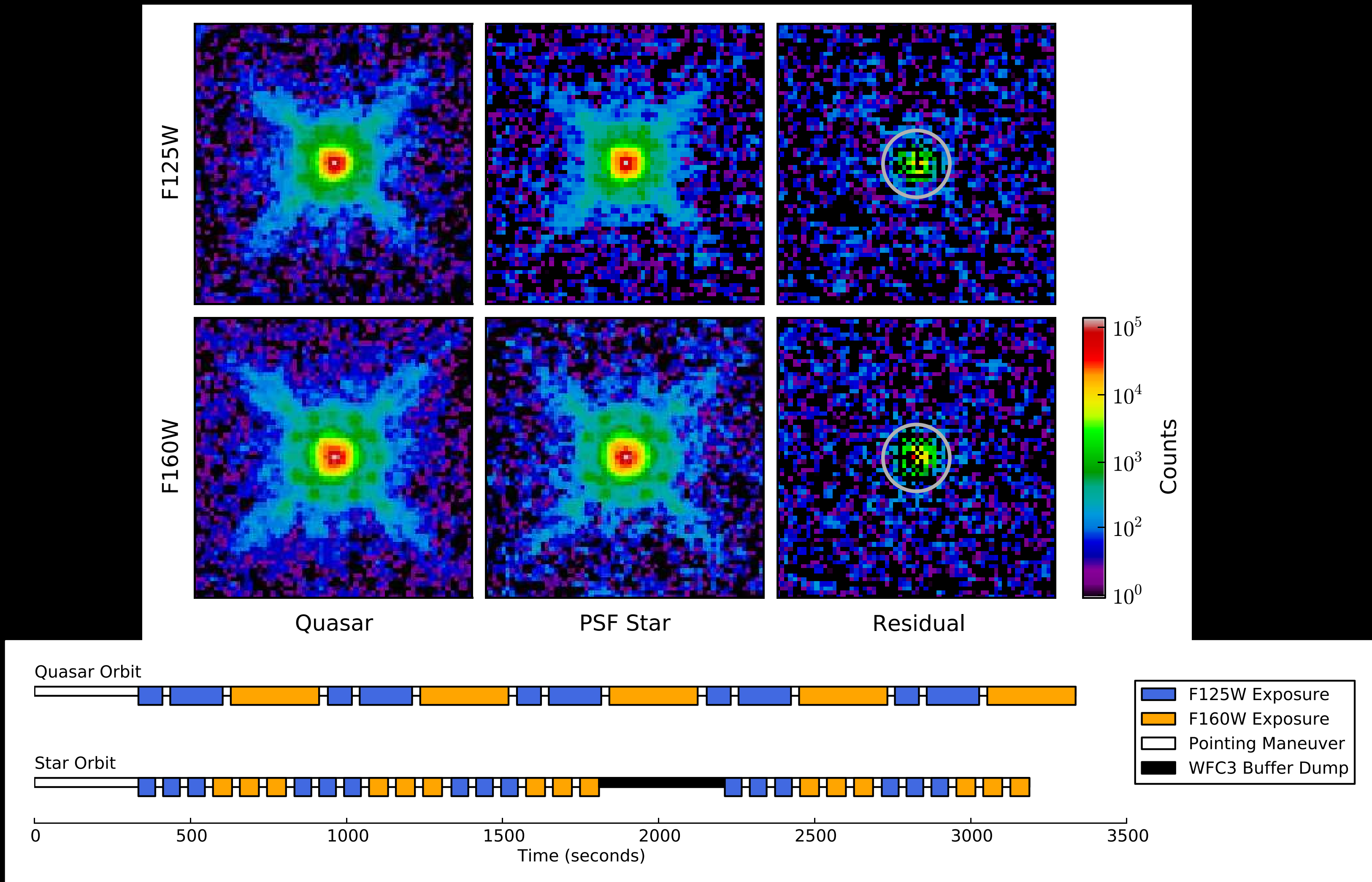




Well determined ages for young (∼2 Myr) stars in Centaurus A jet with star-formation in jet's wake (Crockett et al. 2012, MNRAS, 421, 1602).

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

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

# (2) 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).

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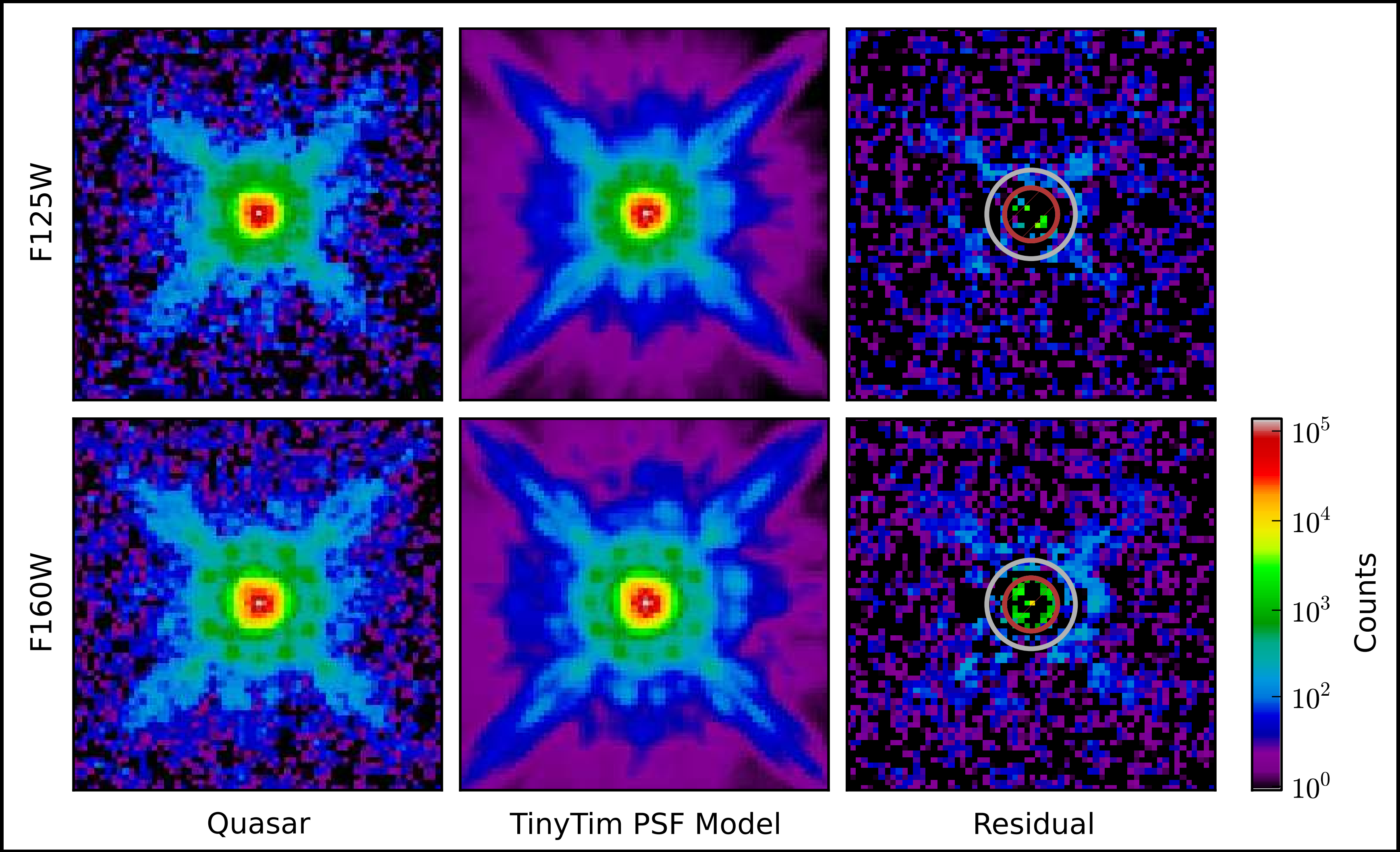


- TinyTim fit of PSF-star + GalFit models QSO nearly to the noise limit: NO z=6.42 host galaxy at AB≳23.5 mag at radius r≃0.″3–0.″5.

