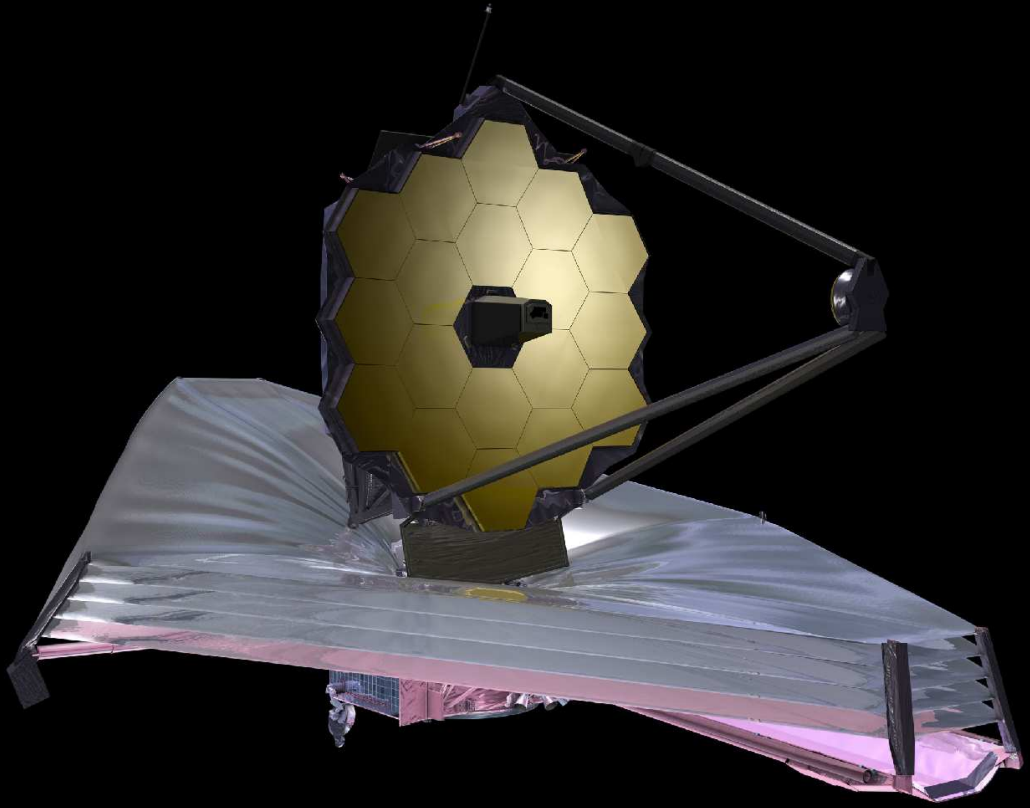
How can the Webb Space Telescope measure First Light, Reionization, & Galaxy Assembly: New Frontier after HST.

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

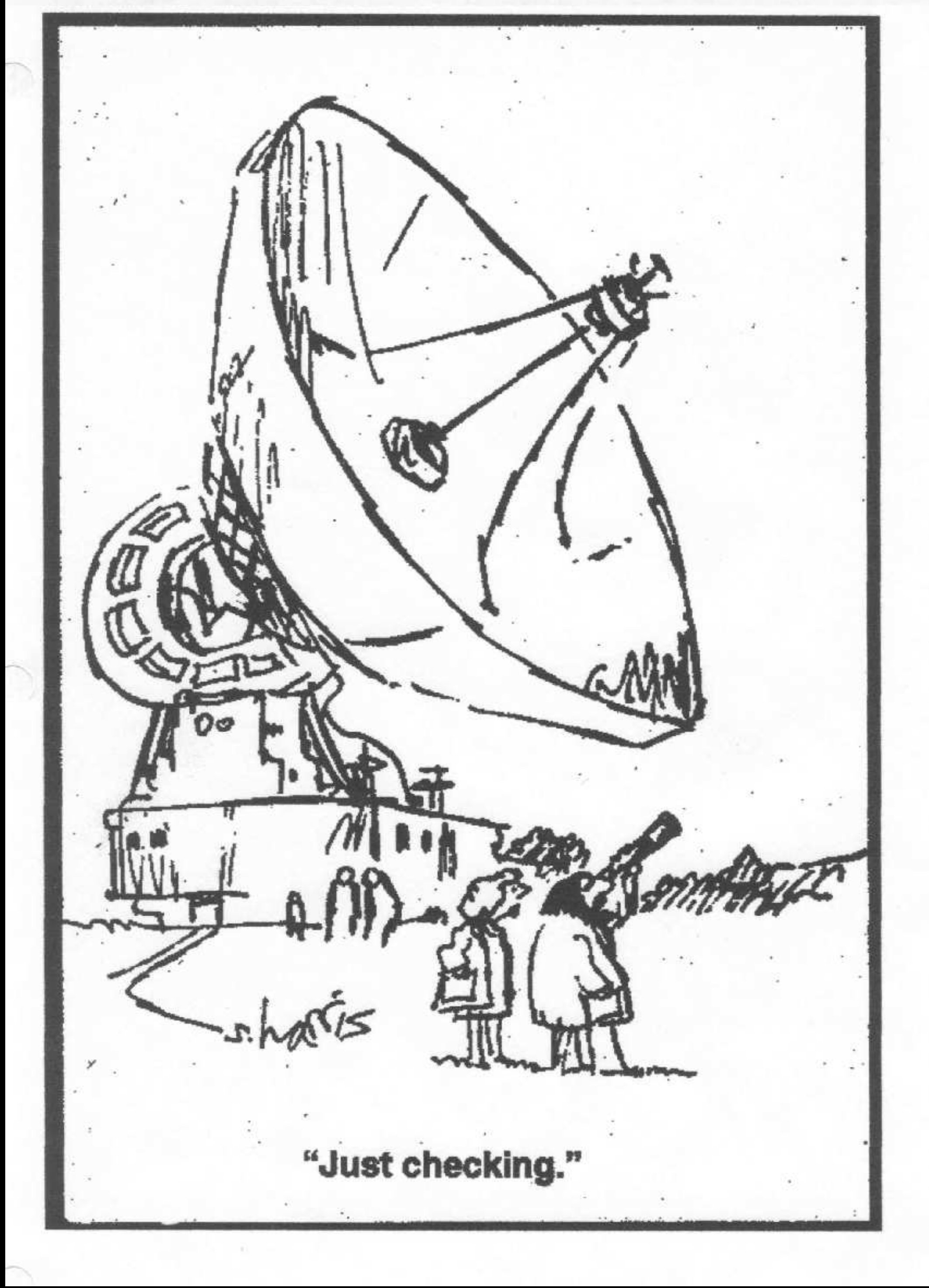
S. Cohen, R. Jansen (ASU), C. Conselice (UK), S. Driver, S. Wyithe (OZ), B. Frye (UofA), & H. Yan (U-MO)

+ ASU Grads: N. Hathi, H. Kim, M. Mechtley, R. Ryan, M. Rutkowski, B. Smith, & A. Straughn



Main Message: The LF($\gtrsim$10) and difference in telescope architecture drives how to best use lensing to find the most First Light objects at z$\gtrsim$10.

Lunch talk at the National Radio Astronomy Observatory, Socorro, NM (Tuesday, Mar 3, 2015)



HST and JWST changed the career of this radio astronomer ...

Outline: Strategies to Observe First Light with JWST: How can we best use Gravitational Lensing after 2018?

(1) JWST hardware to date, and aspects relevant to lensing.

(2) Hubble (Ultra)Deep & Frontier Fields to find z∼9–11 objects:
— Current limitations

(3) How can JWST best observe First Light using lensing?

• How many random Webb Deep Fields (WDFs) compared, to the best lensing targets?

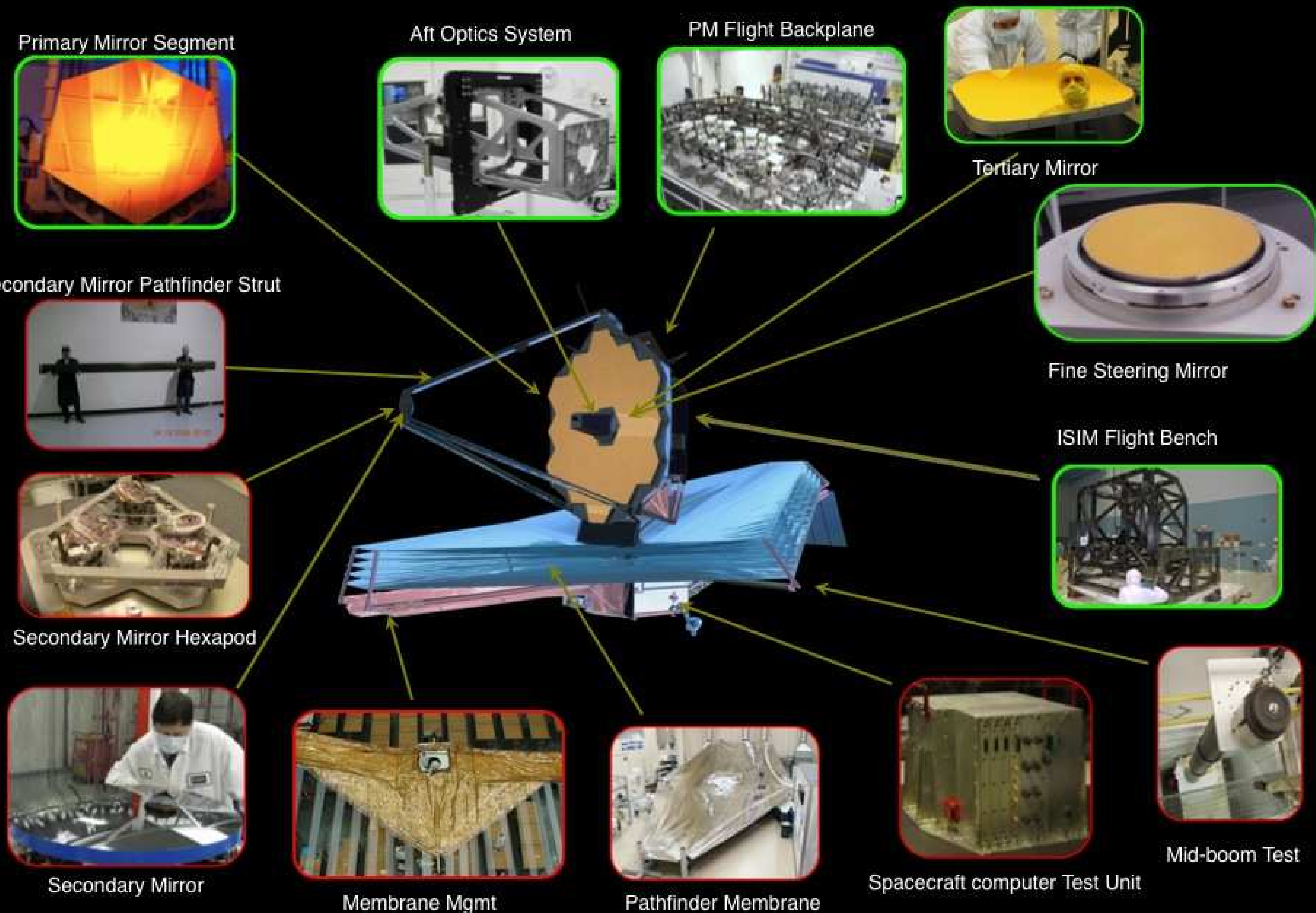
(4) Recommendations and Conclusions.

Sponsored by NASA/HST & JWST

Arizona State University

Talk is on: http://www.asu.edu/clas/hst/www/jwst/jwsttalks/nrao15_jwstfirstlight.pdf

JWST Hardware Status



Early 2015: $\gtrsim$98% of launch mass designed and built ($\gtrsim$65% weighed).

(1) JWST hardware to date, and how to best use it for high redshift lensing.

[LEFT]: Late summer 2014: 5-layer JWST kapton Sunshield done.

[RIGHT]: Nov. 2014: First JWST mirrors mounted onto support structure, using Engineering Demo mirrors — Flight mirrors to be mounted in 2015.

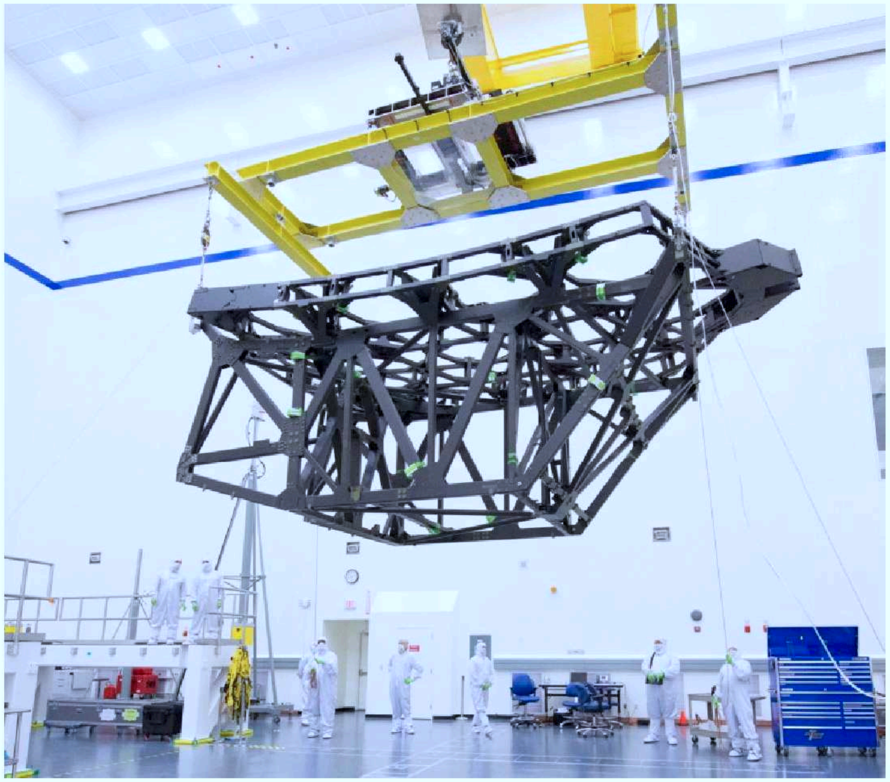
• Our Galaxy is a bright IR source at $\lambda \gtrsim 1$–5μm: In certain directions of sky, some straylight can hit secondary mirror via Sunshield: $\lesssim$40% of Zodi.

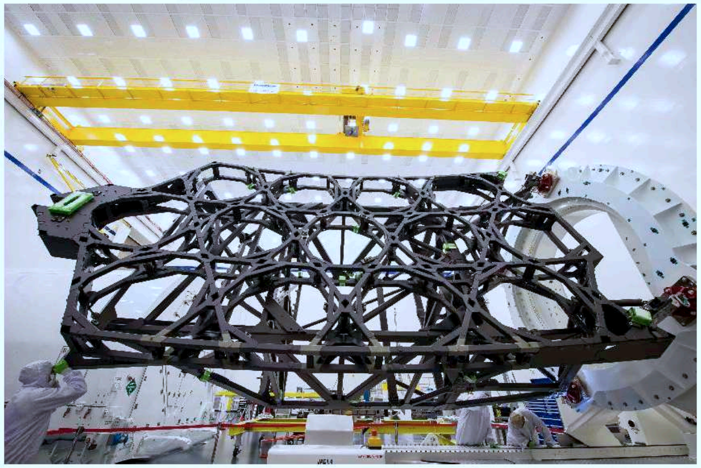
What does this mean for JWST lensing studies of First Light objects?

Backplane Support Frame, Center Section & Wings

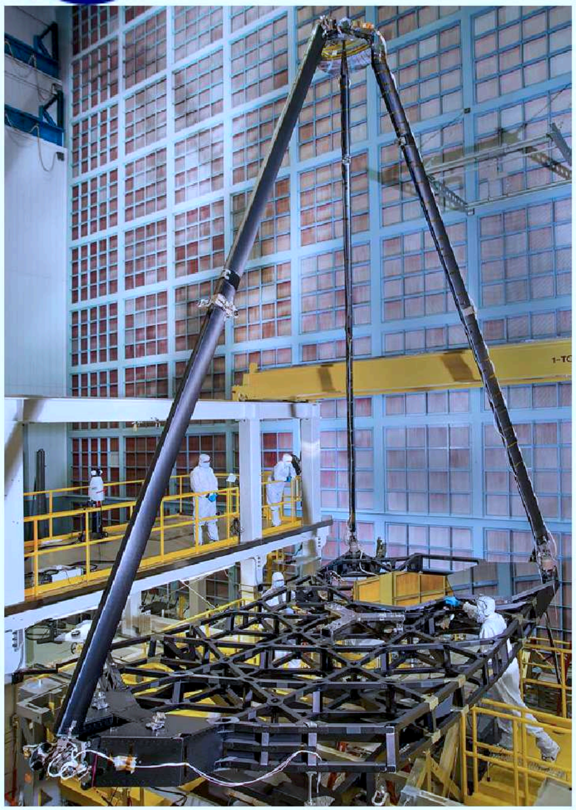
- Integrated BSF/Center Section and Wing completed

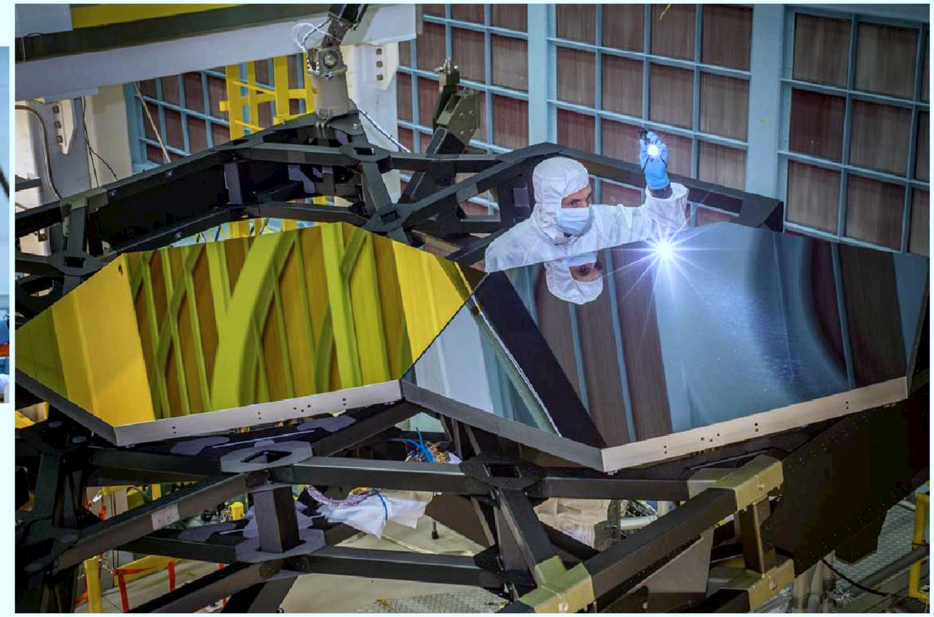
- All flight backplane components are at NGAS in Integration

