The key future observations for understanding reionization: Using the James Webb Space Telescope and Other Facilities

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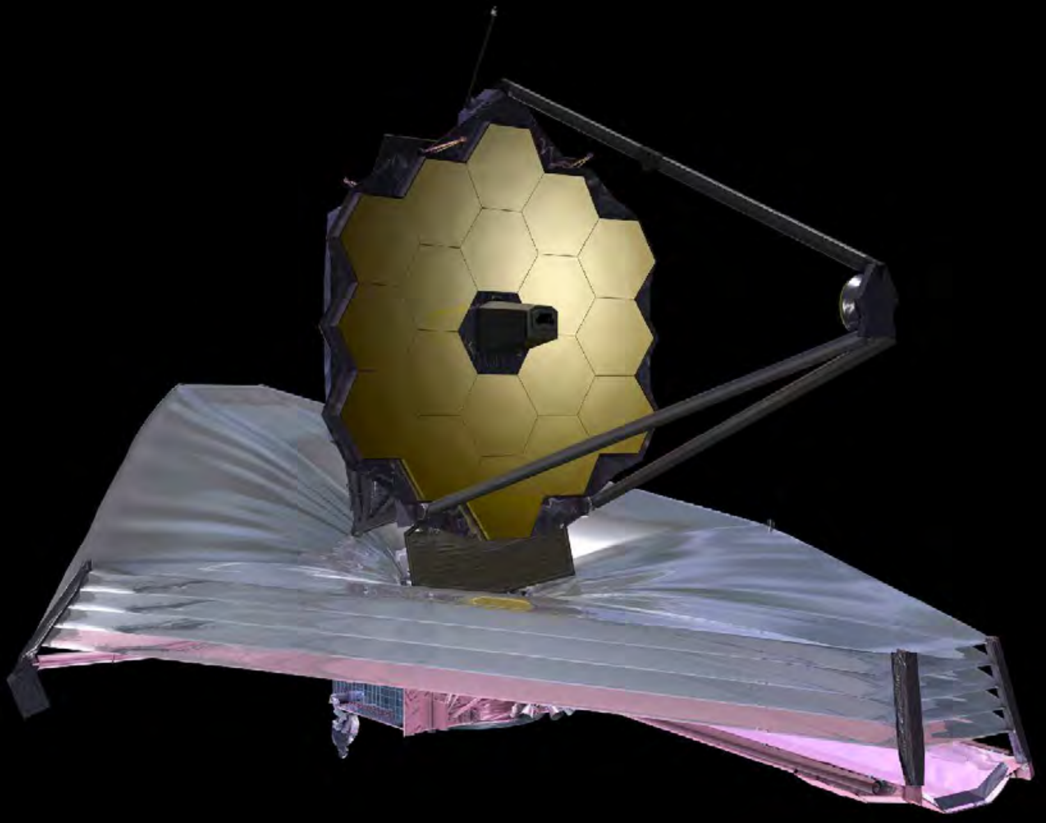


Review at the CAASTRO workshop "Reionization in the Red Centre: New Windows on the High Redshift Universe"

Ayers Rock (Uluru), NT, Australia, Thursday, July 18, 2013. All presented materials are ITAR-cleared.

Outline: Key future observations to understand Reionization

- (1) Dust in QSO host galaxies: first WFC3 $z\simeq6$ QSO host galaxy detection this month ...

- (2) How does the IMF depend on environment, Fe/H, and epoch?

- (3) Lyα at very high redshifts — through holes in the HI and dust?

- (4) What has HST done on Reionization, Galaxy Assembly, & Supermassive Black-Hole Growth, and what will JWST do? (see M. Stiavelli).

- (5) Radio- and GRB-selected unobscured Star-Formation vs. epoch.

- (6) Far-IR-selected unobscured Star-Formation vs. of epoch.

- (7) Gravitational Lensing to see the Reionizing population at $z\gtrsim8$.

- (8) Summary and Conclusions.

Sponsored by NASA/HST & JWST

Red Center First Light Conference — a great week, we learned about:

Monday: Reionization (bubbles): Theory

Monday: Ionization fraction $X_{HII}(z)$

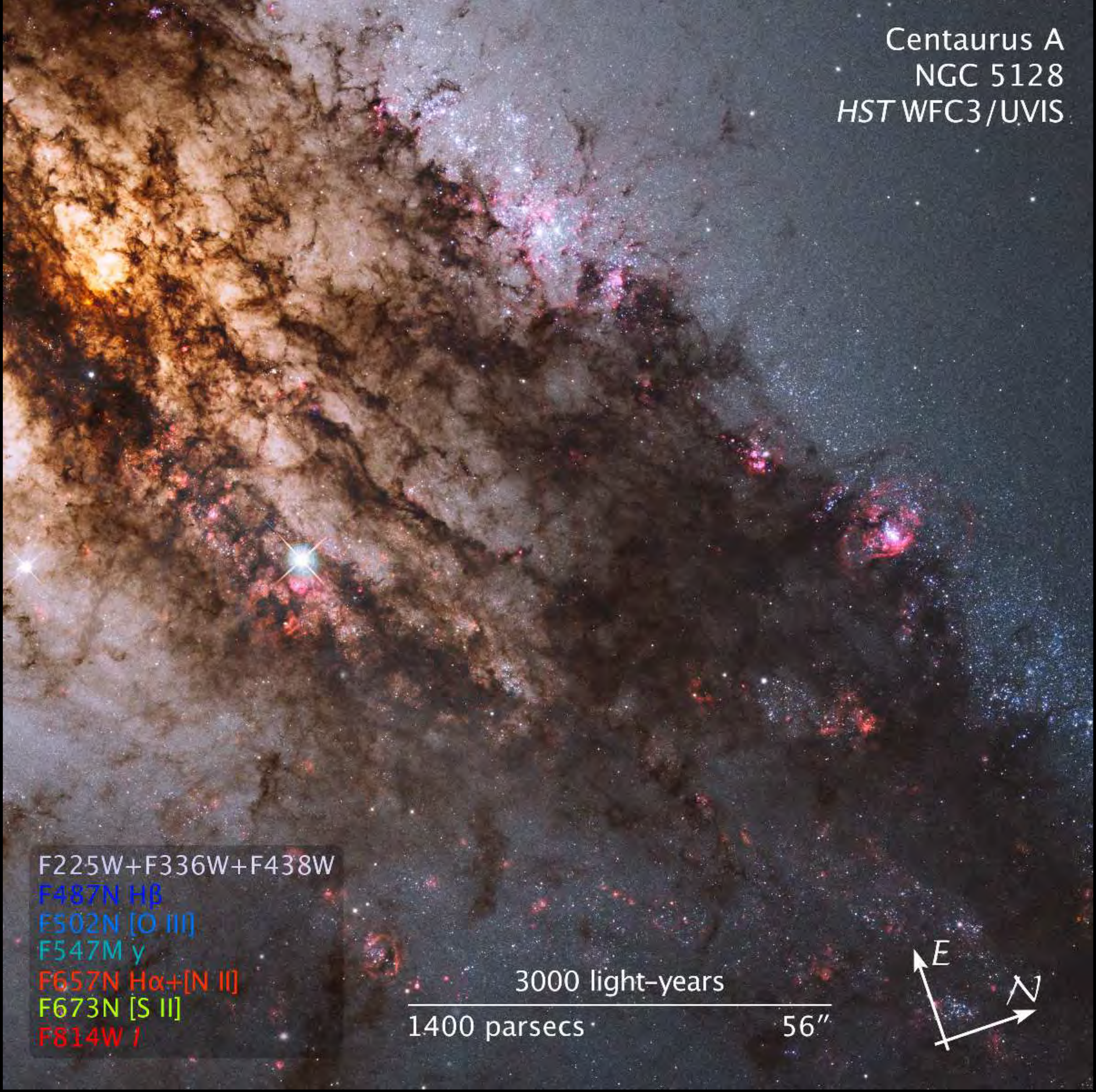
Tuesday: Steep faint-end of galaxy LF

Wednesday am: HI, EOR, & HII bubbles

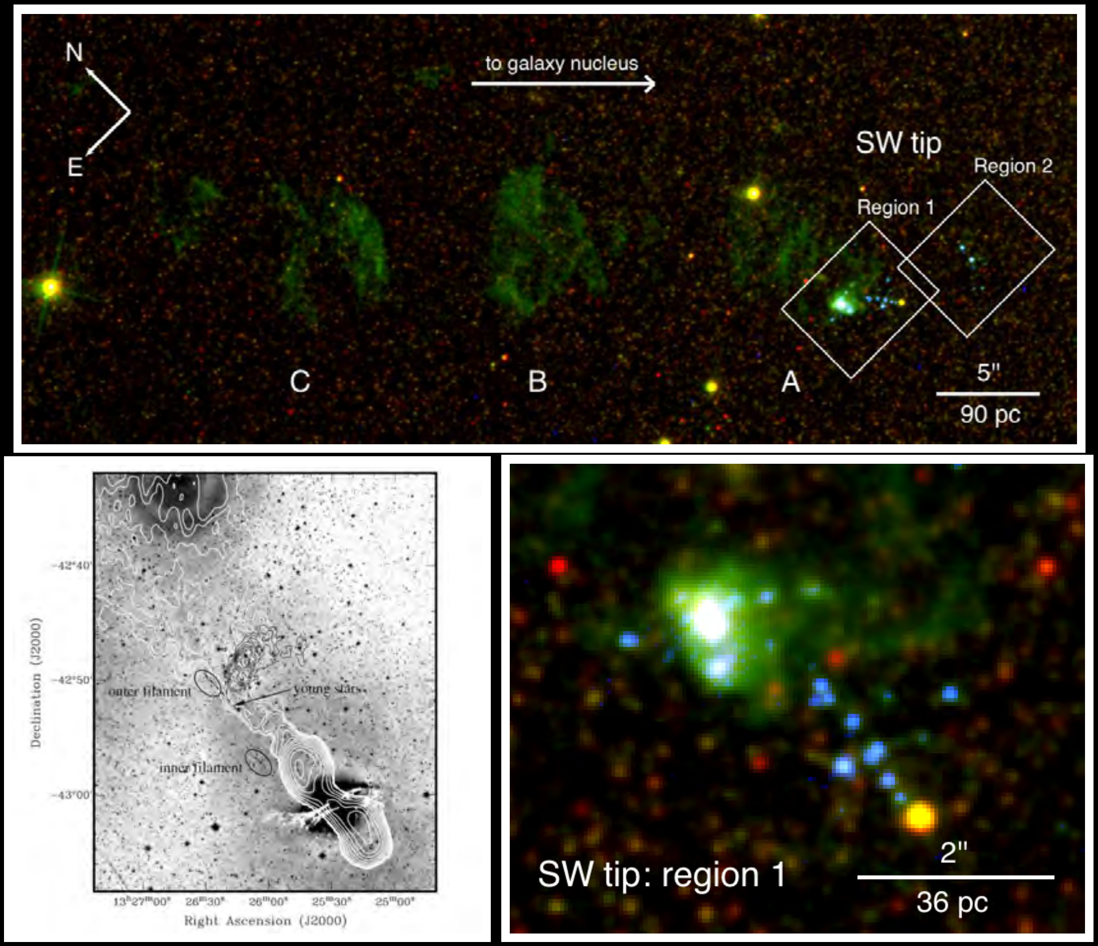
DUST MATTERS (as we all experienced yesterday):

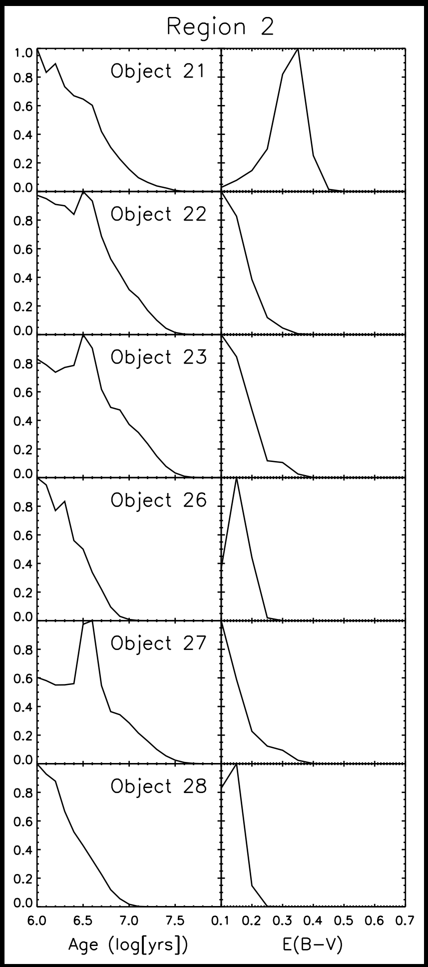
Gas and dust can dim and redden the light from your favorite star(s),

as well as the light from your favorite quasars ...



Focus of Talk: How to find *all* of the Reionizing population despite dust & HI





[Left] CSIRO/ATNF 1.4 GHz image of Cen A (Feain, Cornwell & Ekers (2009).
Fermi GeV source (Yang$^+$ 12); & Auger UHE Cosmic Rays (Abreu$^+$ 2010).
[Middle] SF in Cent A jet's wake (Crockett$^+$ 2012, MNRAS, 421, 1602).
[Right] Well determined ages for young (∼2 Myr) stars near Cen A's jet.

- JWST will trace older stellar pops and SF in much dustier environments.
- We must do all we can with HST in the UV–blue before JWST flies.

One day we will need a UV-optical sequel to Hubble:

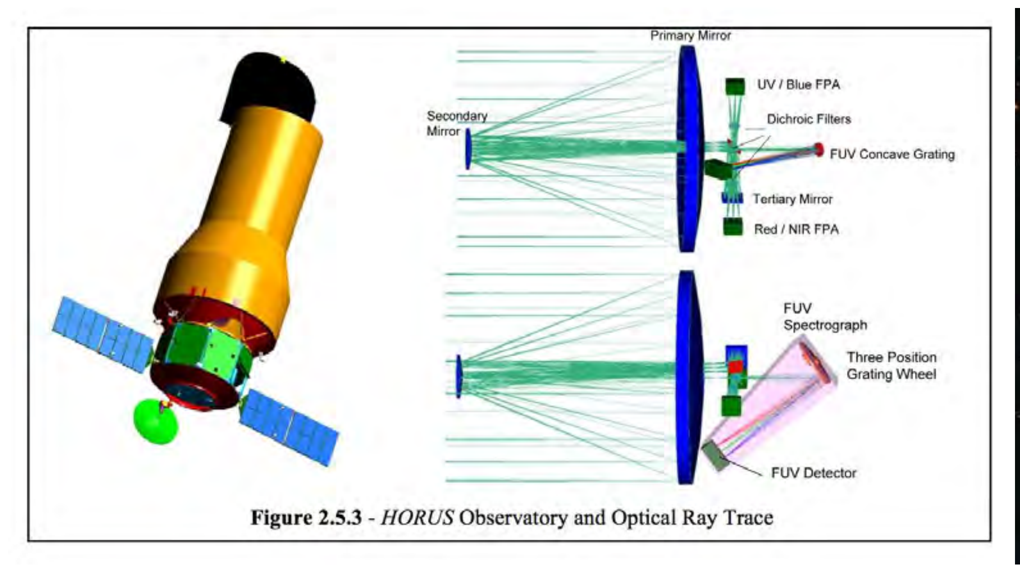
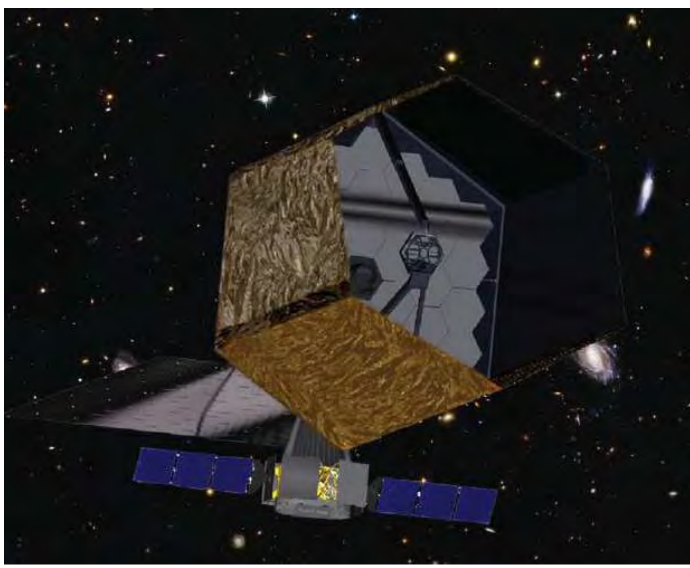


Figure 2.5.3 - *HORUS* Observatory and Optical Ray Trace



[Left] One of two spare 2.4 m NRO mirrors: one will become WFIRST.

- NASA may look for partners to turn 2nd NRO into UV-opt HST sequel.

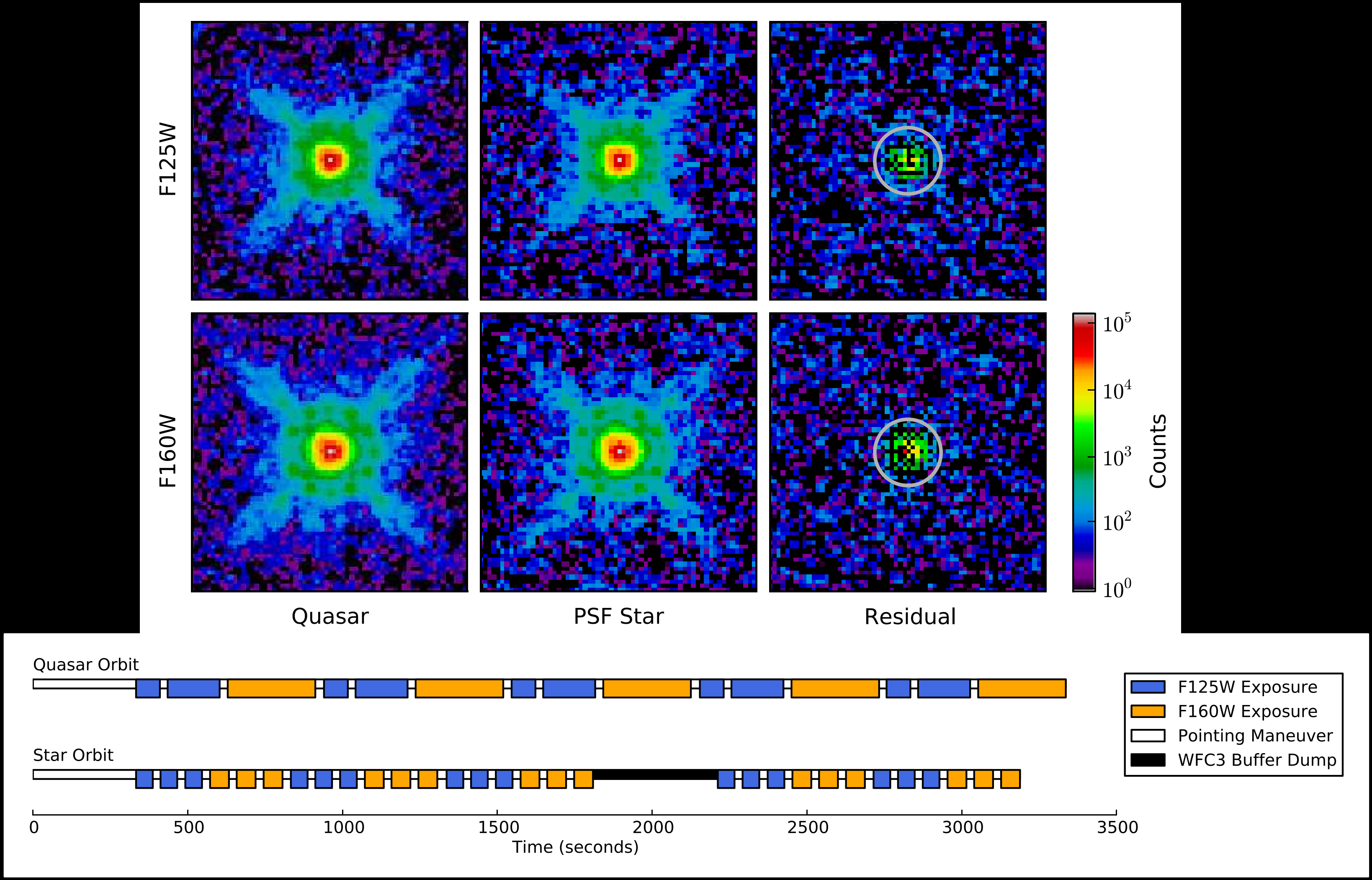
[Middle] HORUS: 3-mirror anastigmat NRO as UV-opt HST sequel.

- Can do wide-field ($\sim$0.25 deg) UV-opt 0″.06 FWHM imaging to AB$\lesssim$29-30 mag, and high sensitivity (on-axis) UV-spectroscopy.

[Right] ATLAST: 8–16 m UV-opt HST sequel, with JWST heritage.

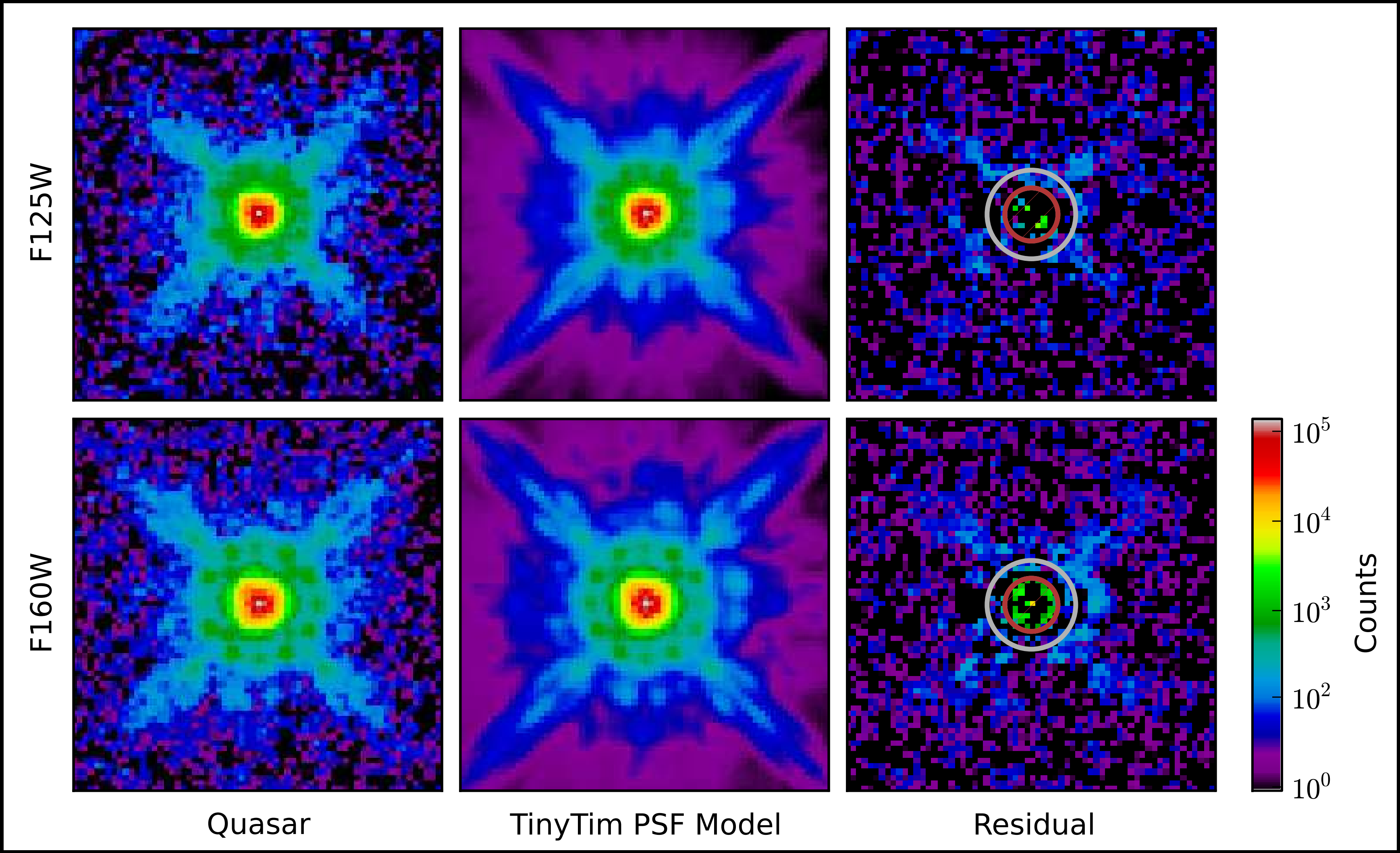
- Can do same at 9 m.a.s. FWHM routinely to AB$\lesssim$32-34 mag, [and an ATLAST-UDF to AB $\lesssim$38 mag $\sim$1 pico-Jy].