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

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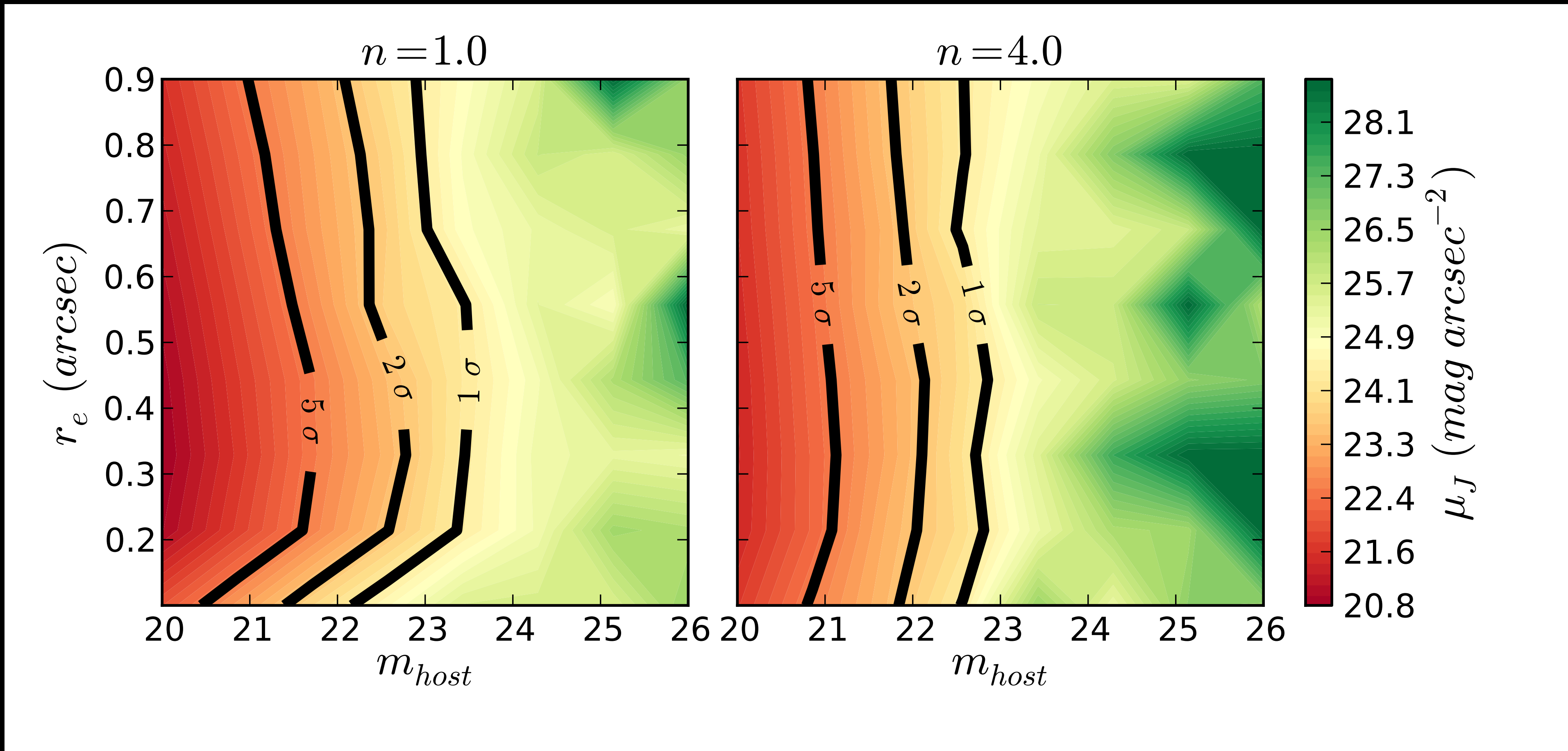
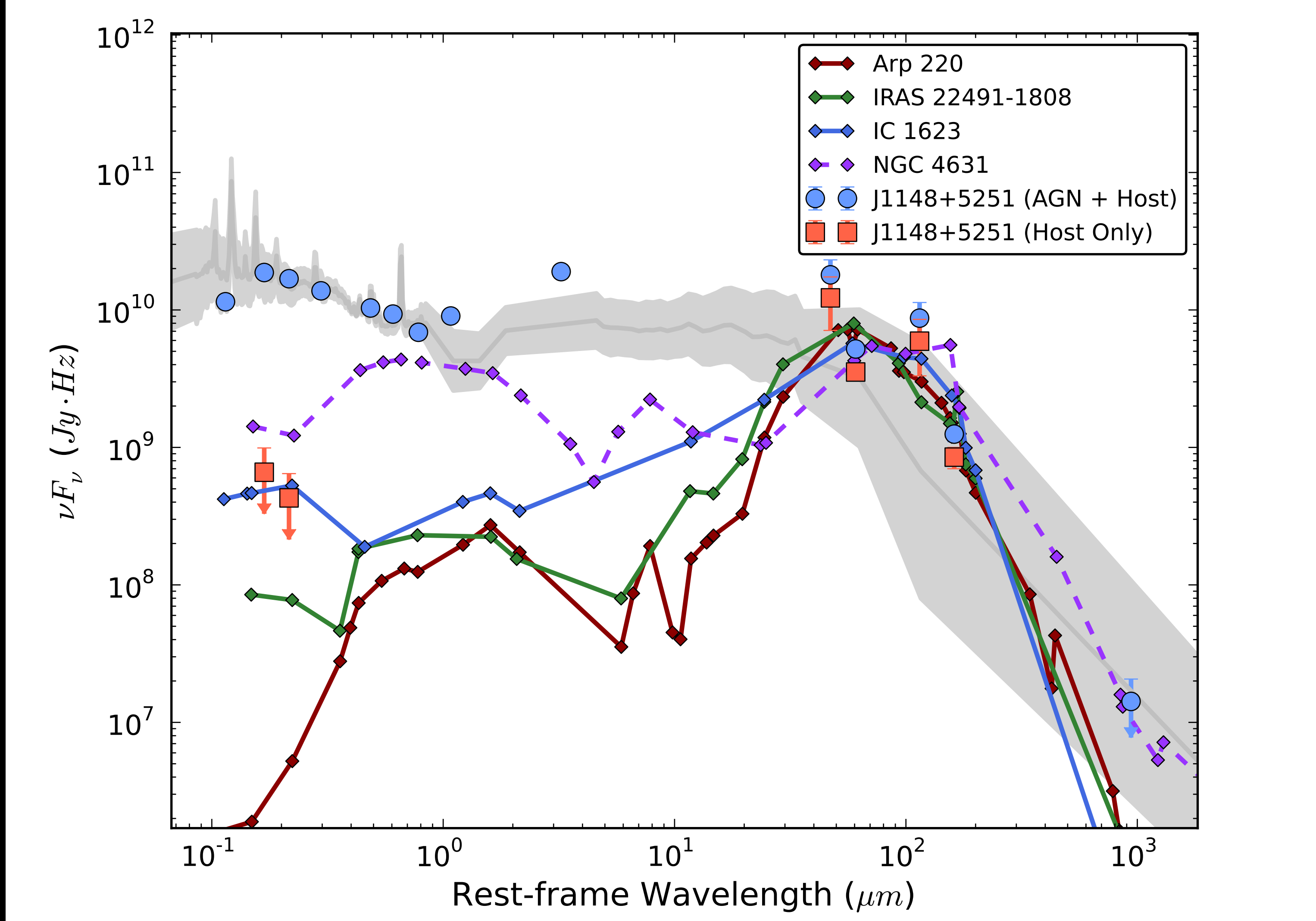



- TinyTim fit of PSF-star + GalFit models of galaxy light-profile, nearly to the noise limit: NO host galaxy at AB≳23.0 mag with $r_e \simeq 0\farcs5$ (Mechtley et al. 2012, ApJL, 756, L23; astro-ph/1207.3283)

- JWST Coronagraphs can do this 10–100× fainter (and for z≲20, $\lambda \lesssim 28\mu$m) — but need JWST diffraction limit at 2.0$\mu$m and clean PSF to do this.

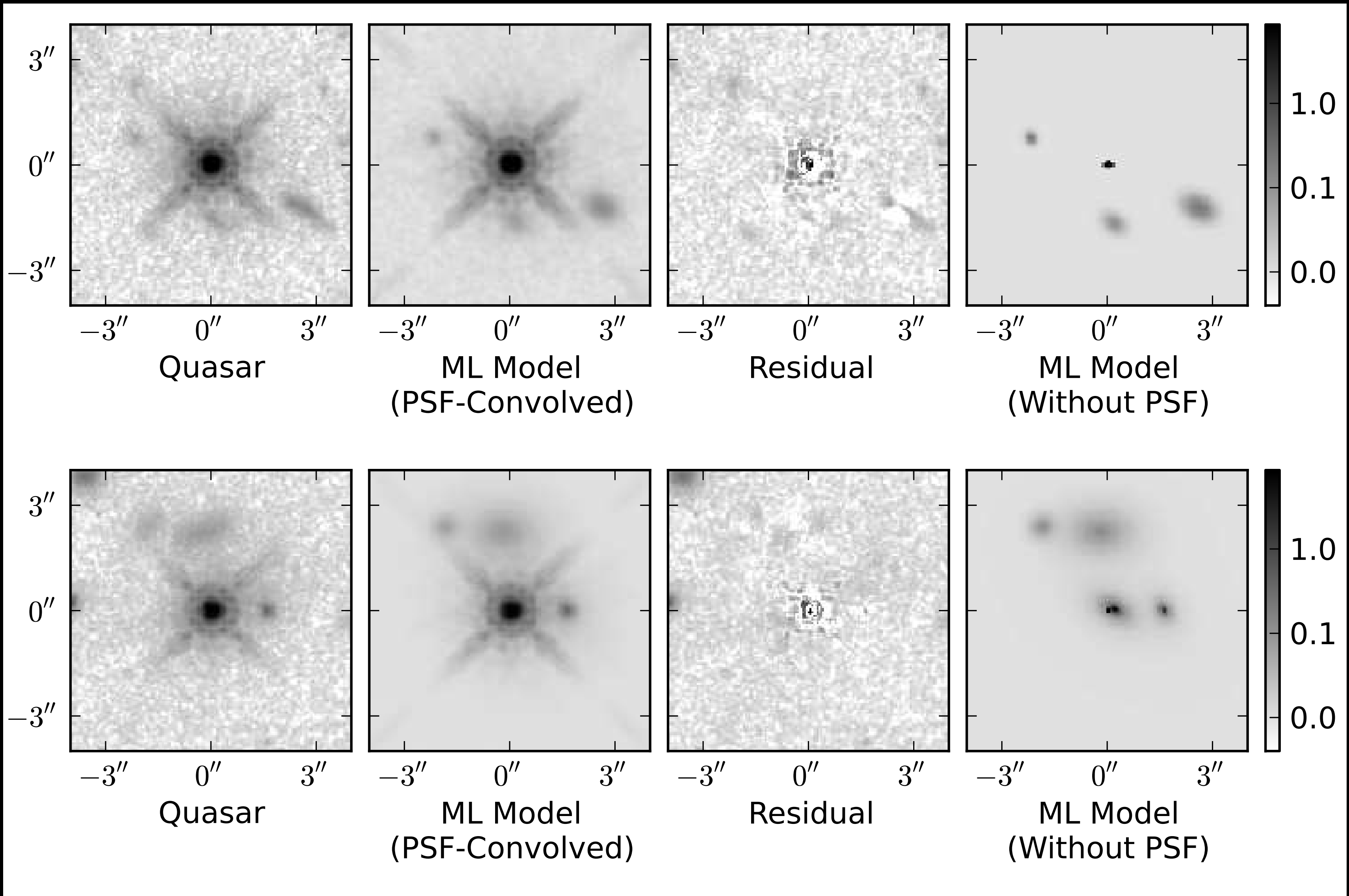



- Blue dots: z=6.42 QSO SED, Grey: Average radio-quiet QSO spectrum at z$\lesssim$1 (normalized at 0.5$\mu$). Red: z=6.42 host galaxy (WFC3+submm).

- Nearby fiducial galaxies (starburst ages$\lesssim$1 Gyr) normalized at 100$\mu$m: Rules out z=6.42 spiral or bluer host galaxy SEDs. (U)LIRGs permitted.

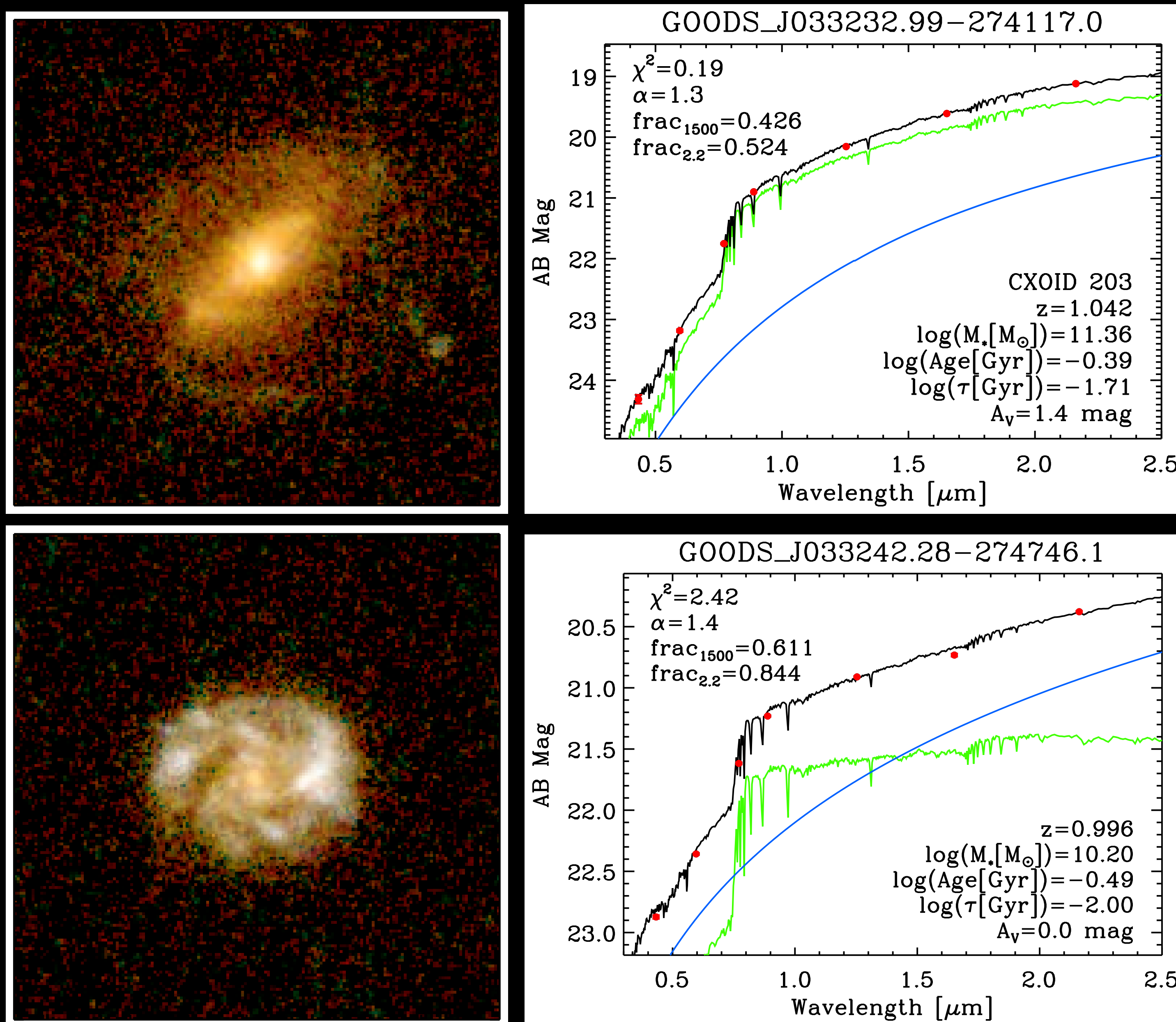
- JWST Coronagraphs can do this 10–100× fainter (& for z$\lesssim$20, $\lambda\lesssim$28$\mu$m).