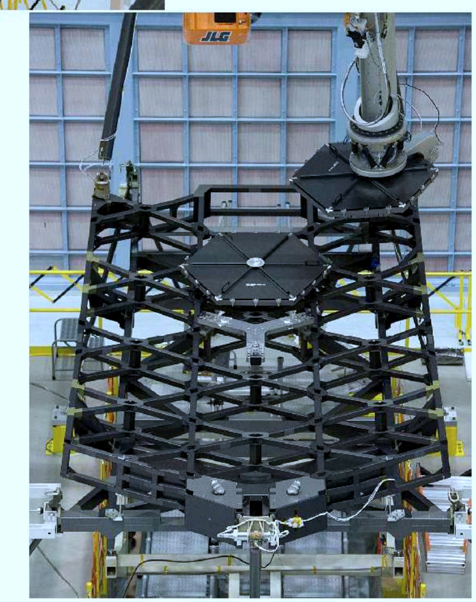


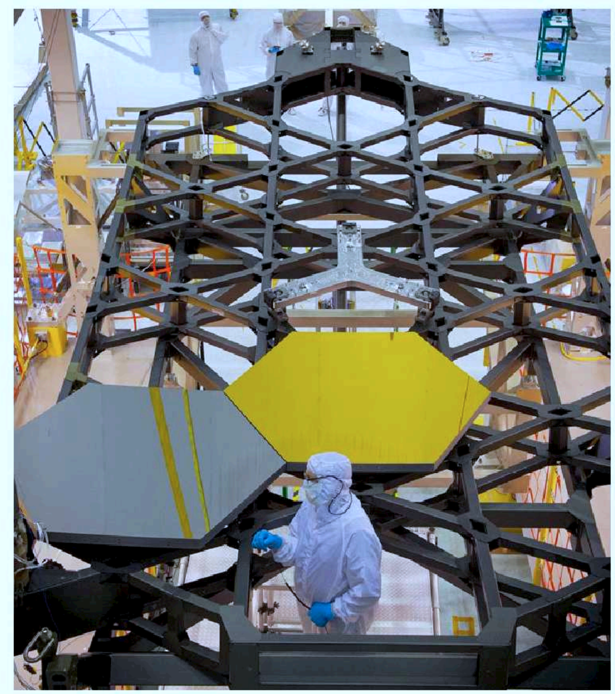


Telescope Pathfinder – Risk Reduction





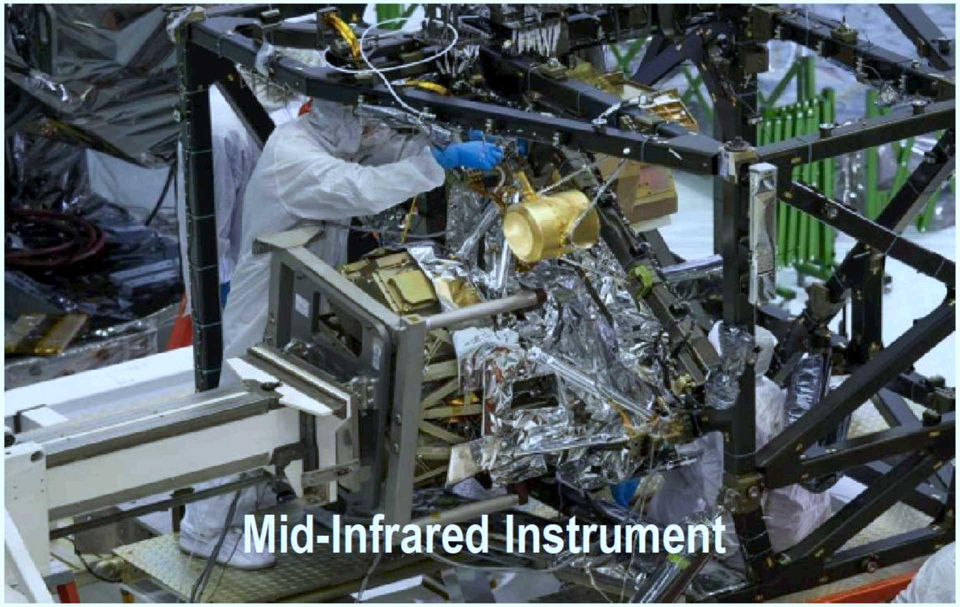




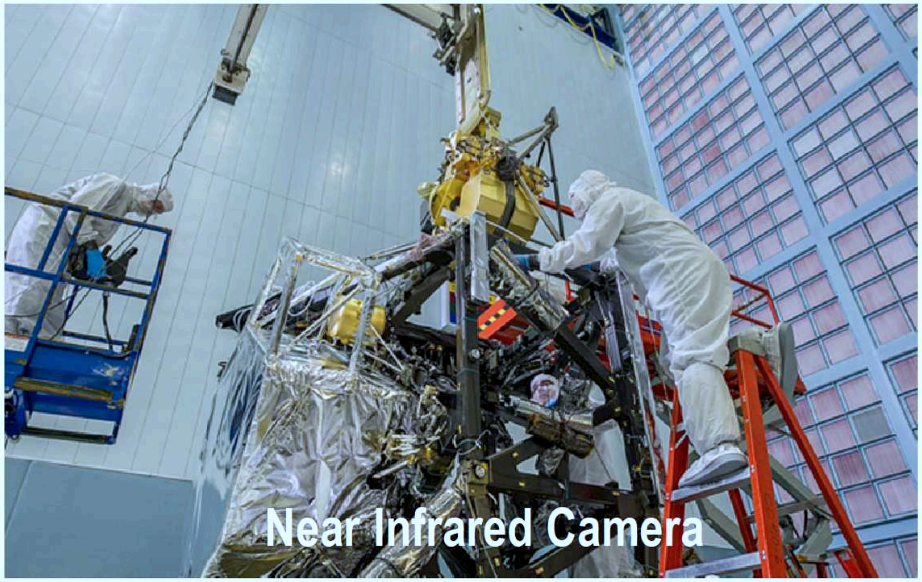
JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly

All Instruments Integrated

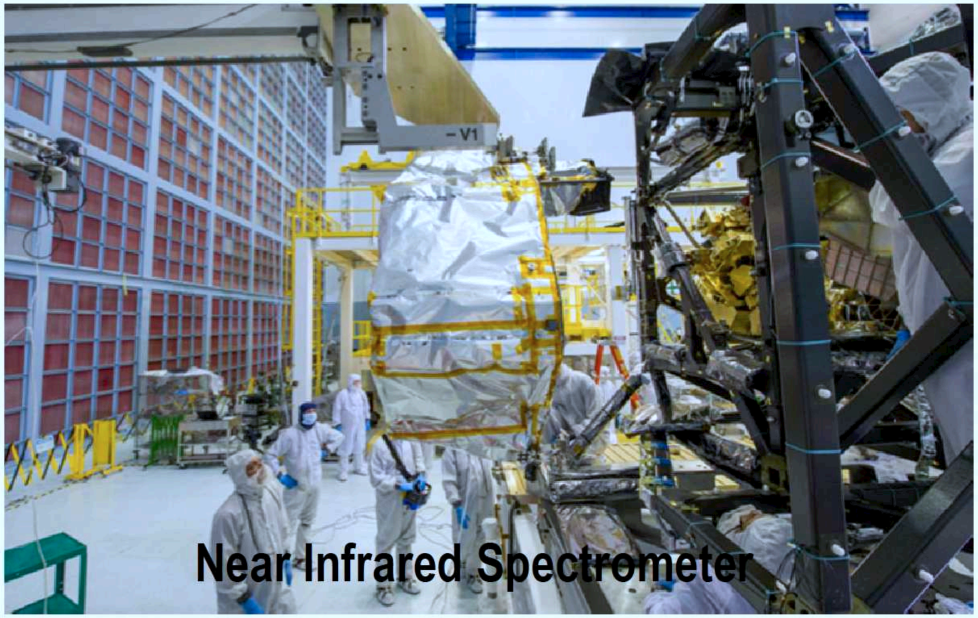
Fine Guidance Sensor



Mid-Infrared Instrument



Near Infrared Camera



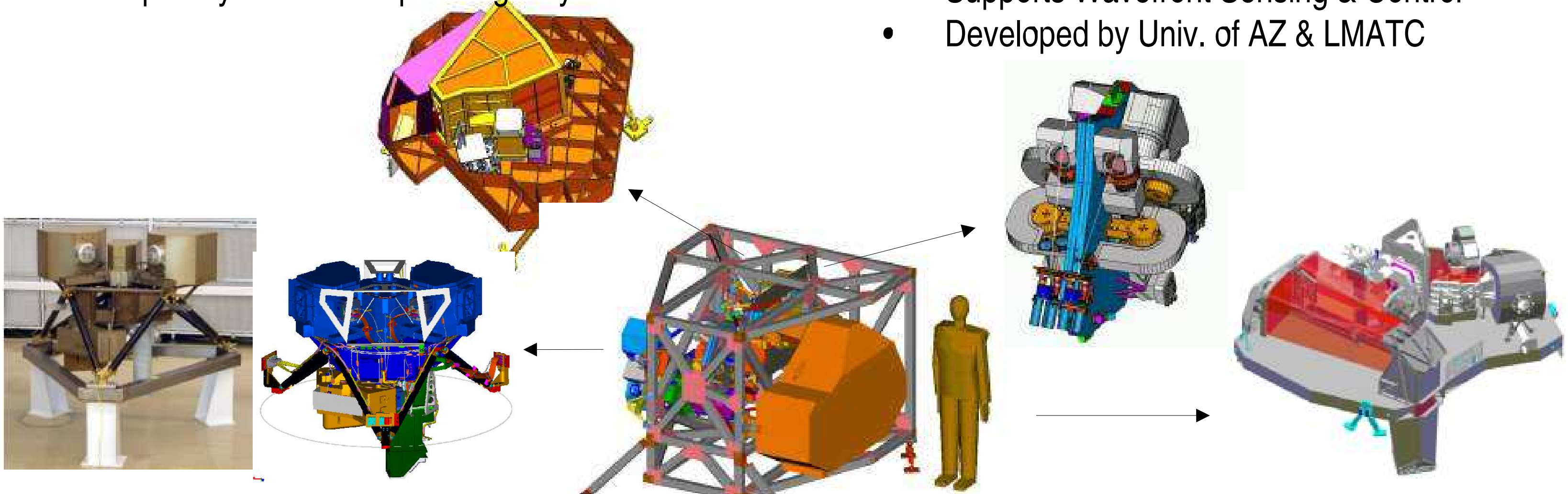
Near Infrared Spectrometer

(1c) JWST instrument update: US (UofA, JPL), ESA, & CSA.

Instrument Overview

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

Near Infra-Red Camera (NIRCam)
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC

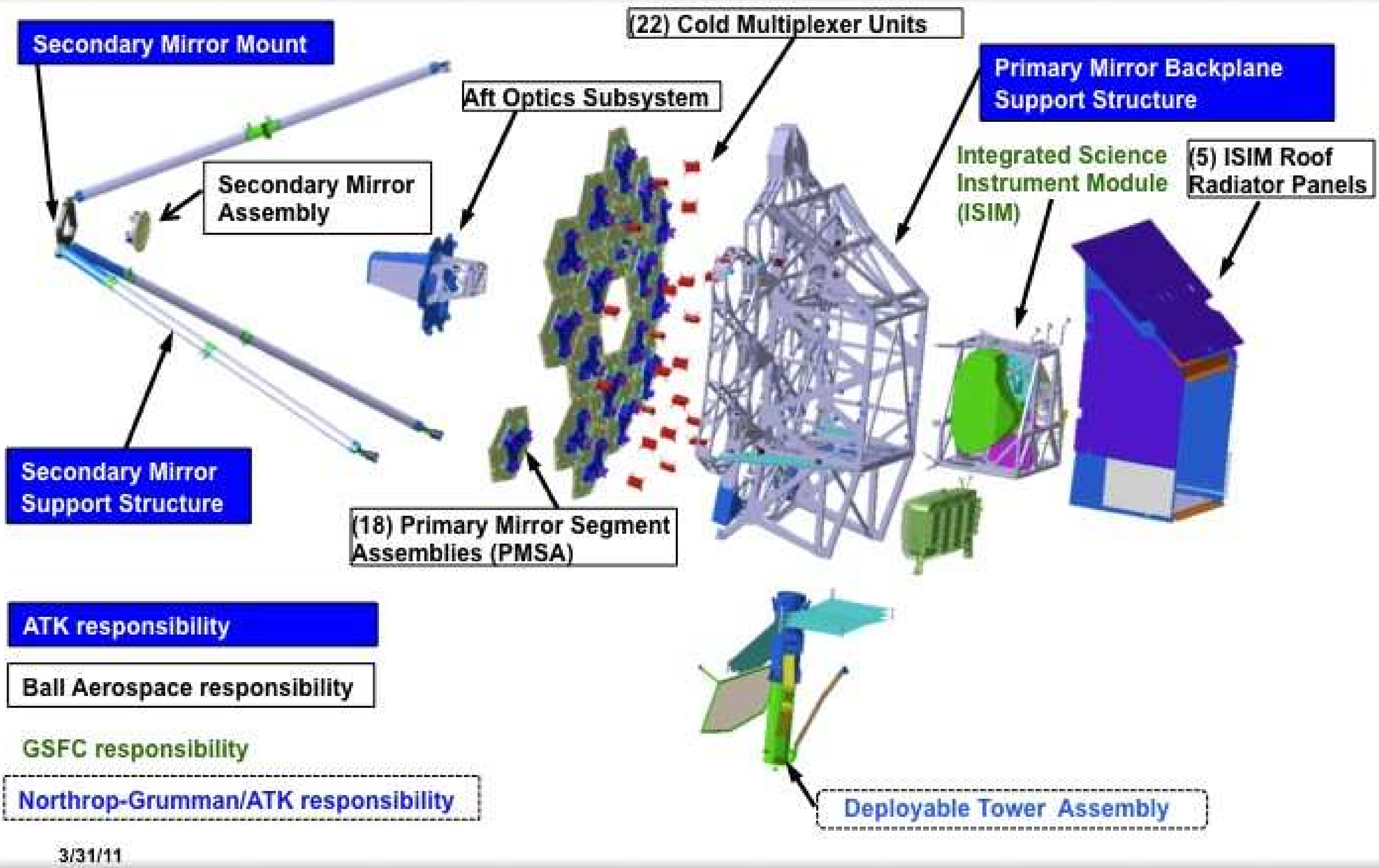


Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

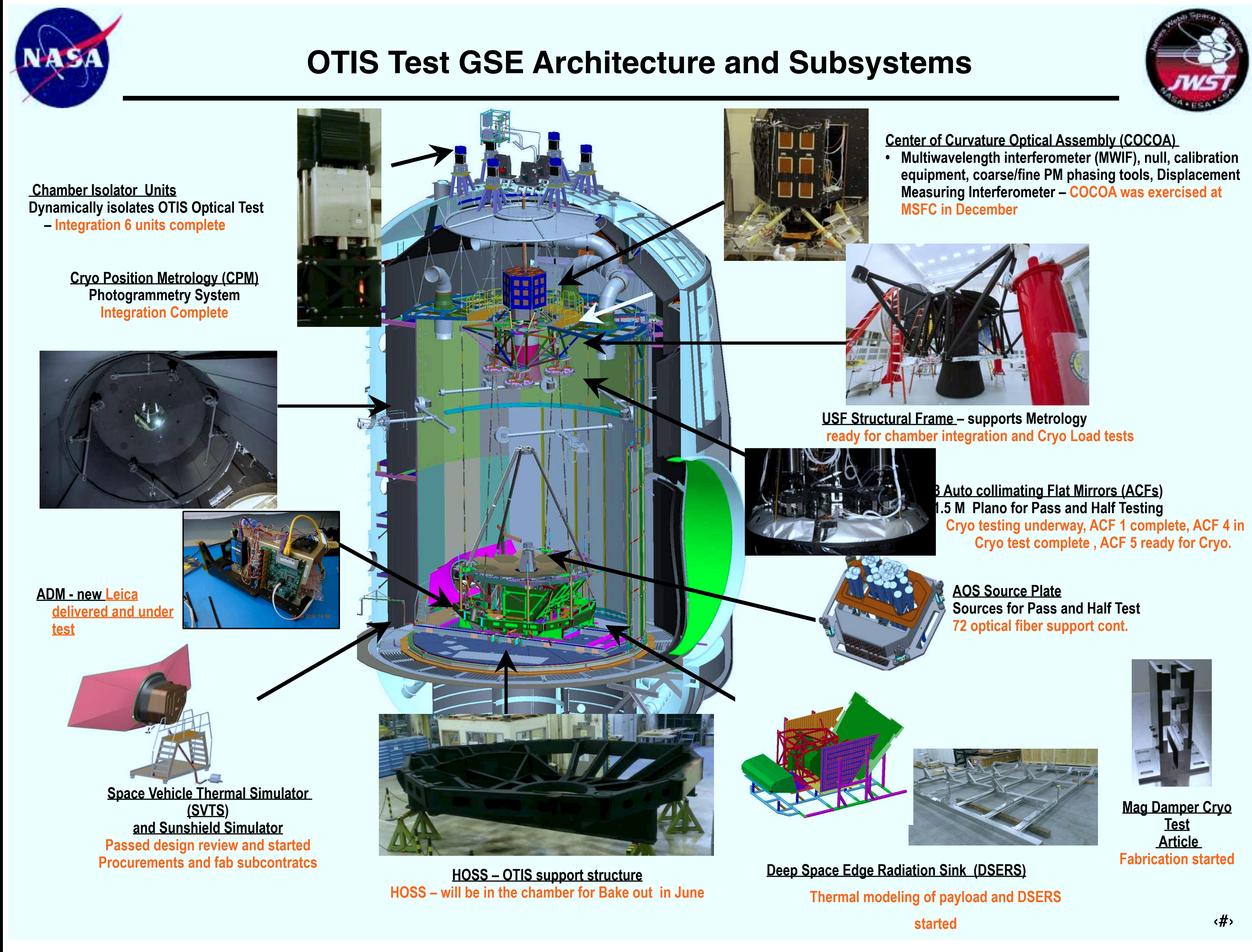
Near Infra-Red Spectrograph (NIRSpec)
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/GSFC Detector & Microshutter Subsystems

All delivered: MIRI 05/12; FGS 07/12; NIRCam 07/13, NIRSpec 9/13.