(1) HST WFC3 observations of QSO host galaxies at $z\simeq6$ (age$\lesssim$1 Gyr)



- Careful contemporaneous orbital PSF-star subtraction: Removes most of “OTA spacecraft breathing” effects (Mechtley ea 2012, ApJL, 756, L38).
- PSF-star (AB$\simeq$15 mag) subtracts z=6.42 QSO (AB$\simeq$18.5) nearly to the noise limit: NO host galaxy detected 100× fainter (AB$\gtrsim$23.5 at $r\gtrsim0.''3$).

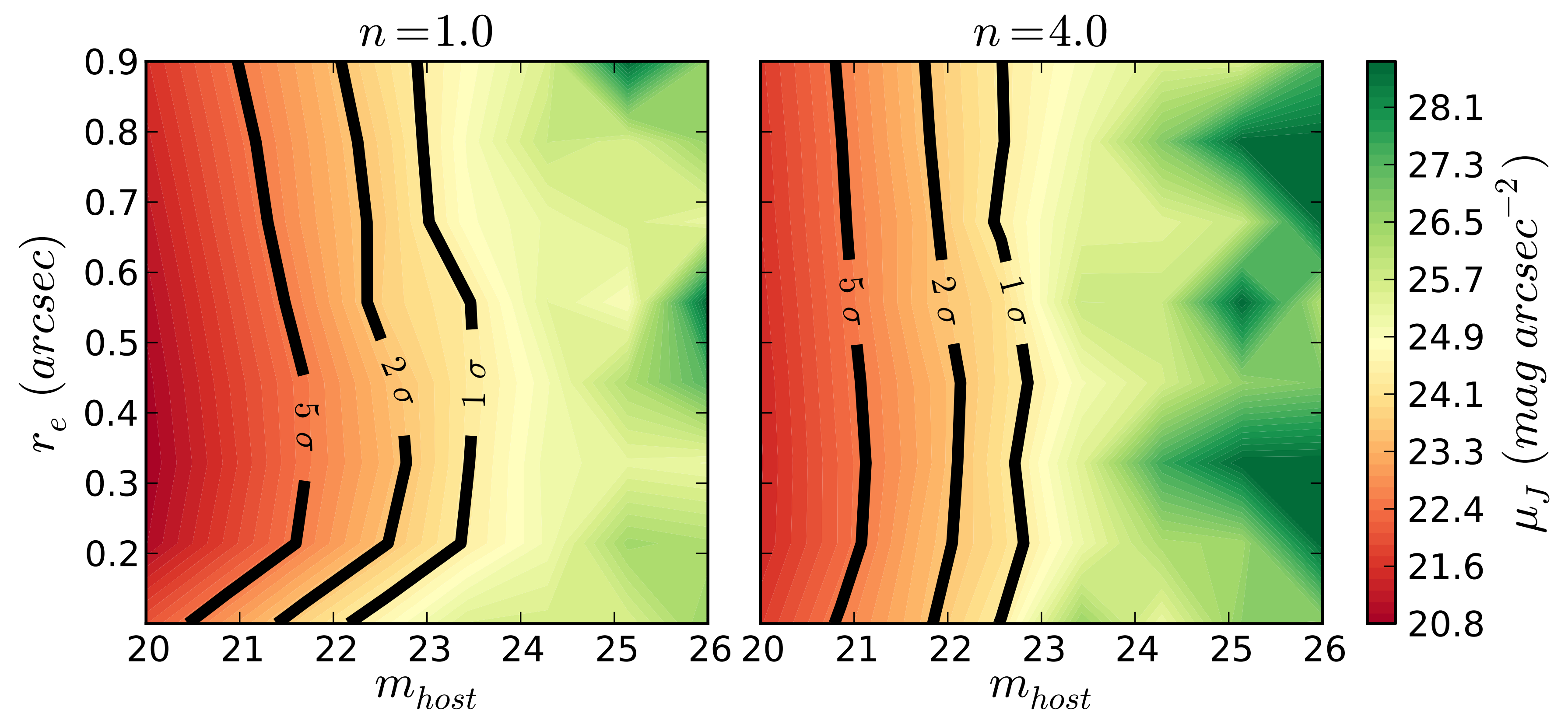
(1) HST WFC3 observations of dusty QSO host galaxies at z$\simeq$6 (age$\lesssim$1 Gyr)



- TinyTim fit of PSF-star + Sersic models QSO nearly to the noise limit: NO z=6.42 host galaxy at AB$\gtrsim$23.5 mag at radius r$\simeq$0$''$.3–0$''$.5.

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

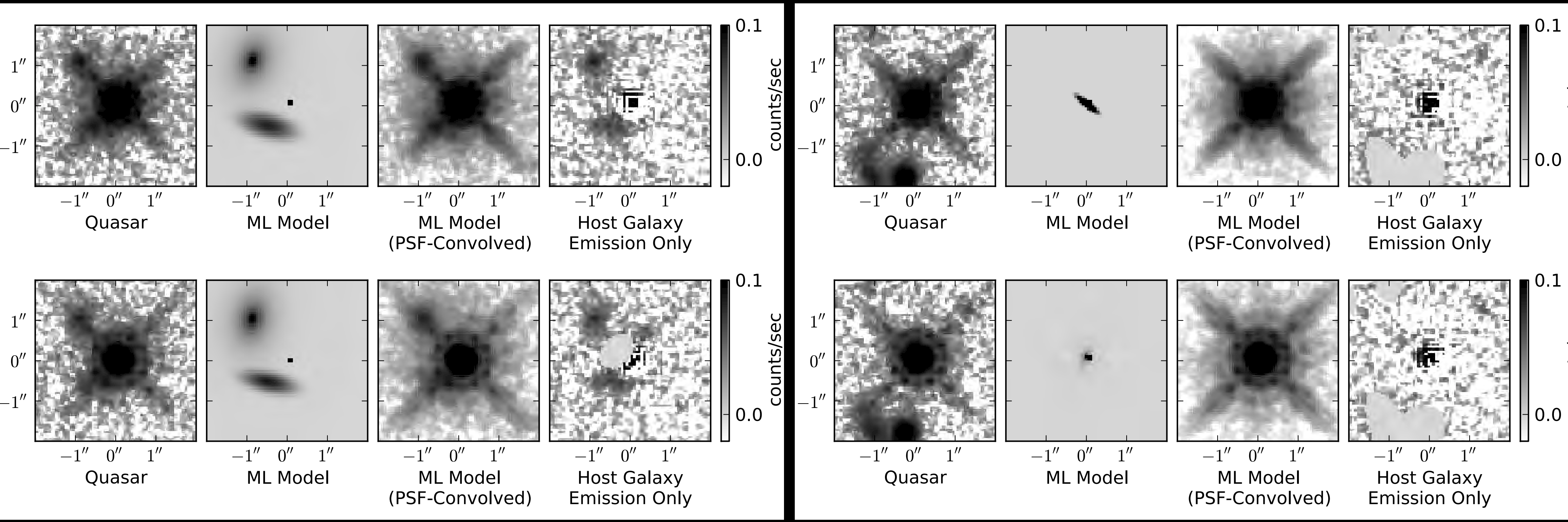
(1) HST WFC3 observations of dusty QSO host galaxies at z≃6



- ● TinyTim fit of PSF-star + Sersic models of galaxy light-profile, nearly to the noise limit: NO host galaxy at AB$\gtrsim$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$\lesssim$20, $\boldsymbol{\lambda}\lesssim 28\boldsymbol{\mu}$m) — but need JWST diffraction limit at 2.0$\boldsymbol{\mu}$m and clean PSF to do this.

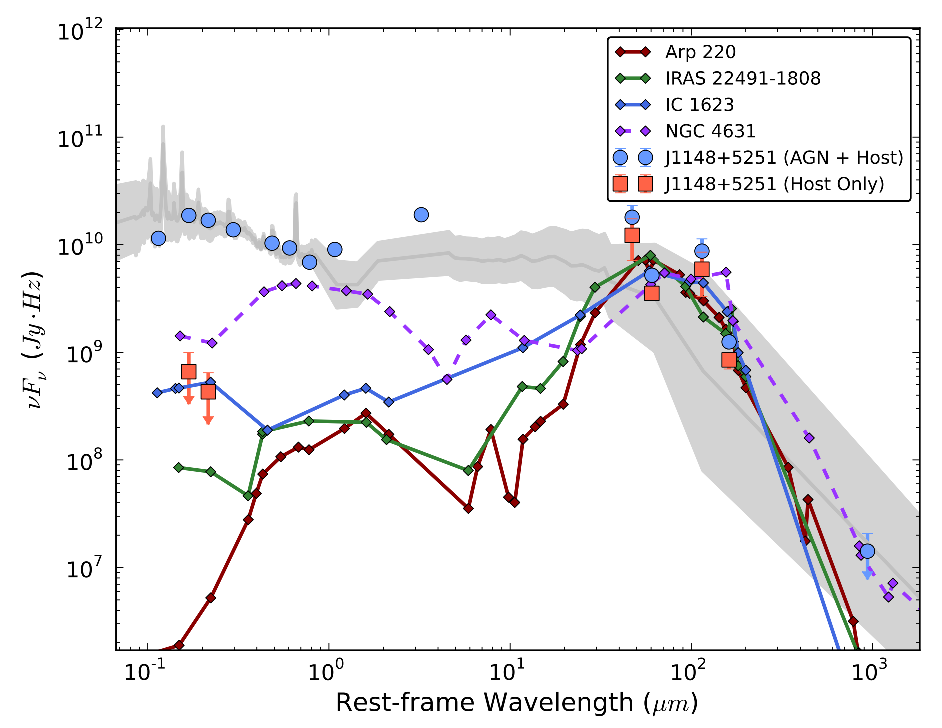
(1) WFC3: First detection of one QSO Host Galaxy at z≃6 (Giant merger?)

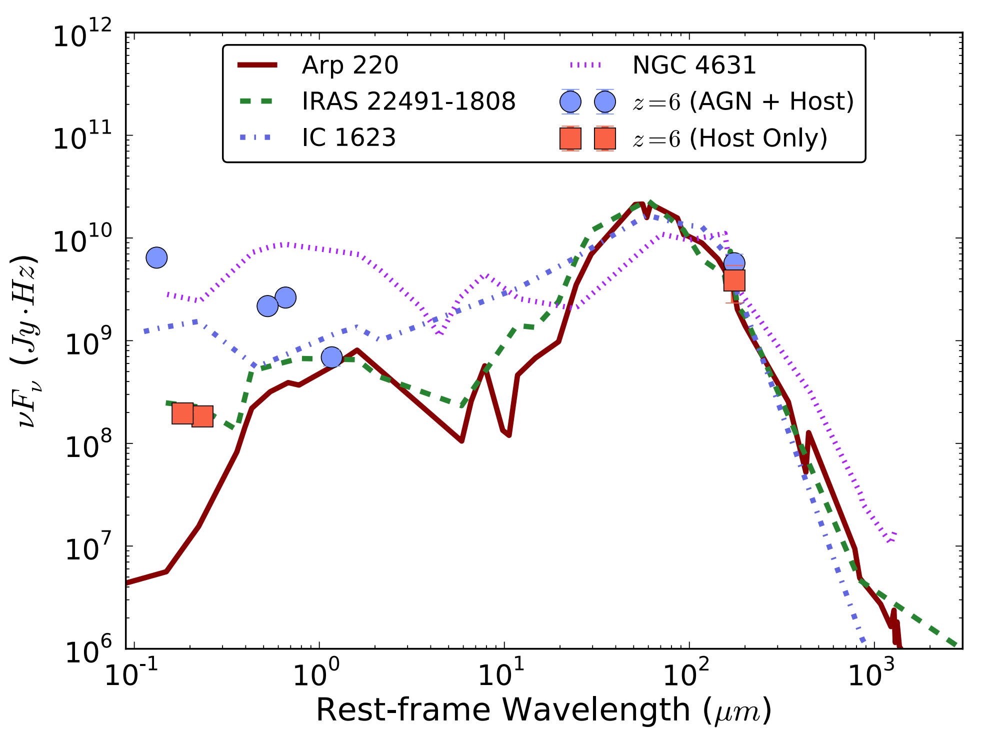


- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile. Gemini AO data critical for PSF stars (Mechtley^{+} 2013).
- First solid detection out of four z≃6 QSOs [3 more to be observed].
- One z≃6 QSO host galaxy: Giant merger morphology + tidal structure??
- Same J+H structure! Blue UV-SED colors: (J–H)≃0.19, constrains dust.
  - IRAS starbursty-like SED from rest-frame UV–far-IR, $A_{FUV}\sim1$ mag.
- M_{AB}^{host}(z≃6)$\lesssim$–23.0 mag, i.e., ∼2 mag brighter than L*(z≃6)!

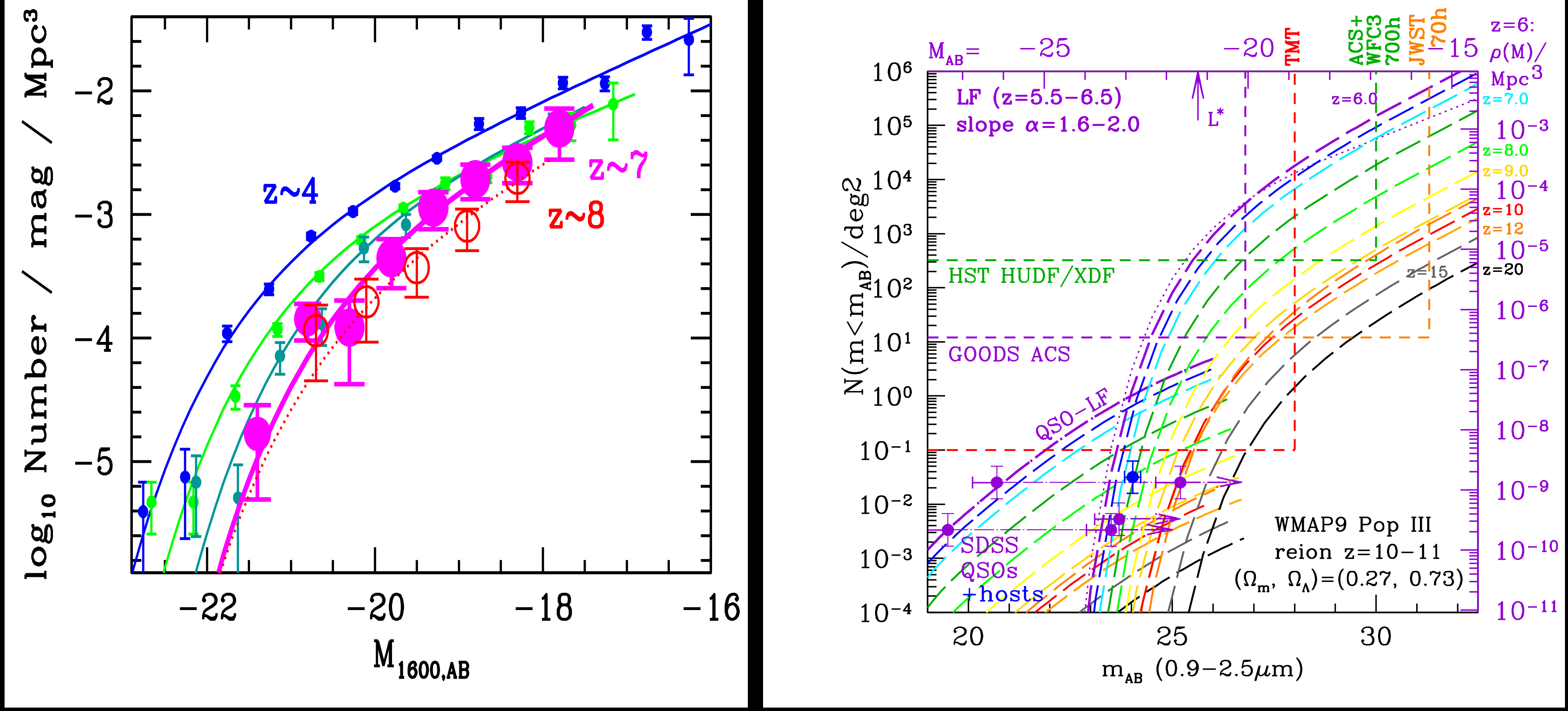
⇒ z≃6 QSO duty cycle $\lesssim10^{-2}$ ($\lesssim$10 Myrs); 1/4 QSO's close to Magorrian.

(1) HST WFC3 observations of dusty QSO host galaxies at z≃6





- Blue dots: z≃6 QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at z≳1 (normalized at 0.5μ). Red: z≃6 host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages≲1 Gyr) normalized at 100μm: [LEFT] Rules out z=6.42 spiral or bluer host galaxy SEDs for 1148+5251. (U)LIRGs & Arp 220s permitted (Mechtley et al. 2012, ApJL, 756, L38). [RIGHT] Detected QSO host has IRAS starburst-like SED from rest-frame UV–far-IR, A_{FUV}(host)∼1 mag (Mechtley et al. 2013b).
- JWST Coronagraphs can do this 10–100× fainter (& for z≲20, λ≲28μm).

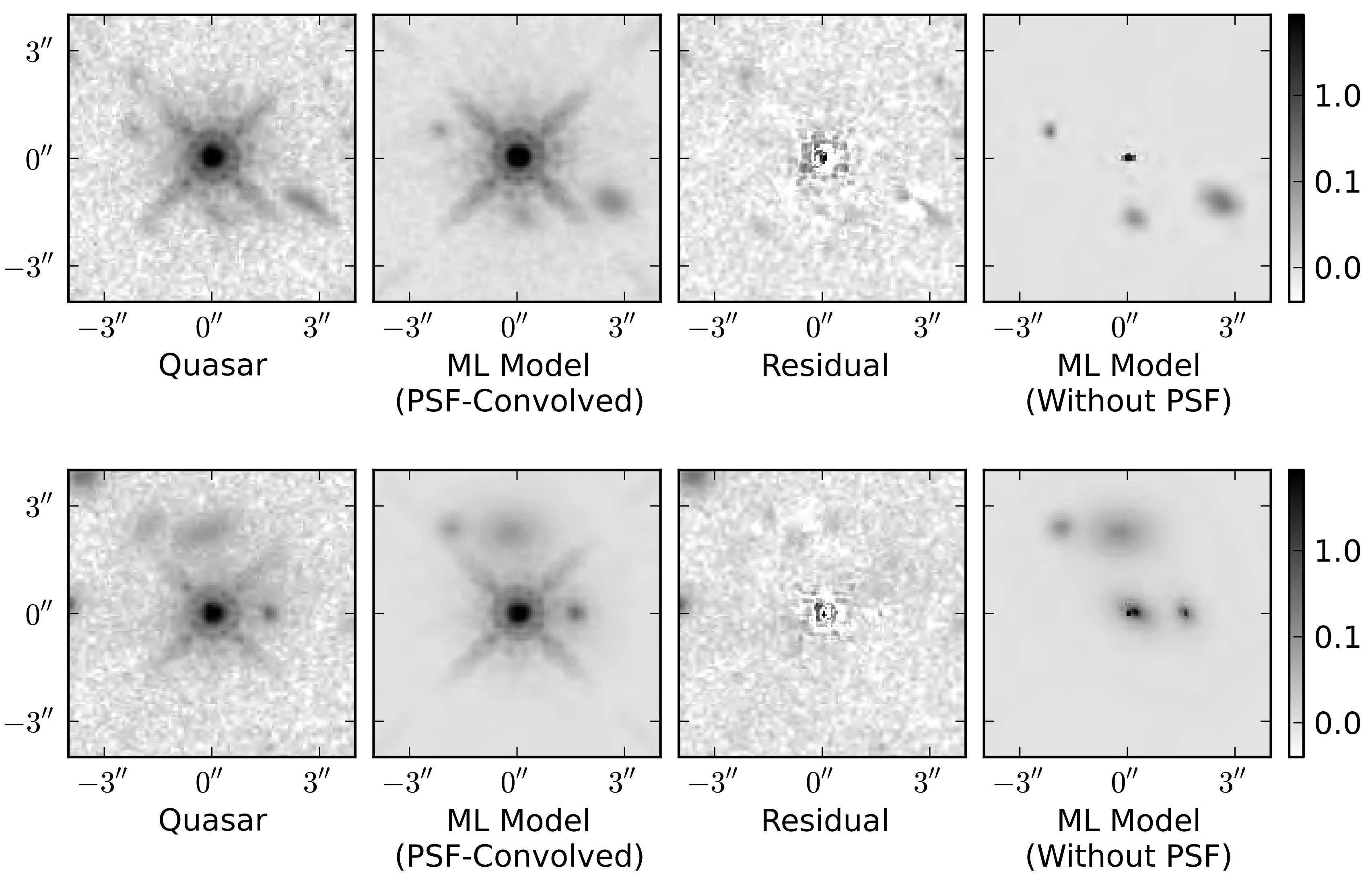


- M_{AB}^{host}(z≃6)≲–23.0 ≃ M*–2 mag at z≃6; 1/4 QSOs @ Magorrian.
⇒ z≃6 QSO duty cycle (A_{FUV}≃0→1) ≲0.01→1.0 (≲10→950 Myrs).

- To study co-evolution of SMBH-growth & proto-bulge assembly for z≲10–15 requires new AGN finding techniques for JWST (e.g., Mortlock).

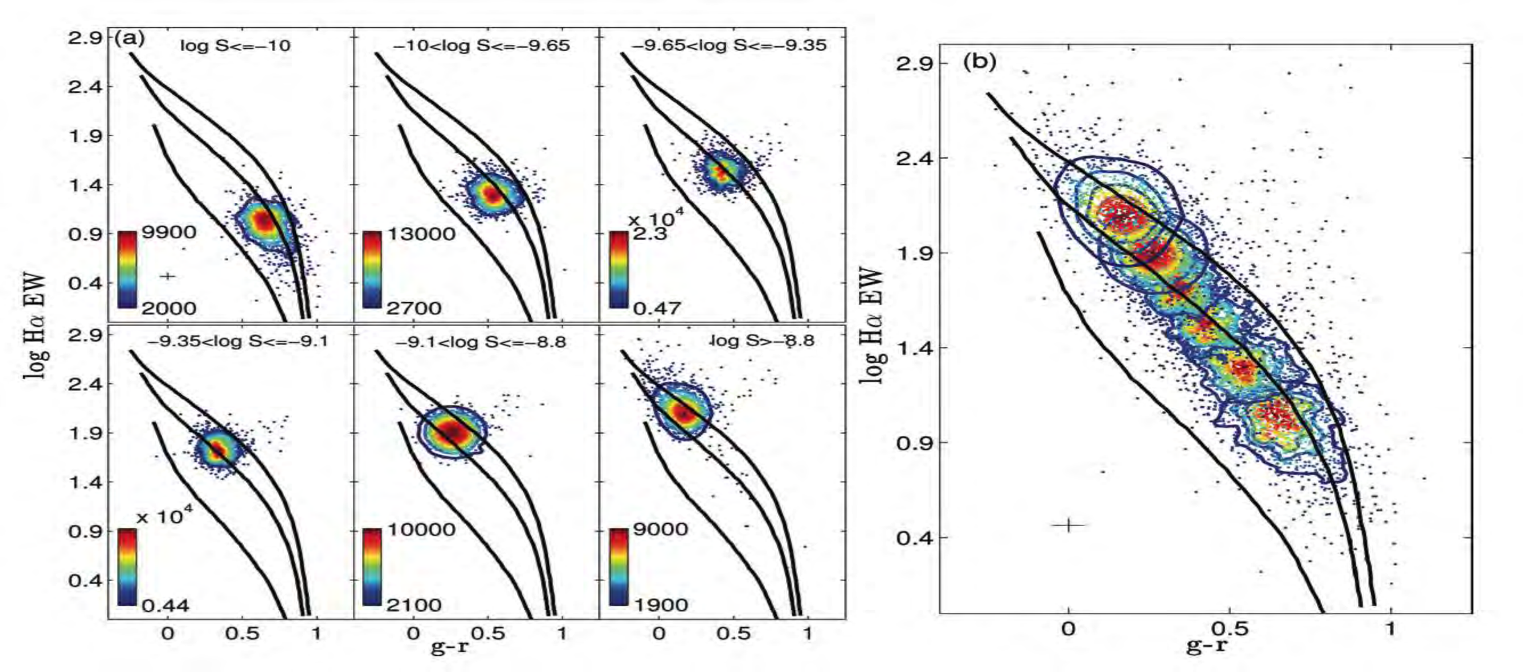
- JWST Coronagraphs can also trace super-massive black-holes as faint quasars in young galaxies: JWST needs 2.0μm diffraction limit for this.