# (2) WFC3 observations of Quasar Host Galaxies at z≃2 (evidence for mergers?)




- Monte Carlo Markov-Chain runs of observed PSF-star + GalFit-like ML light-profile models: merging neighbors (some with tidal tails?; Mechtley, Jahnke, Koekemoer, Windhorst et al. 2013).
- JWST Coronagraphs can do this 10–100× fainter (& for z$\lesssim$20, $\lambda\lesssim 28\mu$m).

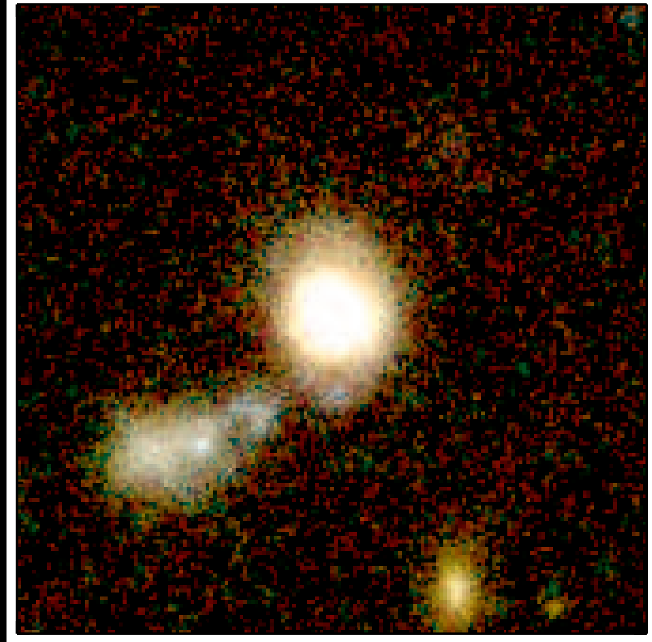
# (3) Radio & X-ray host SED-ages: trace AGN growth directly?

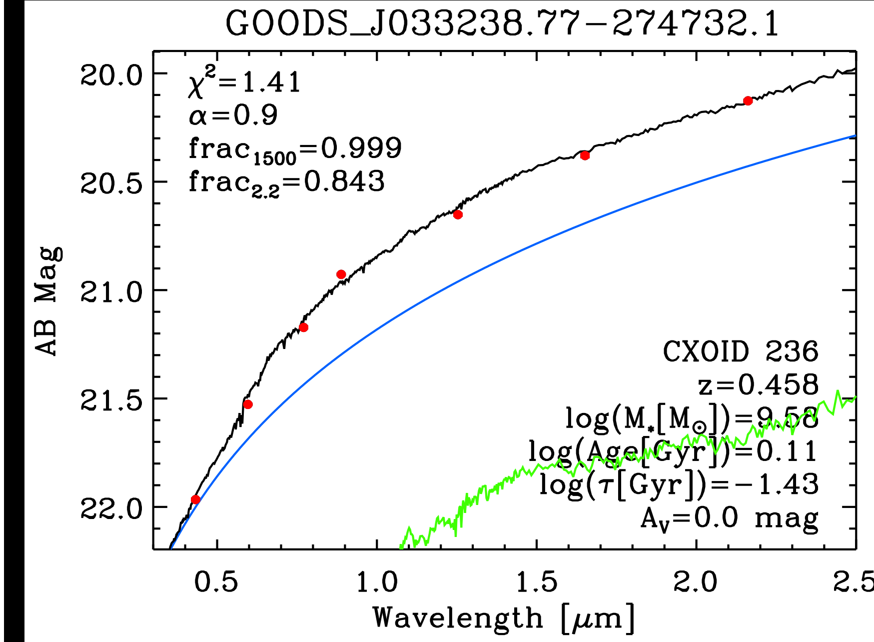



Cohen+ (2013): GOODS/VLT UV+BVizJHK images + 1549 VLT redshifts.

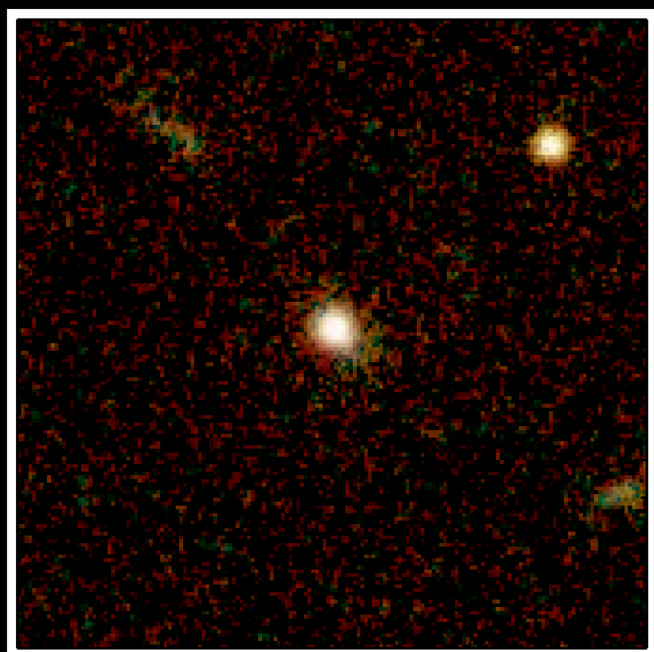
Best fit Bruzual-Charlot (2003) SED + power law AGN.

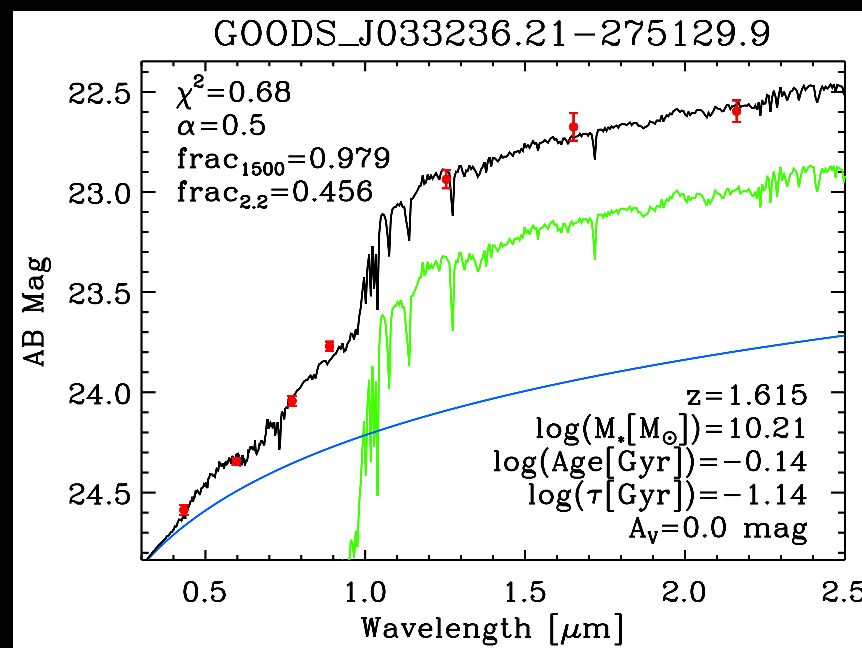
Method: Multi-component SED fits (see spare charts & Jeff Newman's talk).













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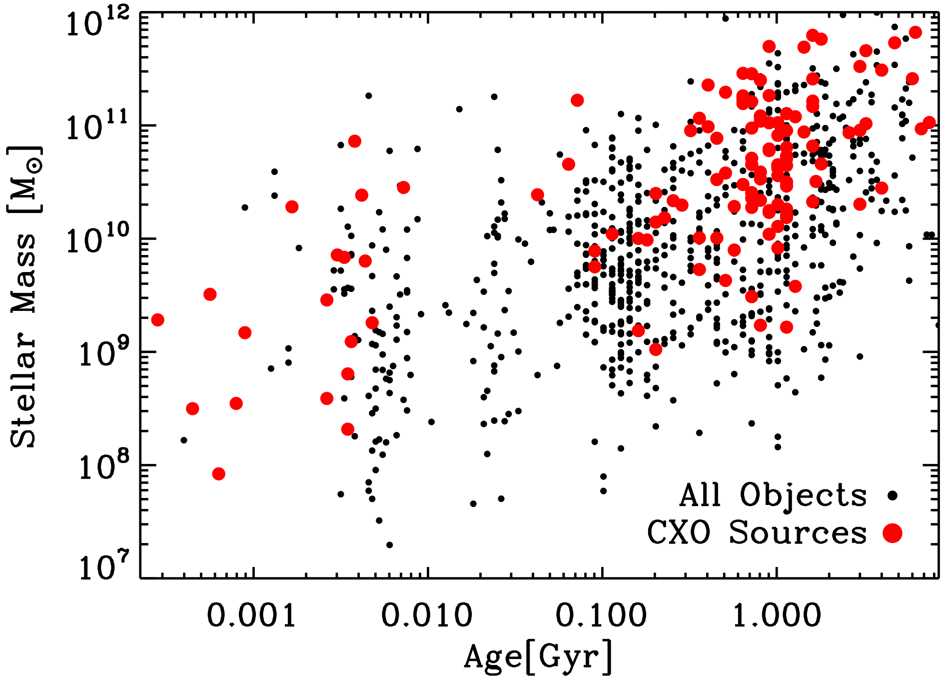
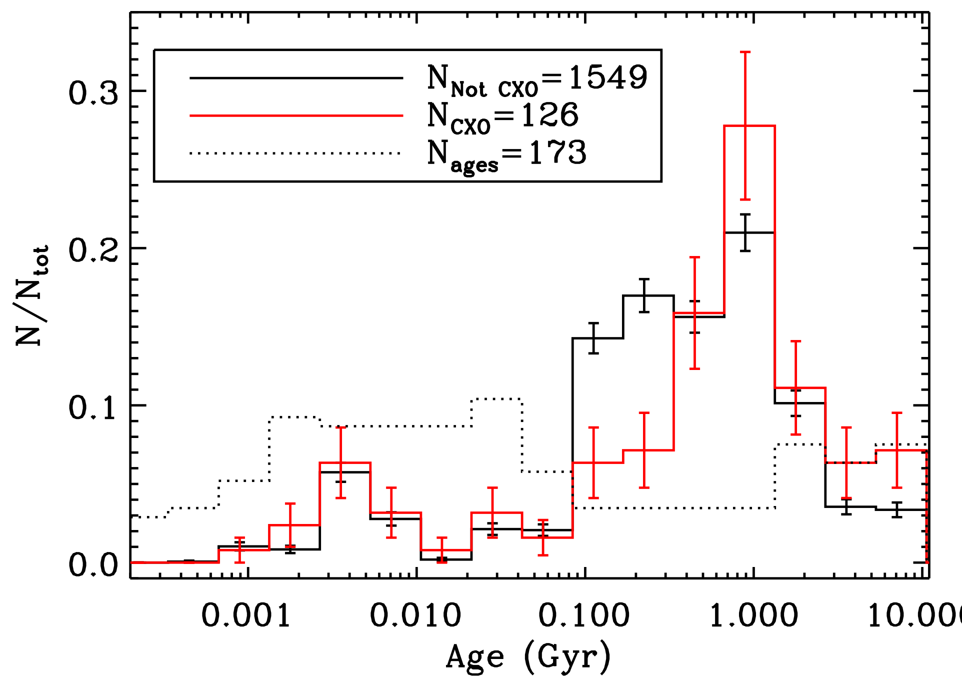
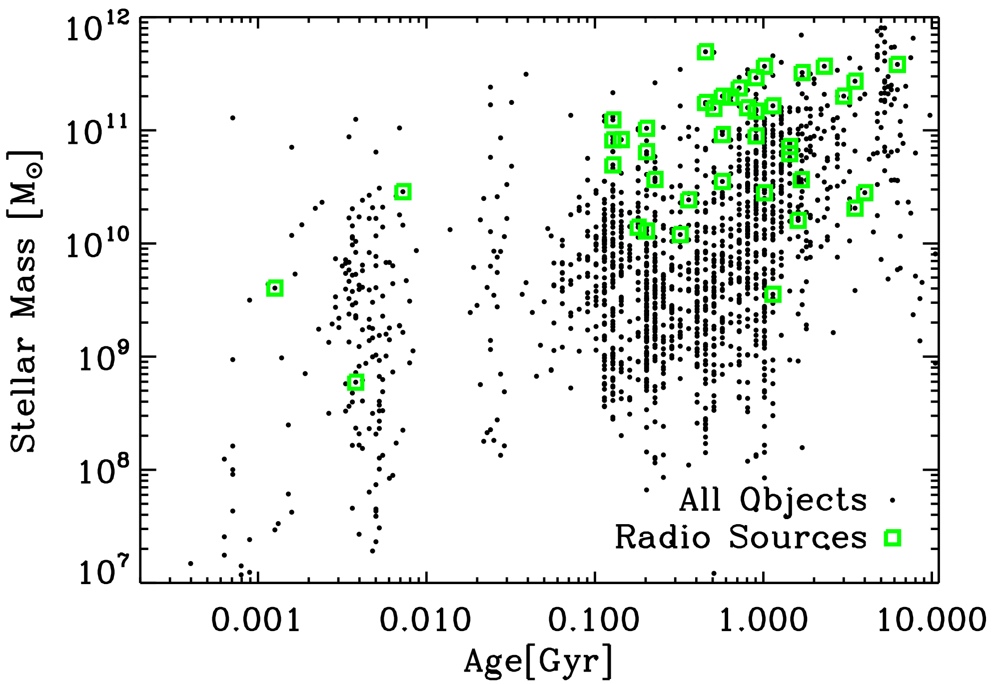