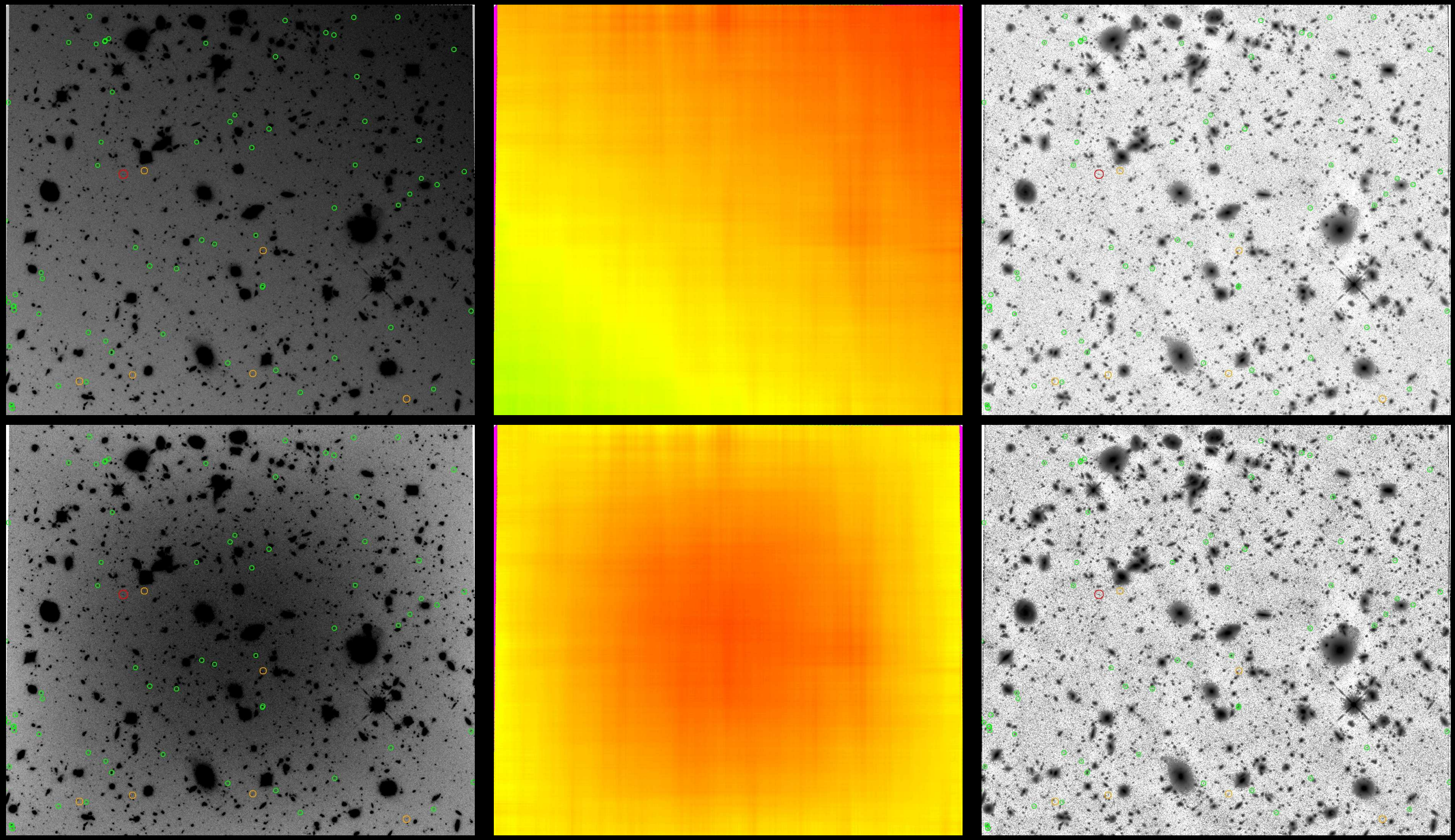
TELESCOPE ARCHITECTURE



2014–2016: Complete system integration at GSFC and Northrop.



World’s largest TV chamber OTIS: will test whole JWST in 2016–2017.



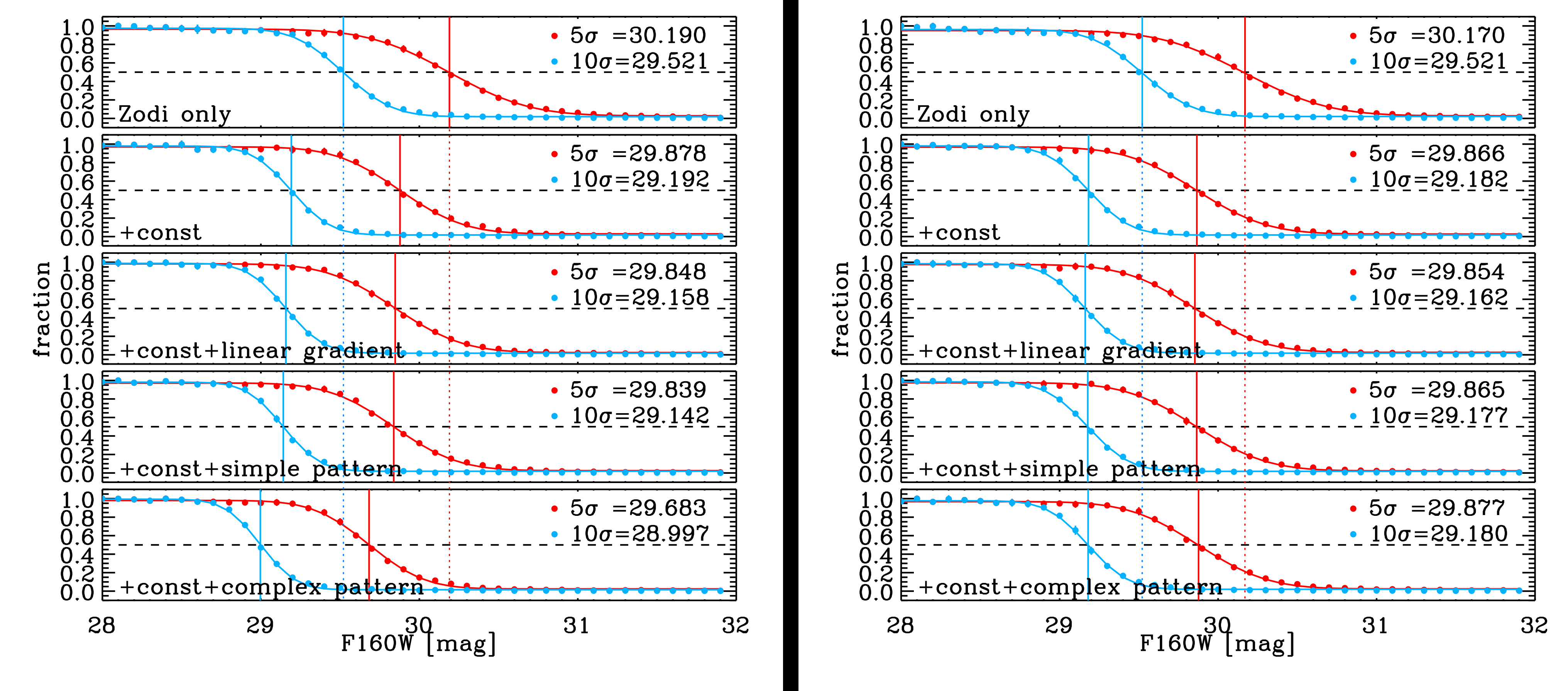
[TOP]: [Left] HUDF F160W image with *worst case* (95% of Zodi) rogue-path amplitude imposed ± a 4% *linear gradient* from corner-to-corner.

[Middle]: Best fit to sky-background with R. Jansen's "rjbgfit.pro".

[Right]: HUDF image from left with best-fit sky-background subtracted.

[BOTTOM]: Same as top row, but with a *single-component simple 2D pattern* superimposed, modeled and removed, respectively.

- If JWST rogue-path straylight has slight or complex gradients, we must carefully plan JWST imaging of lensing clusters with strong ICL.



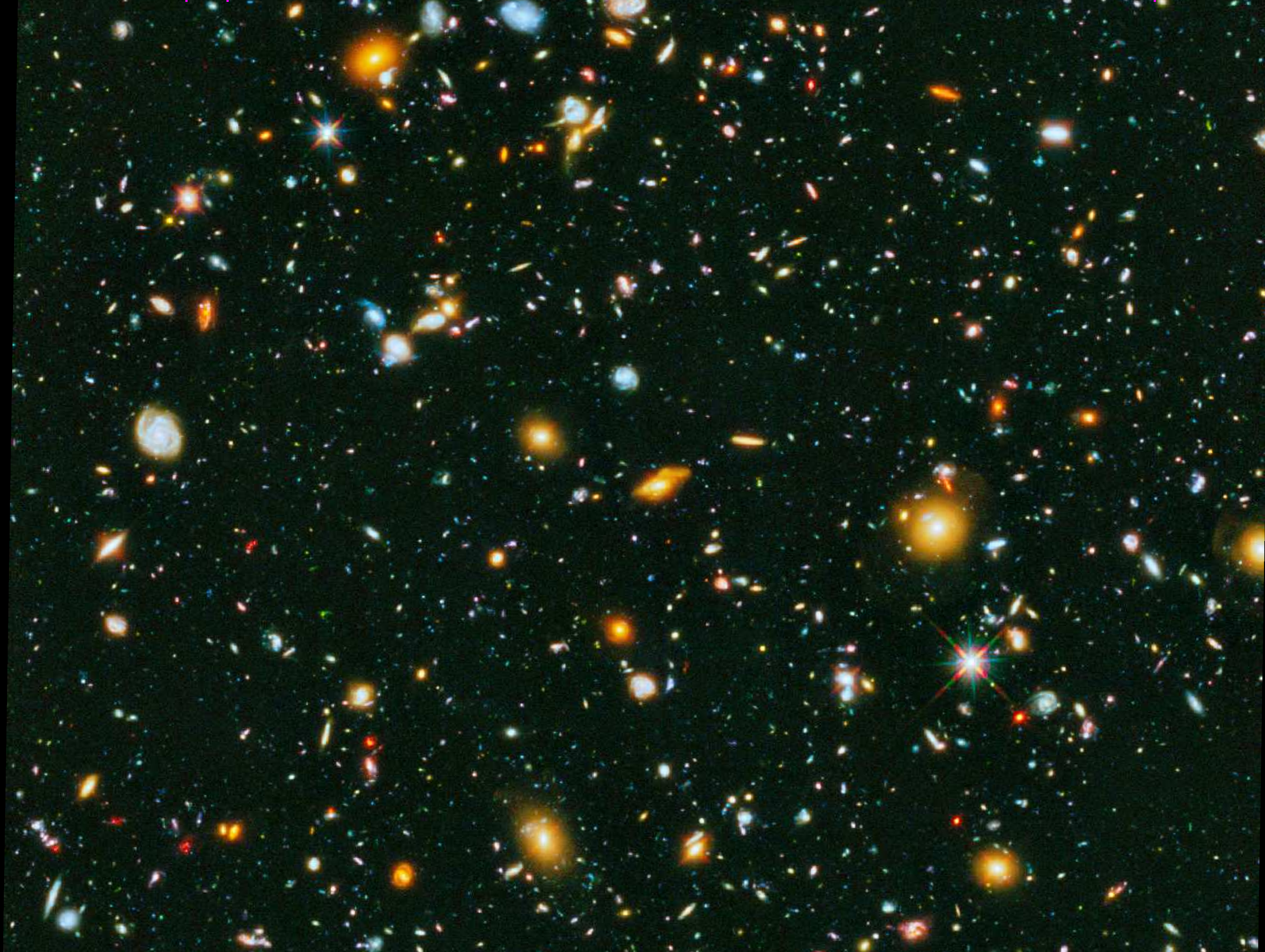
[LEFT]: Completeness tests in HUDF F160W image *before* imposing on top of Zodi (=22.70 H-mag arcsec^{-2}; Petro 2001) [2nd–5th row]: *Constant 95% of Zodi amplitude*; + *a ±4% linear gradient*; or *simple 2D pattern of ±4%*; or *a more complex pattern*.

[RIGHT]: Same as left *after* best fit to + removal of image sky-background.

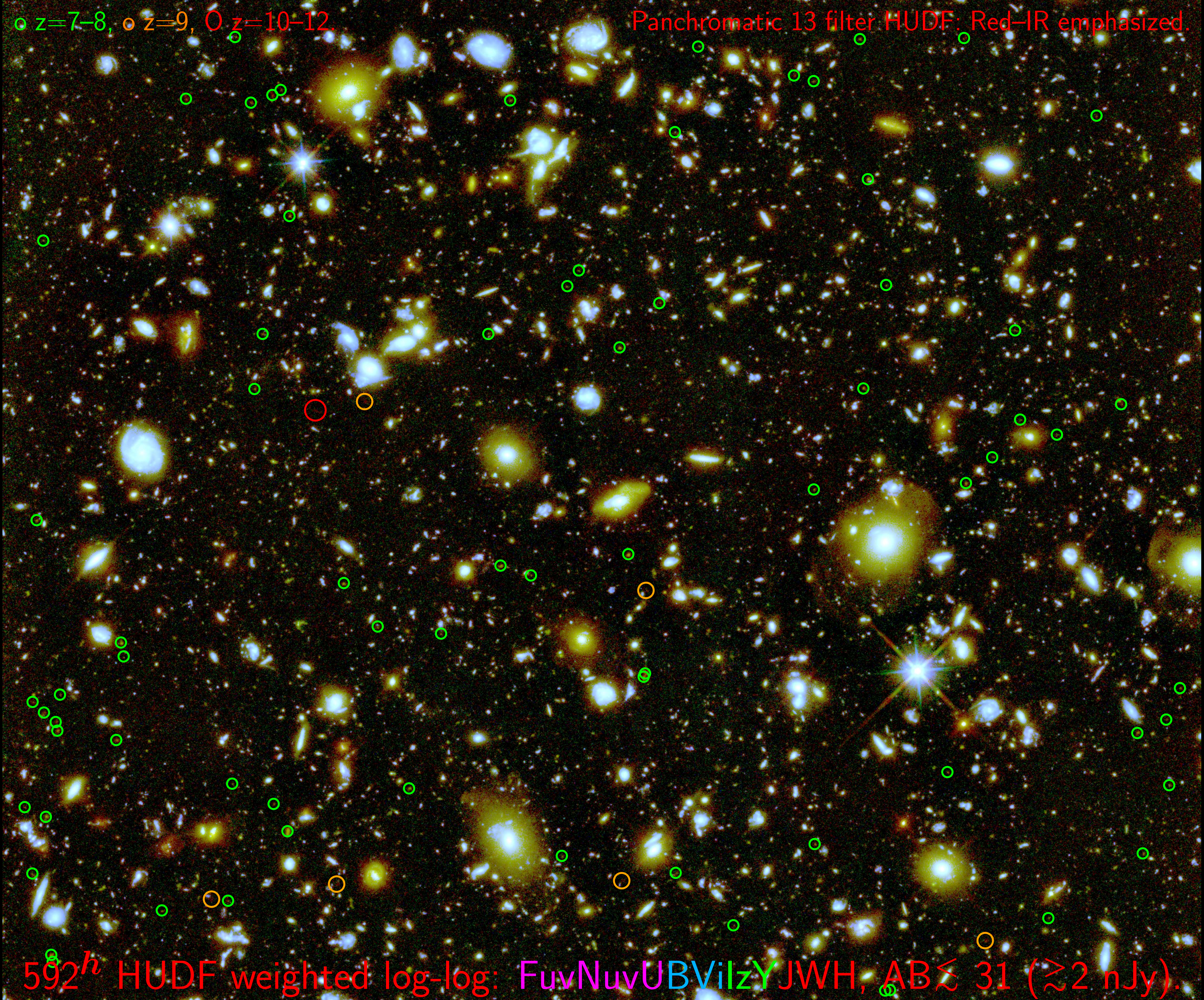
Red and blue lines: 50% 5-σ and 10-σ AB-completeness limits, resp.