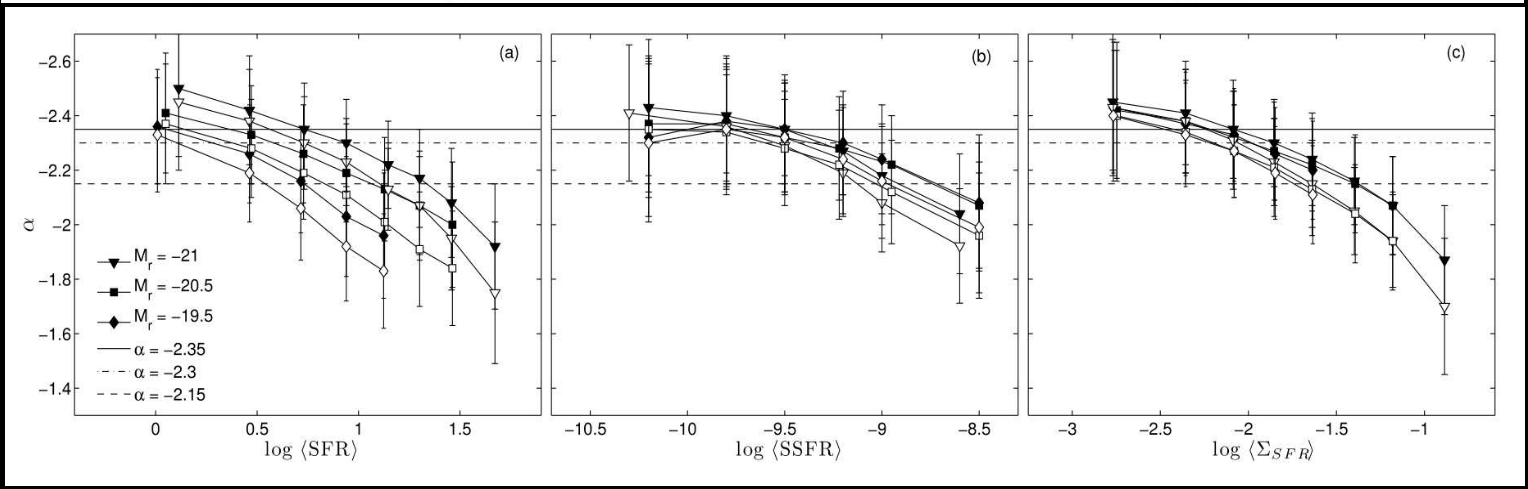
(1) WFC3 observations of QSO host galaxies at z≃2 (evidence for mergers?)



- Monte Carlo Markov-Chain runs of observed PSF-star + Sersic 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).

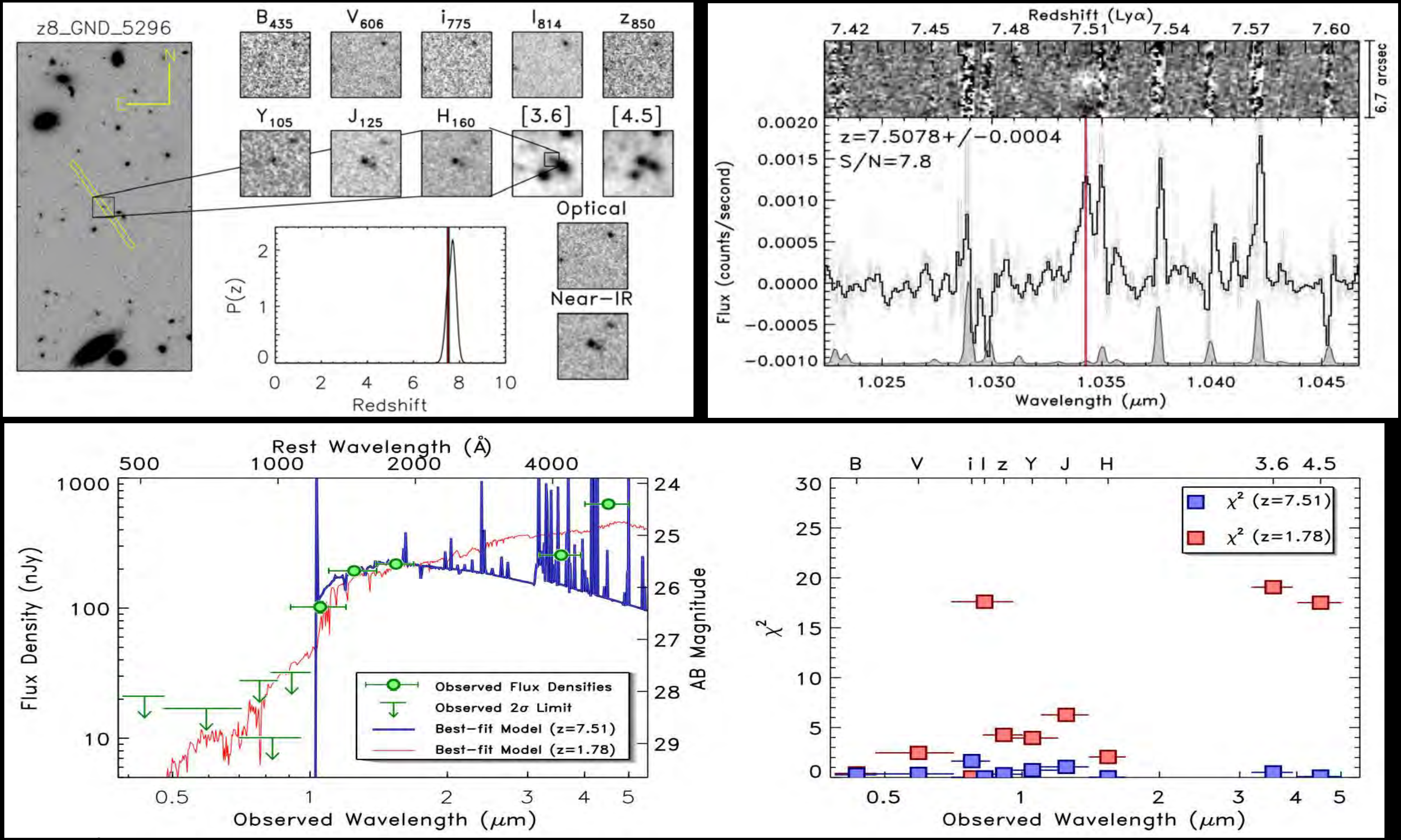
(2) (How) does the IMF depend on environment, Fe/H, and epoch?





- Gunawardhana^{+} (2011): GAMA AAT — 300 k-redshifts z$\lesssim$0.4: IMF-slope clearly depends on M_{AB}, Specific Star-Formation Rate (sSFR), & and similarly on SF-density (SFD). Critical for Reionization studies.
- JWST NIRSpec can do this 10^{3}–$10^{4}\times$ fainter (survey Hα for 0.5$\lesssim$z$\lesssim$6.5).

(3) Lyα at very high redshifts — through holes in the HI and dust? (see many talks & posters this Conf, e.g.,: Dijkstra, McLinden, Schenker).

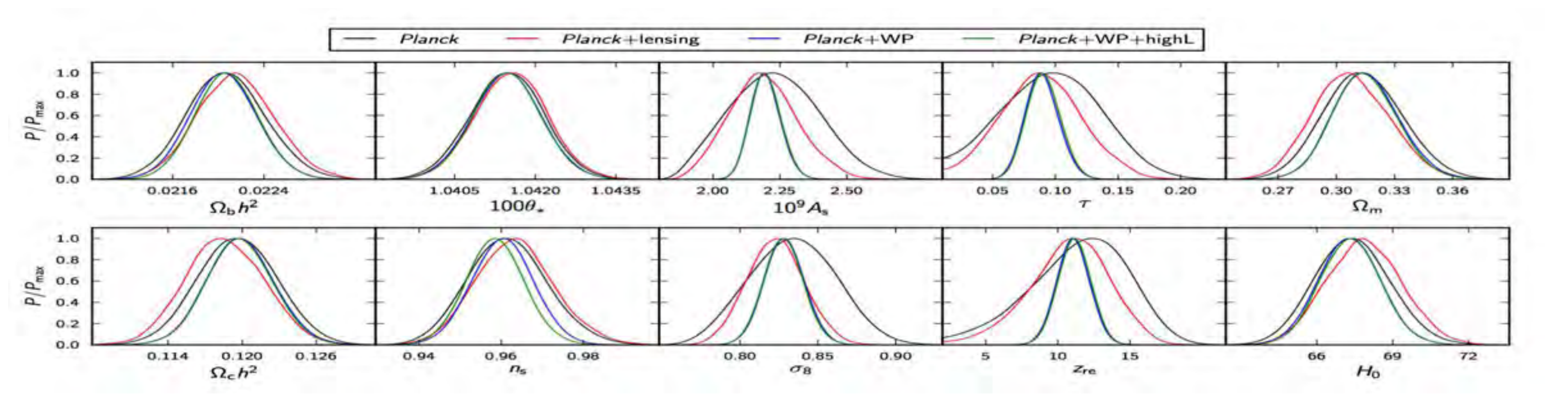


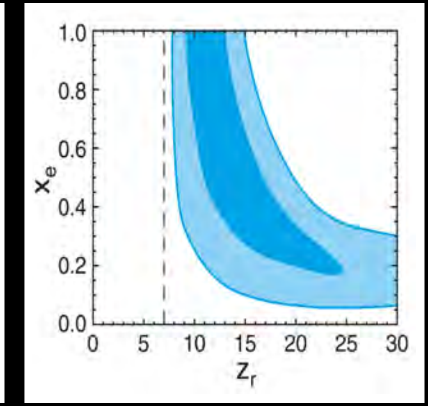
- Finkelstein$^+$ (2013, Nature, subm.): Keck MOSFIRE spectra of z-drops.

Possible z$\simeq$7.51 Lyα confirmation of AB$\sim$25.5 mag z-drop in CANDELS.

- JWST NIRSpec can do this 100× fainter (survey/detect Lyα for $4.5 \lesssim z \lesssim 40$).

Implications of the WMAP year-9 & Planck results for JWST science:





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

The year-9 WMAP data provided better foreground removal (Komatsu$^+$ 2011; Hinshaw$^+$ 2012; but see: Planck XVI 2013; see Reichardt's talk):

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

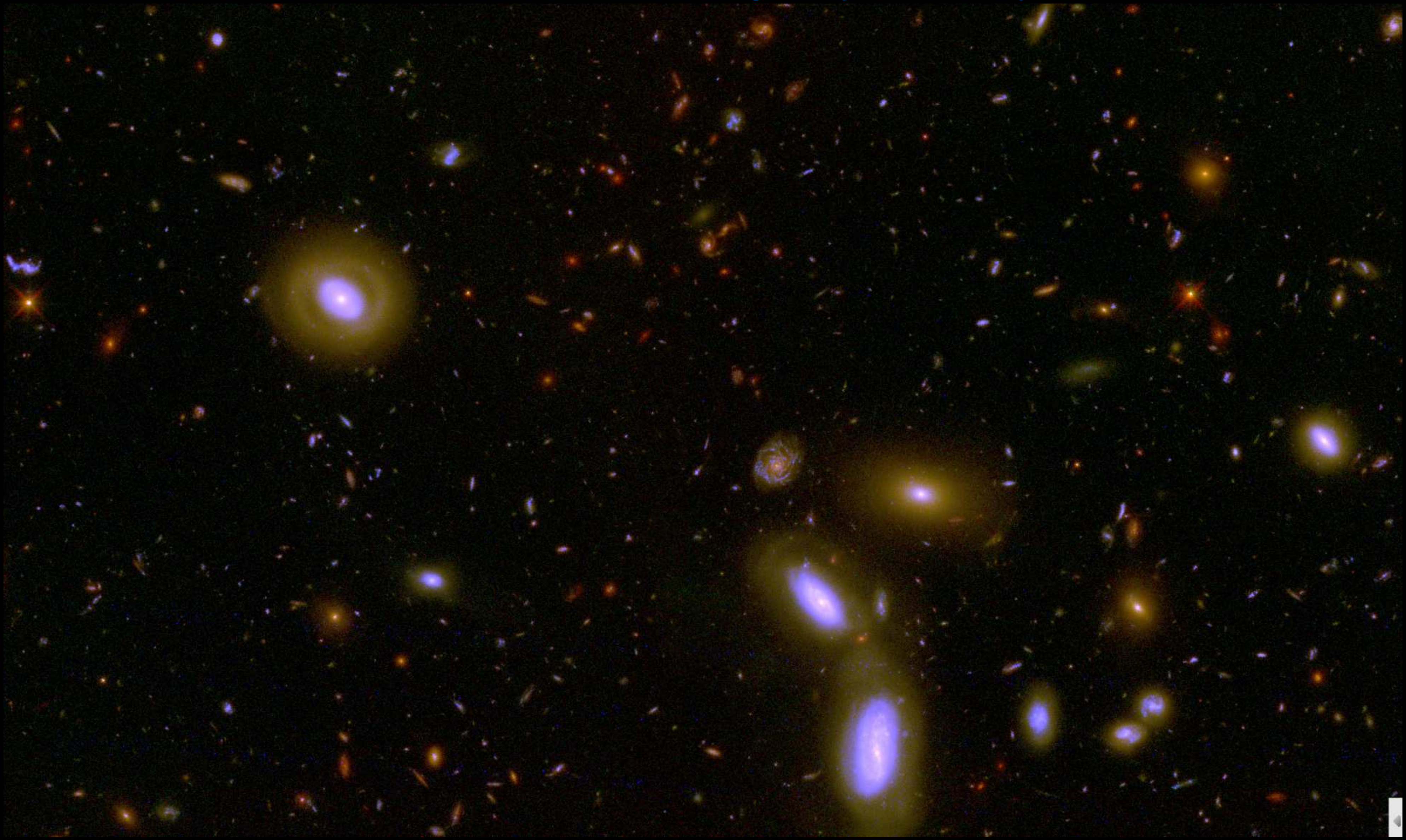
- (1) Instantaneous at z$\simeq$11.1$\pm$1.1 (τ=0.089$\pm$0.013), or, more likely:
- (2) Inhomogeneous & drawn out: starting at z$\gtrsim$20, peaking at z$\lesssim$11, ending at z$\simeq$7. The implications for HST and JWST are:

- HST/ACS has covered z$\lesssim$6, and WFC3 is covering z$\lesssim$7–9.

- For First Light & Reionization, JWST will survey z$\simeq$8 to z$\simeq$15–20.

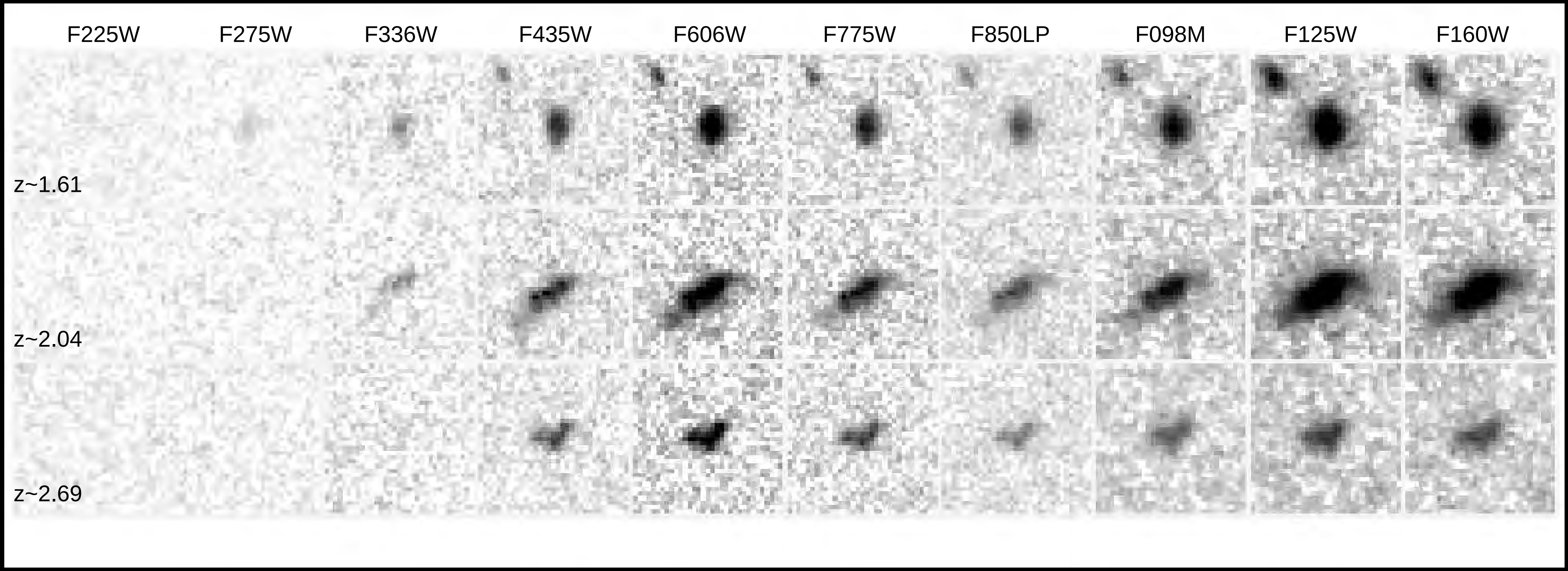
Question: If Planck-τ $\downarrow$ $\lesssim$0.08 (TBD), then how many reionizers will JWST see at z$\simeq$10–20?

4) What has HST done on reionization & galaxy assembly; what will JWST do?

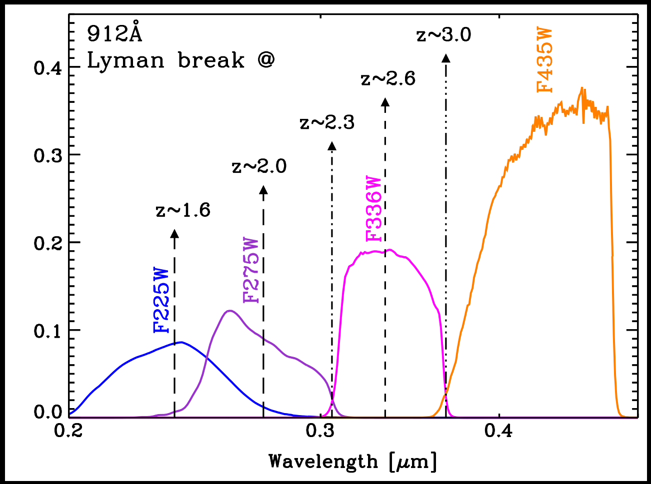


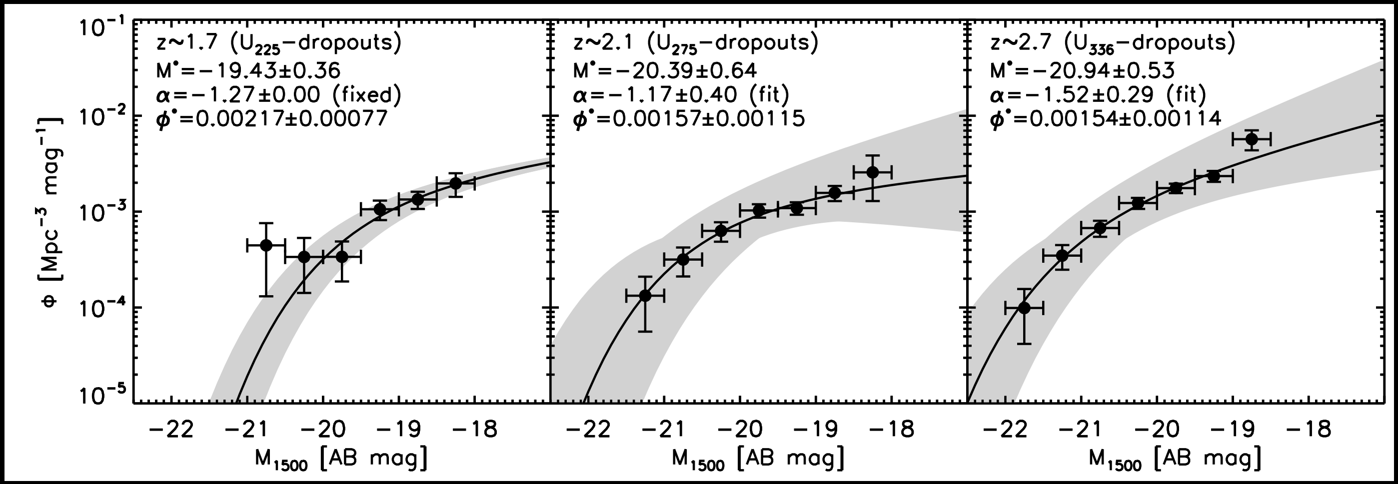
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

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.



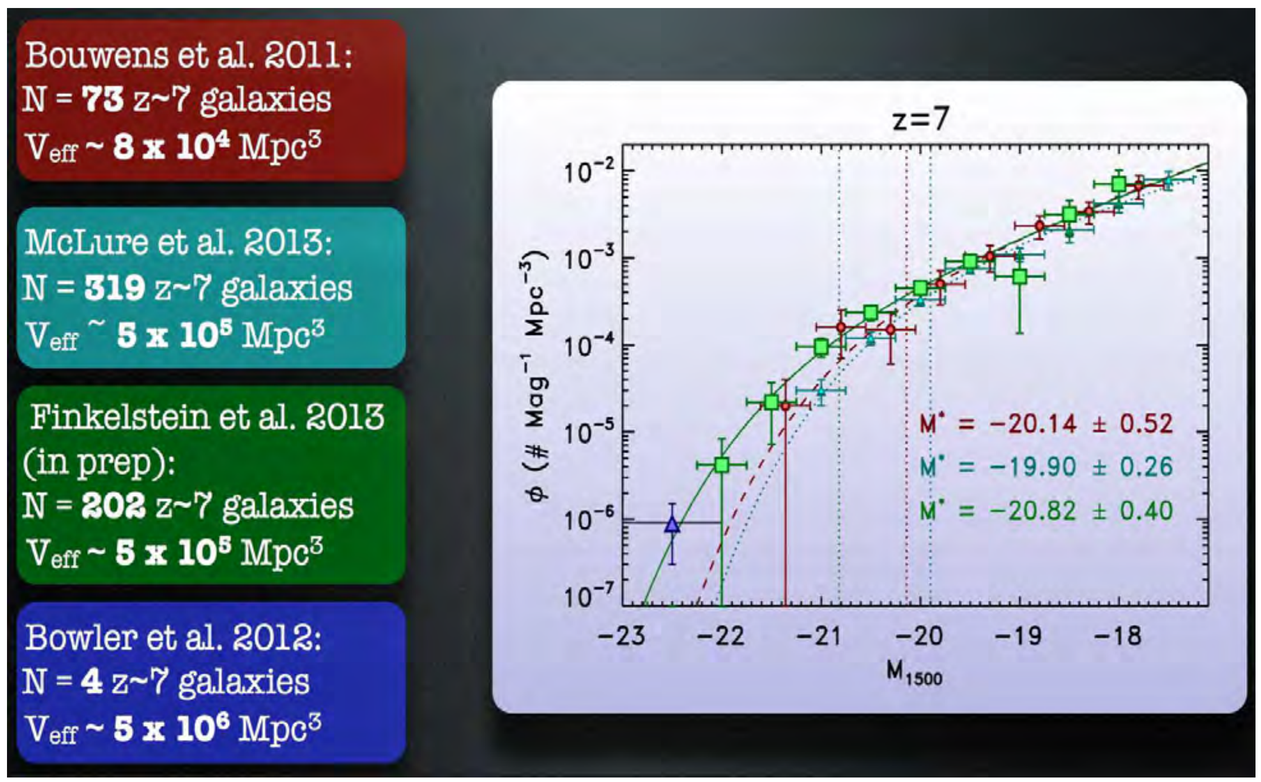
Lyman break galaxies at the peak of cosmic SF ($z\simeq$1-3; Hathi$^+$ 2010, 2013)





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

(e.g., Bouwens$^+$ 2010, 2013; Hathi$^+$ 2010, 2013; Oesch $^+$ 2010; Robinson$^+$ 2013; see also talks by Ellis, Bouwens, & Oesch).