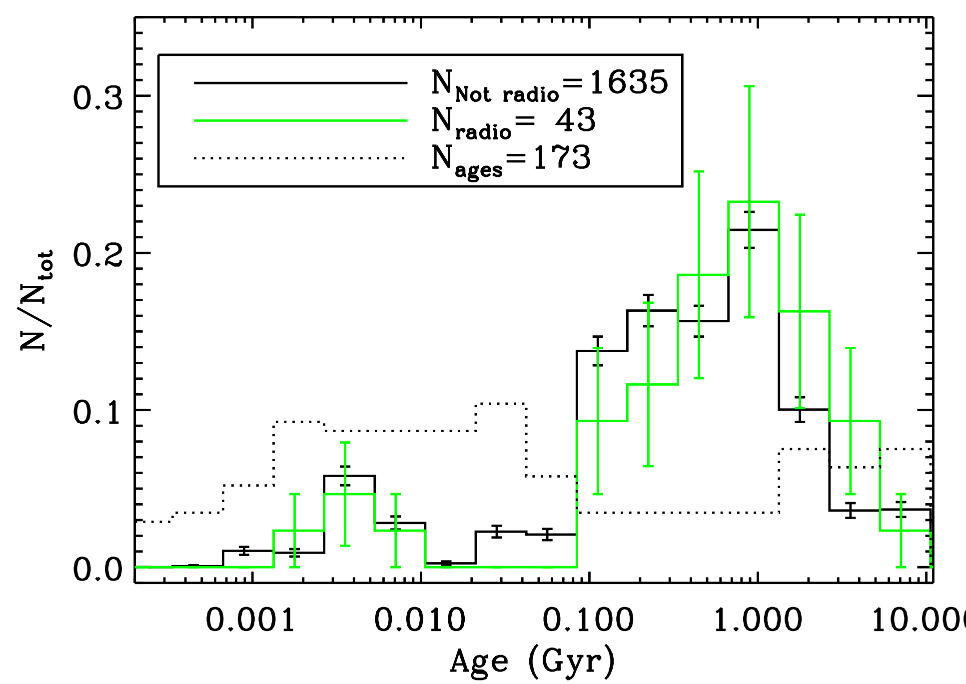




Cohen et al. (2013): Best fit Stellar Mass vs. Age: X-ray and field galaxies.

Field galaxies have: Blue cloud of $\sim$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$10.
- JWST can trace AGN-growth, host galaxy masses and ages since z$\sim$10.

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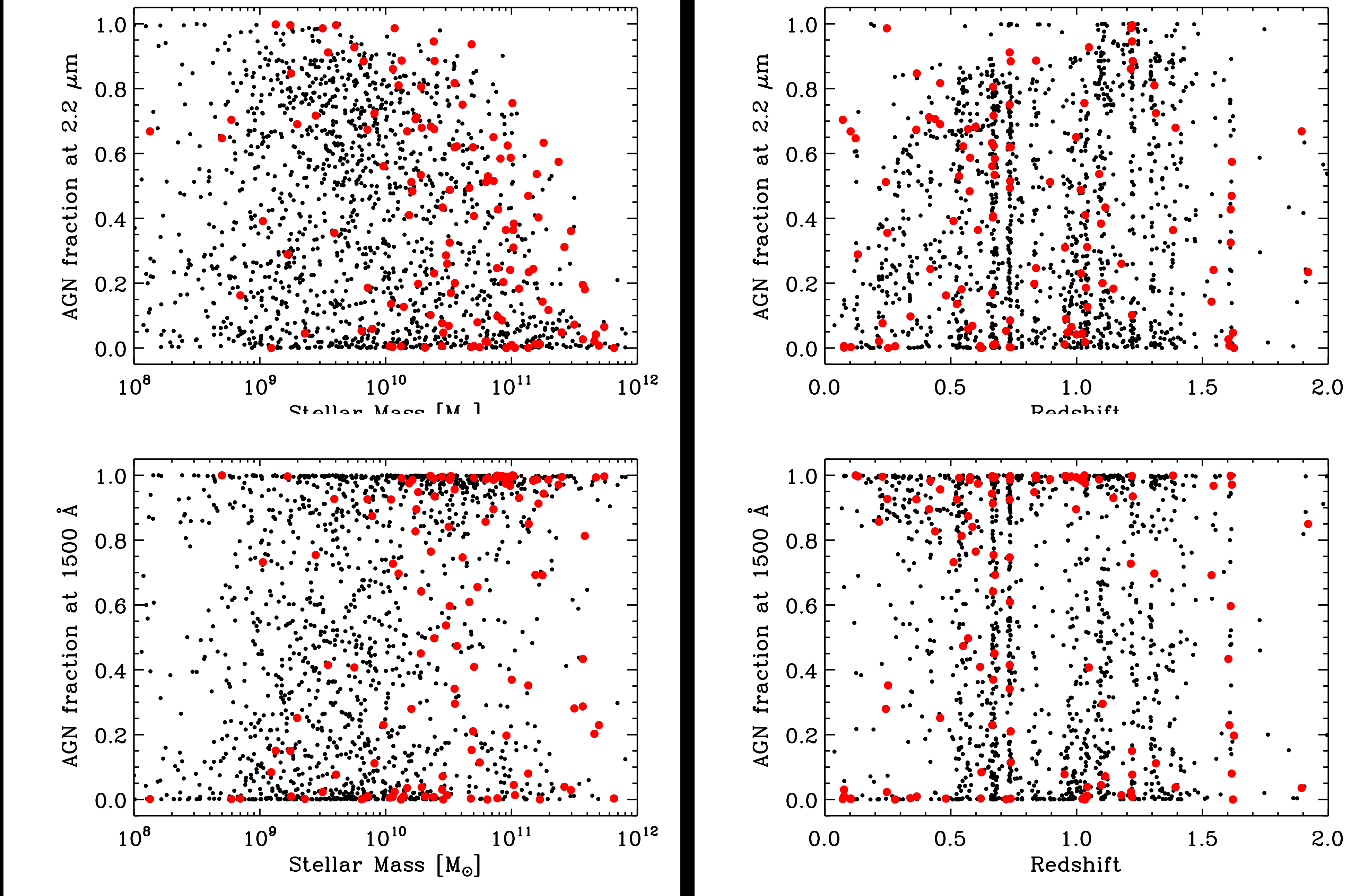
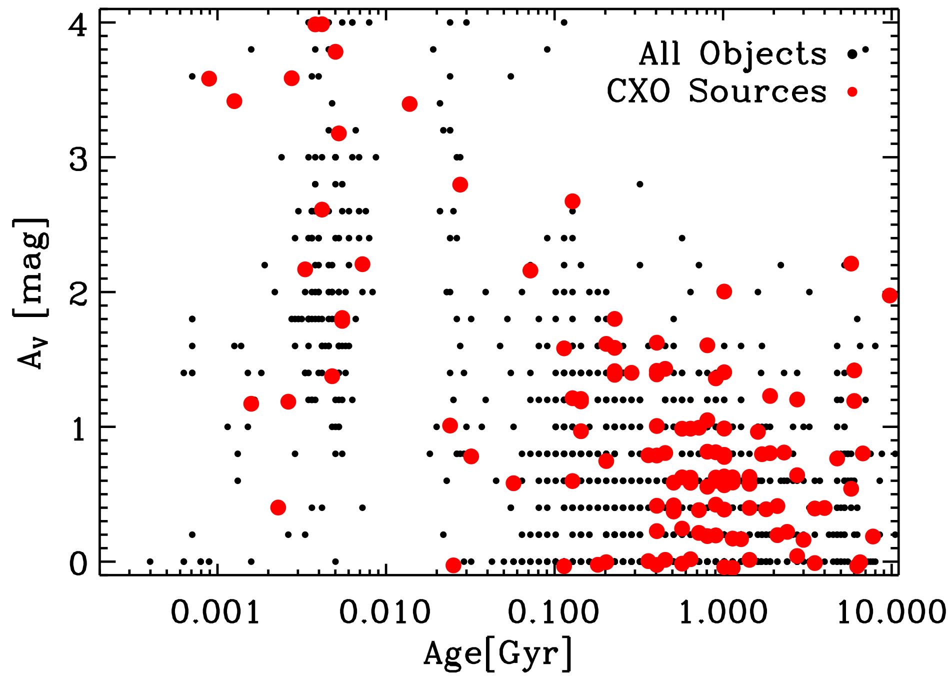
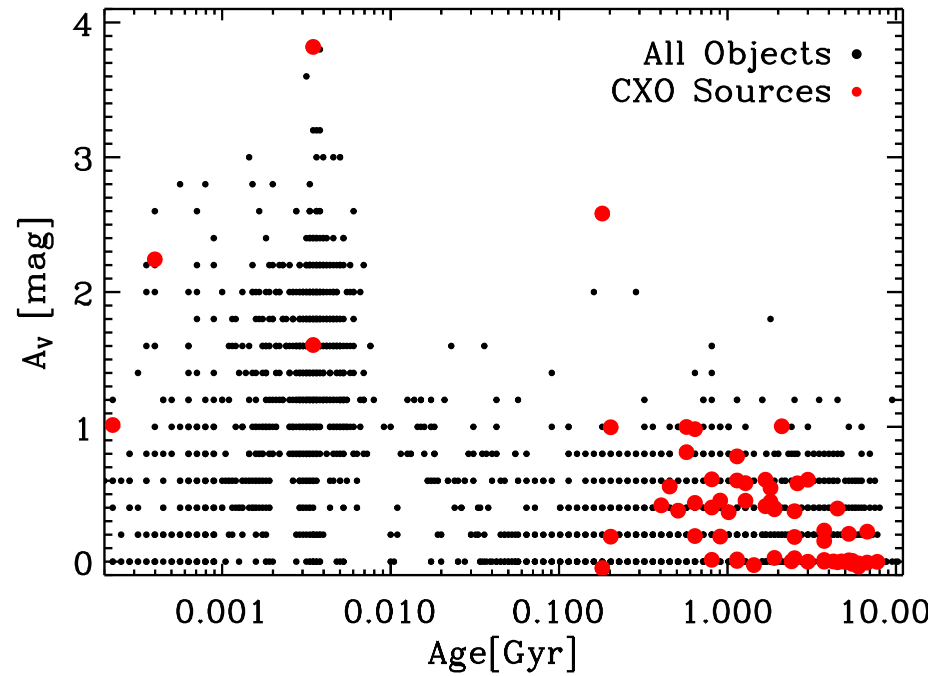