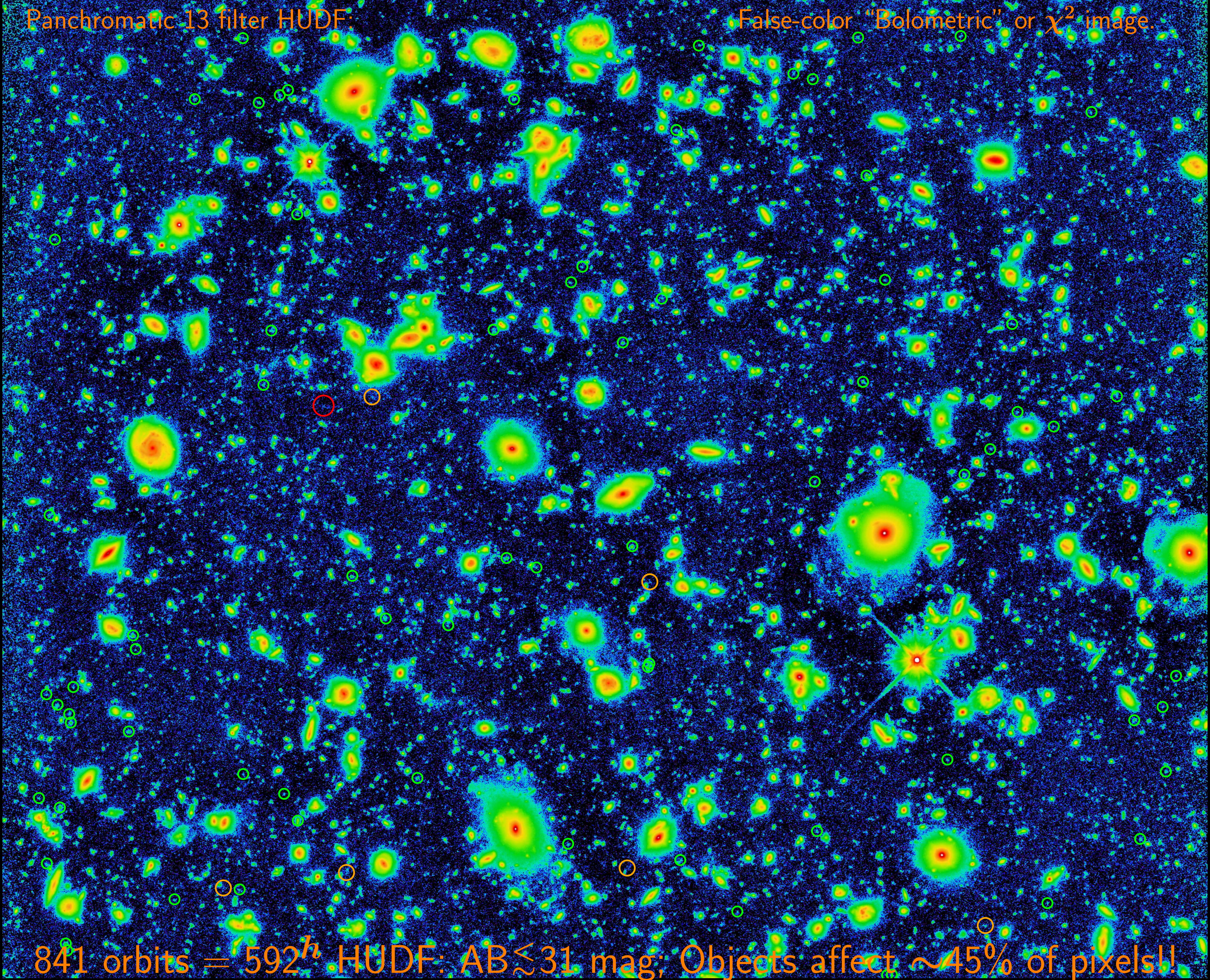
• Simple low-frequency rogue-path gradients can be removed from "random" deep fields, without much extra loss in sensitivity. Clusters: TBD.

The HST-unique part for JWST: Panchromatic 13 filter HUDF: UV–Blue emphasized.

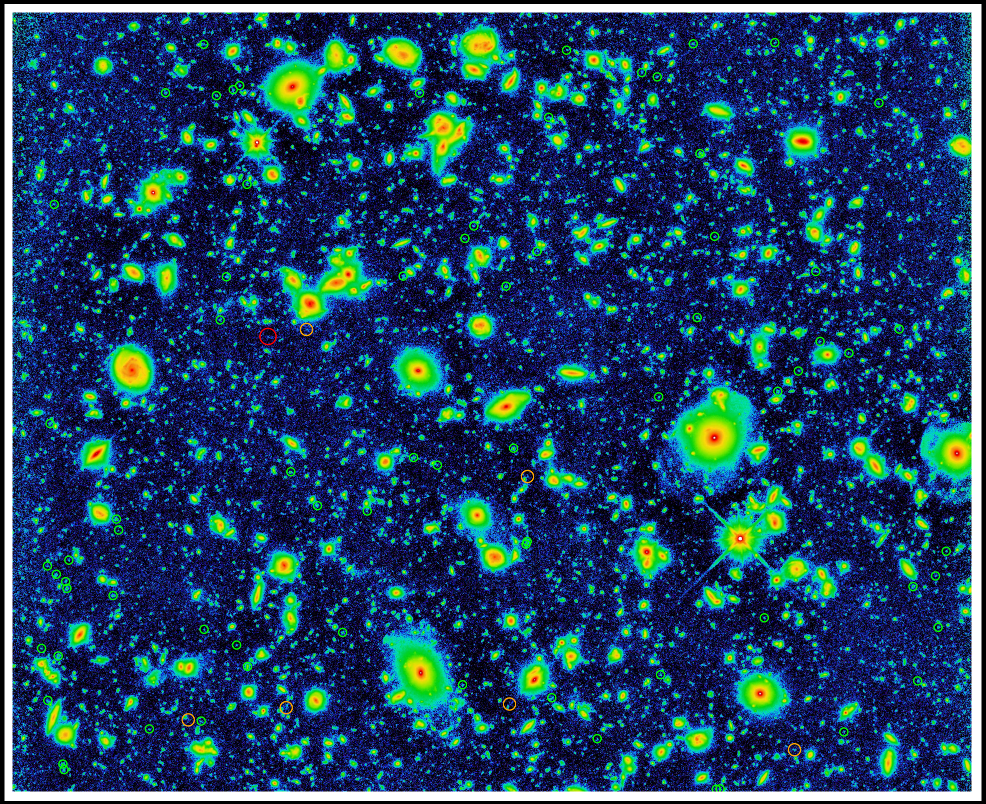


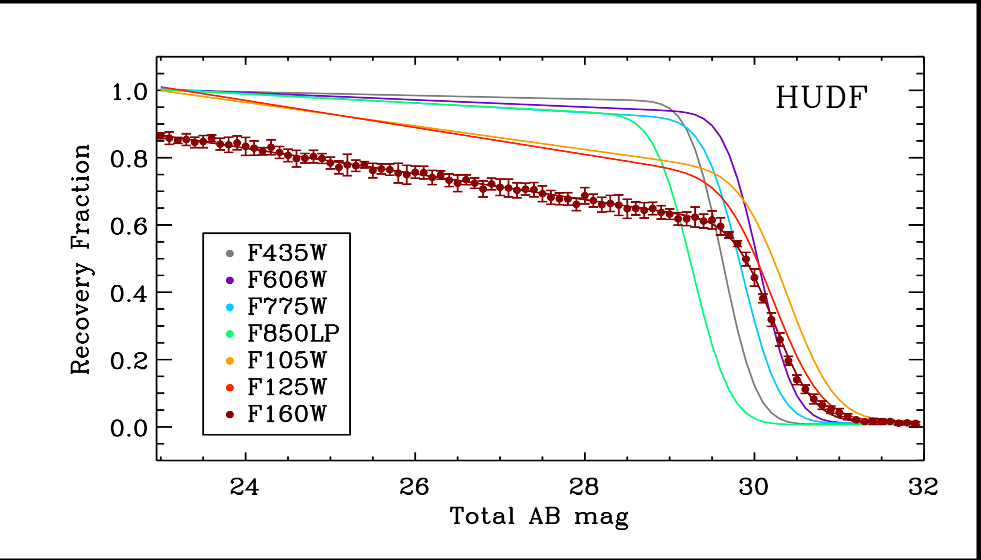
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$28–31 ($\gtrsim$2 nJy).


o z=7–8, o z=9, O z=10–12.
Panchromatic 13 filter HUDF: Red–IR emphasized.
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$ 31 ($\gtrsim$2 nJy).


Panchromatic 13 filter HUDF:
False-color "Bolometric" or χ^2 image.
841 orbits = 592^h HUDF: AB$\lesssim$31 mag; Objects affect ~45% of pixels!!

(2) Current limitations: Wavelength-dependent Deep-Field Completeness limits





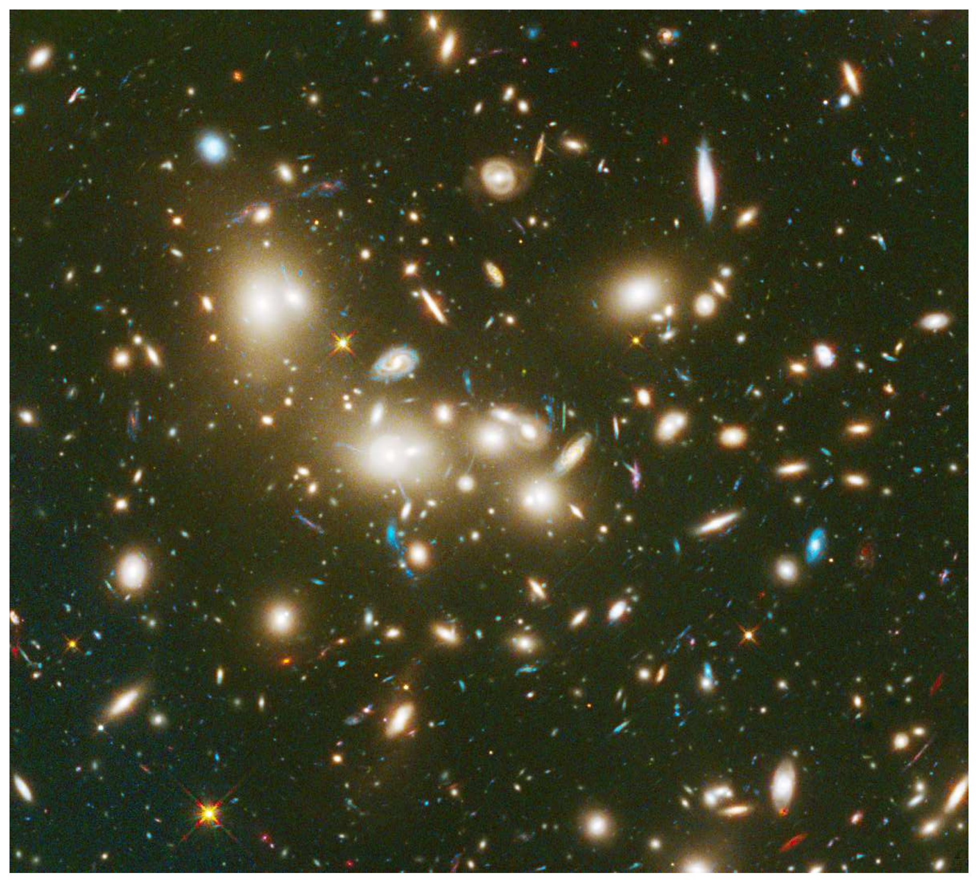
[LEFT]: HUDF bolometric or χ^2-image (false-color log-log stretch): weighted average of 841 orbits (592 hr) in 13 filters reaching AB$\lesssim$31 mag.

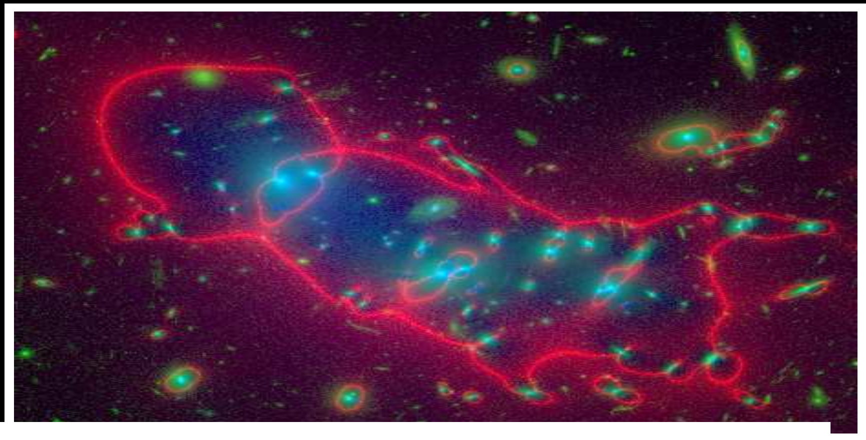
- Faint object wings cover ∼45% of all pixels (Koekemoer et al. 2013)!

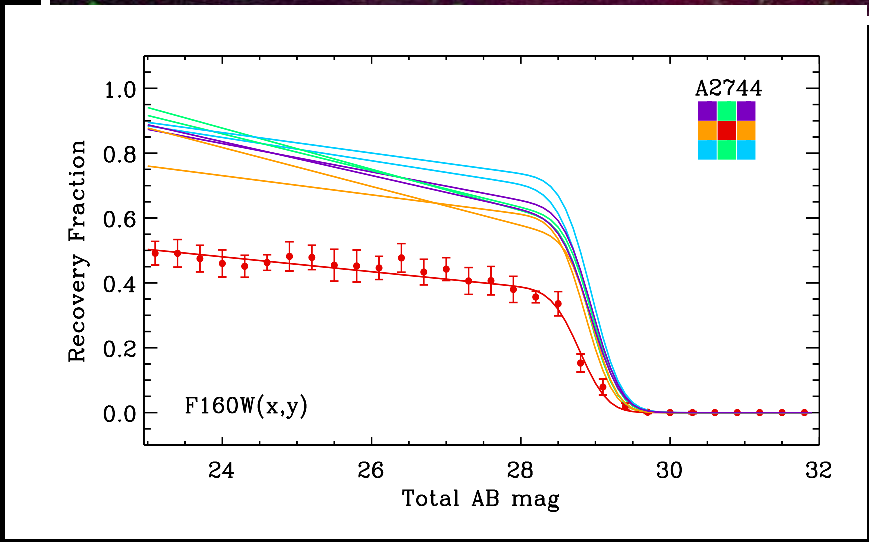
[RIGHT]: HUDF *wavelength-dependent* completeness functions from Monte Carlo (MC) insertions:

- Faint-end recovery fractions drop to ∼60% at longer wavelengths.
- Even the bright-end at H$\simeq$23 AB-mag is ∼15% incomplete!

(1) Cluster-Position Dependence of Deep-Field Completeness limits







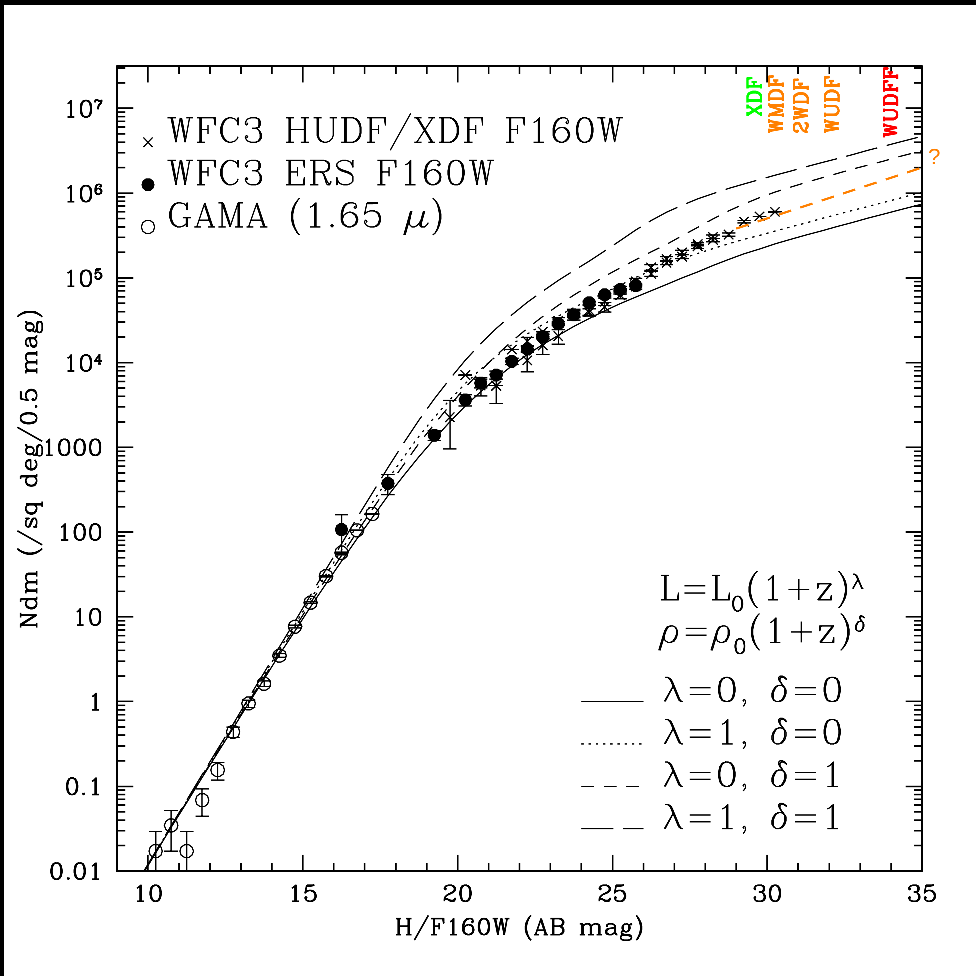
[LEFT]: HFF cluster A2744 in: F435W+F606W, F814W+F105W, F125W+F140W+F160W.

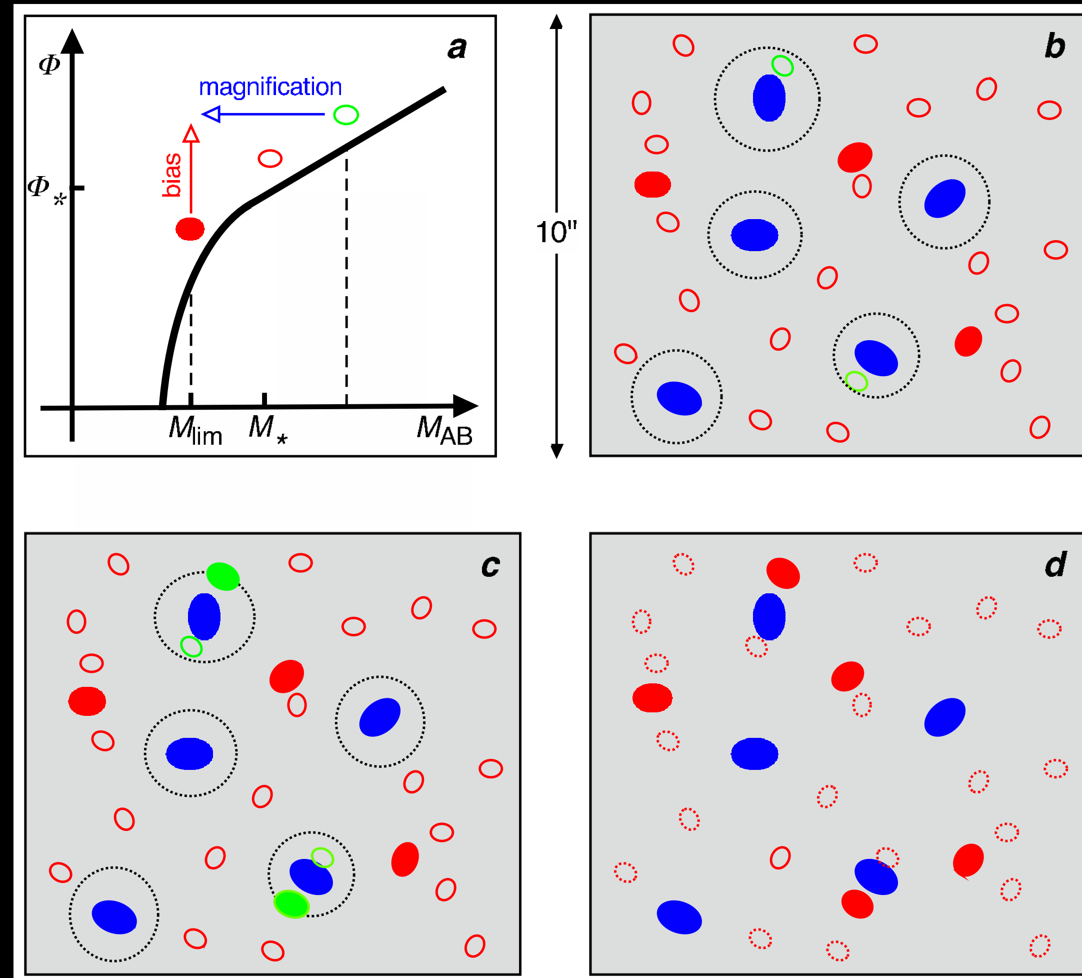
[RIGHT, TOP]: Lensing map for A2744 from Ebeling et al. (2014) [see updated models this Workshop].