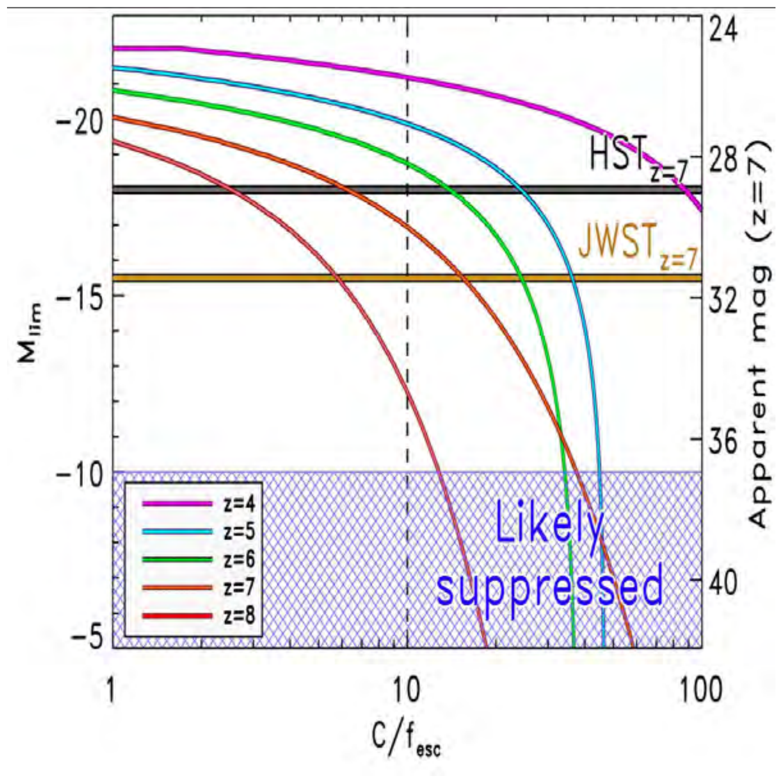


Bouwens et al. 2011:
N = **73** z~7 galaxies
V_{eff} ~ **8 x 10^4** Mpc^3

McLure et al. 2013:
N = **319** z~7 galaxies
V_{eff} ~ **5 x 10^5** Mpc^3

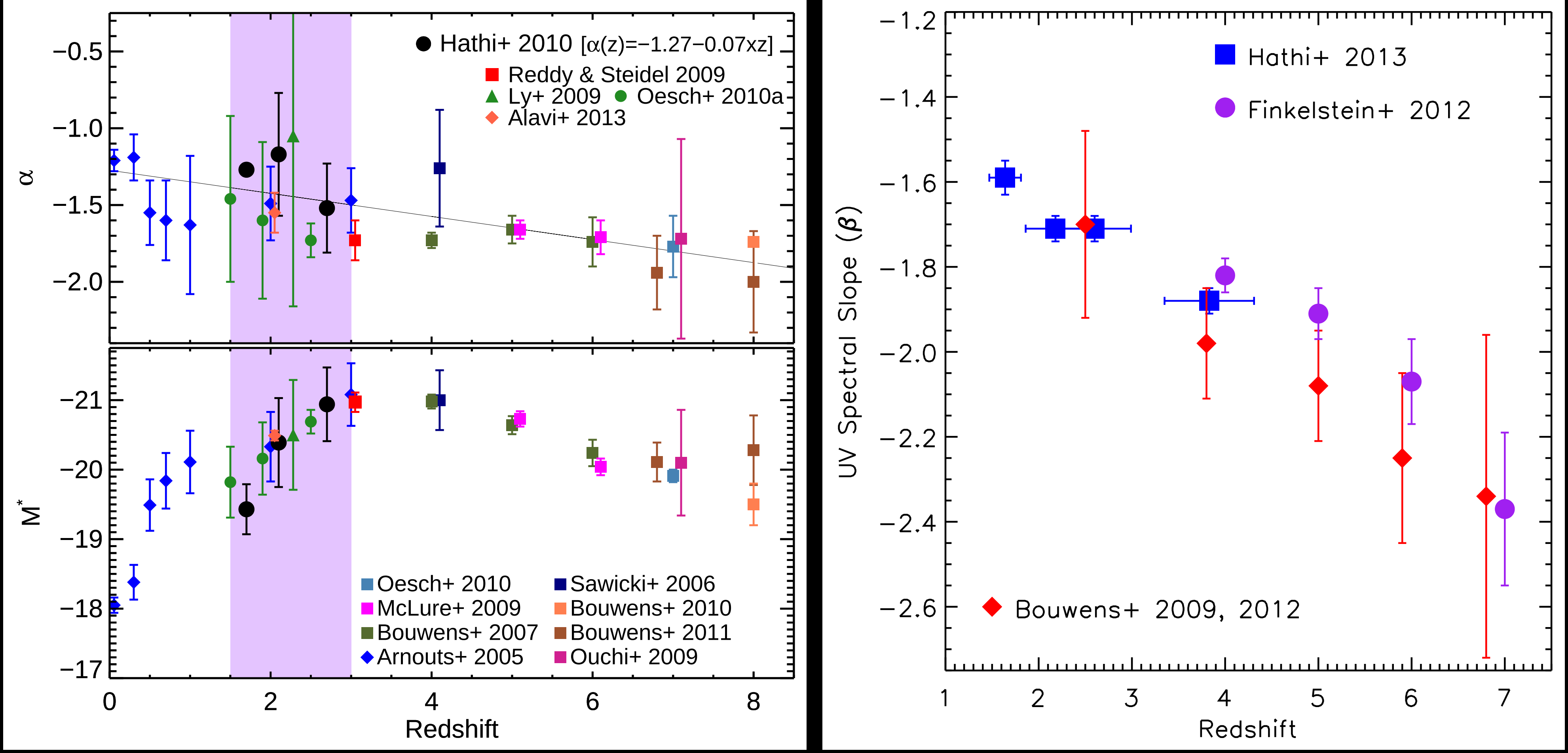
Finkelstein et al. 2013 (in prep):
N = **202** z~7 galaxies
V_{eff} ~ **5 x 10^5** Mpc^3

Bowler et al. 2012:
N = **4** z~7 galaxies
V_{eff} ~ **5 x 10^6** Mpc^3



Finkelstein et al. (2013): Depending on how quickly faint-end of LF α(z) and Clumping factor/escape fraction C/f_{esc} evolve with epoch at z$\gtrsim$7, faint-end of galaxy LF may complete reionization.

- JWST will be able to identify many of the reionizing dwarf galaxies to AB$\lesssim$31 mag, depending on C/f_{esc} .



Evol of LF-slope α (top), M^* (bottom), & UV-slope β (right; Hathi$^+$ 10,13)

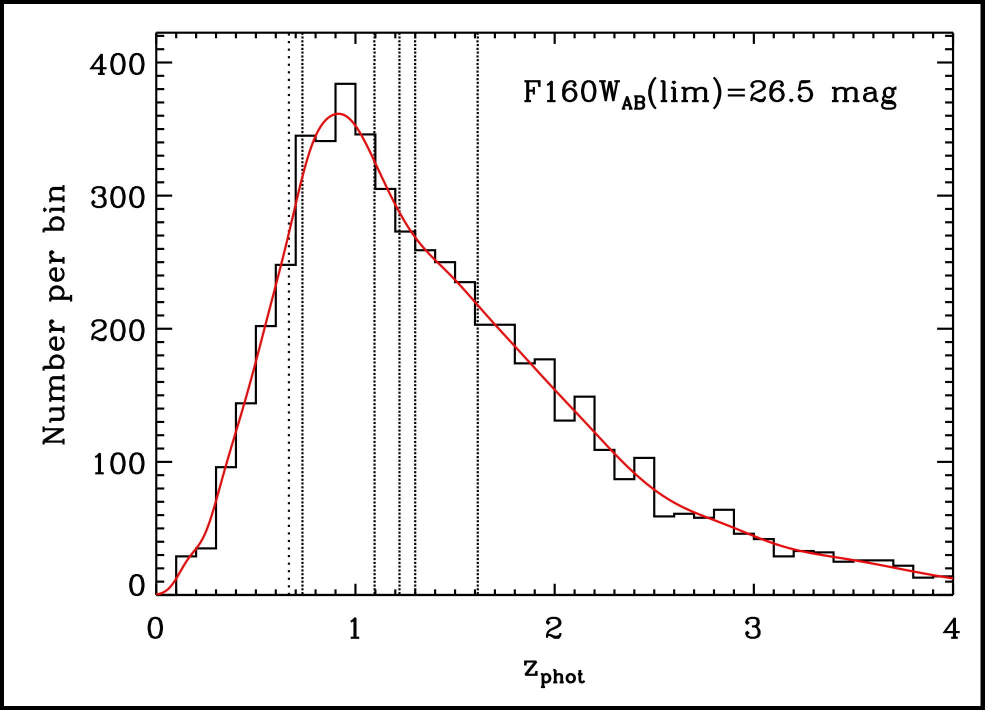
- JWST $z\gtrsim8$, expect faint-end slope $\alpha\simeq-2.0$ (see Bouwens' talk).
- JWST $z\gtrsim8$, expect UV $\beta\lesssim-2.2$ (Finkelstein$^+$12; Bouwens, Jiang talks).

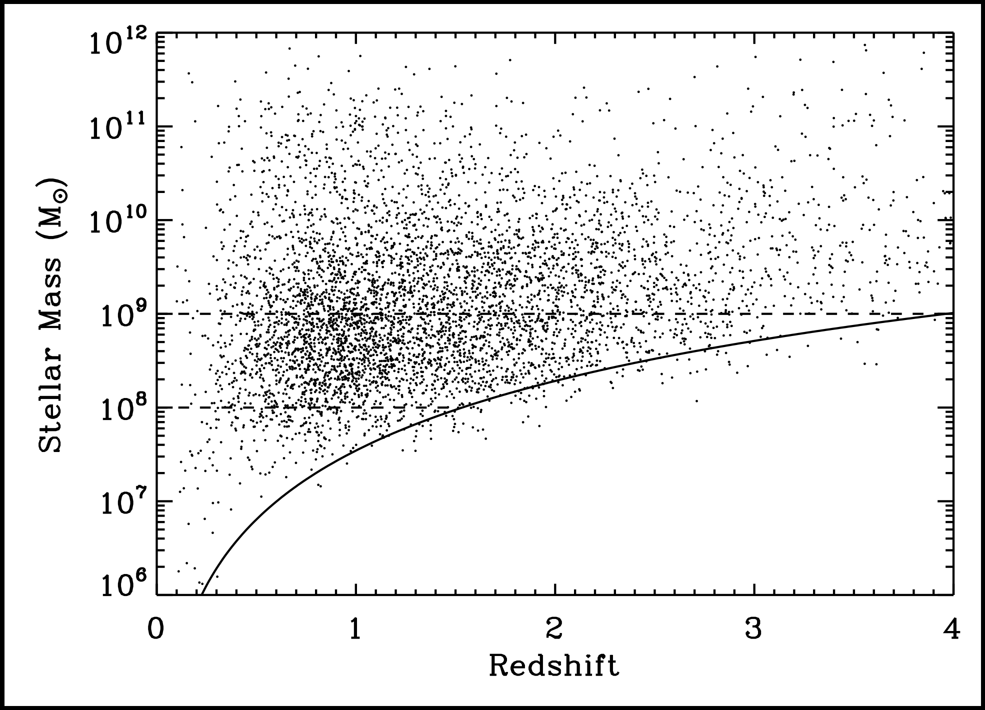
$\Rightarrow$ Both important for cosmic reionization at $z\gtrsim6$ by dwarf galaxies.

NOTE: Faint-end slope α–1.5 to –1.6 at $z\simeq1.5$–2 (also Siana 2012).

- JWST at $z\gtrsim8$: see if characteristic luminosity $M^*\gtrsim-19$ mag.

$\Rightarrow$ Could cause significant gravitational lensing bias at $z\gtrsim8$–10.





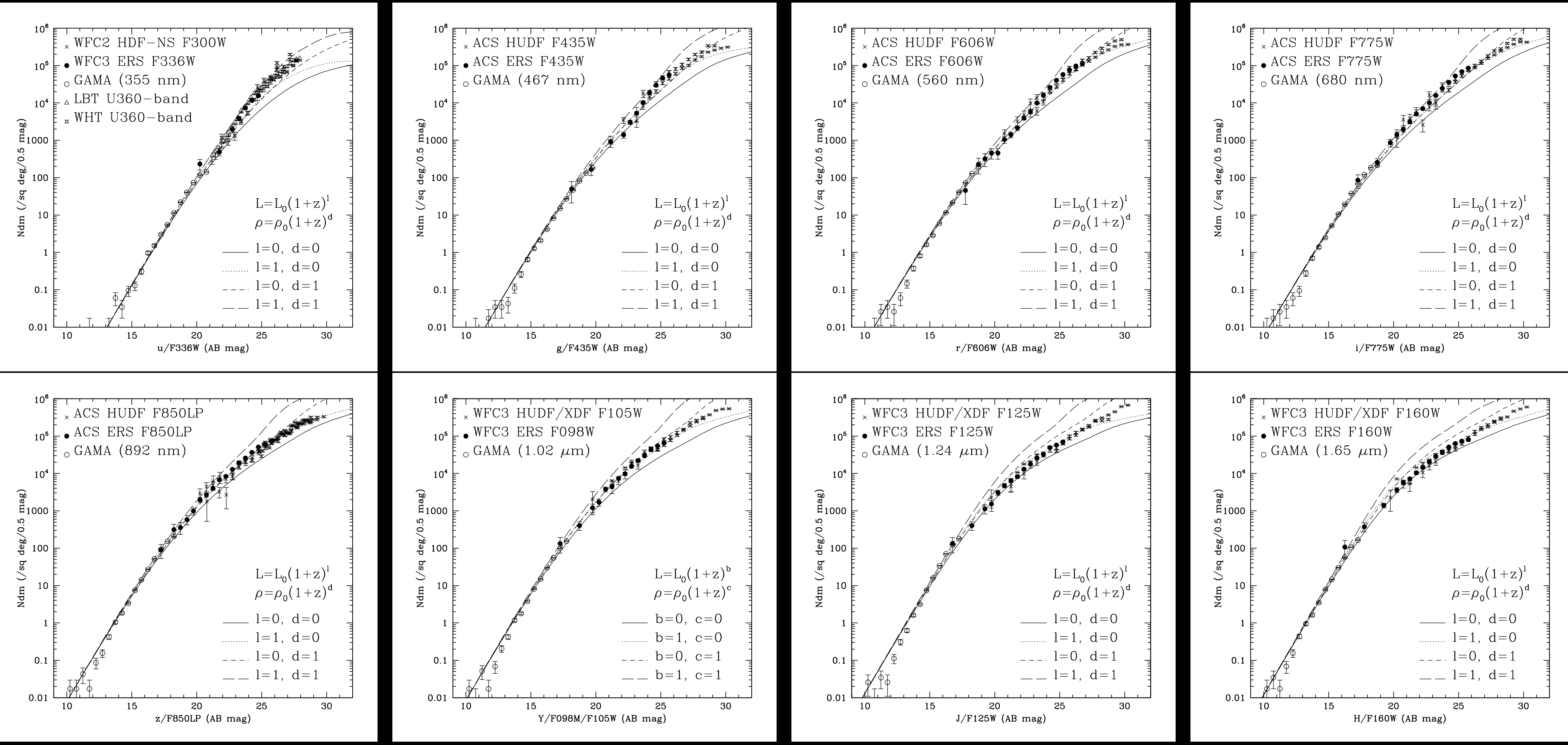
WFC3 ERS 10-band redshift estimates accurate to $\lesssim$4% with small systematic errors (Hathi et al. 2010, 2013), resulting in a reliable N(z).

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

$\Rightarrow$ Median redshift in (medium-)deep fields is $z_{med} \simeq$1.5–2.

- JWST will trace mass assembly and dust content $\lesssim$5 mag deeper from z$\simeq$1–12, with nanoJy sensitivity from 0.7–5μm.

Panchromatic Galaxy Counts from $\lambda \simeq$0.2–2μm for AB$\simeq$10–31 mag

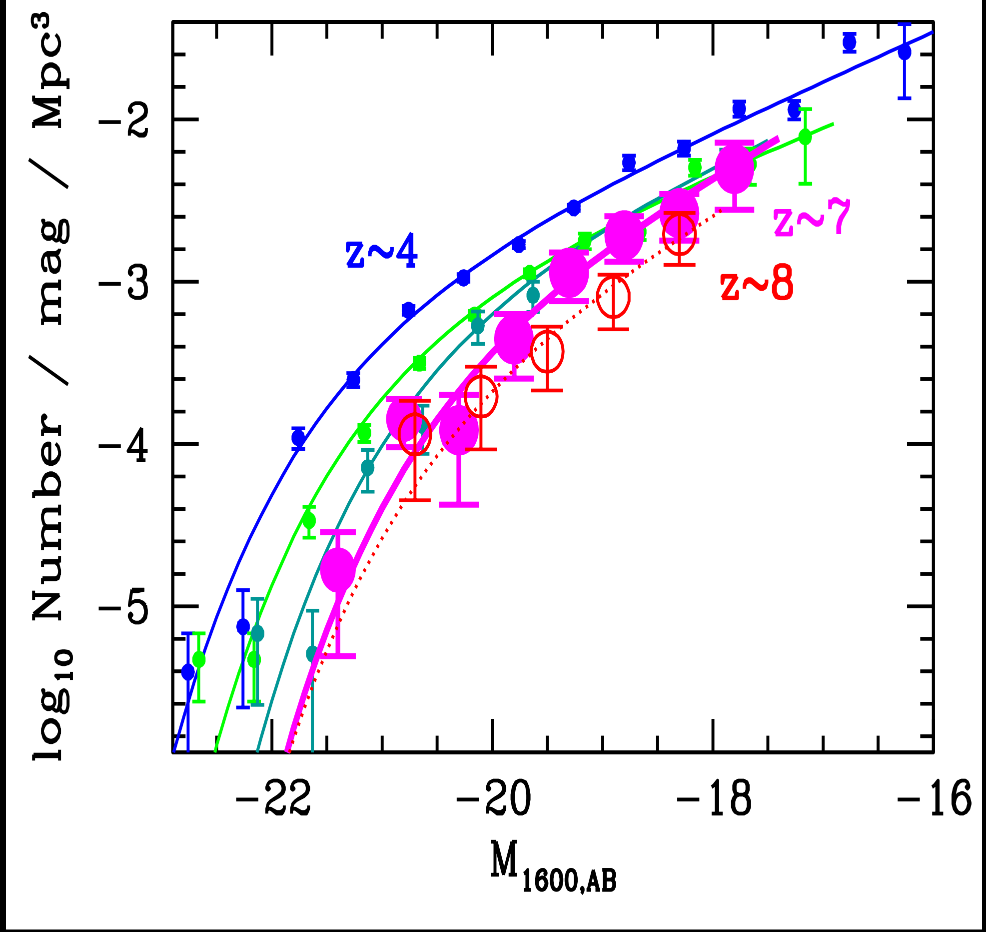


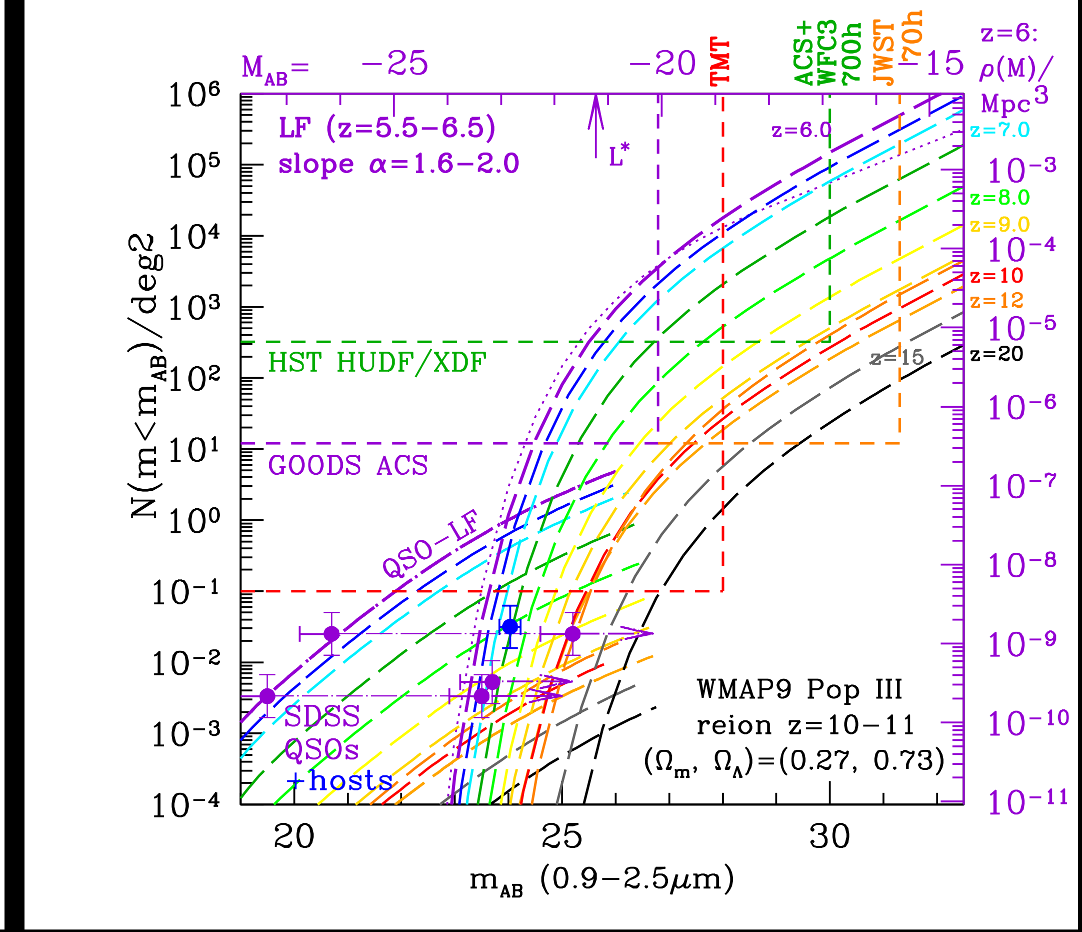
Data: GALEX, GAMA, HST ERS + HUDF/XDF ACS+WFC3 (*e.g.*, Windhorst et al. 2011; Ellis$^+$ 2012; Illingworth$^+$ 2012; Teplitz$^+$2013): F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F098M/F105W, F125W, F140W, F160W.

- HUDF: Faint-end near-IR mag-slopes $\simeq$ 0.22±0.02 to AB$\lesssim$31 mag $\Longleftrightarrow$

At z_{med} $\simeq$1.6, faint-end LF-slope $\alpha\simeq$–1.5–1.6 to M$_{AB}\simeq$–14 mag !

$\Rightarrow$ Extrapolation of LF(z$\gtrsim$2) to AB$\simeq$–10 is entirely plausible.