Cohen$^{+}$ (2013): "AGN" fraction vs. stellar mass & $z$: X-ray and field gxys.

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

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




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

Cohen et al. (2013): 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.

## (5) Summary and Conclusions

(1) HST/WFC3 has mapped Galaxy Assembly in detail, now reaching into the end of the epochs of Reionization and First light (z$\simeq$7–11).

- Faint-end LF-slope evol: (how) did dwarf galaxies finish reionization?
- The origin of the Hubble sequence in hierarchical formation scenarios.

(2) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly in detail (Gardner's talk). JWST will determine:

- The formation and evolution of the first (reionizing) Pop III star-clusters.

(3) 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.

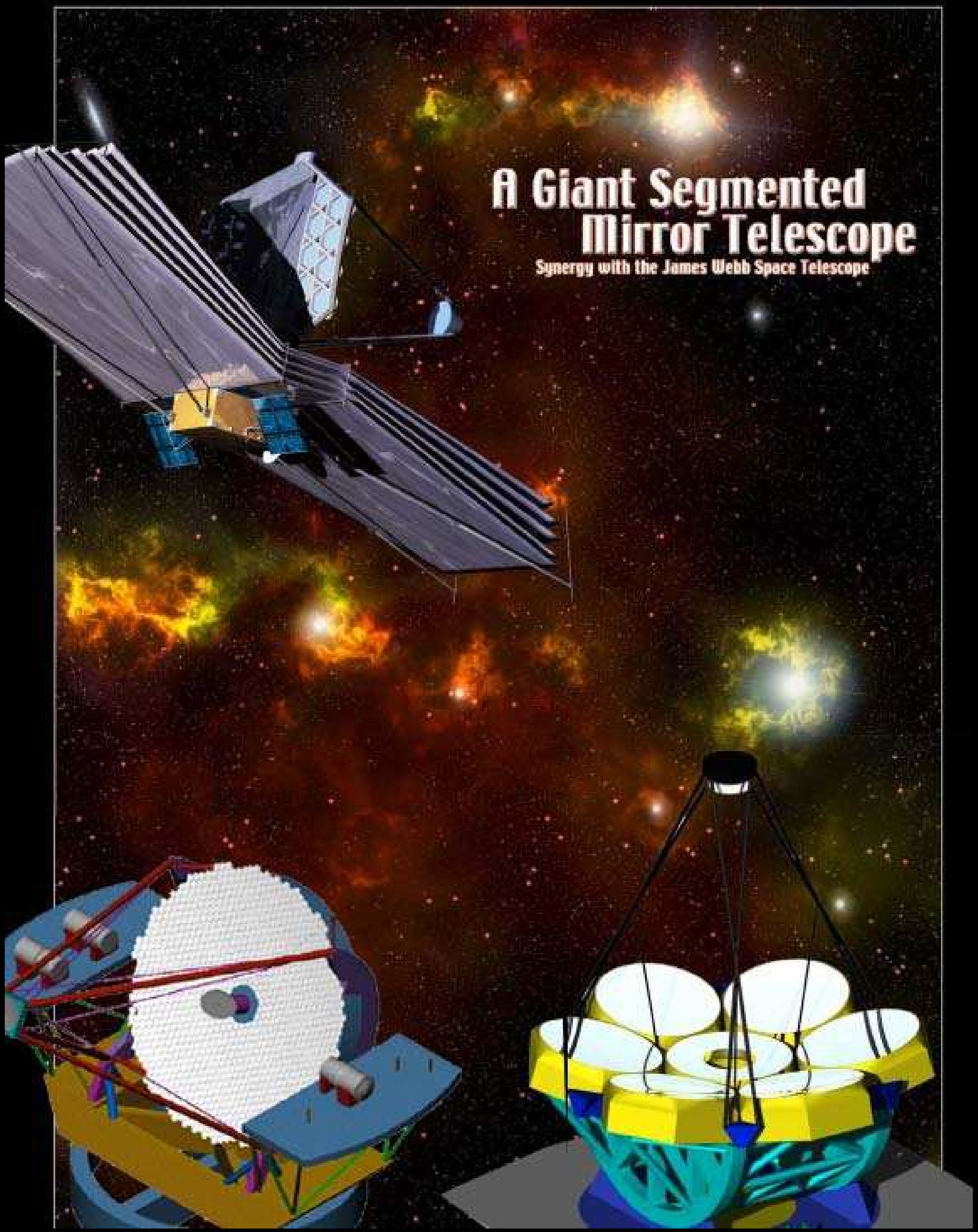
(4) AGN growth likely stays in pace with Galaxy Assembly, but Radio &/or X-ray source may appear $\lesssim$1 Gyr *after* merger/starburst.

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

(6) JWST provides a critical *concurrent* complement to GMT: Panchromatic near–mid-IR imaging & spectral follow-up of GMT discoveries:

# SPARE CHARTS

(4) GMT/TMT & JWST Synergy:
(Kudritzki, Frogel+ 2005):




- (1) Are the top two priority missions of the 2001 Decadal Survey in Astronomy & Astrophysics.
- (2) Each give orders of magnitude gain in sensitivity over existing ground and space telescopes, resp.
- (3) Have complementary capabilities that open a unique new era for cosmic and planetary discovery.
- (4) Maximize concurrent operation of GMT/TMT/E-ELT and JWST!

# (4) Unique Capabilities of the 6.5 meter JWST in L2

- (1) Full sky coverage & high observing efficiency.

- (2) Above the atmosphere, JWST will have:
- Continuous wavelength coverage for 0.6 $\lesssim \lambda \lesssim$ 28.5 $\mu$m.
- High precision and high time-resolution photometry and spectroscopy.

(3) JWST is a cold telescope ($\lesssim$40 K):

- Minimizes thermal background (for $\lambda \lesssim$10 $\mu$m, set by the Zodi: $10^3$–$10^4\times$ or 7–10 mag lower than ground-based sky!).
- Very high sensitivity for broad-band IR imaging ($\Leftarrow$ no atm OH-lines).

(4) Diffraction limited for $\lambda \gtrsim$2.0 $\mu$m over a wide FOV ($\gtrsim 5'$ ), hence:

- PSF nearly constant across the FOV.
- PSF stable with time — WFS updates on time-scales of ($\sim$10) days.
- Very high dynamic range.

# (4) Unique Capabilities of the GMT/TMT/E-ELT

(1) Sensitivity 25× greater than JWST in accessible spectral regions.

• Very high optical sensitivity (0.32–1.0 $\mu$m) over a wide FOV ($\gtrsim$10$'$ ).

(2) Very high spatial resolution, diffraction-limited imaging in mid- and near-IR — with AO can get PSF 4–6× better than JWST.

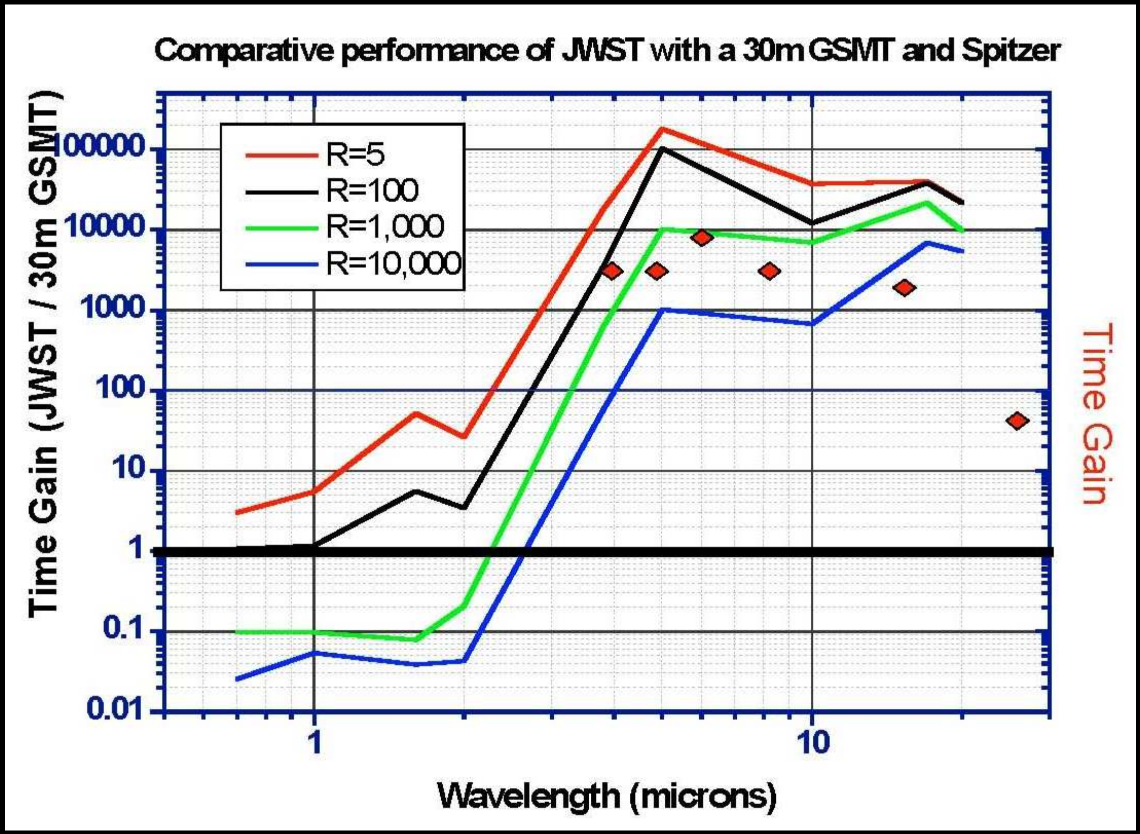
• High sensitivity for non-background limited IR imaging and high-resolution spectroscopy (between OH-lines).