[RIGHT BOTTOM]: *Position-dependent* completeness in a 3×3 MC-grid.

- Faint-end lensing sample *incompleteness* increases from ∼10–40% in the cluster outskirts/corners to ∼50–65% in cluster center [but see MUSE results!].
- Even bright-end of the cluster image is incomplete at the 5–50% level.

(3) How can JWST best observe First Light using lensing?





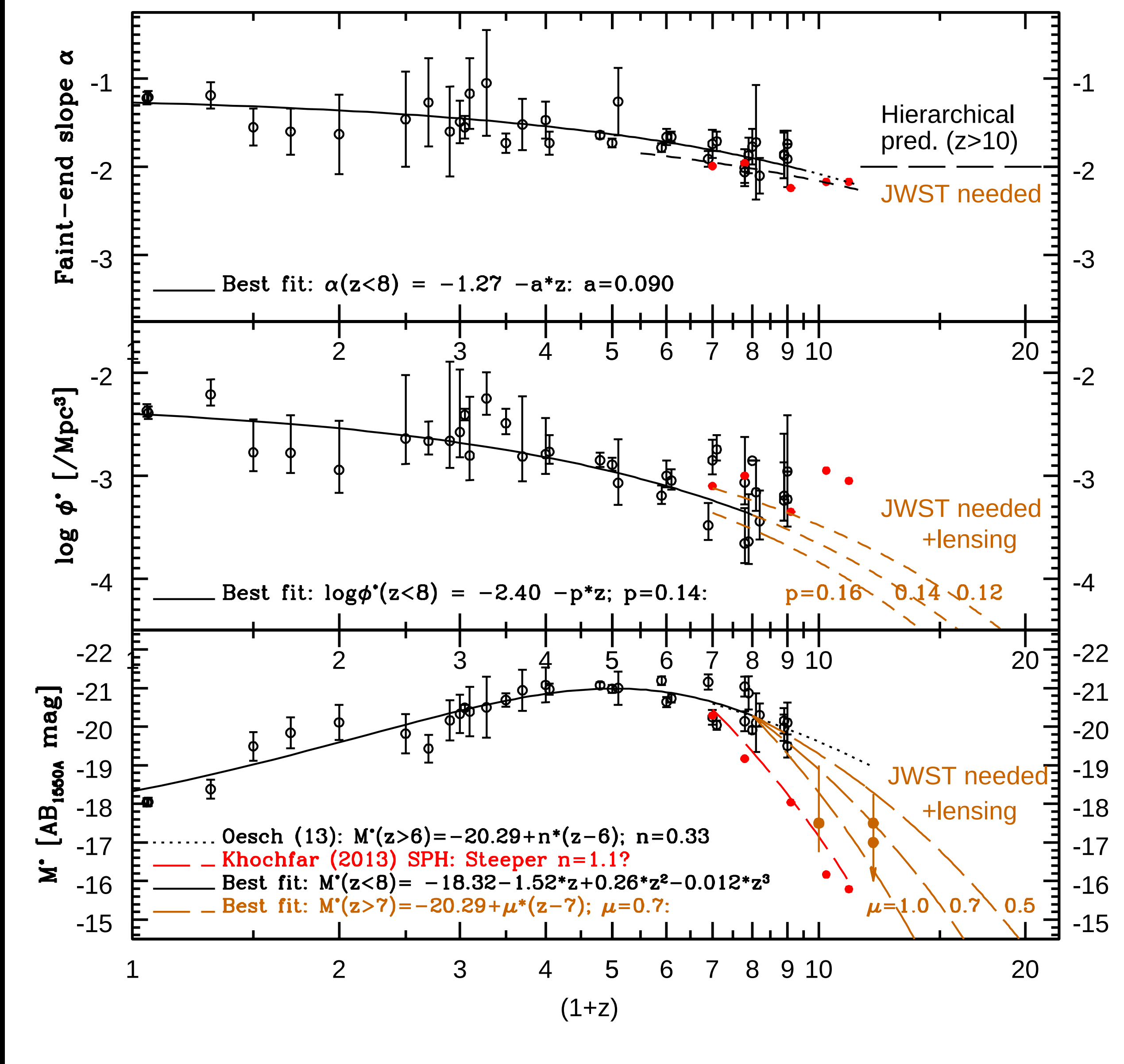
1.6μm counts (Windhorst+2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

- Faint-end near-IR count-slope≃0.16±0.02 dex/mag ⟺

Faint-end LF-slope $\alpha(z_{med} \sim 1.6) \simeq -1.4 \Rightarrow$ reach $M_{AB} \simeq -14$ mag.

- 800-hr WUDF can see AB≲32 objects: $M_{AB} \simeq -15$ (LMCs) at z≃11.

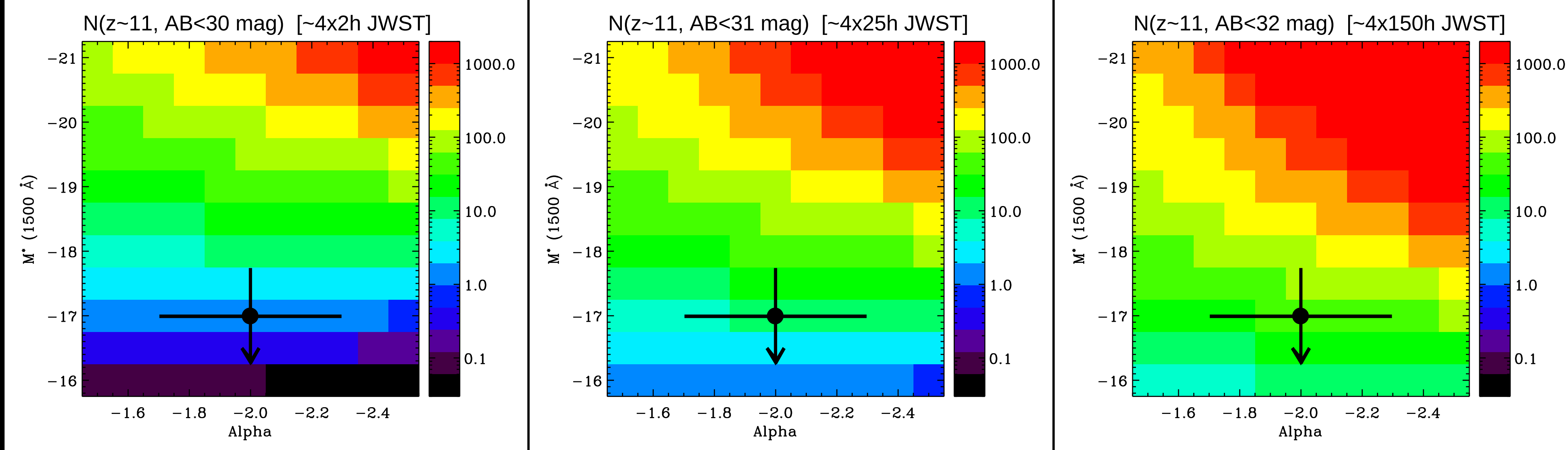
- Lensing will change the landscape for JWST observing strategies (WUDFF).



Evolution of Schechter UV-LF: faint-end LF-slope α(z), Φ^* (z) & M^* (z):

- For JWST z$\gtrsim$8, expect $\alpha\lesssim$–2.0; $\Phi^* \lesssim 10^{-3}$ (Mpc^{-3}) (Bouwens$^+$ 14).
- HUDF: Characteristic M^* may drop below –18 or –17.5 mag at z$\gtrsim$10.

⇒ Will have significant consequences for JWST survey strategy.



What do the 6 possible z≃9 and single z≳10 HUDF candidate mean?

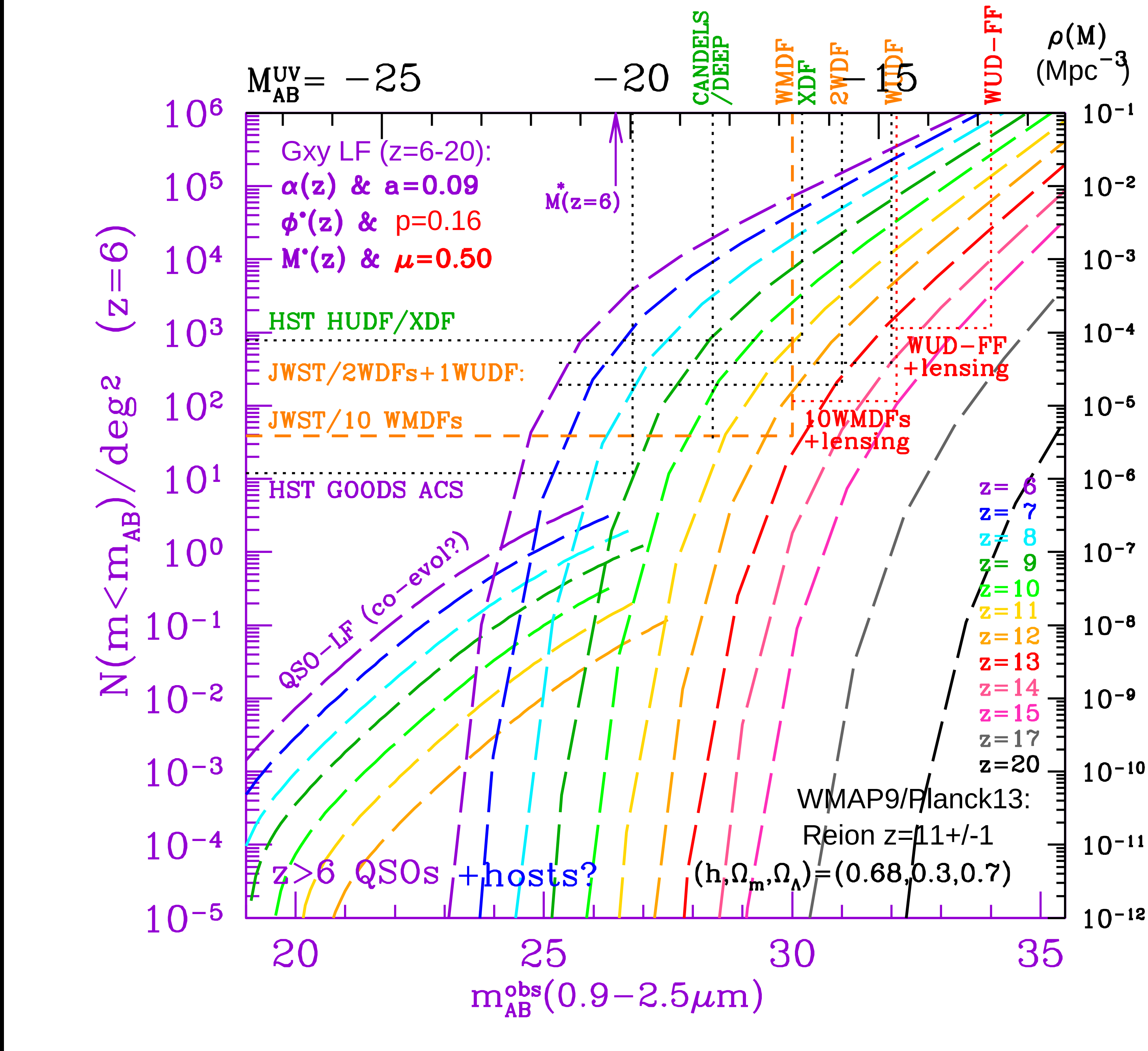
Integrate Schechter LFs with α(z), Φ^* (z) and M^* (z): ≲45% sky-coverage by AB≲30 objects (Koekemoer+13). Cosmic Variance ≳30%.

For any α(z≳10), implies M^* (z≳10)≳–18 or Φ^* ≲$10^{-3.5}$, so plan:

- (1) [Left] Webb "Medium-Deep" Fields (**WMDF**) (10×4×2h GTO):
Expect few z≃10–12 objects to AB≲30 mag, so plan lensing targets.

- (2) [Middle] Webb Deep Field (**WDF**) (4×25h 7-filt NIRCam GTO):
Expect 8–25 objects at z≃10–12 to AB≲31 mag.

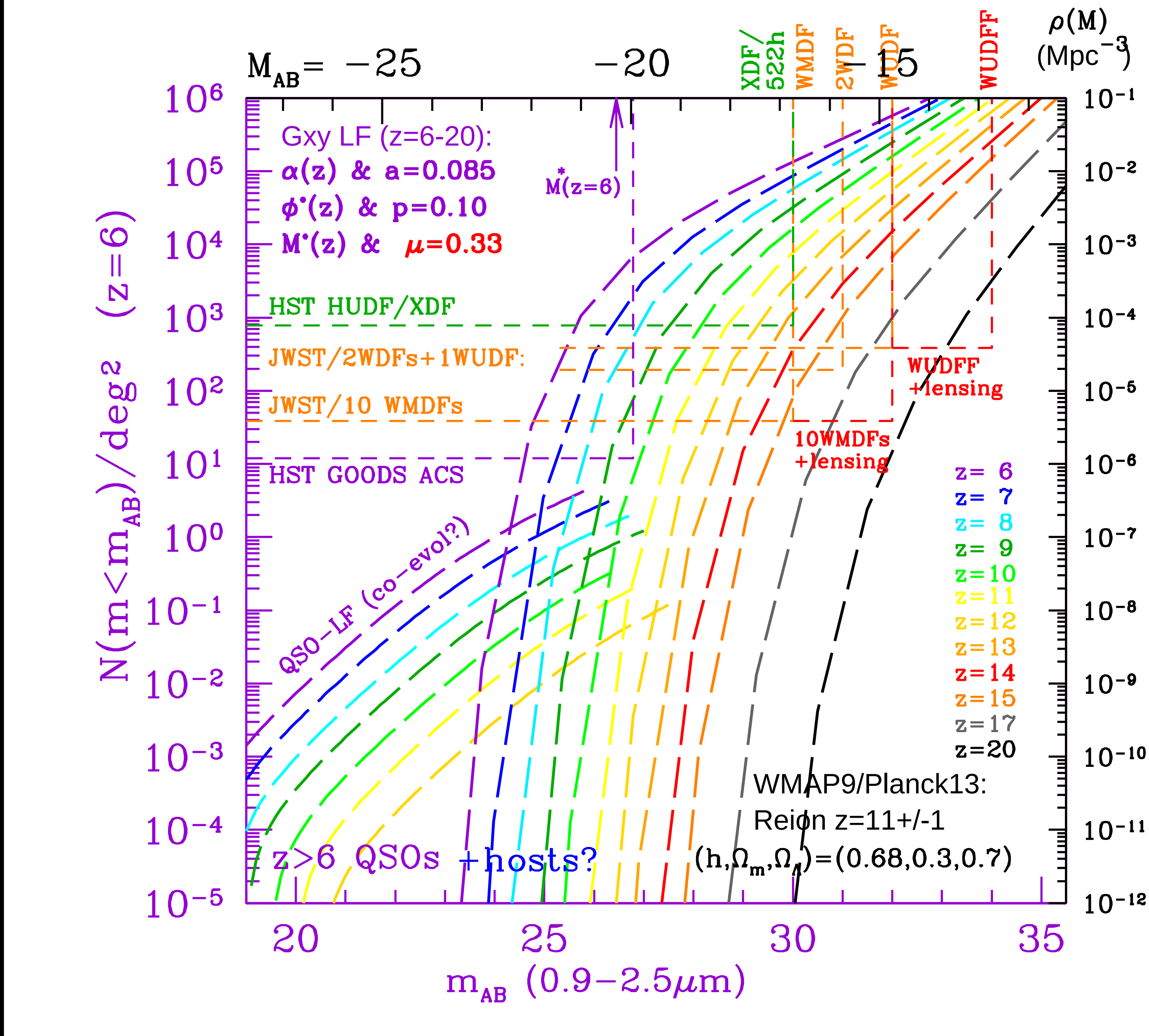
- (3) [Right] Webb UltraDeep Field (**WUDF**) (4×150h; NIRCam DD?]:
Expect 30–90 objects to AB≲32 mag, many more if lensing targets.



Schechter LF (6≲z≲20) with best-fit α(z), Φ^* (z), M^* (z) & μ=0.50.

Area/Sensitivity for: HUDF/XDF, **10 WMDFs**, 2 WDFs, & 1 WUDF.