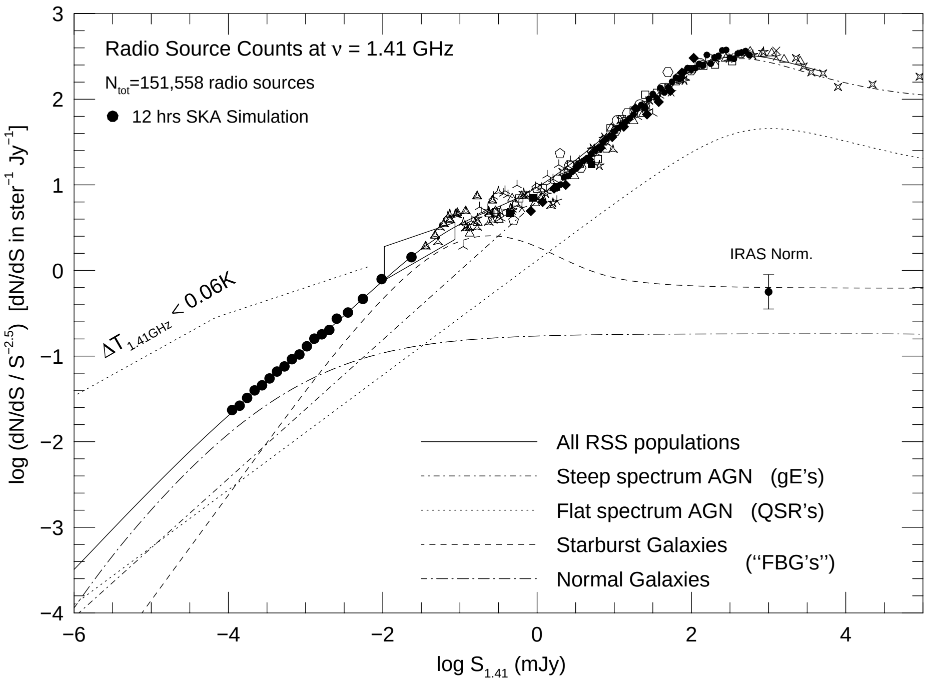
- Objects at $z \gtrsim 9$ are rare (Bouwens$^+$ 12; Trenti,$^+$ 10; Yan$^+$ 10), since volume elt is small, and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ-range (0.7-29 μm).

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

- JWST Coronagraphs can also trace super-massive black-holes as faint quasars in young galaxies: JWST needs 2.0μm diffraction limit for this.

(5) Radio- and GRB-selected unobscured Star-Formation vs. epoch.

RLF: Spirals, Starburst galaxies, AGN (Ell+Quasars).



1.41 GHz counts (Windhorst$^+$ 1993, 2003) from 100 Jy to 100 nJy:

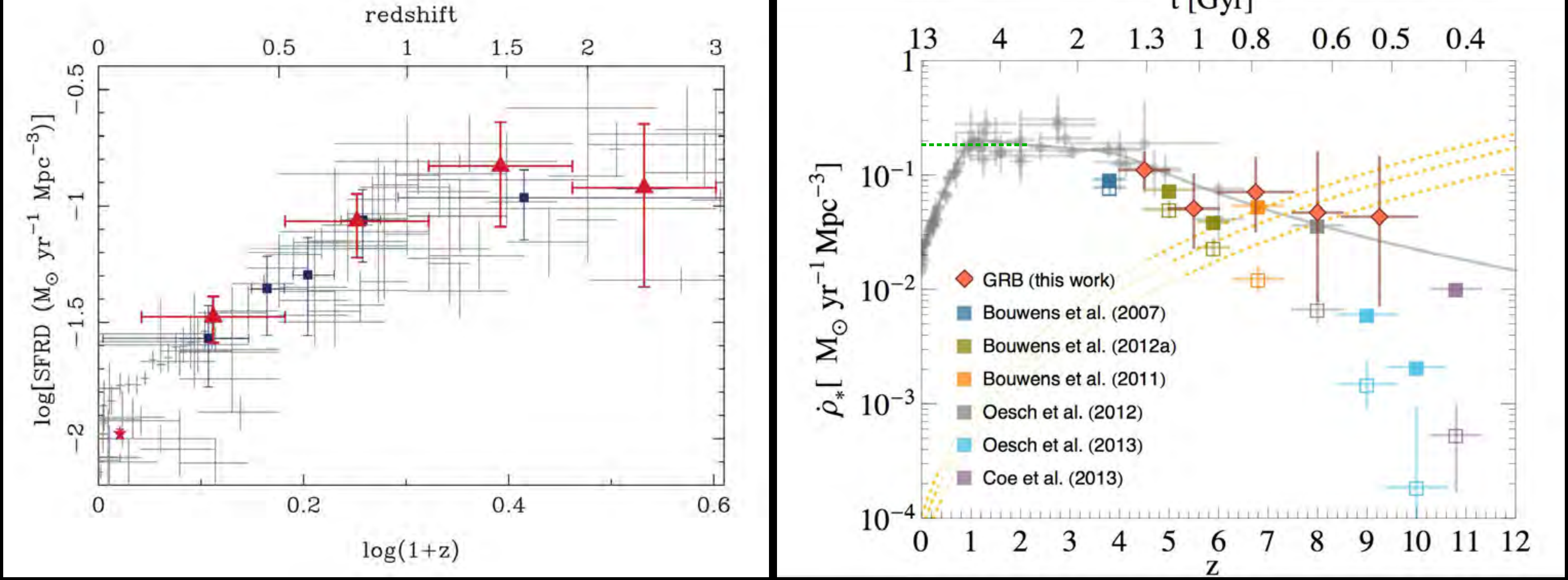
Filled circles below 10 μJy: 12-hr SKA simulation (Hopkins$^+$ 2000).

Models: Ellipticals (dot-dash) and Quasars dominate counts $\gtrsim$1 mJy.

$\Longrightarrow$ For $S_{1.4}$ $\lesssim$0.3–1 mJy, radio population traces unobscured SF:

SF-galaxies (dashed) $\lesssim$1 mJy; spirals (dot-long dash) $\lesssim$100 nJy.

Need: LOFAR/ASKAP/SKA to see all radio-selected SF at z$\lesssim$10-20.



[Left] Seymour$^+$ (2008): radio-selected SFR(z): hi-res radio morphology, radio spectra, 24μm/1.4 & far-IR/1.4GHz removes AGN; ν-normalized.

Haarsma$^+$ (2000): radio-selected RLF(z) for SF galaxies at z$\lesssim$2.

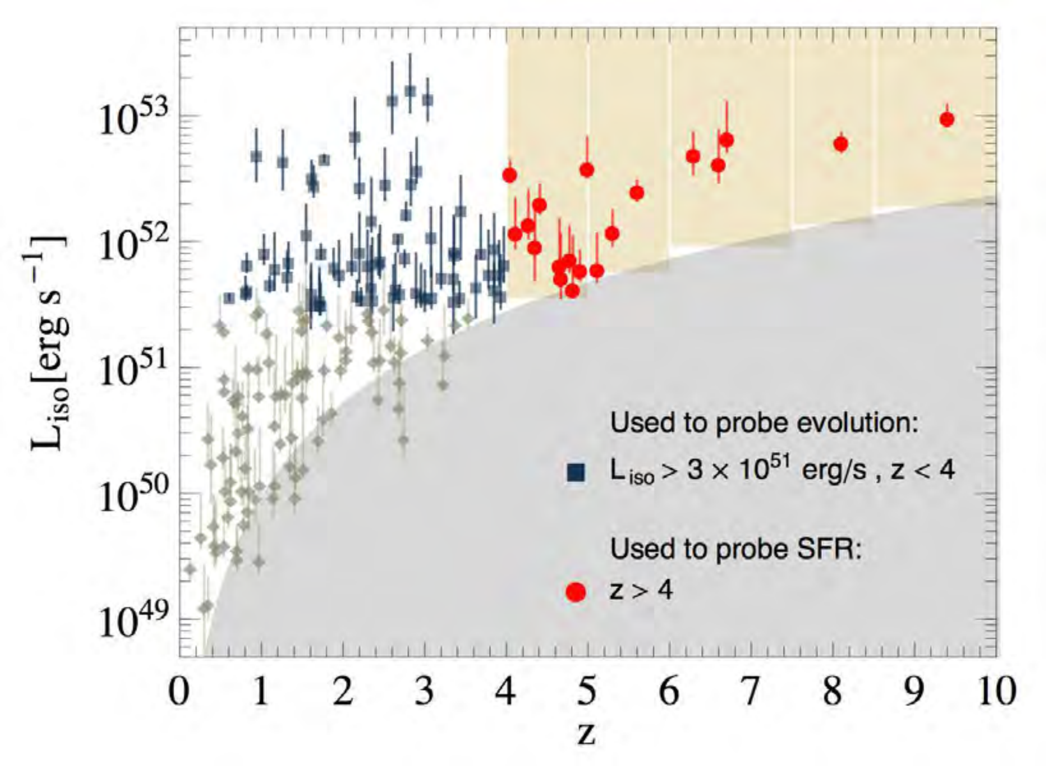
Grey: UV-optically selected SFR(z).

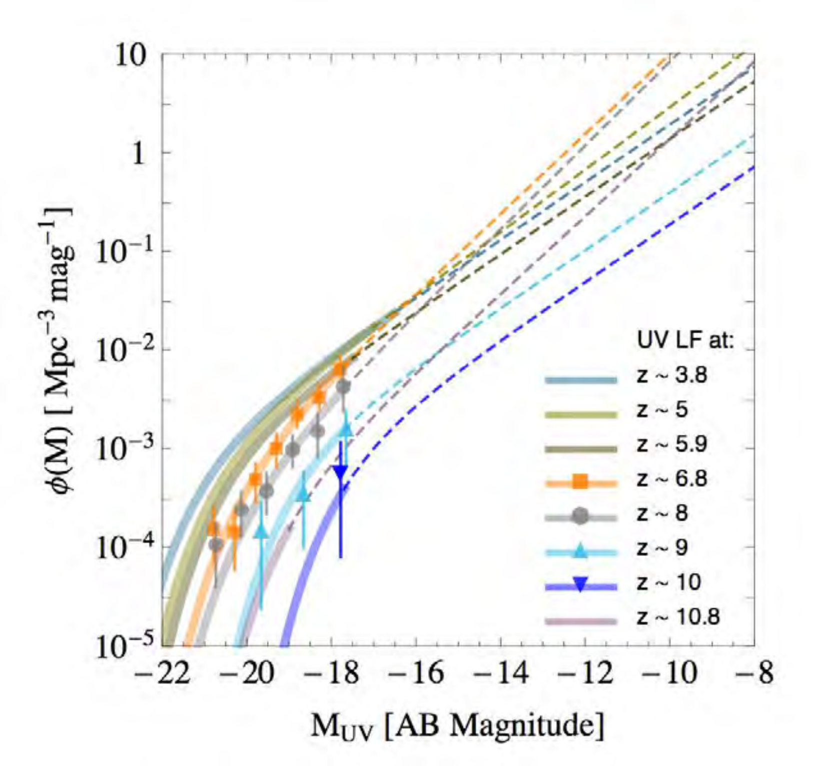
[RIGHT] Kistler$^+$ (astro-ph/1305.1630): GRB-selected SFR(z):

Open squares = HST ACS and WFC3 data;

Closed = LF extrapolated to M$_{AB}\simeq$–10 mag, using α(z).

- UV-optical selection could miss $\gtrsim$0.5 dex of SFD(z) for z$\gtrsim$6, unless extrapolation to M_{AB} $\simeq$–10 is justified; OR: dusty SF in faint galaxies.
- JWST will use Balmer breaks for z$\lesssim$12 and Hα for z$\lesssim$6.5.





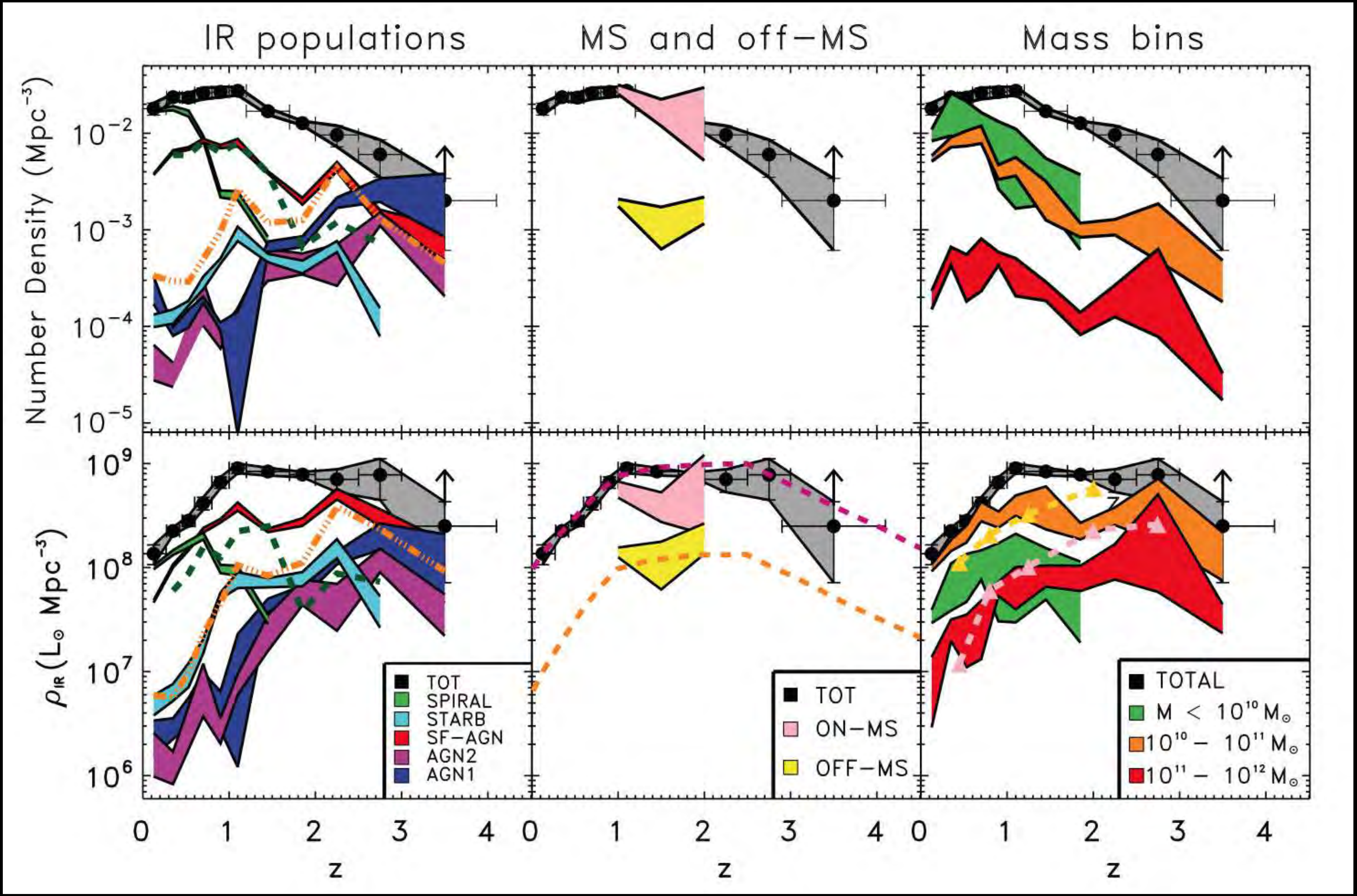
[Left] Kistler$^+$ (astro-ph/1305.1630): Actual GRB-selected SFR(z) sample.

[Right] Extrapolation of LF(z) used to compute SFD(z), using known α(z) for z$\lesssim$8, extrapolation of α(z) [$\simeq$–2] for z$\gtrsim$8, and cutoff M$_{AB}\simeq$–10.

Need decades of SWIFT + *sequels* to GRB–select unobscured SFR(z$\gtrsim$7).

- Ultradeep JWST samples can confirm GRB hosts for z$\lesssim$12–20: using 100's of hours integration, or lensing in rich clusters, and/or lensing bias from random foreground halos.

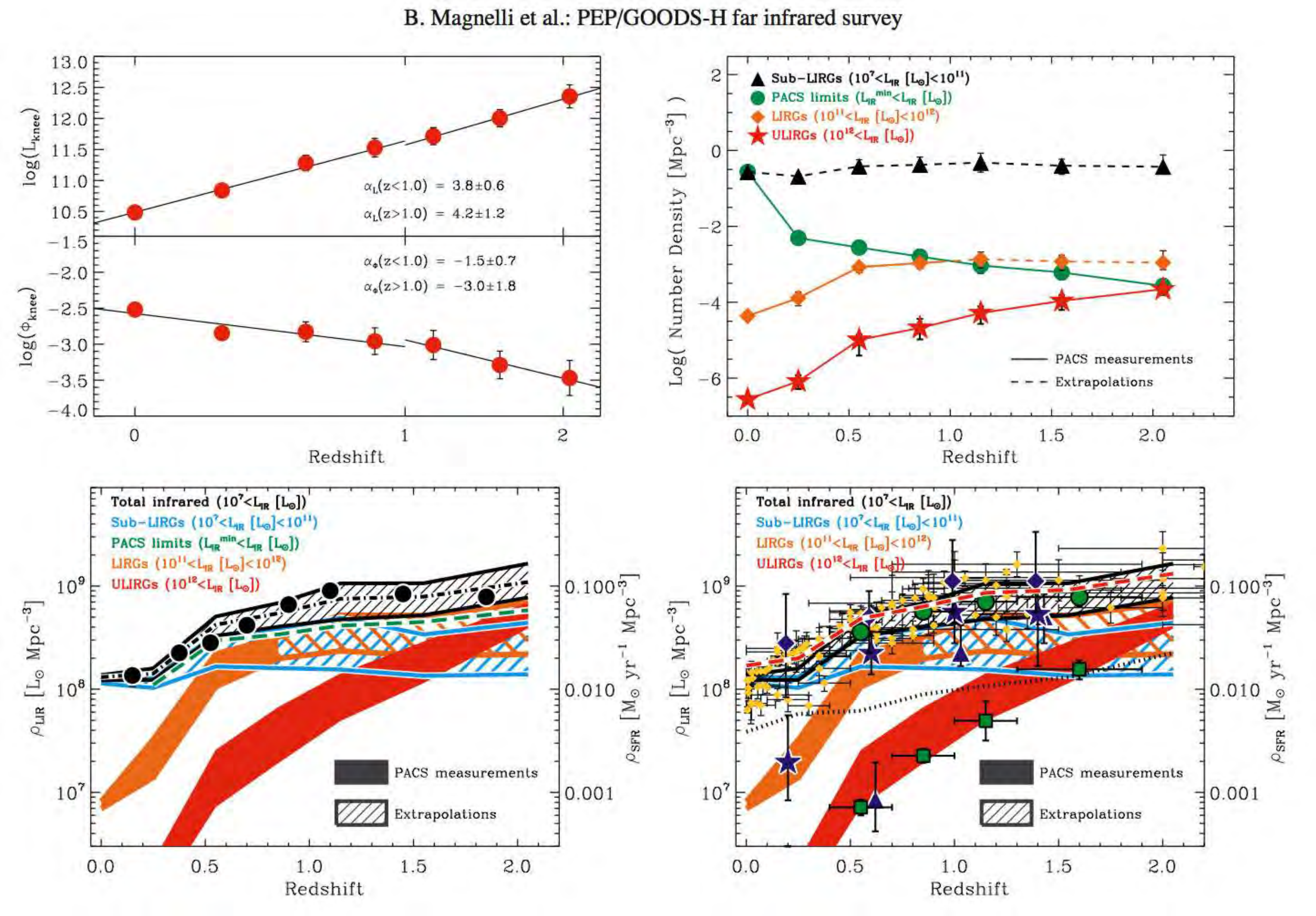
(6) Far-IR-selected unobscured Star-Formation vs. of epoch.



Gruppioni et al. (2013): Herschel far-IR selected cosmic SFR(z) increases significantly for $z\gtrsim1$–3, especially for Type 1 & 2 AGN.

Spirals and Starbursts less so — cosmic downsizing.

- JWST can trace SF using Balmer breaks at $z\lesssim11.5$.

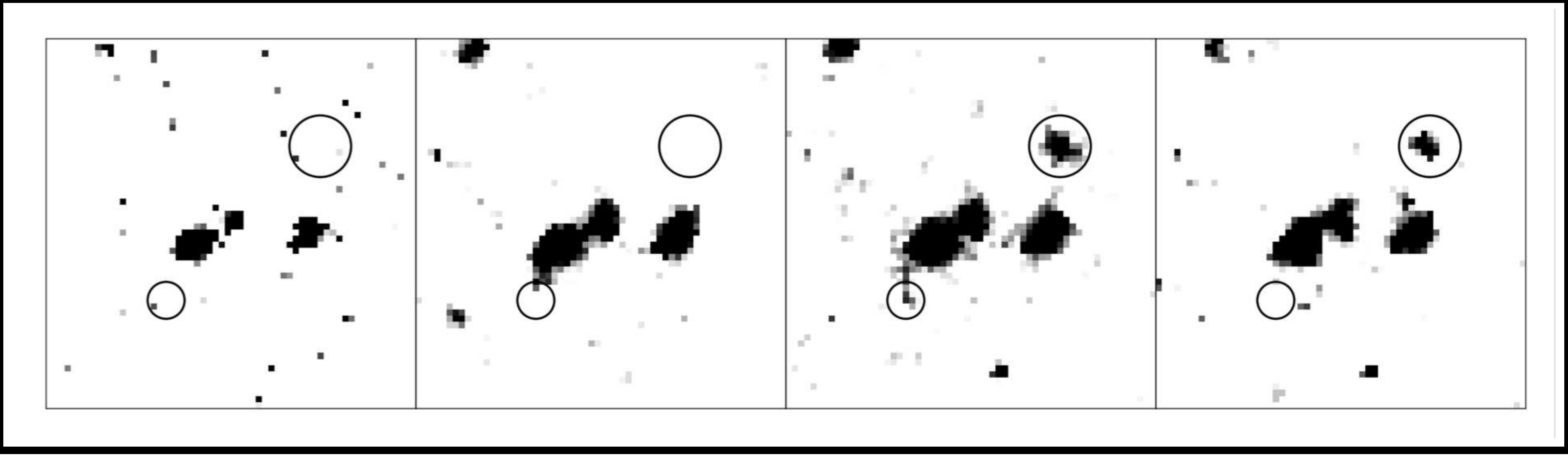


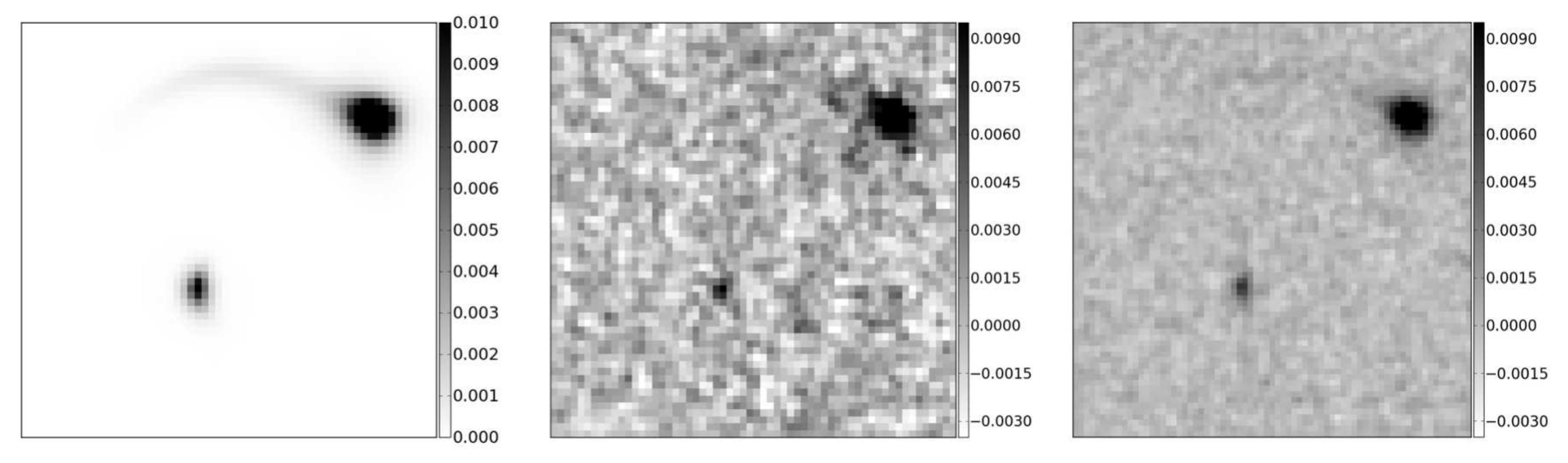
Magnelli et al. (2013): Herschel far-IR selected cosmic SFR(z) increases significantly for $z \gtrsim 1$, especially for LIRG's and ULIRG's.

- Herschel limited by resolution and sensitivity: Need: space-based far-IR sequel to Herschel and JWST to survey dust-obscured SFR at $z \lesssim 10$.
- ALMA can map individual objects (see X. Fan's talk).