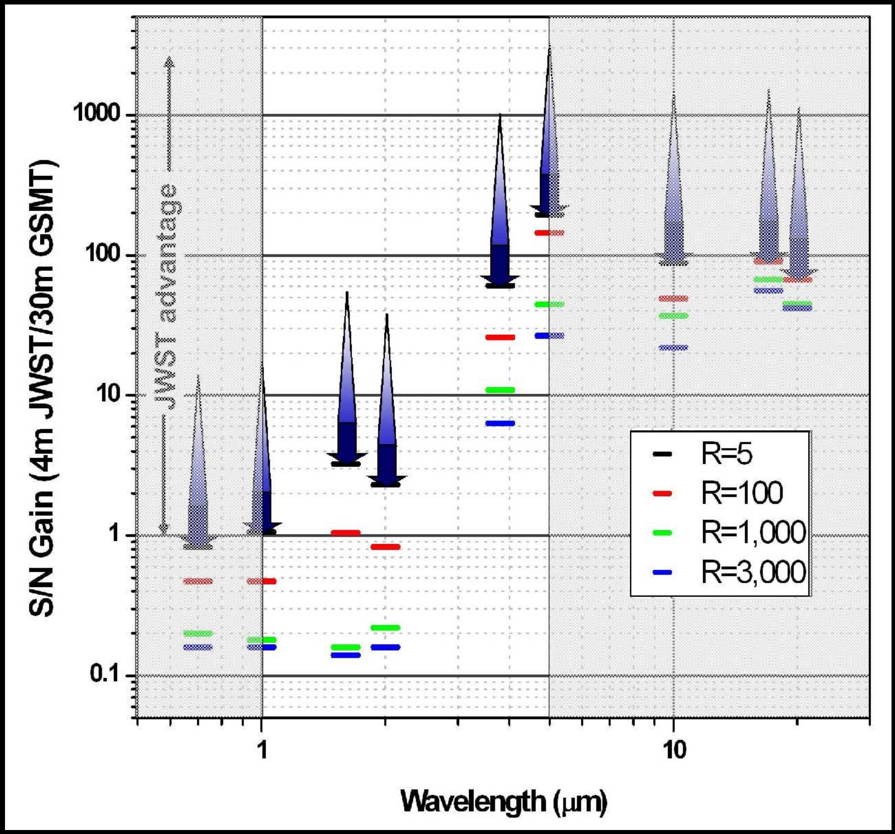
(3) Very high resolution spectroscopy — (R $\gtrsim 10^5$) in optical–mid-IR.

(4) Short response times — few minutes for TOO's.

(5) Flexible and upgradable — take advantage of new developments in instrumentation in the next decades.

# (4) Synergy between the GMT/TMT/E-ELT and JWST




LEFT: Time-gain($\lambda$) of JWST compared to GMT/TMT and Spitzer.
GMT/TMT-AO competition is why JWST no longer has specs at $\lambda \lesssim 1.7\mu$m.

RIGHT: S/N-gain($\lambda$) of JWST compared to ground-based:

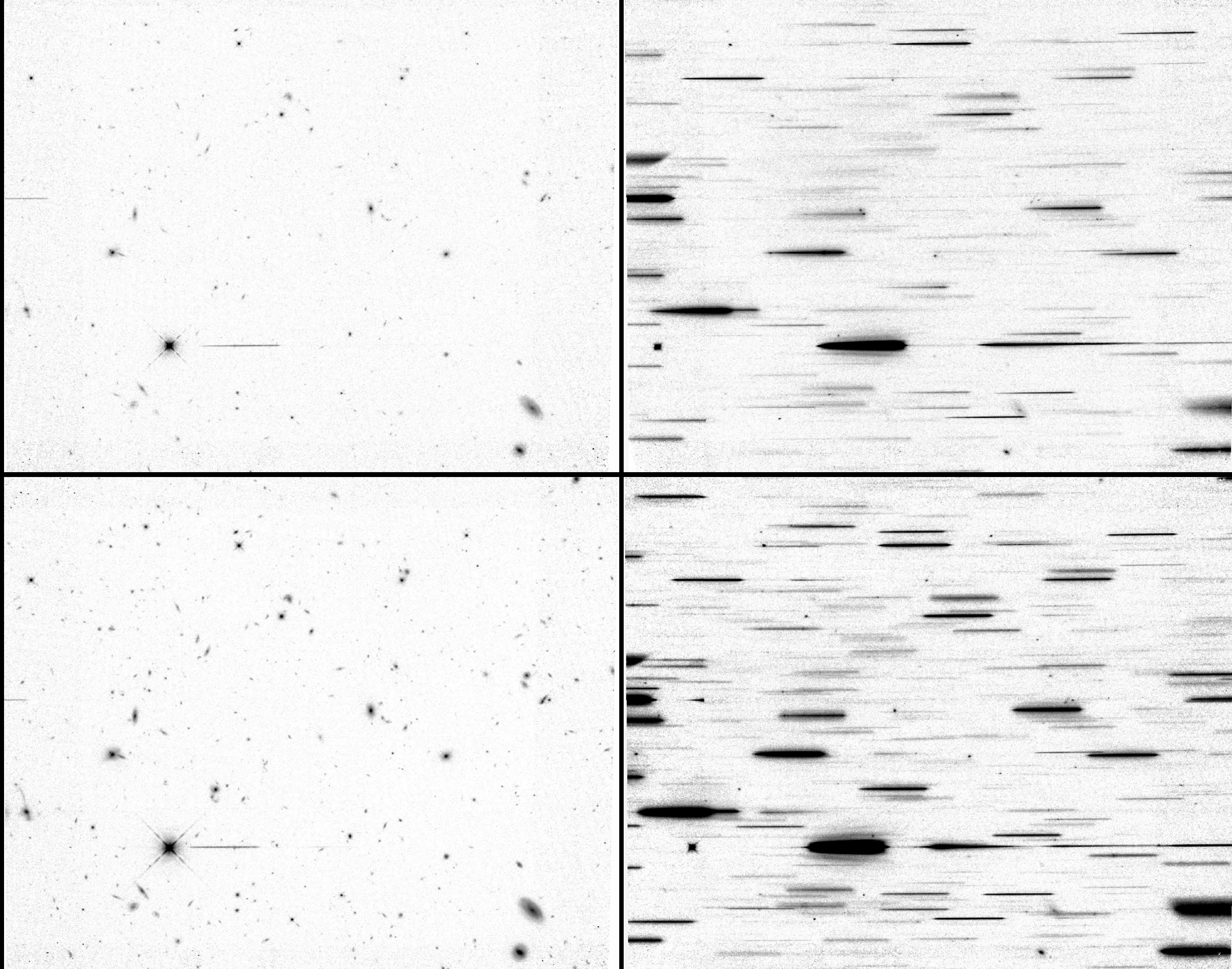
- Top of arrows: 6m JWST/Keck; Middle: 6m JWST/TMT; Bottom: 4m JWST/TMT.

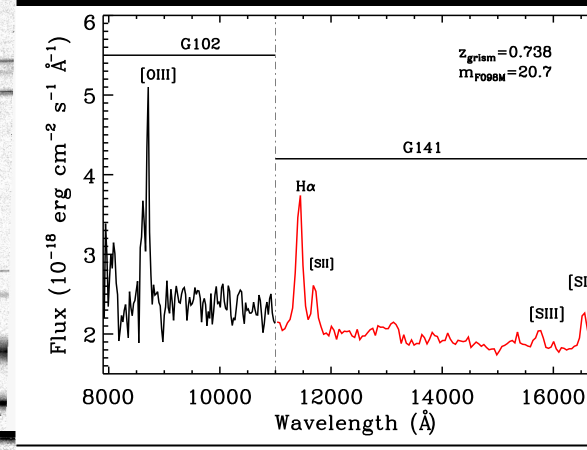
# (4) Comparison of GMT/TMT/E-ELT and JWST — areas of unique strength

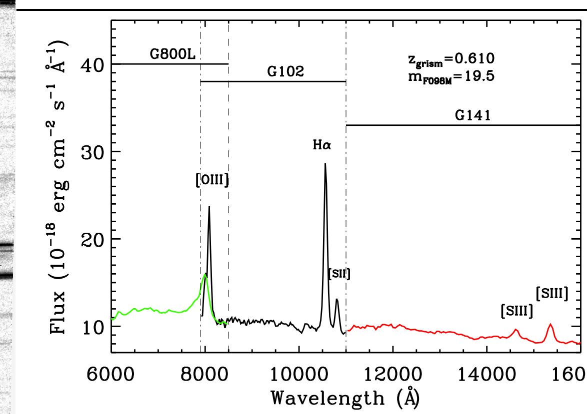
| *Instrument Capabilty* | *Uniqueness* |
|---|---|
| Imaging 0.7-1.7 microns | 20-30m MCAO will be comparable |
| Imaging 1.7 - 5.0 microns | JWST Unique |
| Imaging 5-28 microns | JWST Unique |
| Coronagraphy 0.7 - 2.3 microns | Extreme AO on 8-10m superior |
| Coronagraphy 2.4 - 5 microns | JWST Unique |
| Coronagraphy 5 - 28 microns | JWST in principle unique |
| Tunable filter 1.0 - 2.0 microns | 8-10m AO & narrow band filters comparable |
| Tunable filter 2.4 - 5 microns | JWST in principle unique |
| Slit Spectroscopy 0.7-1.7 microns | 20-30m MCAO superior |
| Slit Spectroscopy 1.6 - 5 microns | JWST Unique |
| MOS spectroscopy 0.7- 1.7 microns | 20-30m MCAO superior |
| MOS spectroscopy 1.7 - 5 microns | JWST Unique |
| IFU spectroscopy 1.0- 1.7 microns | 20-30m MCAO superior |
| IFU spectroscopy 1.7 - 5 microns | JWST Unique |
| (IFU) spectroscopy 5-28 microns | JWST Unique |

JWST: diffraction limited wide-FOV imaging and low-res spectra at $\gtrsim 2\mu$m.

GMT/TMT: high-res imaging, coronagraphy, TF-imaging & IFU spectra at $\lesssim 1.7\mu$m, and high-res spectroscopy at $\lesssim 2\ \mu$m (with AO beyond).






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 $\mu$m.

## (3) 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 $\mu$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 $\tau$ 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: $A_V$ = [0, 4.0] in 0.2 mag steps (n=21).
- $\alpha$=[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 $\chi^2$ 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.