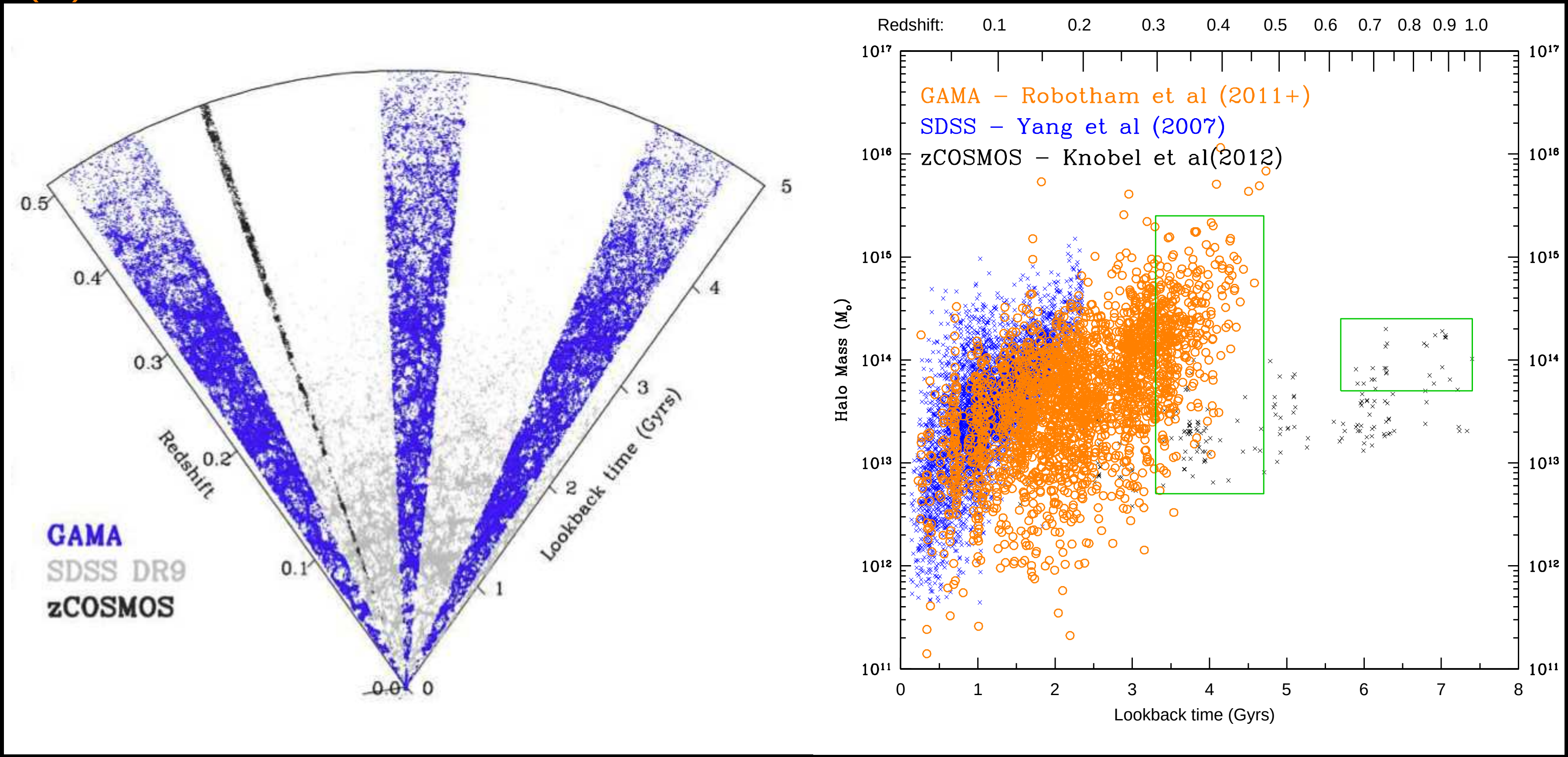
- Will need lensing targets for WMDF–WUDFF to see z≃12–15 objects.



Same as p. 15, but optimistic M^* (z) drop: μ=0.33 (Oesch et al. 2013).

• If so, far more 9≲z≲12 objects expected in XDF, even though N(6≲z≲8) remains the same ⟺ M^* (z≃11) fainter than −18±0.5 mag?

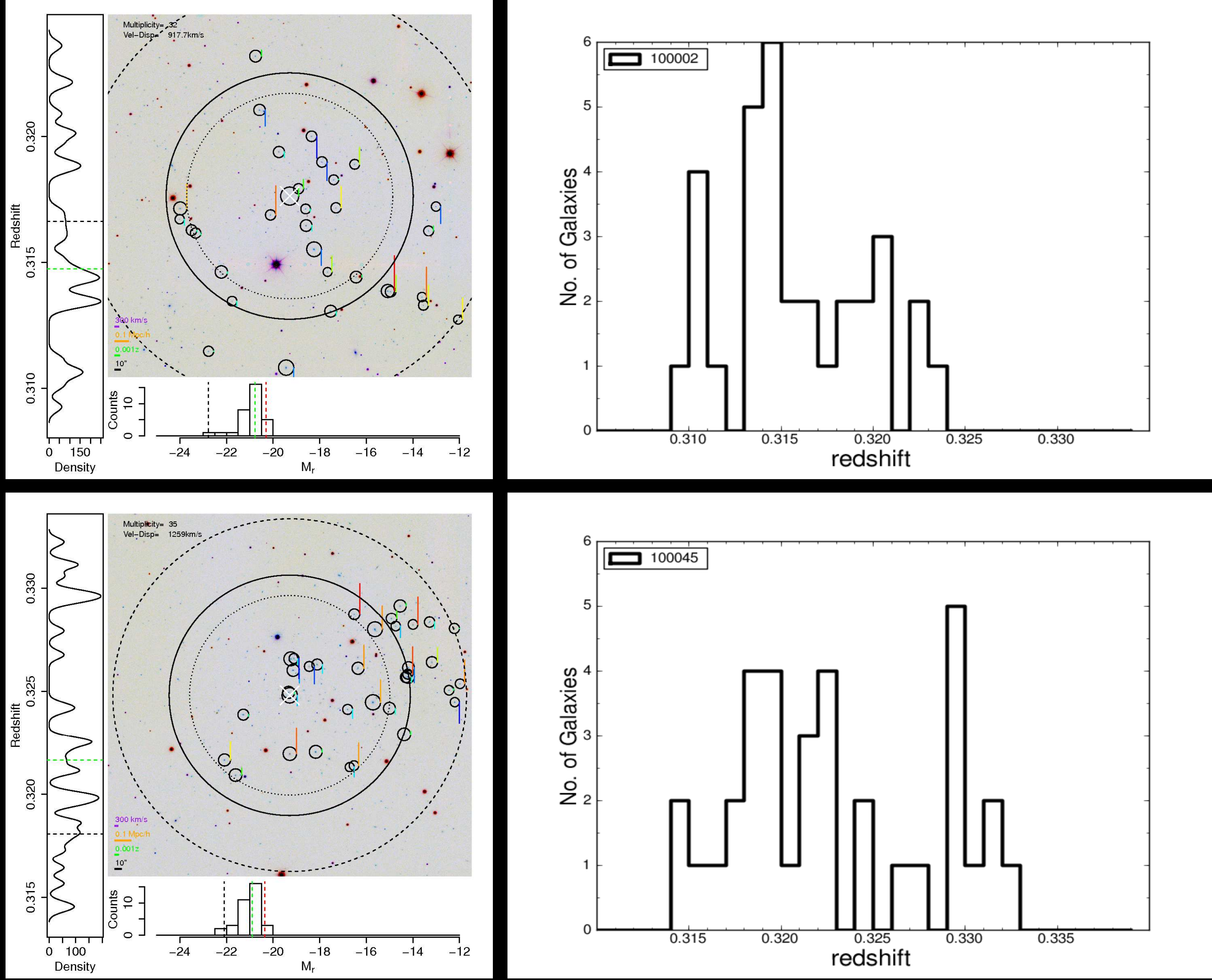
(3) What are the best lensing targets for JWST to see First Light?



For JWST, use the best lenses in 2018: Rich clusters or (compact) groups!

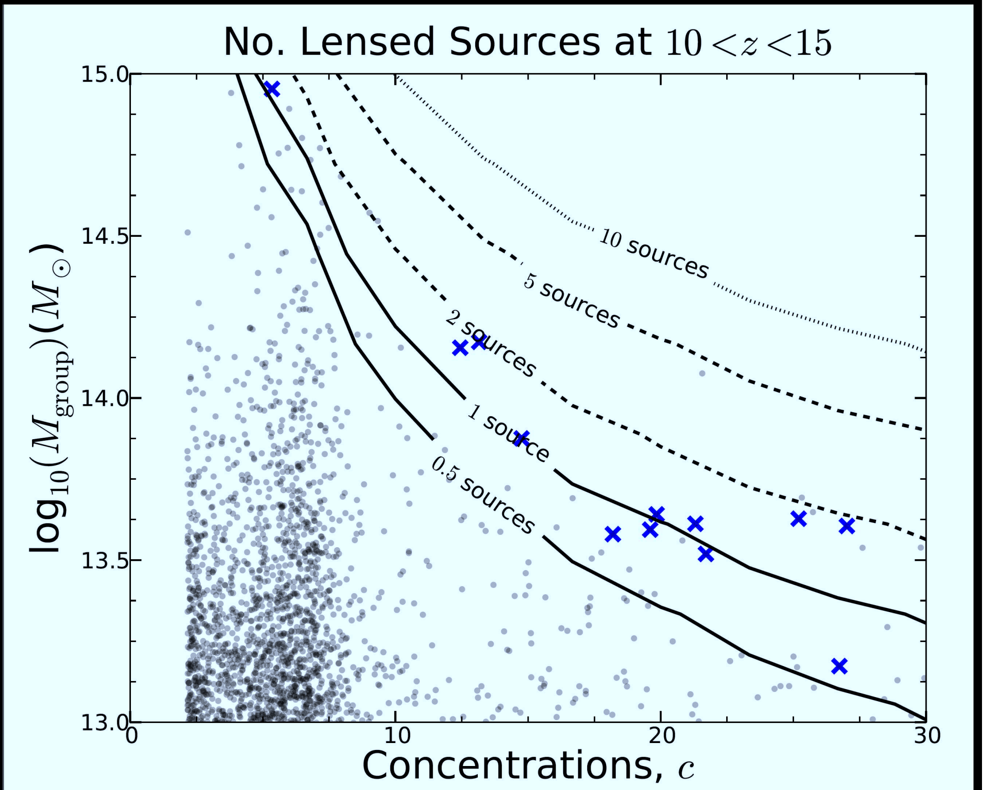
[Left] Redshift surveys: SDSS z$\lesssim$0.25 (Yang+ 2007), GAMA z$\lesssim$0.45 (Robotham+ 2011), and zCOSMOS z$\lesssim$1.0 (Knobel+ 2012).

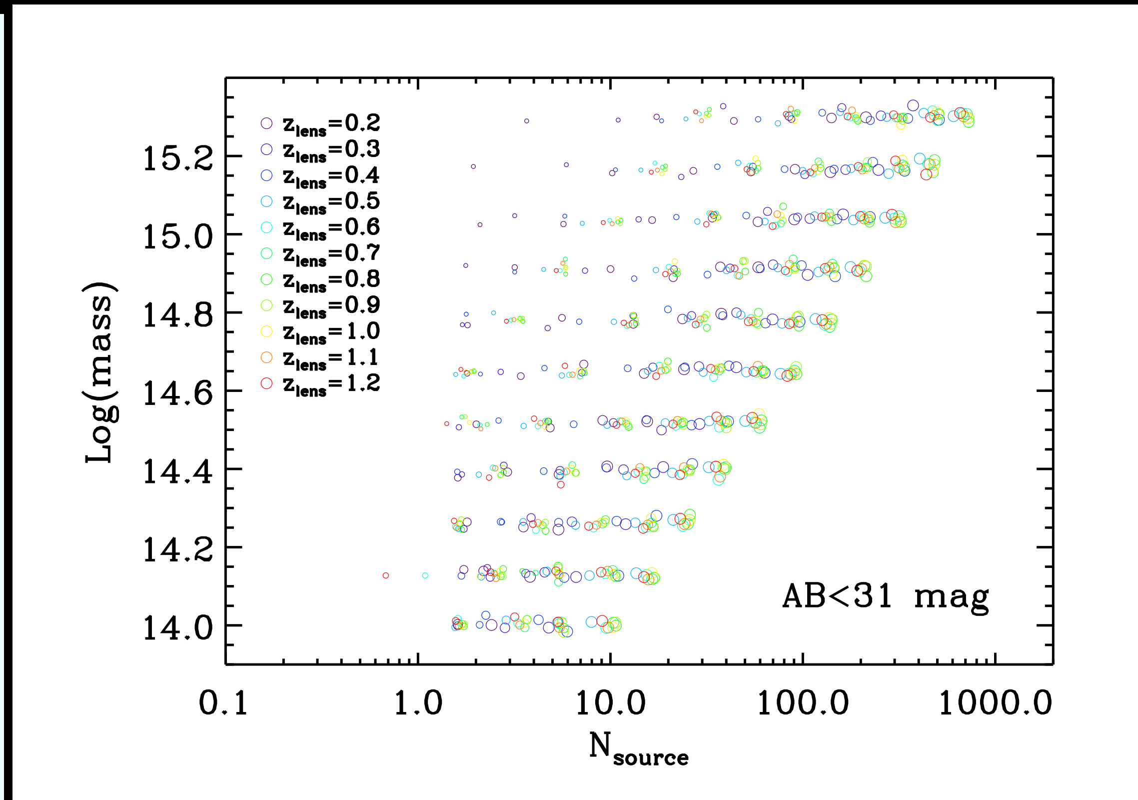
- GAMA: 22,000 groups z$\lesssim$0.45; 2400 with $N_{spec}\gtrsim5$ (Robotham+ 11).
- $\lesssim$10% of GAMA groups compact for lensing (Konstantopoulos+ 13).
- Need large sample to identify best lenses to find z$\sim$6–15 sources.



[Left] GAMA groups with secure AAT redshifts for R≲19.8 AB-mag.
Also show redshift probability and absolute magnitude (M_r) distributions.
[Right] Measured group redshift distribution for two GAMA groups.

- Will select our WMDF IDS targets on groups (+ some clusters).





GAMA group mass versus concentration assuming NFW DM halo profiles.

[LEFT] = Nr of expected lensed sources (AB$\lesssim$30; Barone-Nugent$^+$ 15).

[RIGHT] = Nr of expected lensed sources at 6$\lesssim$z$\lesssim$15 (AB$\lesssim$31 mag).

- 10 WMDFs on best 10^{15} $M_\odot$ clusters: ∼100 z≃6–15 sources (AB$\lesssim$30).
- WDF (AB$\lesssim$31 mag) will get ∼250 lensed sources at z≃6–15.

WUDFF (AB$\lesssim$32) on best cluster yields ∼800 lensed sources at 6$\lesssim$z$\lesssim$15!

Conclusion: JWST First Light strategy must consider three aspects:

(1) The rapid drop in the LF Φ^* (z) and/or M^* (z) for z$\gtrsim$8.

(2) Cannot-see-the-forest-for-the-trees effect ["Natural Confusion" limit]:
Background objects blend into foreground because of their own diameter $\Rightarrow$
Need multi-λ deblending algorithms & object subtraction (e.g., wavelets).

(3) Gravitational Lensing: JWST may need to find most First Light objects at z$\gtrsim$12–15 through the best lensing clusters or groups.

- Need multi-λ object-finder that works on sloped backgrounds.
- If M*(z$\gtrsim$10)$\gtrsim$–18 or Φ^* $\lesssim$$10^{-3.5}$, must image, (subtract,) & model the entire gravitational foreground. Be mindful of extra (rogue-path) straylight.

Conclusions re. JWST First Light Strategies

(1) JWST First Light studies will require an optimal mix of Medium-Deep, Deep and Ultradeep Fields:

• My IDS team will do ten ∼7 hr Webb Medium-Deep Fields (10 WMDF's), anticipating that:

• NIRCam team & GO's will do two (∼200 hr) Webb Deep Fields;

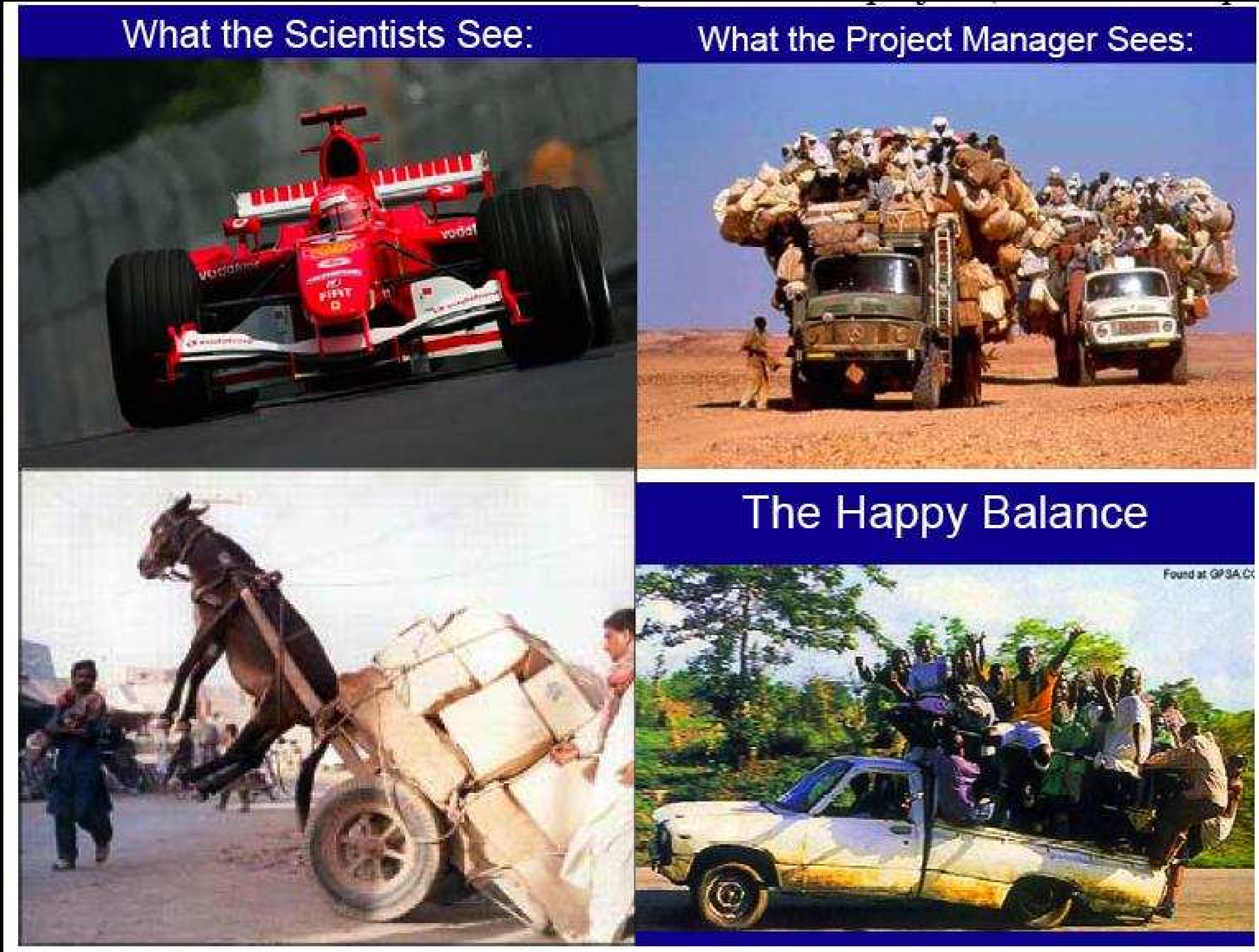
• JWST GO's will hopefully do an Webb Ultradeep Field (800 hr WUDF).