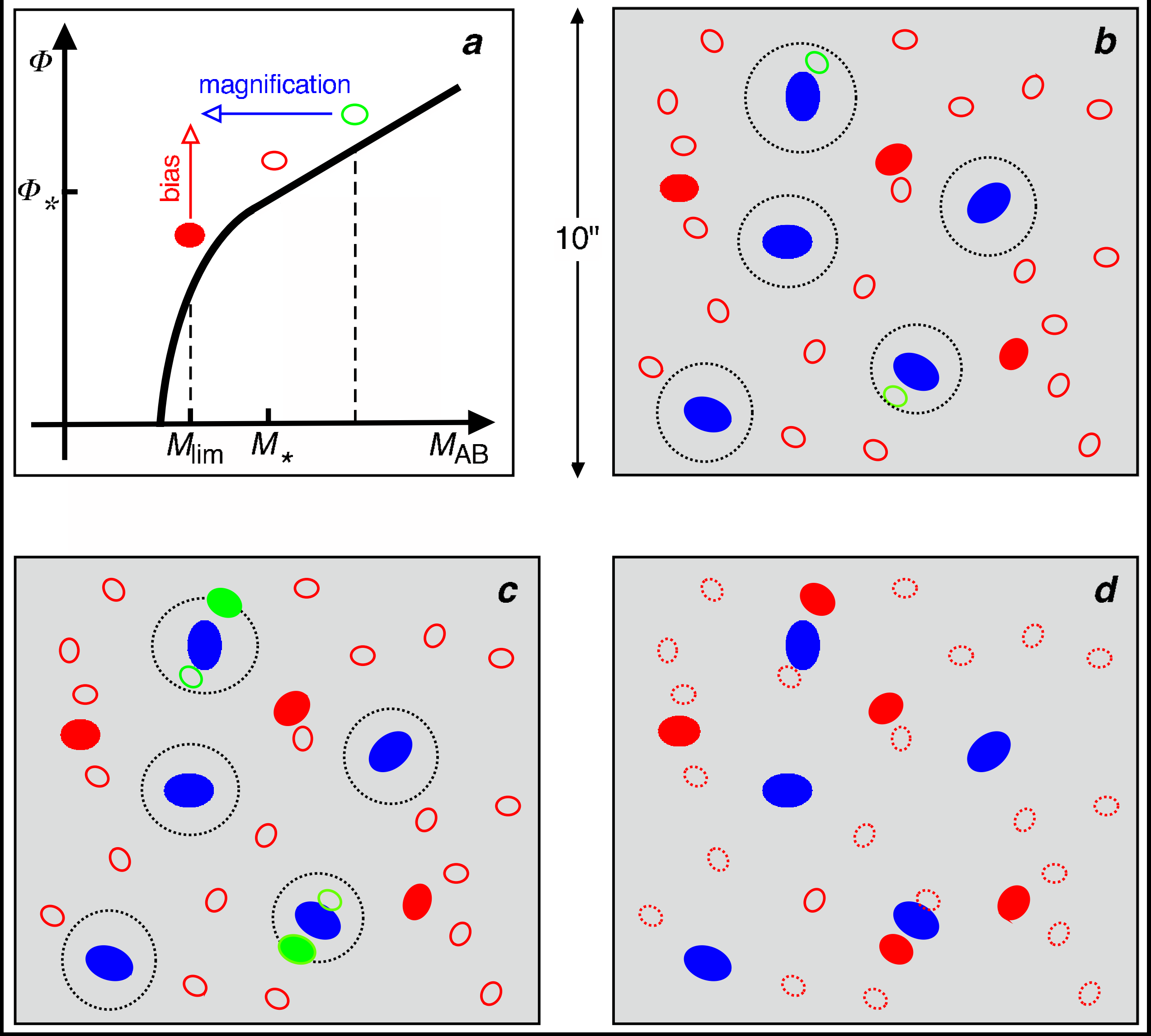
(7) Gravitational Lensing to see the Reionizing population at $z \gtrsim 8$.

(7) Gravitational Lensing to see the Reionizing population at z$\gtrsim$8.





- Barone-Nugent$^+$ (2012): Possible z=8 galaxy in WFC3 BoRG survey (Trenti$^+$ 2011) lensed by foreground group: Foreground halos (z$\simeq$1–2) may gravitationally lens or amplify galaxies at z$\gtrsim$8–10 (Wyithe et al. 2011).
- If common, this could change the landscape for JWST observing strategies.



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.
- Strength of effect at z≳8–10 depends on how fast M^* declines with z.

Two fundamental limitations may determine ultimate JWST image depth:

(1) Cannot-see-the-forest-for-the-trees effect [Natural Confusion limit]: Background objects blend into foreground neighbors because of their own diameter $\Rightarrow$ Need multi-λ deblending algorithms!

(2) House-of-mirrors effect ["Gravitational Confusion"]: First Light objects at $z \gtrsim 8$–10 may be gravitationally lensed by foreground halos.

$\Rightarrow$ May have to model/correct for this: Need new SExtractor!

$\Rightarrow$ If $M^*(z \gtrsim 10) \gtrsim -19$, may need to model entire gravitational foreground.

- Proper JWST 2.0μm PSF and straylight specs essential to handle this.

(8) Conclusions

(1) HST set stage to measure galaxy assembly in the last 12.7-13.0 Gyrs:

- Most $z \simeq 6$ QSO host galaxies faint (dusty?), with 1 exception: $L >> L^*$.
- Need: 2.4m (NRO)—16 meter UV-optical HST sequel after WFIRST.

(2) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly & SMBH-growth in detail. JWST will determine:

- How dwarf galaxies formed at $z \lesssim 20$, and reionized the Universe by $z \gtrsim 6$.
- How SMBH's grew during the onset of galaxy assembly at $z \lesssim 20$.
- Constrain IMF as function of Mass/environment, Fe/H, epoch.
- Trace Hα at $0.5 \lesssim z \lesssim 6.5$, and Ly$\alpha$ at $z \gtrsim 8$ through holes in HI and dust.

(3) Need: LOFAR/ASKAP/SKA for Radio–selected unobscured SFR(z).

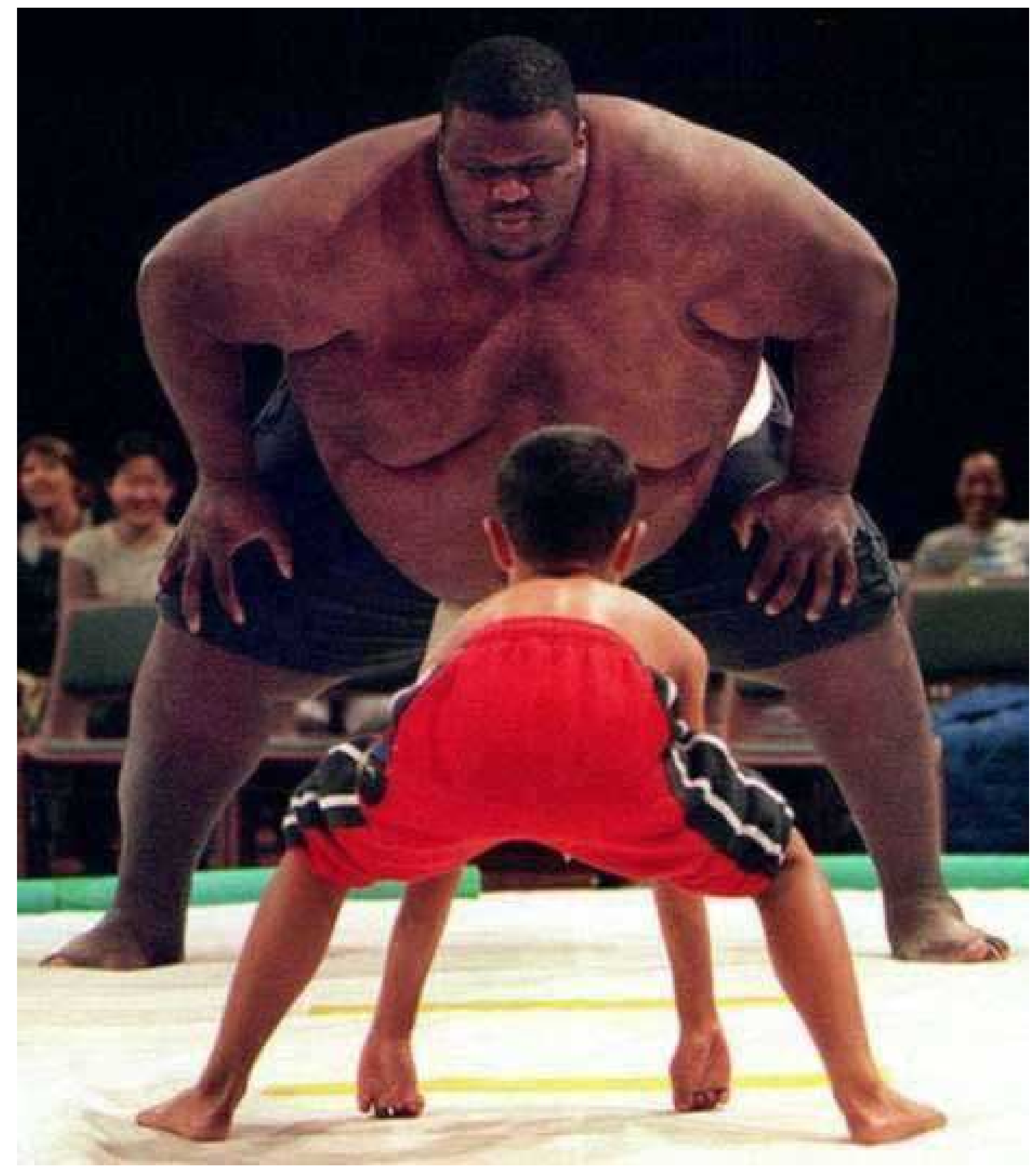
(4) Need: Chandra sequel to select weak AGN in faint galaxies at $z \lesssim 20$.

(5) Need: SWIFT *+sequels* for GRB–selected unobscured SFR(z).

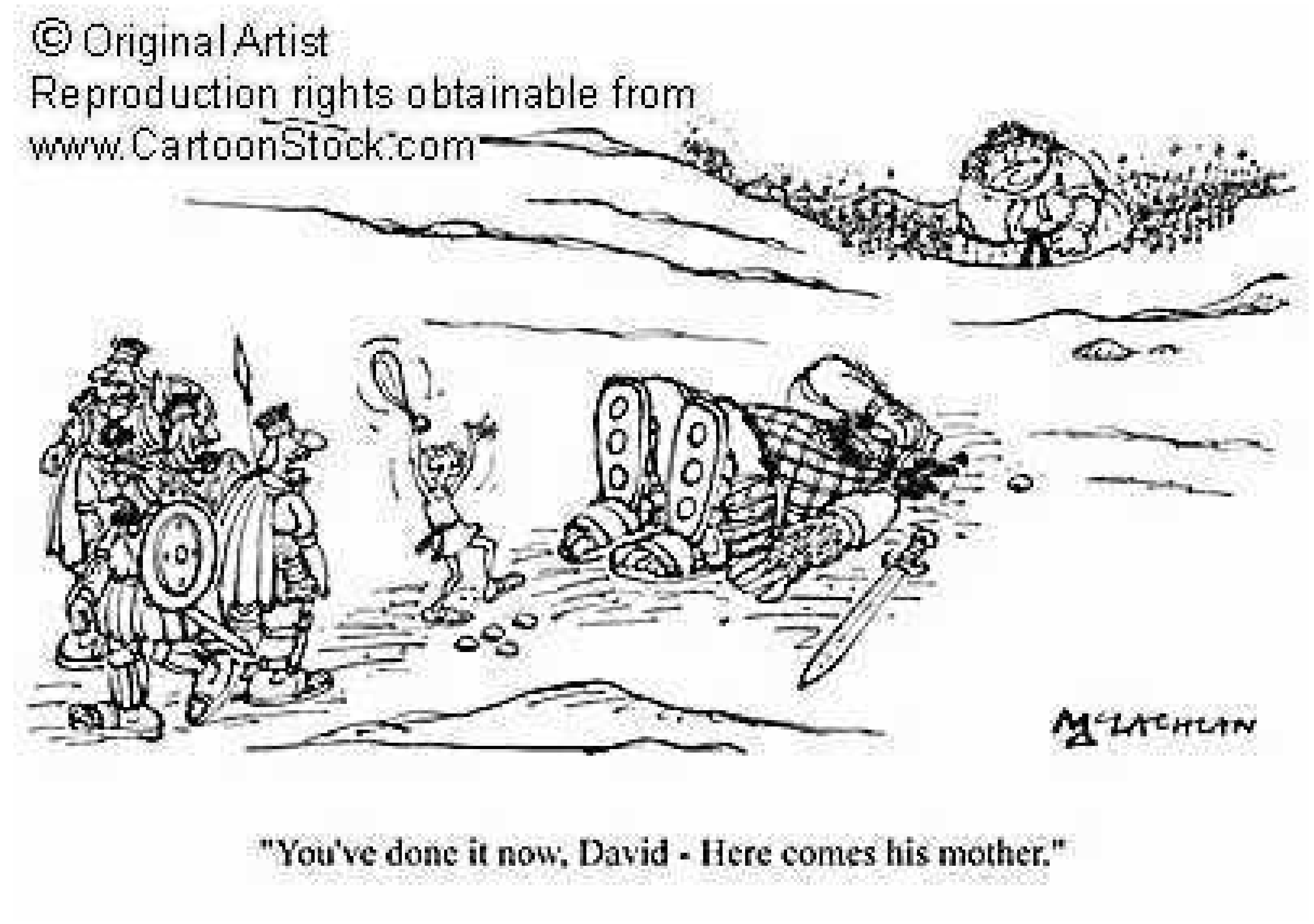
(6) Need: ALMA *+Herschel sequel:* Far-IR-selected unobscured SFR(z).

(7) Need: Use gravitational lensing (bias) to survey Reionizers at $z \gtrsim 8$.

SPARE CHARTS



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



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

What comes around, goes around ...

- 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

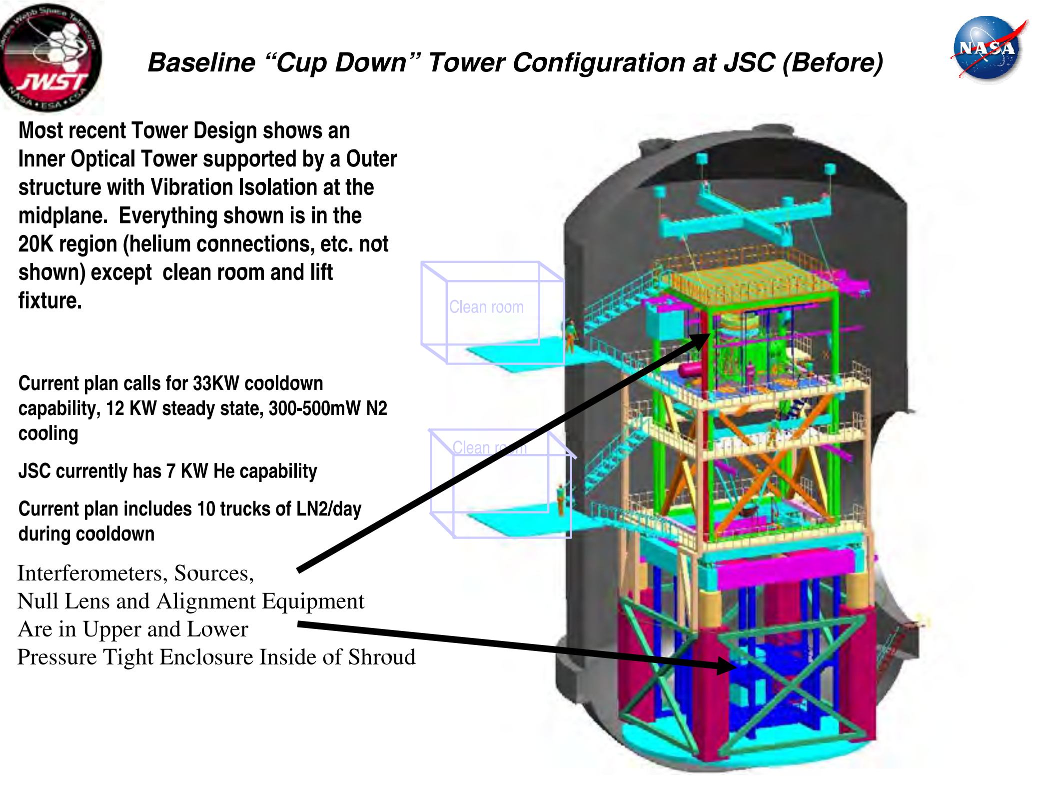
Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

Windhorst, R., et al. 2011, ApJS, 193, 27 (astro-ph/1005.2776).

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



Baseline "Cup Down" Tower Configuration at JSC (Before)

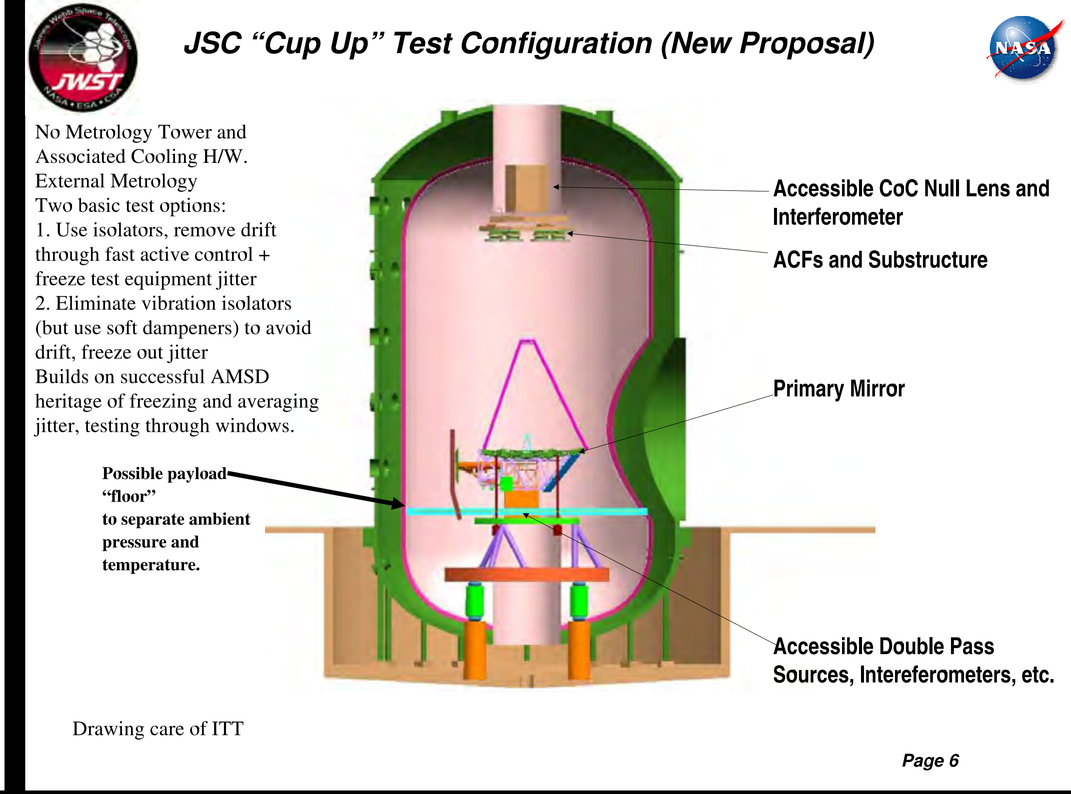
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

Current plan calls for 33KW cooldown capability, 12 KW steady state, 300-500mW N2 cooling

JSC currently has 7 KW He capability

Current plan includes 10 trucks of LN2/day during cooldown

Interferometers, Sources, Null Lens and Alignment Equipment Are in Upper and Lower Pressure Tight Enclosure Inside of Shroud



JSC "Cup Up" Test Configuration (New Proposal)

No Metrology Tower and Associated Cooling H/W.
External Metrology
Two basic test options:
1. Use isolators, remove drift through fast active control + freeze test equipment jitter
2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter
Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.

Possible payload "floor" to separate ambient pressure and temperature.

Accessible CoC Null Lens and Interferometer

ACFs and Substructure

Primary Mirror

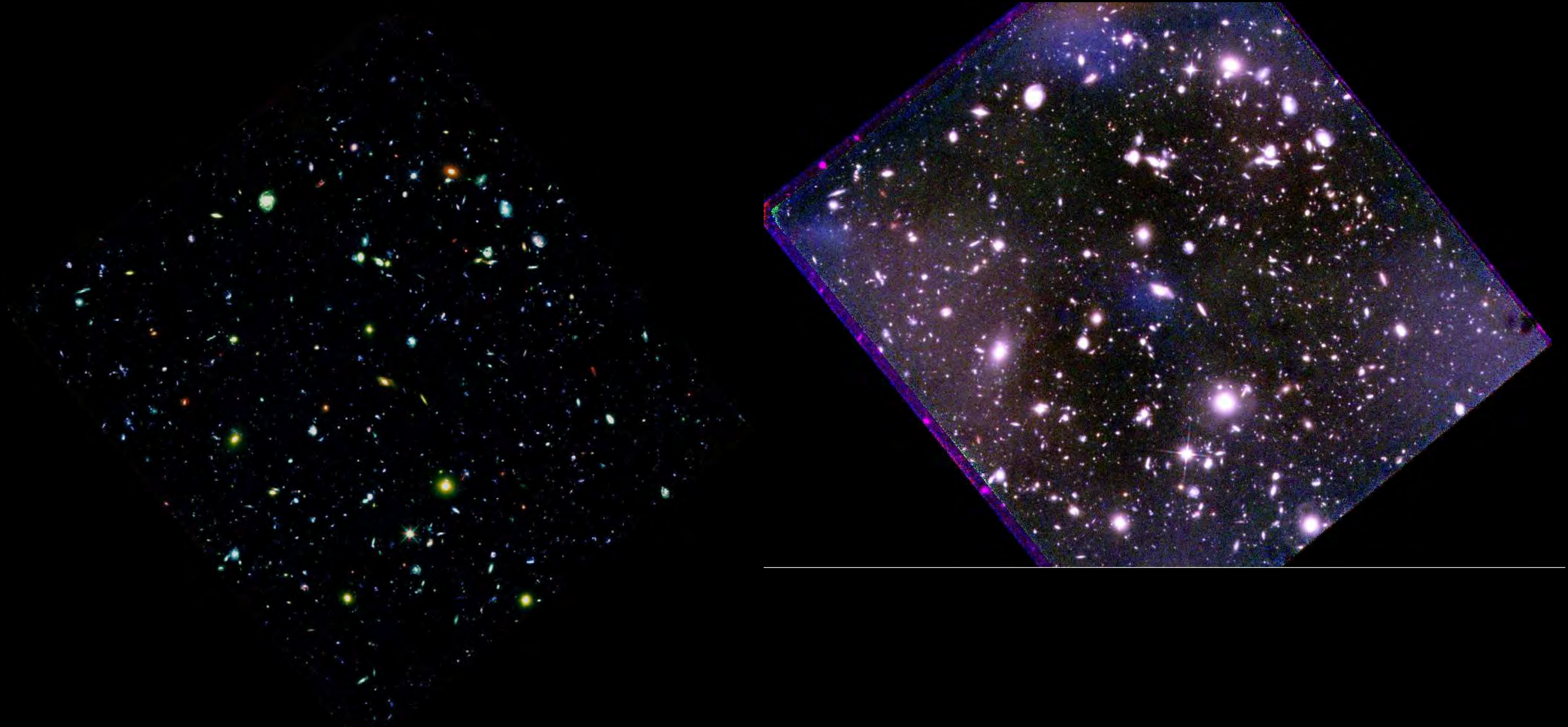
Accessible Double Pass Sources, Intereferometers, etc.

Drawing care of ITT

Page 6

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).
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010, 2011: Passes Mission Critical Design Review: Replan Int. & Testing.



(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.