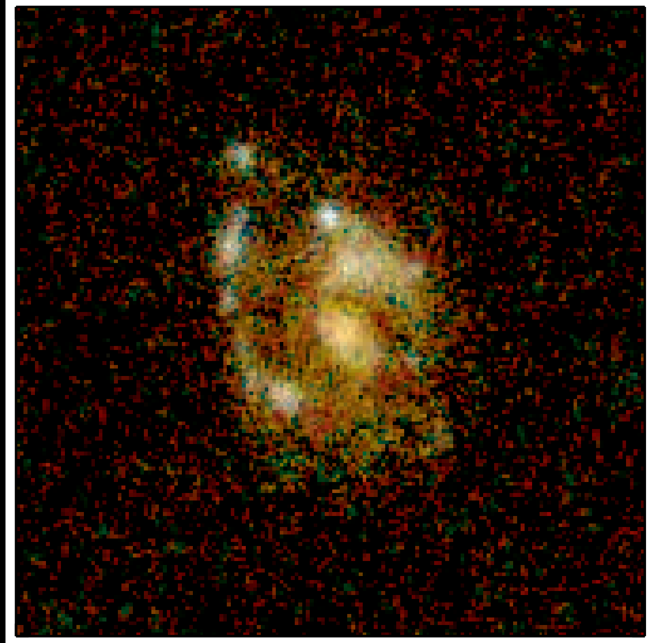
[5] Work in progress on other potential caveats:

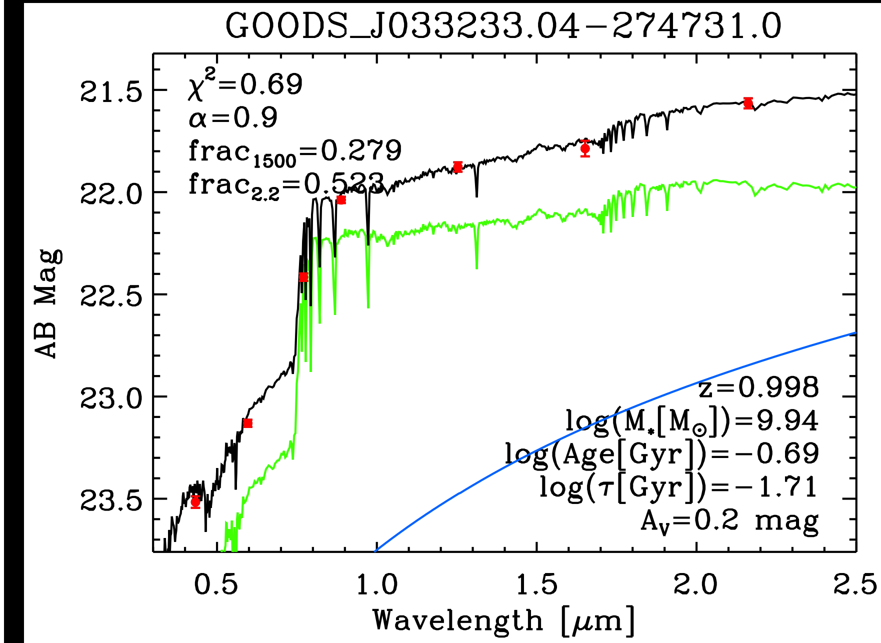
• Young stellar populations have power-law UV spectra (Hathi et al. 2008), and may overestimate UV AGN power-law.

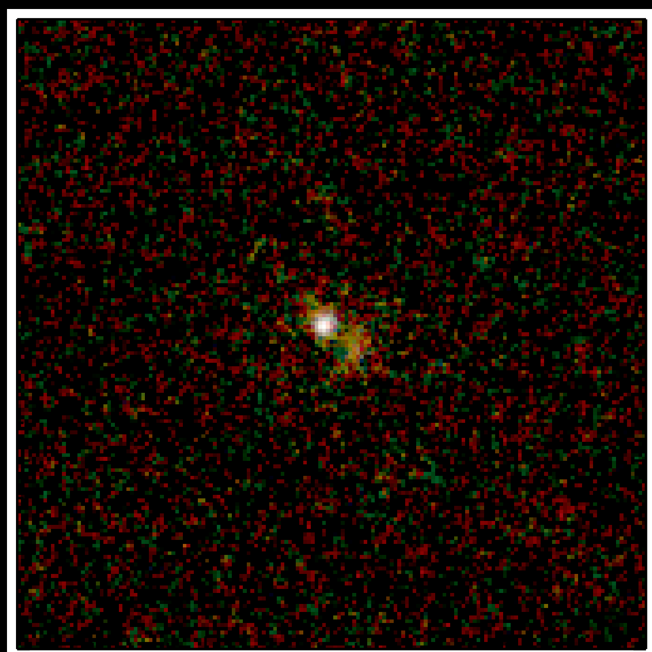
• Include IRAC data and incorporate 1–2 Gyr red AGB population.

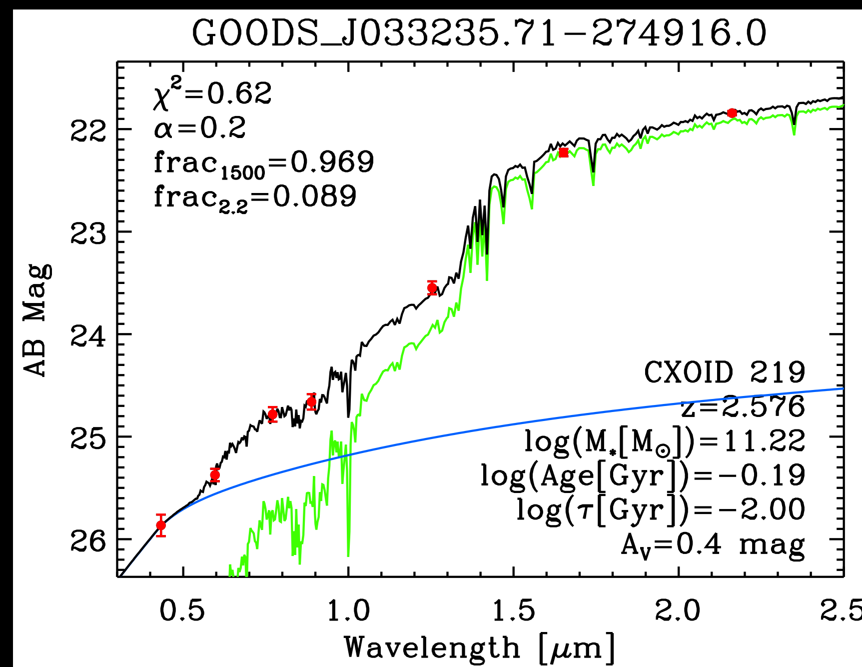
[6] Repeat [1]–[5] for 7000 ERS objects with 10-band spz's to AB=27 mag.

• Fit the BC03 stellar SED only to objects where $\chi^2$ doesn't require both.