(2) Recommendation: To maximize seeing First Light, ∼65% of these should target the best lensing groups/clusters!

(3) The best JWST lensing targets need to consider the brightness of — and low-level gradients in — IntraCluster Light (ICL) *and* low-level out-of-field (rogue-path) straylight (which may not be easily separable).

• **Your JWST proposals are due $\lesssim$3 years from today!**

SPARE CHARTS



Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).

• 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

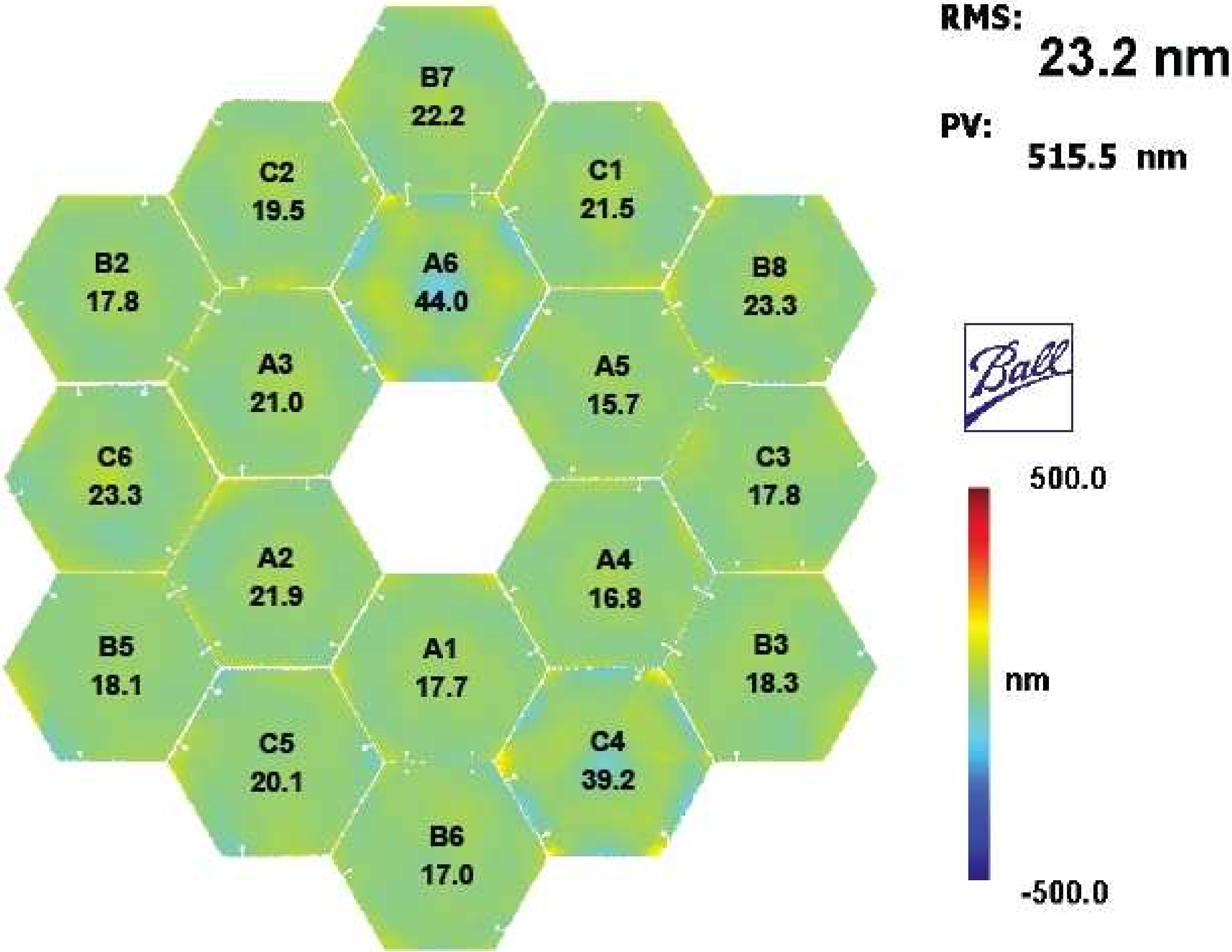
Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

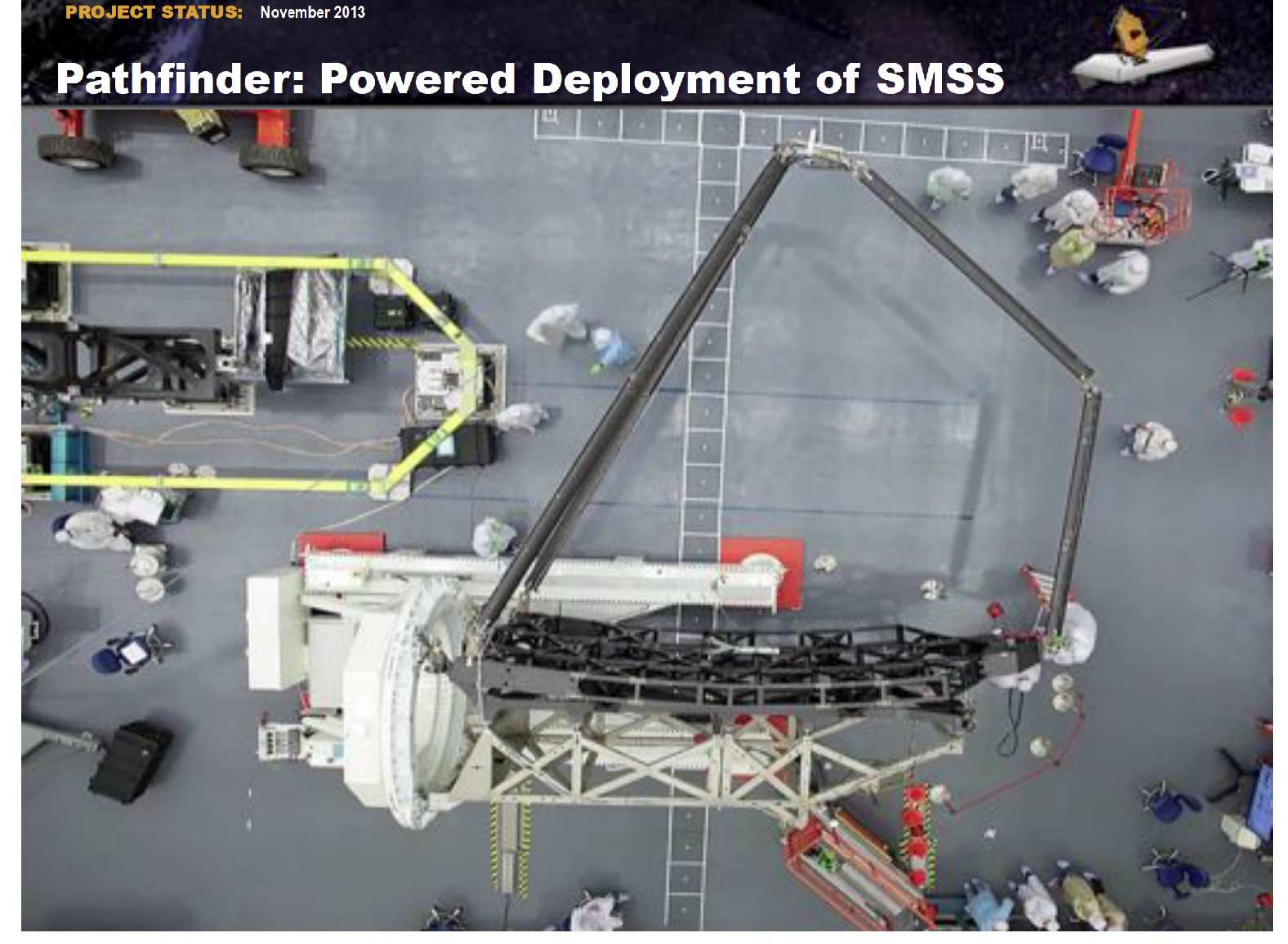
Mirror Status

- **15 flight primary mirrors and the flight secondary mirror are at GSFC in storage**
  - All spares were at GSFC in storage (SM spares, 3 PMSA spares)
    - 2 EDU mirrors sent back to Ball for gear motor rework
  - All flight gear motor refurbishment is complete
  - All flight mirrors will be at GSFC by end of year, needed in 2015

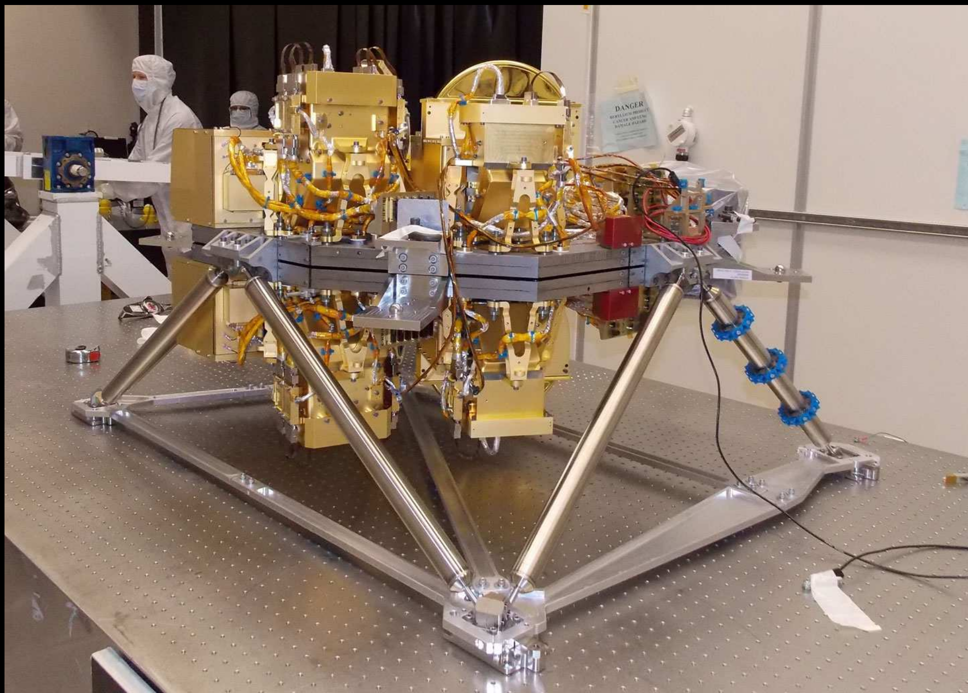
Spring 2014: All 18 flight mirrors delivered to NASA GSFC (MD).

Primary Mirror Composite



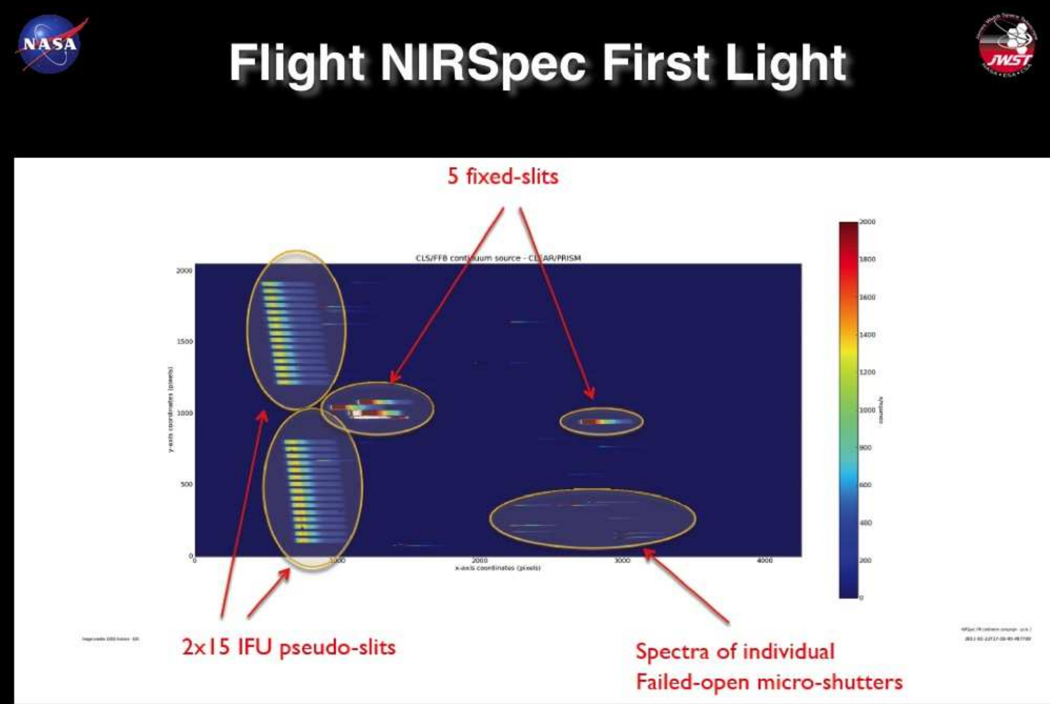


July 2014: Secondary Mirror Support deployment successfully tested.



JWST's short-wavelength (0.6–5.0μm) imagers:

- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (& 1–5 μm grisms) — built by CSA (Montreal).
- FGS includes very powerful low-res Near-IR grism spectrograph (NIRISS).
- FGS delivered to GSFC 07/12; NIRCam delivered July 28, 2013.

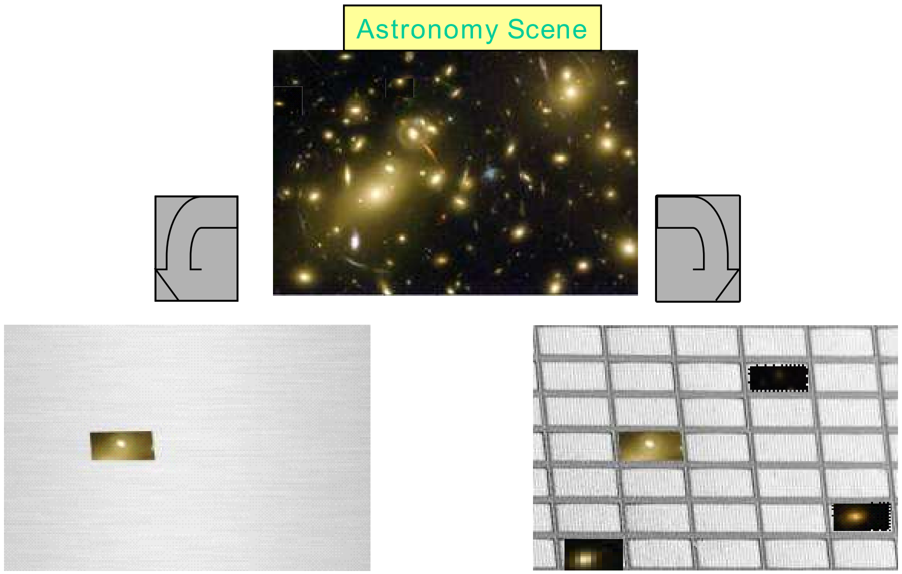


JWST's short-wavelength (0.6–5.0μm) spectrograph:

- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

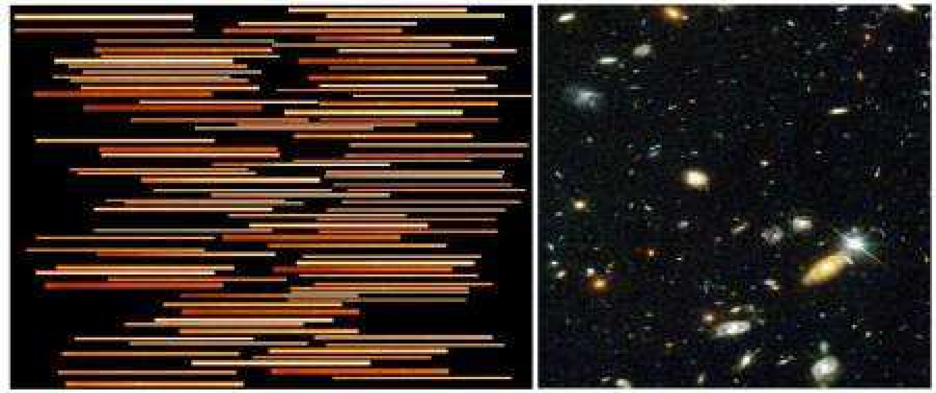
NIRSpec delivered to NASA/GSFC in Sept. 2013.