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

(4) Recent results of Hubble WFC3 on Galaxy Assembly, & what JWST will do:

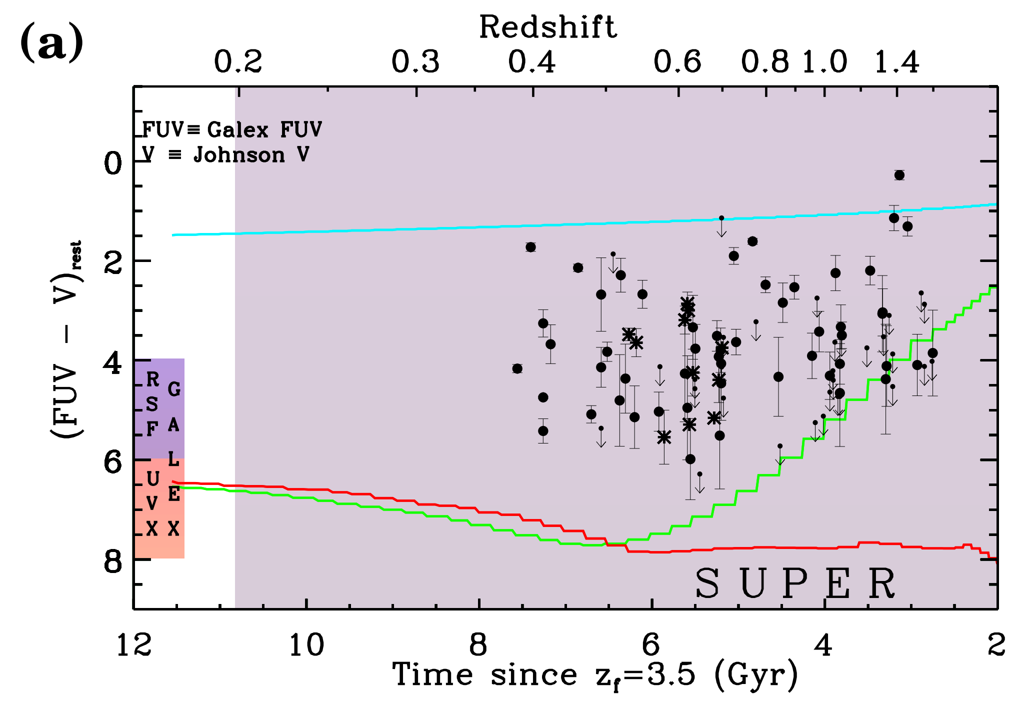
Galaxy structure at the peak of the merging epoch ($z \simeq 1$–2) is very rich: some resemble the cosmological parameters $\boldsymbol{H_0}$, $\boldsymbol{\Omega}$, $\boldsymbol{\rho_o}$, $\boldsymbol{w}$, and $\boldsymbol{\Lambda}$, resp.

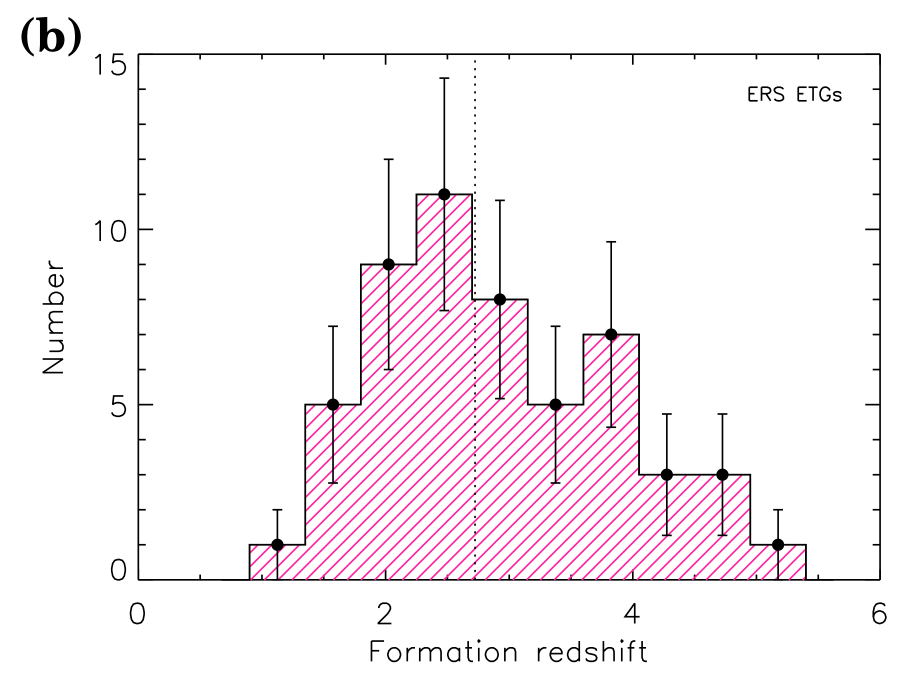
Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

(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.

(4) Rest-frame UV-evolution of Early Type Galaxies since $z \lesssim 1.5$.



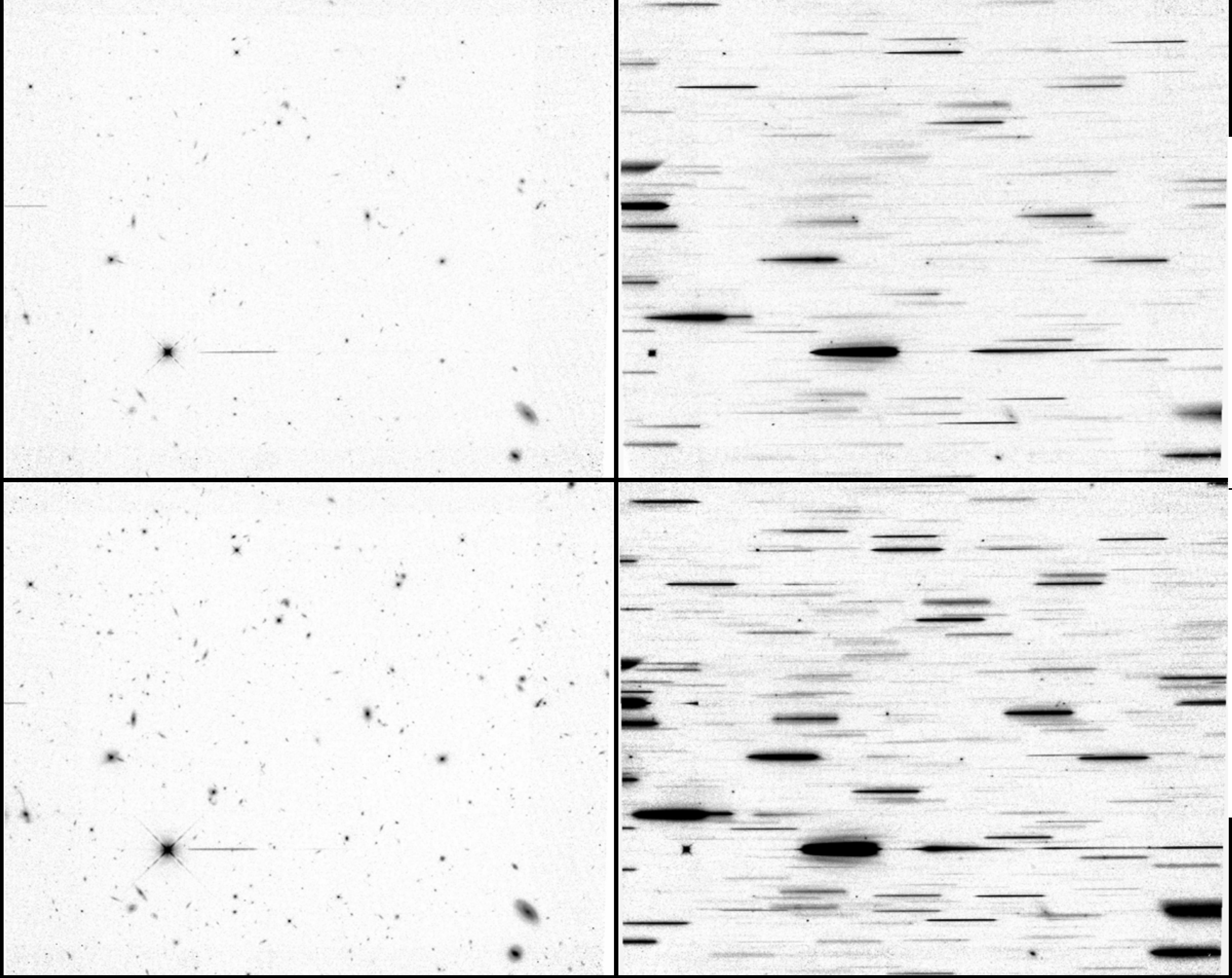


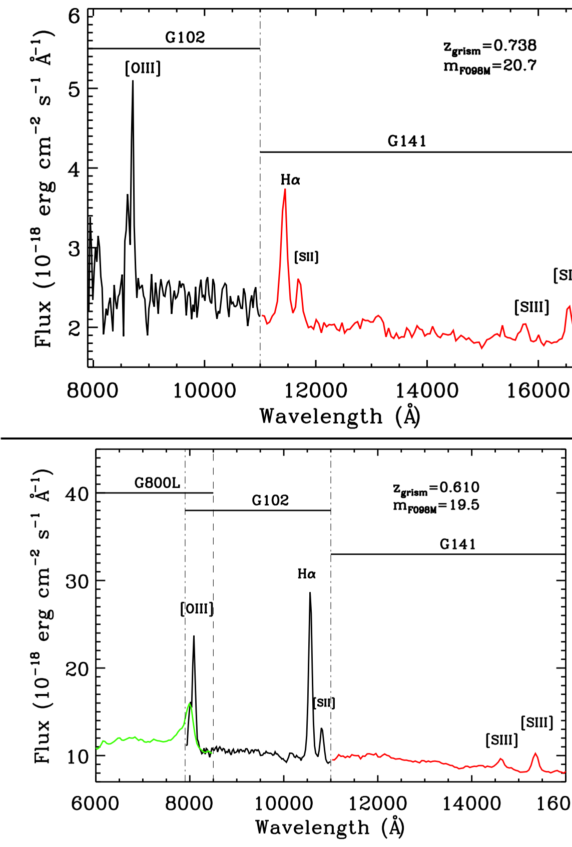
- 10-band WFC3 ERS data measured rest-frame UV-light in nearly all early-type galaxies at $0.3 \lesssim z \lesssim 1.5$ (Rutkowski et al. 2012, ApJS, 199, 4).

$\Longrightarrow$ 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 this to all redshifts with Balmer+4000Å-break ages.



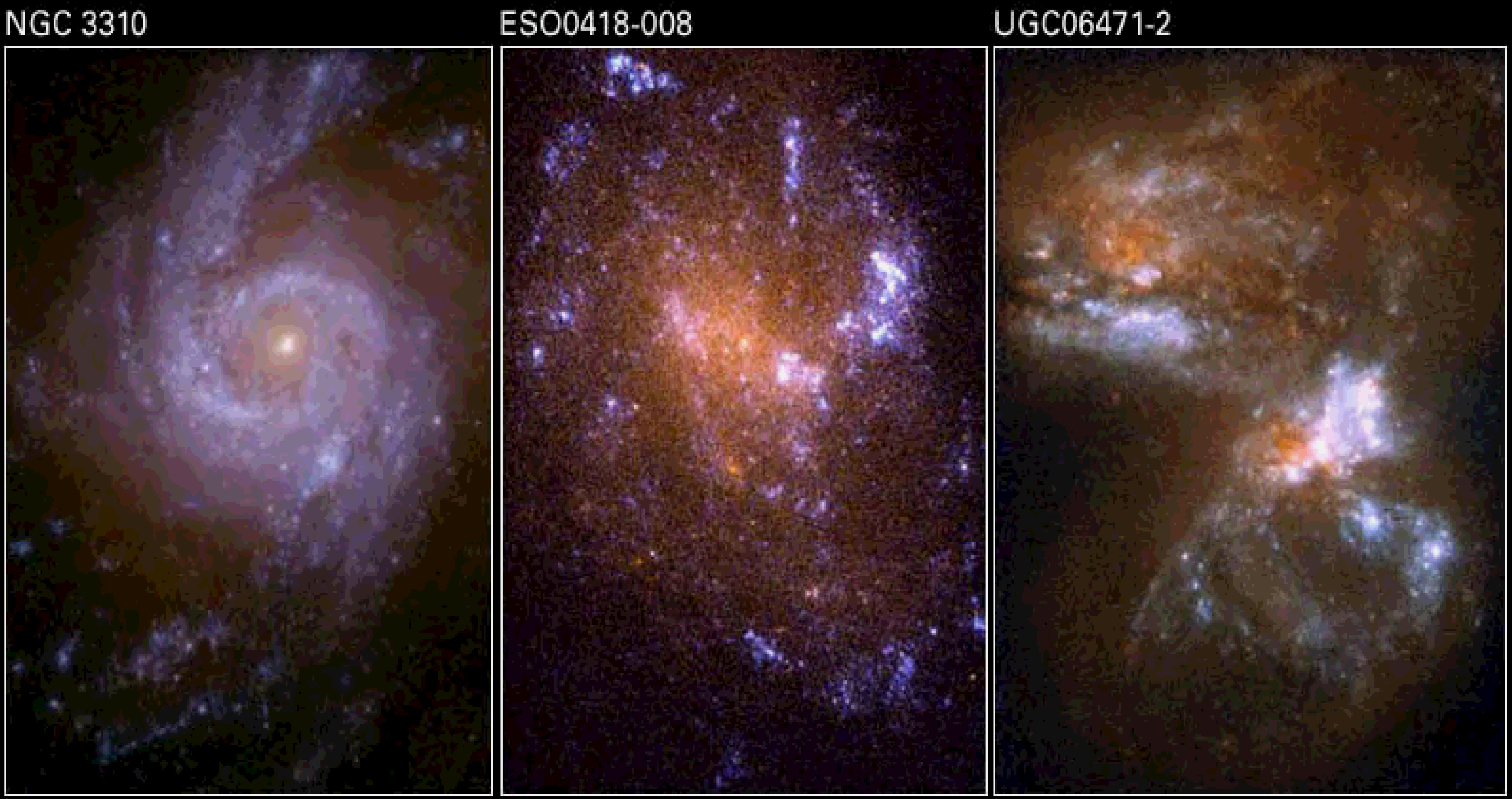


HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn^{+} 2010)

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.

(4b) Predicted Galaxy Appearance for JWST at redshifts z≃1–15



Ultraviolet Galaxies

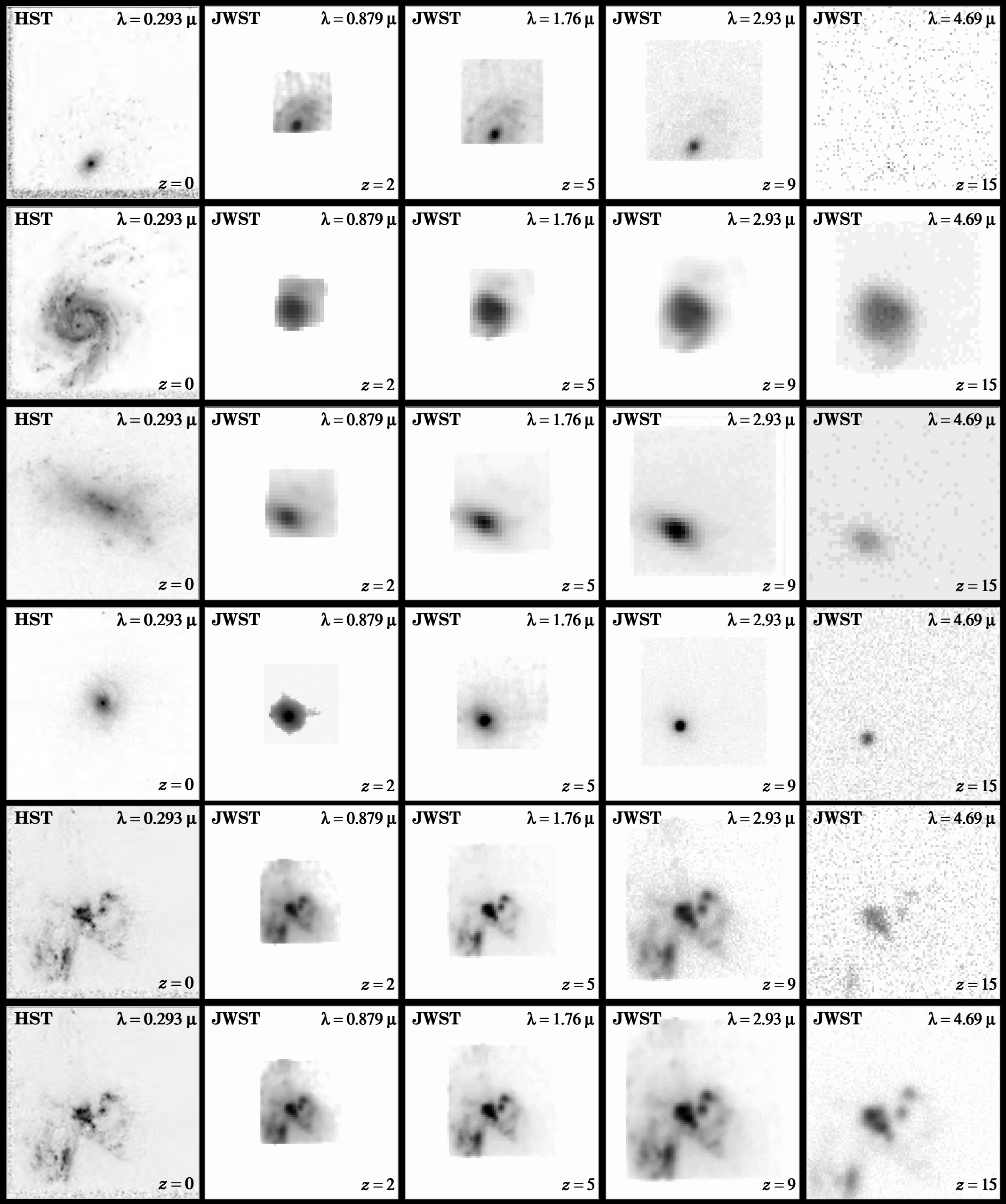
HST • WFPC2

NASA and R. Windhorst (Arizona State University) • STScI-PRC01-04

- 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.

(4b) Predicted Galaxy Appearance for JWST at redshifts z≃1–15

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



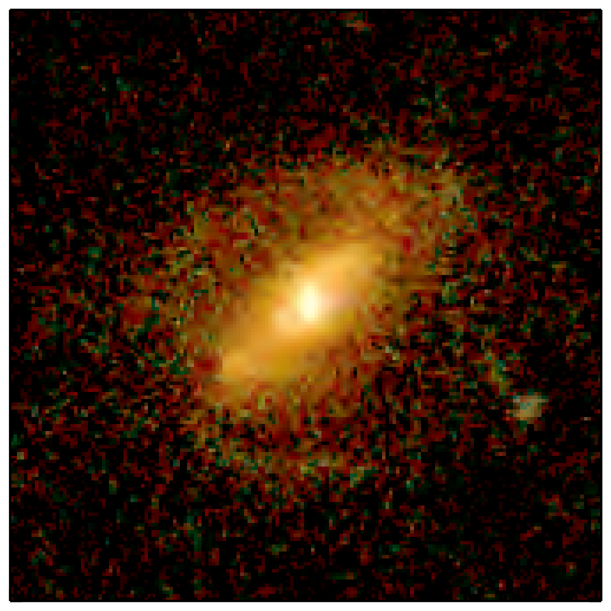
With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

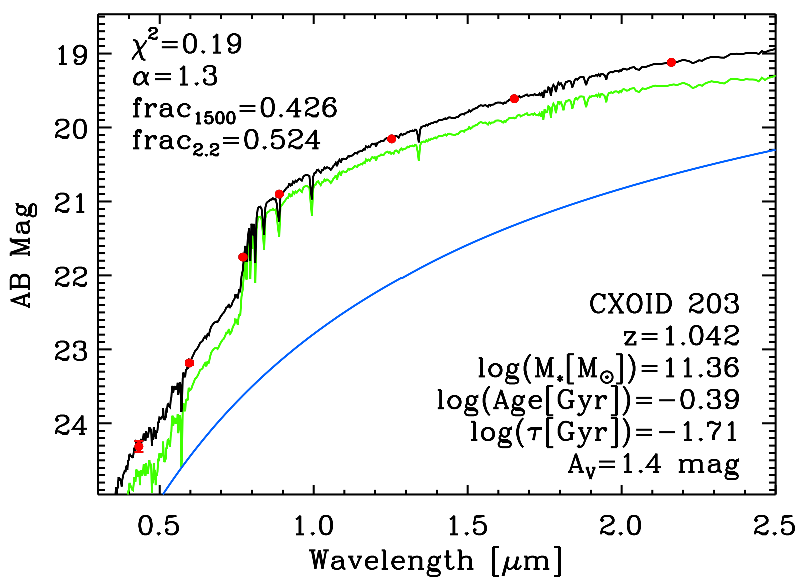
- (1) Most spiral disks will dim away at high redshift, but most formed at z$\lesssim$1–2.

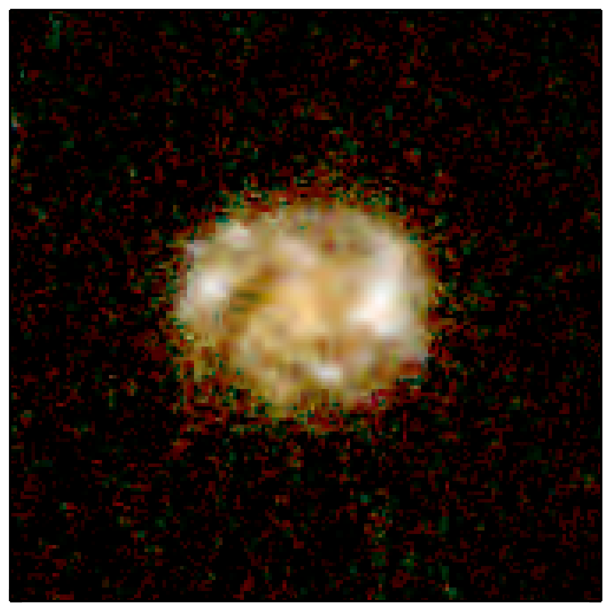
Visible to JWST at very high z are:

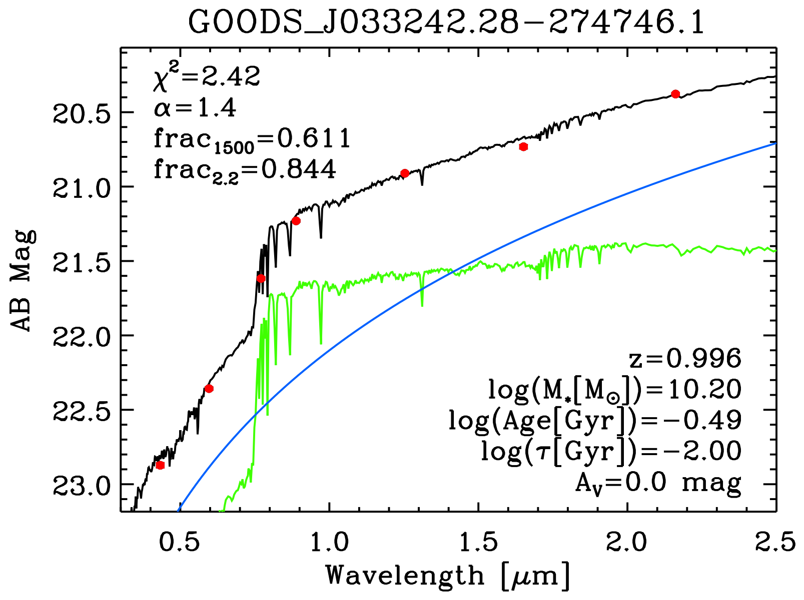
- (2) Compact star-forming objects (dwarf galaxies).
- (3) Point sources (QSOs).
- (4) Compact mergers & train-wrecks.