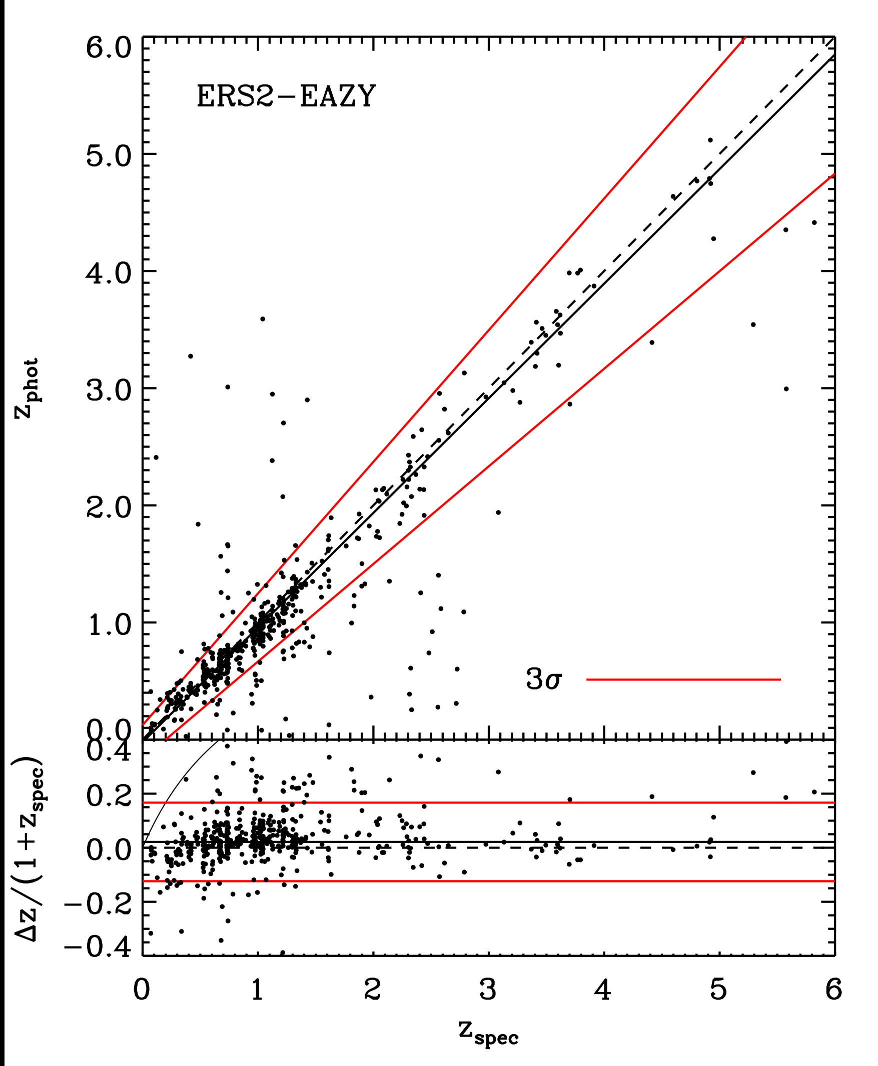


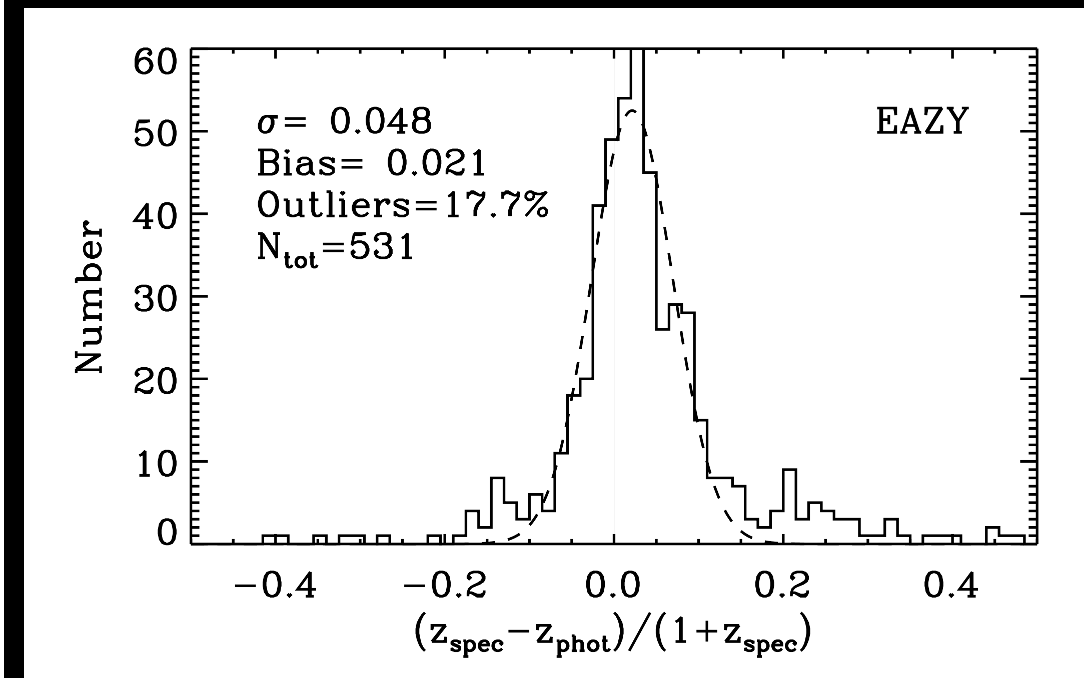






Cohen et al. (2013): GOODS/VLT BVizJHK images

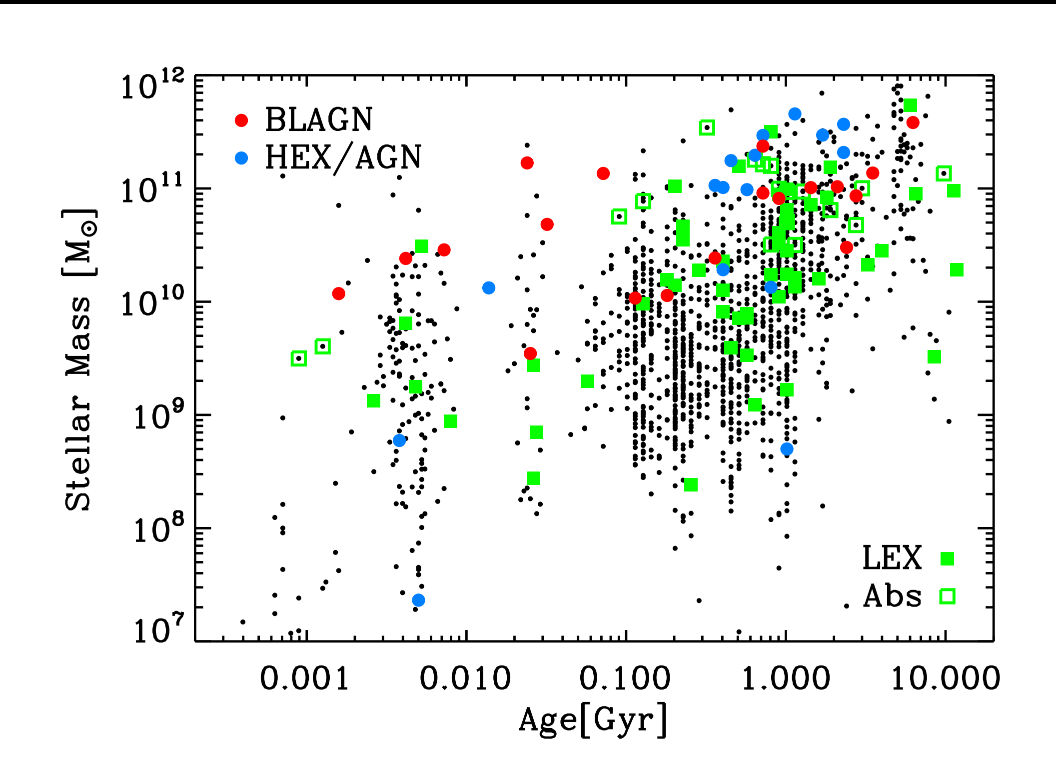
Best fit Bruzual-Charlot (2003) SED + power law AGN.

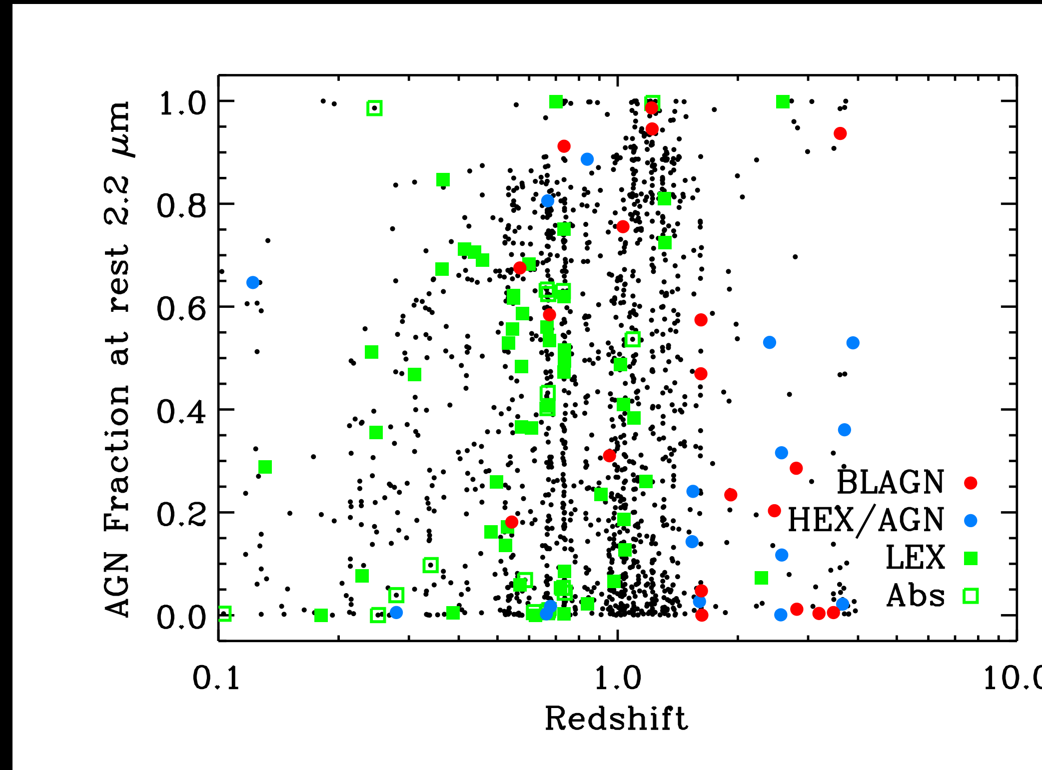



WFC3 ERS 10-band redshift estimates accurate for AB$\lesssim$27 mag to $\sim$4%, especially at 1$\lesssim$z$\lesssim$2, with small systematics (Cohen et al. 2013).

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




Cohen et al. (2013): At all ages, the most massive hosts are QSO-1/2's (based on AGN lines in *optical spectra* by Szokoly et al. 2004):

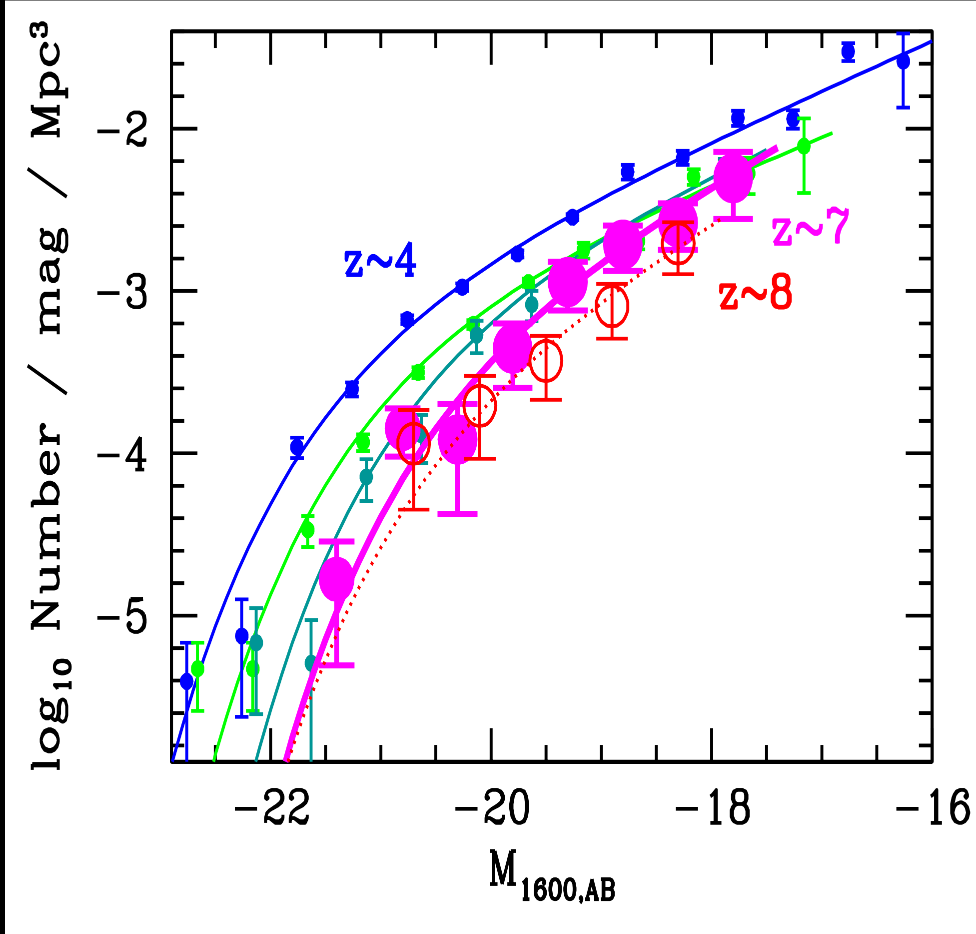
- This is illustrates the well known $L_X$-$L_{opt}$ correlation.

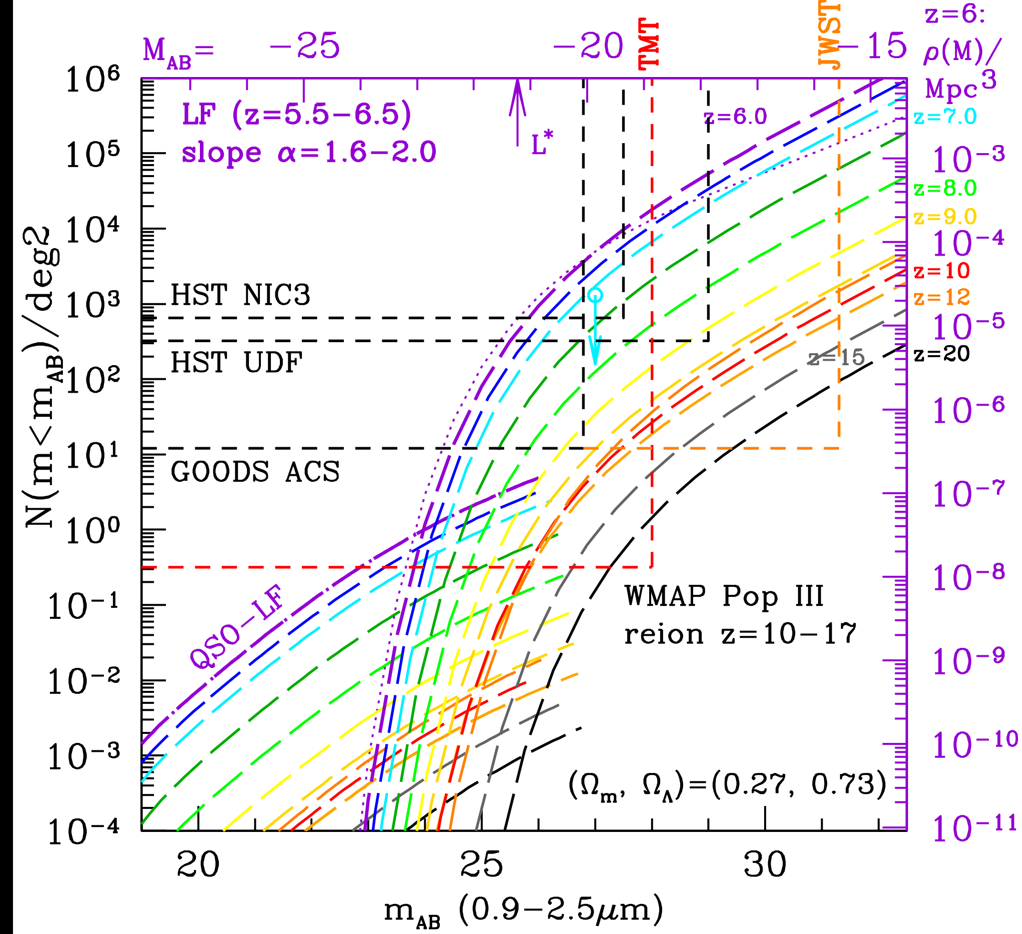
All optical AGN types: emission lines and absorption features.

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 $\mu$m-flux comes from the AGN !?

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




- 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 ($\Omega$), and $\lambda$-range (0.7-29 $\mu$m).
- 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 2.0$\mu$m diffraction limit for this.

- 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).