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





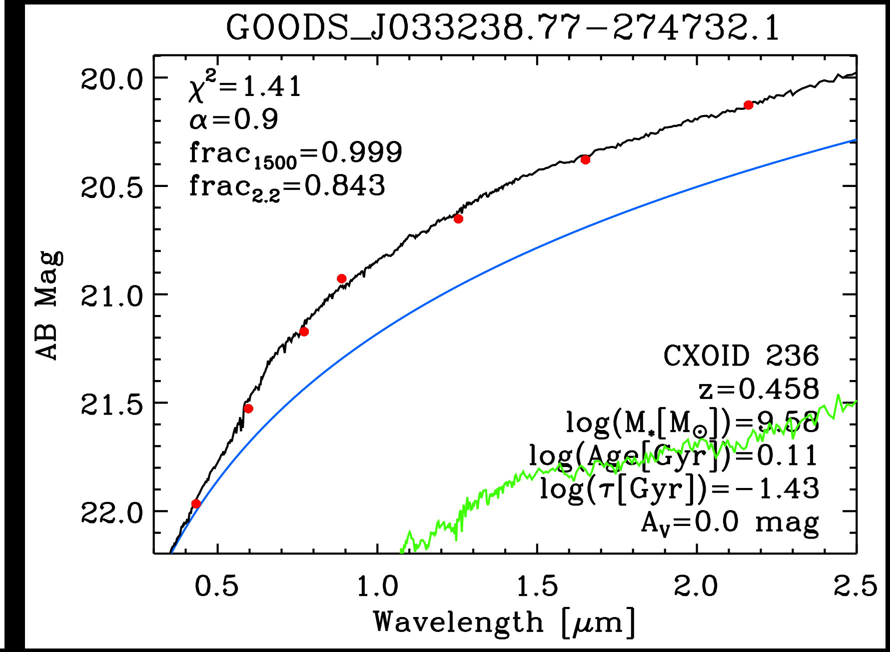


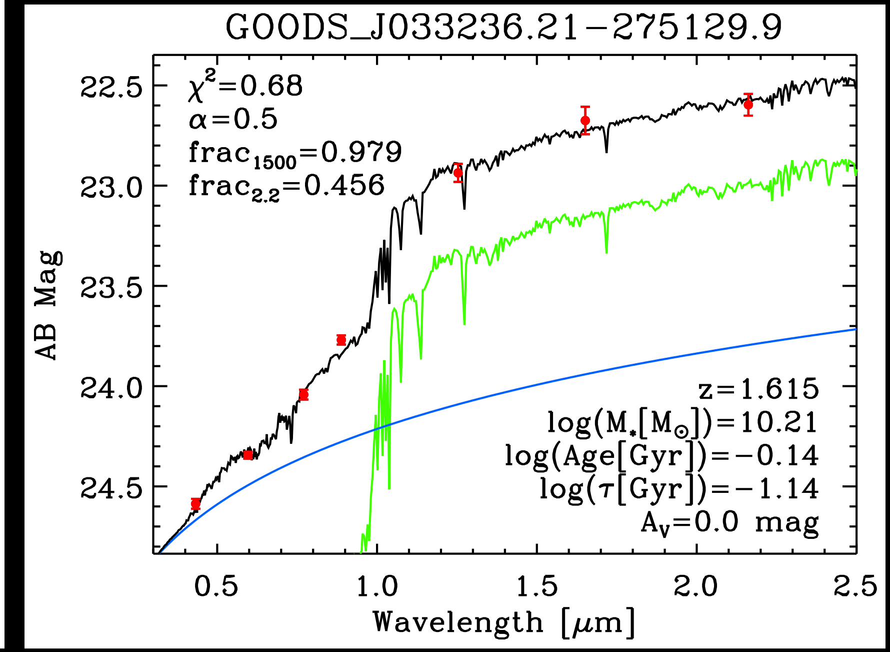


Cohen+ (2013): GOODS/VLT UV+BVizJHK images + 1549 VLT redshifts.

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

Method: Multi-component SED fits (Windhorst & Cohen (2010).





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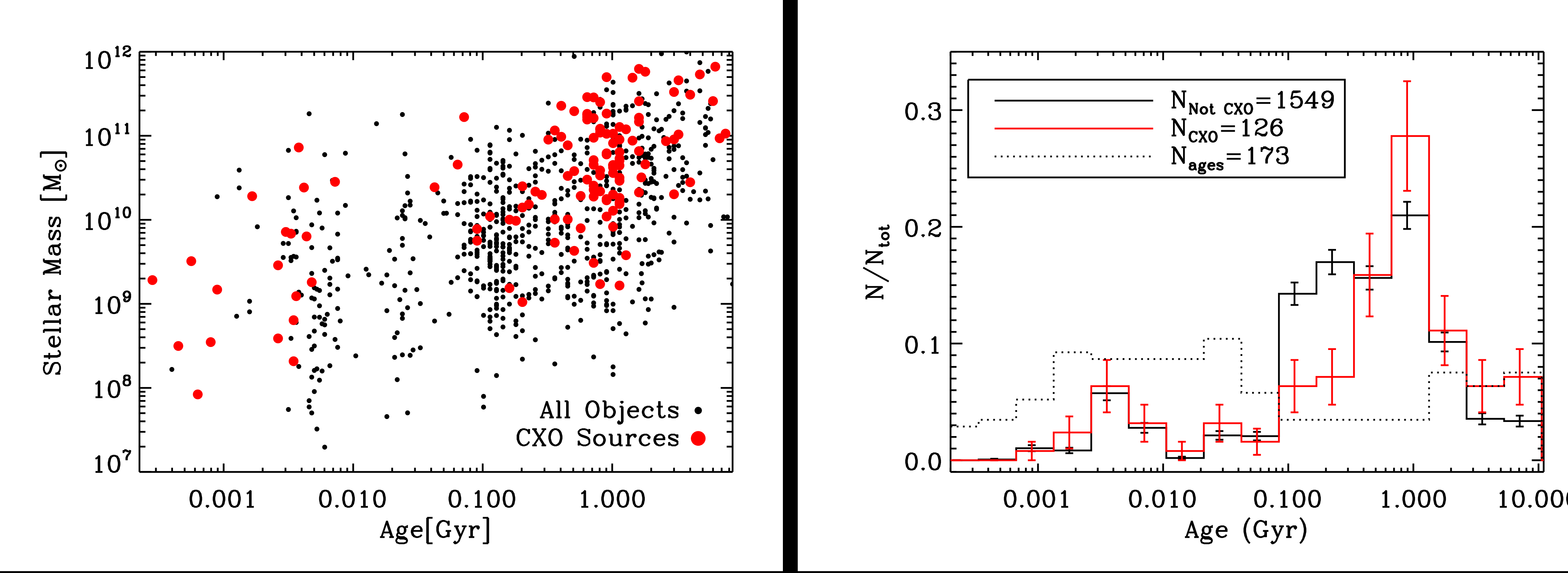
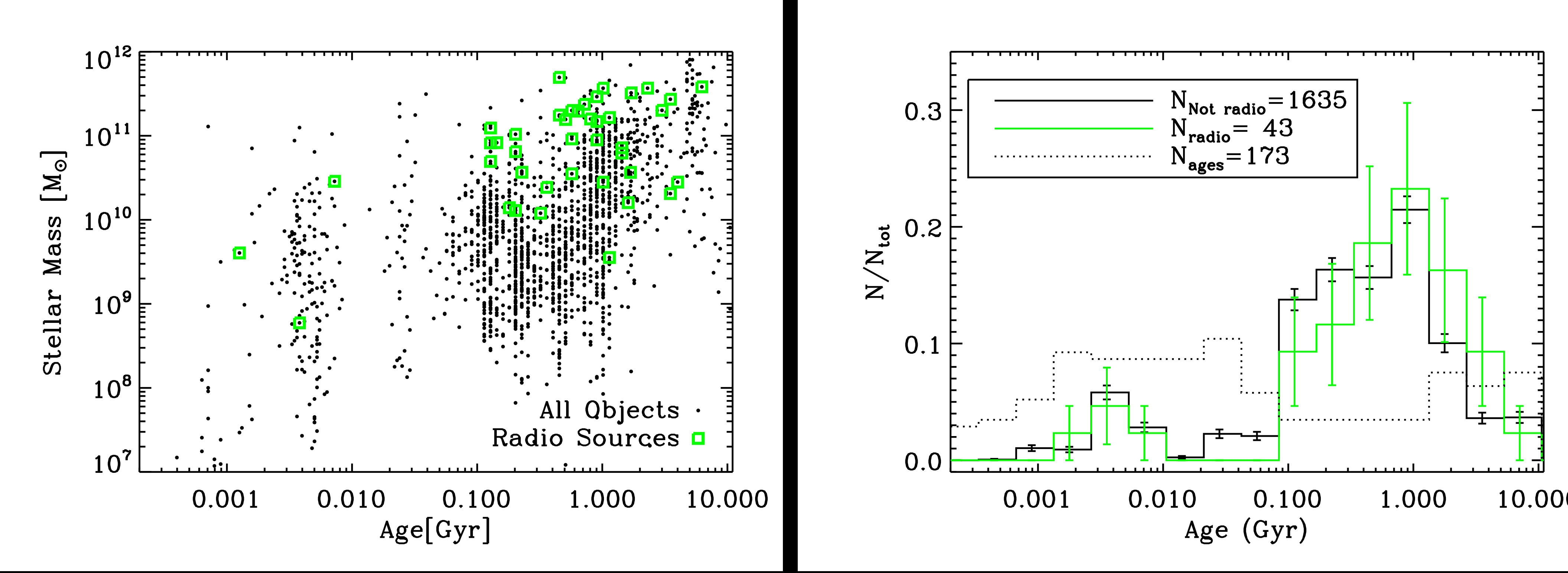


Cohen et al. (2013): Best fit Stellar Mass vs. Age: X-ray and field galaxies.

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

- X-ray sources reside in galaxies that are a bit older than the general field population, but by no more than $\lesssim$0.5–1 Gyr on average.
- JWST+WFC3 can disentangle multiple SED + AGN power-law from 15-band photometry to AB=30 mag for z$\lesssim$10.
- JWST can trace AGN-growth, host galaxy masses and ages since z∼10.



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

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

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

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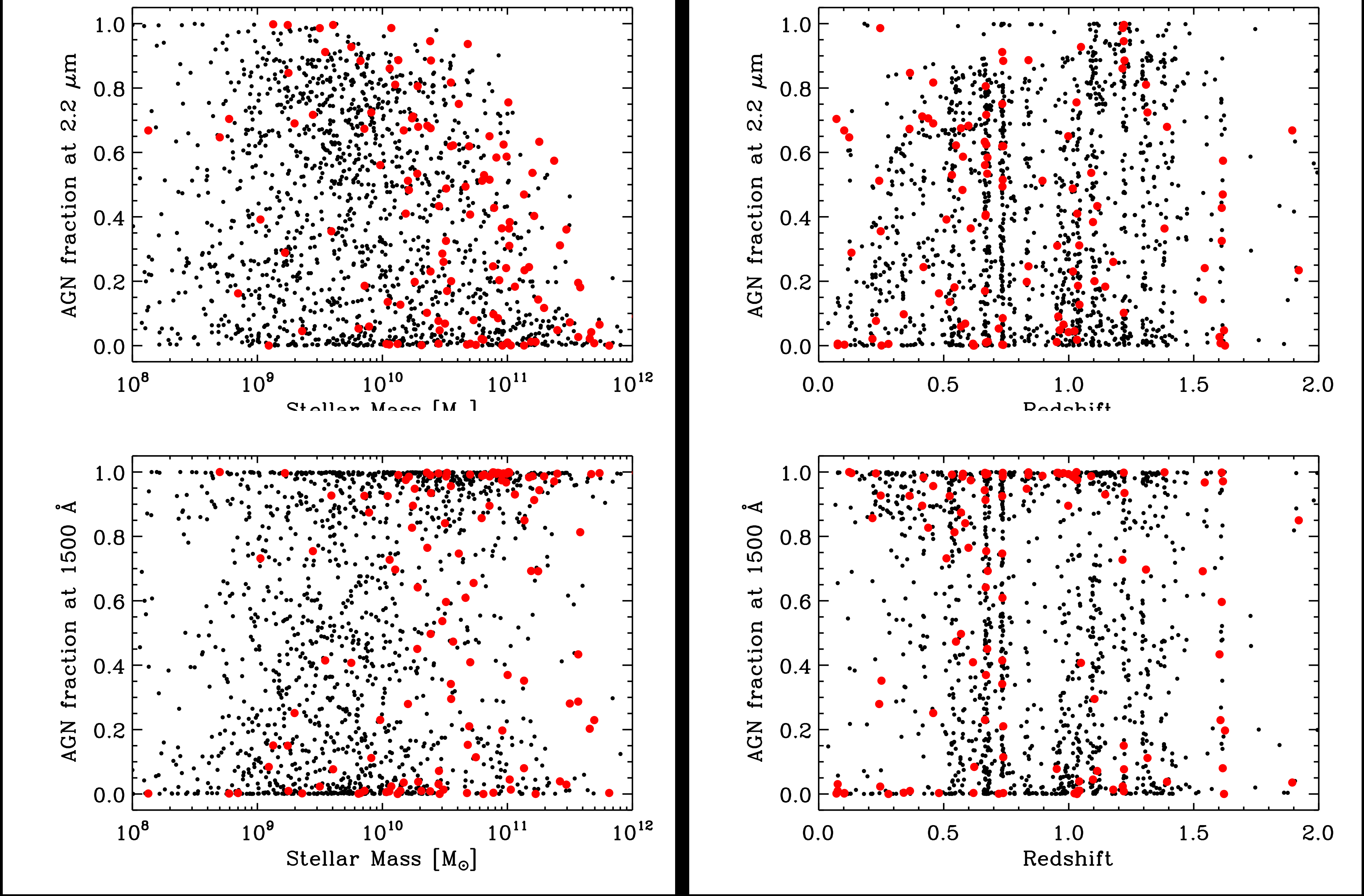
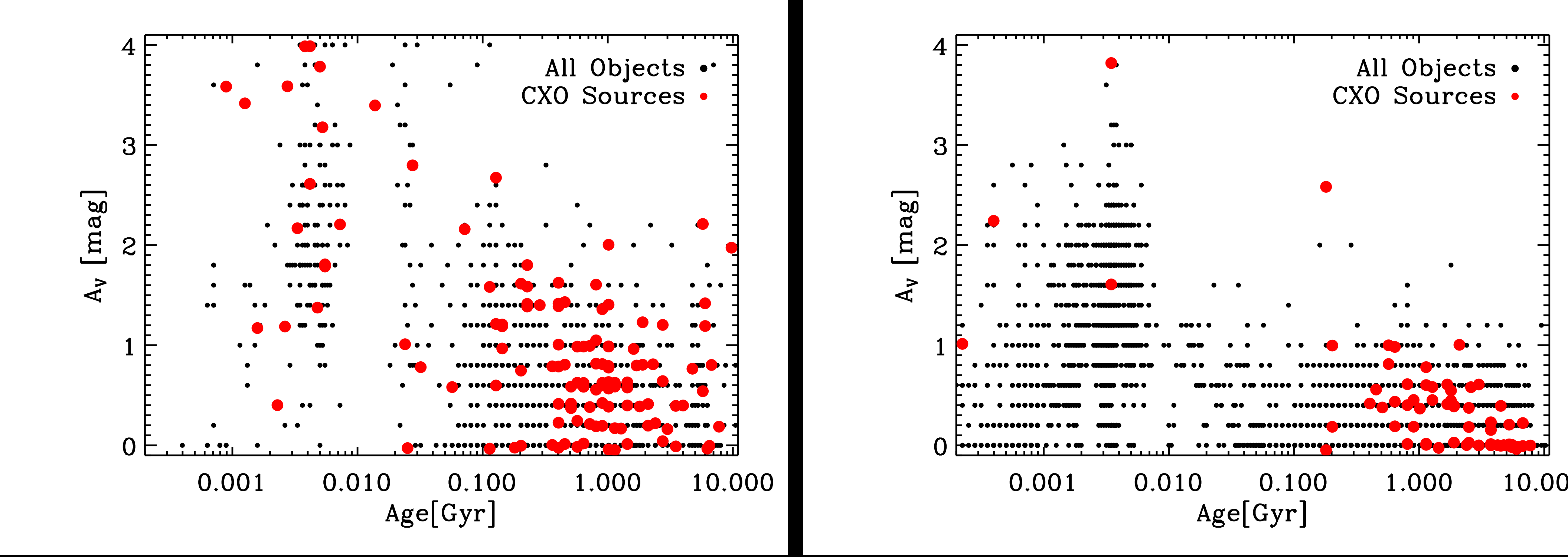


Cohen$^+$ (2013): "AGN" fraction vs. stellar mass & z: X-ray and field gxys.

⇒ 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.

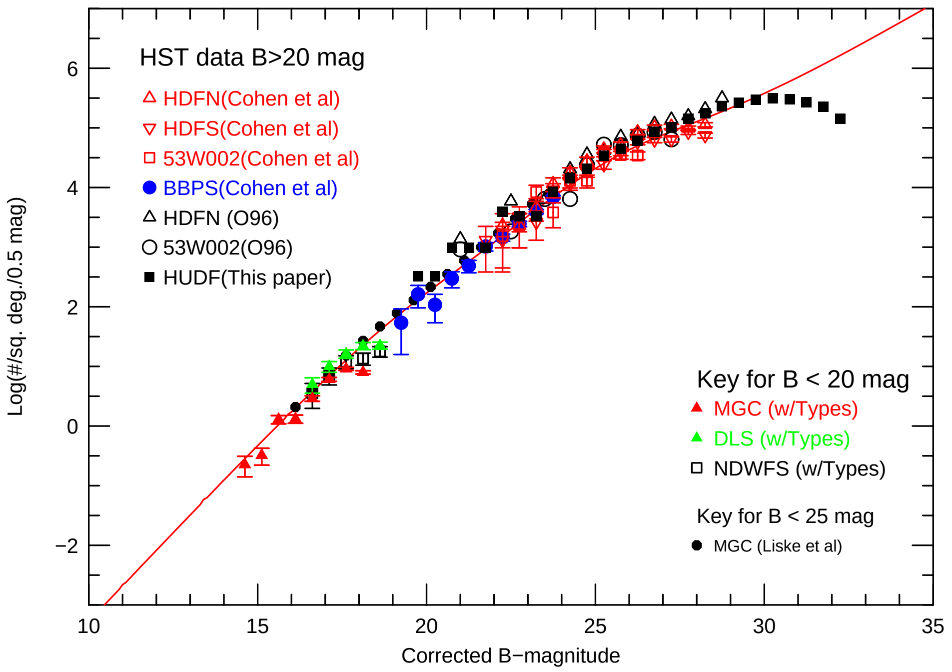


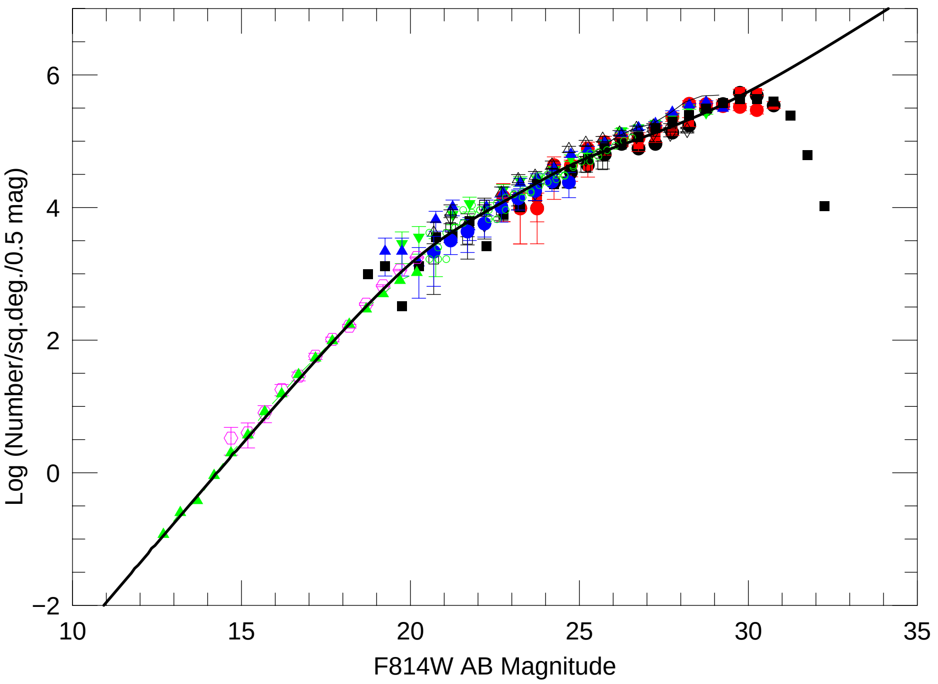
LEFT: 1549 CDF-S objects with z's. RIGHT: 7000 CDF-S ERS with spz's.

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.

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



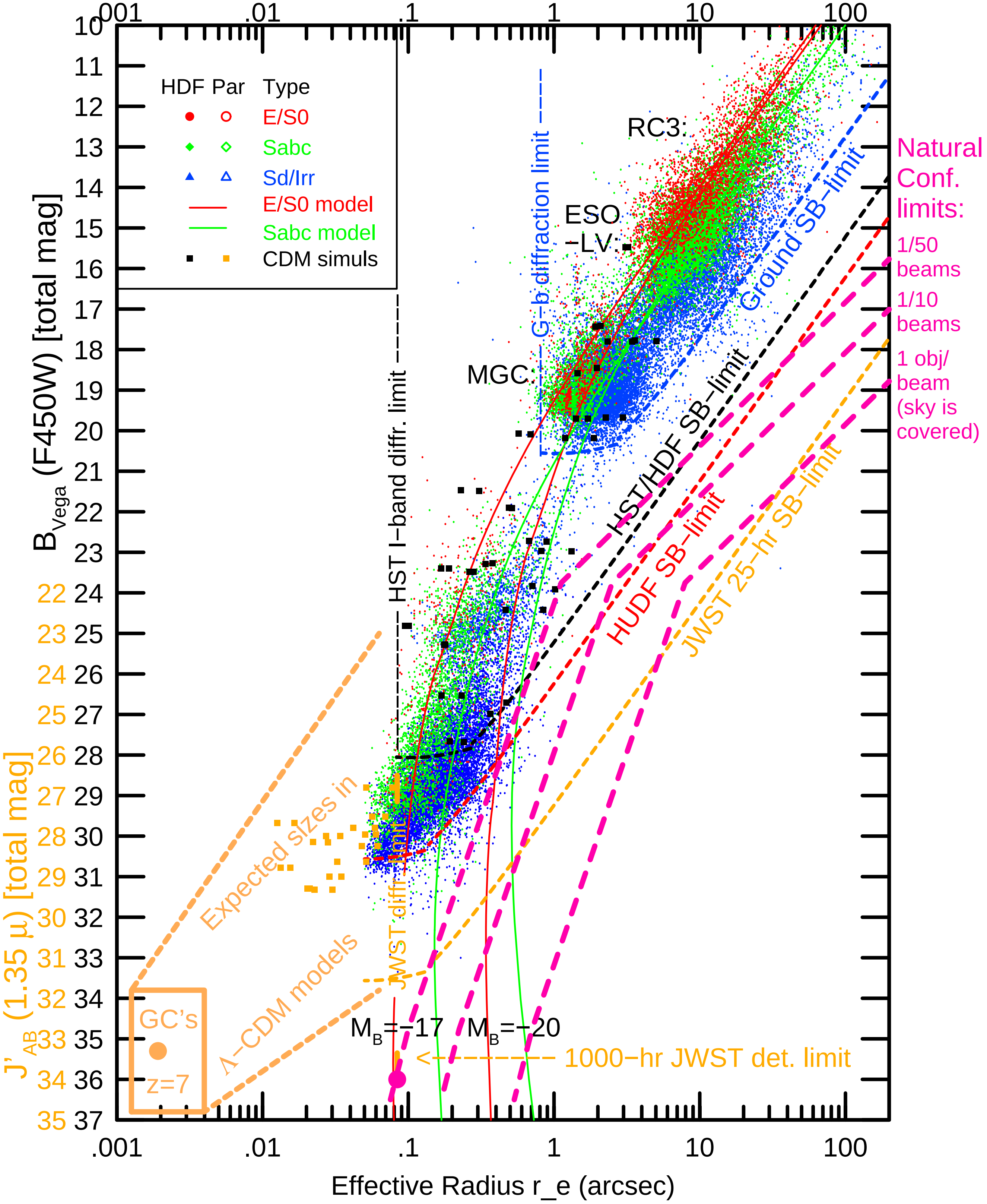


- HUDF galaxy counts (Cohen et al. 2006): expect an integral of $\gtrsim 2\times10^{6}$ galaxies/deg^{2} to AB=31.5 mag ($\simeq$ 1 nJy at optical wavelengths). JWST and SKA will see similar surface densities to $\simeq$1 and 10 nJy, resp.

- $\Rightarrow$ 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.

The natural confusion limit slowly sets in for AB≲25.



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"