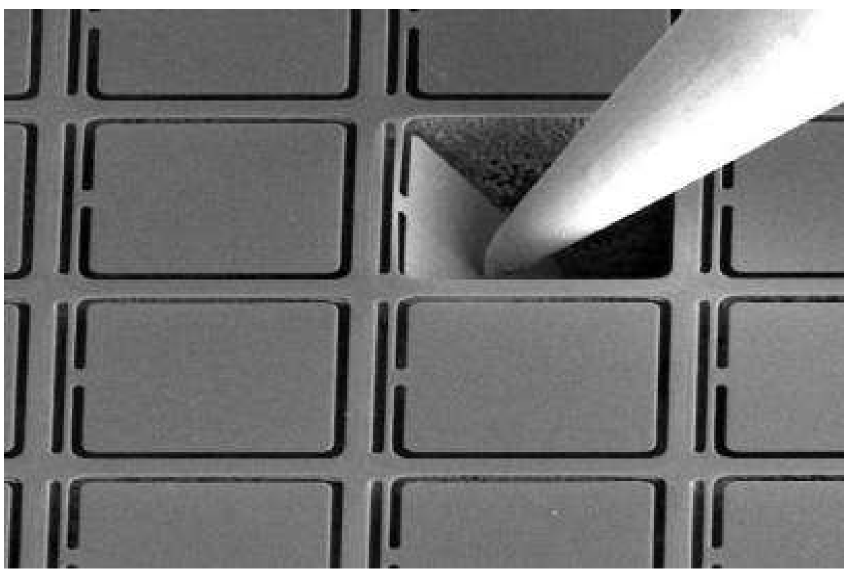
Micro Shutters



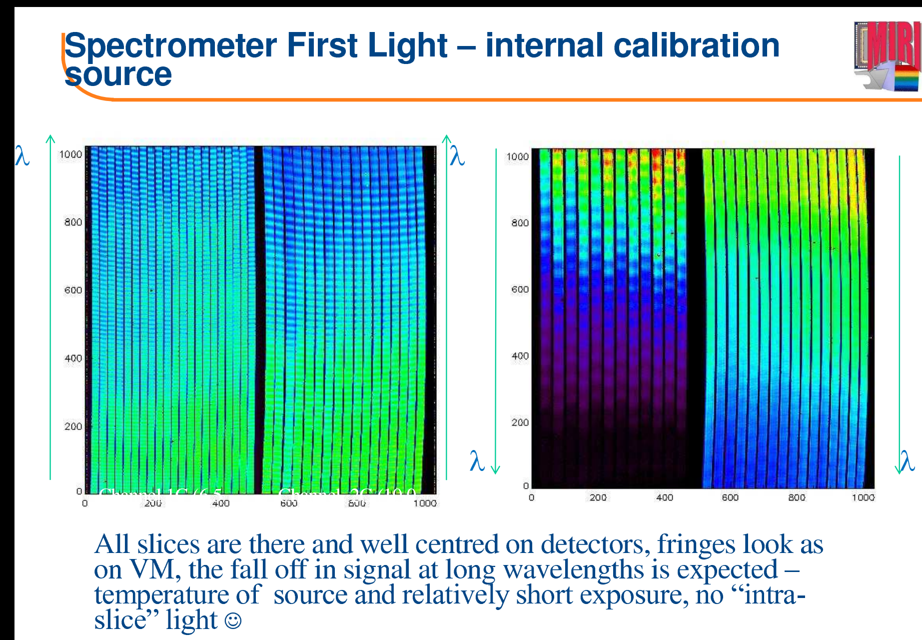
Metal Mask/Fixed Slit

Shutter Mask





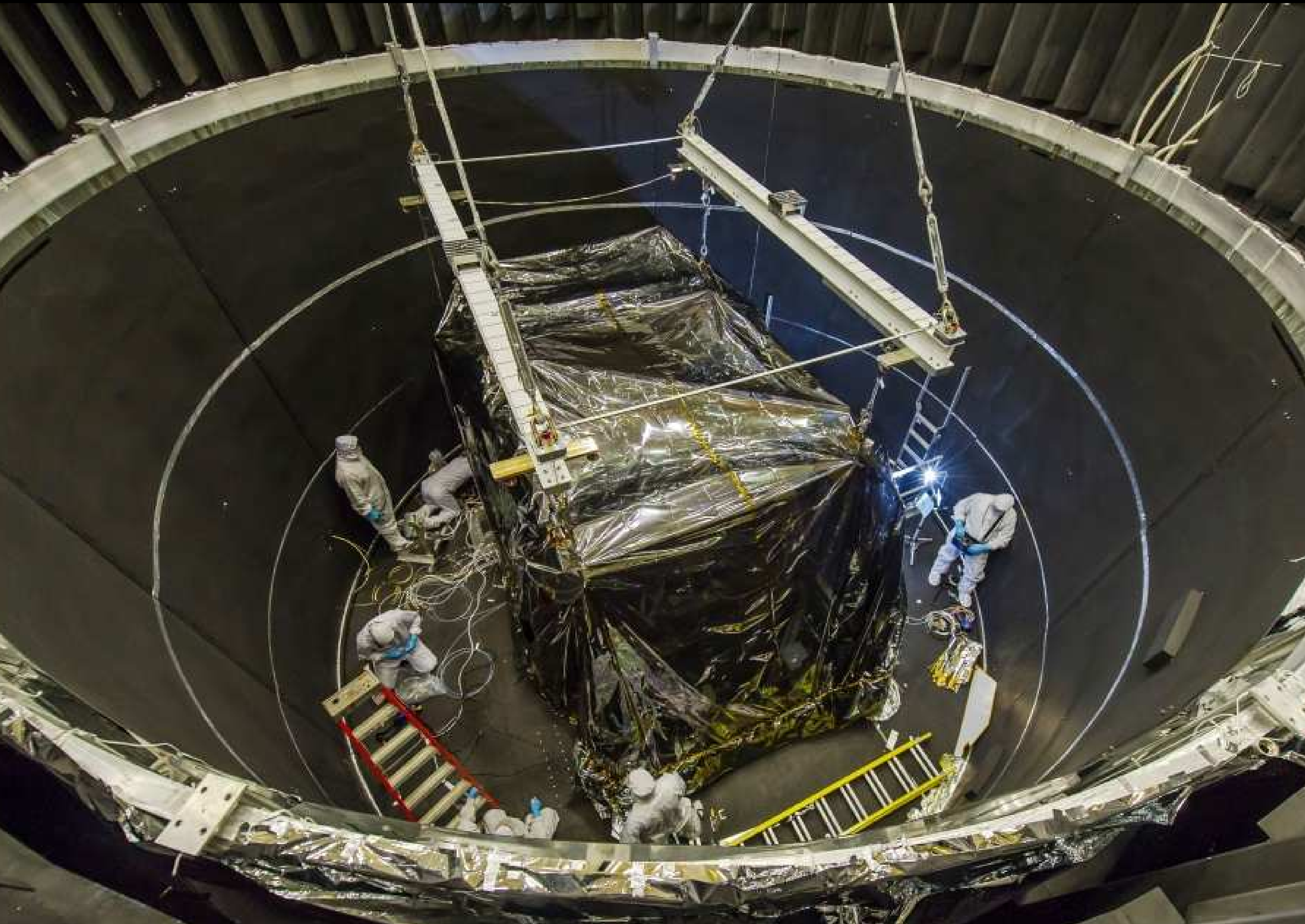
Flight MIRI



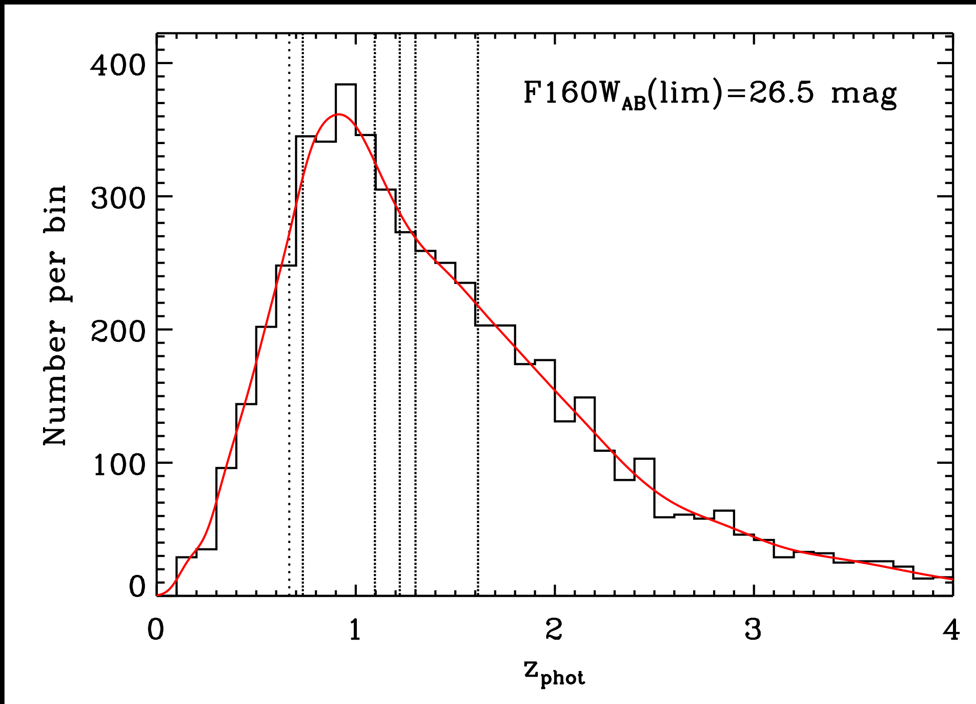
JWST's mid-infrared (5–29μm) camera and spectrograph:

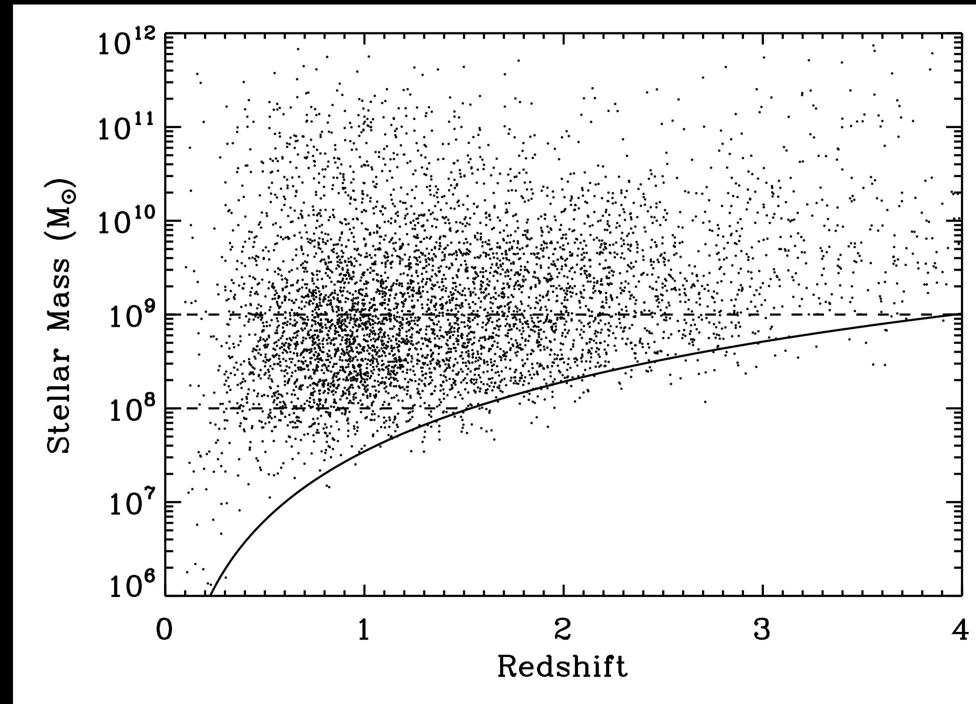
- MIRI — built by ESA consortium of 10 ESA countries & NASA JPL.
- Flight build completed and tested with First Light in July 2011.

MIRI delivered to NASA/GSFC in May 2012.



Summer 13, 14 & 15: Actual Flight ISIM (with 4 instruments) tested in OSIM.





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).

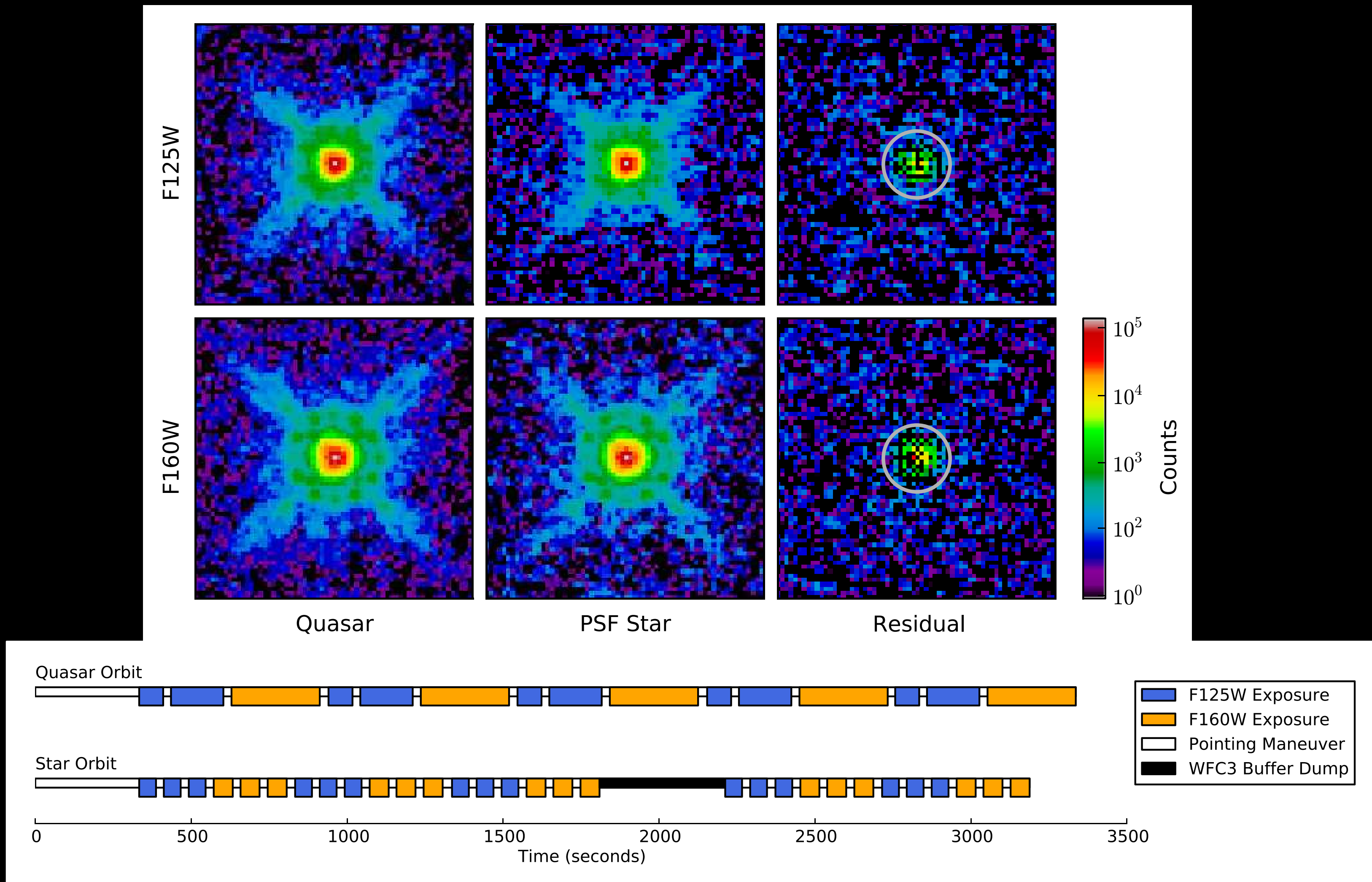
• Measure masses of faint galaxies to AB=26.5 mag, tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?).

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

• HUDF shows WFC3 z$\simeq$7–9 capabilities (Bouwens$^+$ 2010; Yan$^+$ 2010).

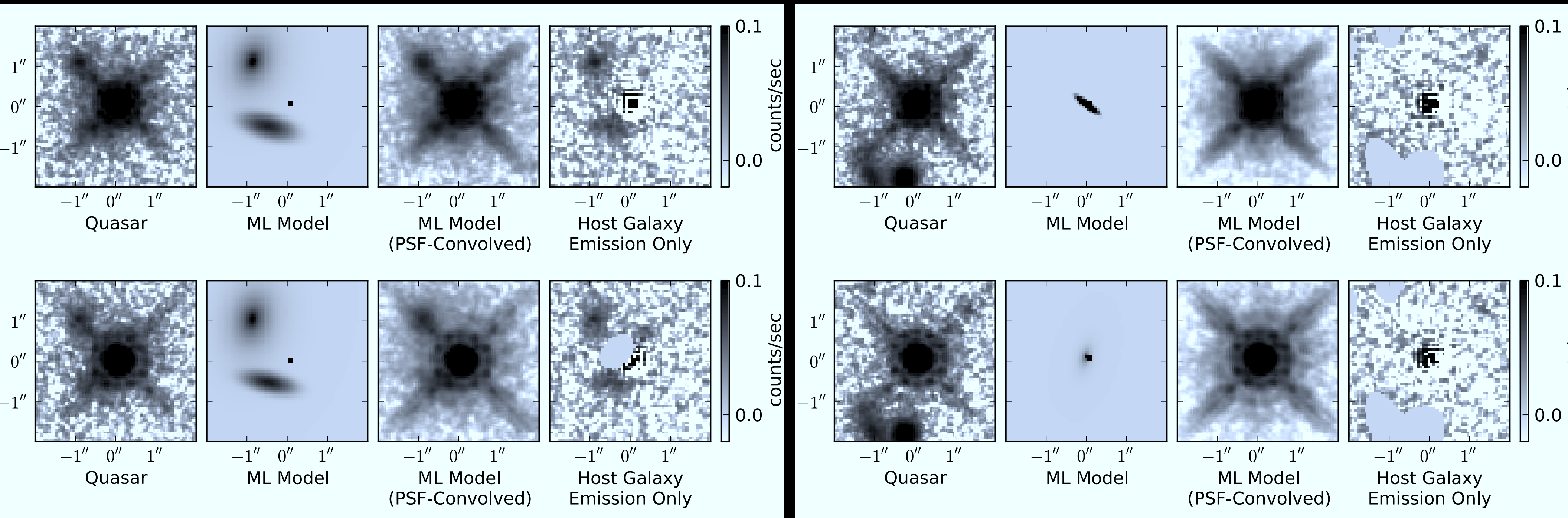
• JWST will trace mass assembly and dust content $\lesssim$5 mag deeper from z$\simeq$1–12, with nanoJy sensitivity from 0.7–5μm.

(2b) HST WFC3 observations of QSO host systems 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≃18.5) nearly to the noise limit: NO host galaxy detected 100×fainter (AB≳23.5 at r≳0.″3).

(2b) WFC3: Detection of one QSO Host System at z≃6 (Giant merger?)



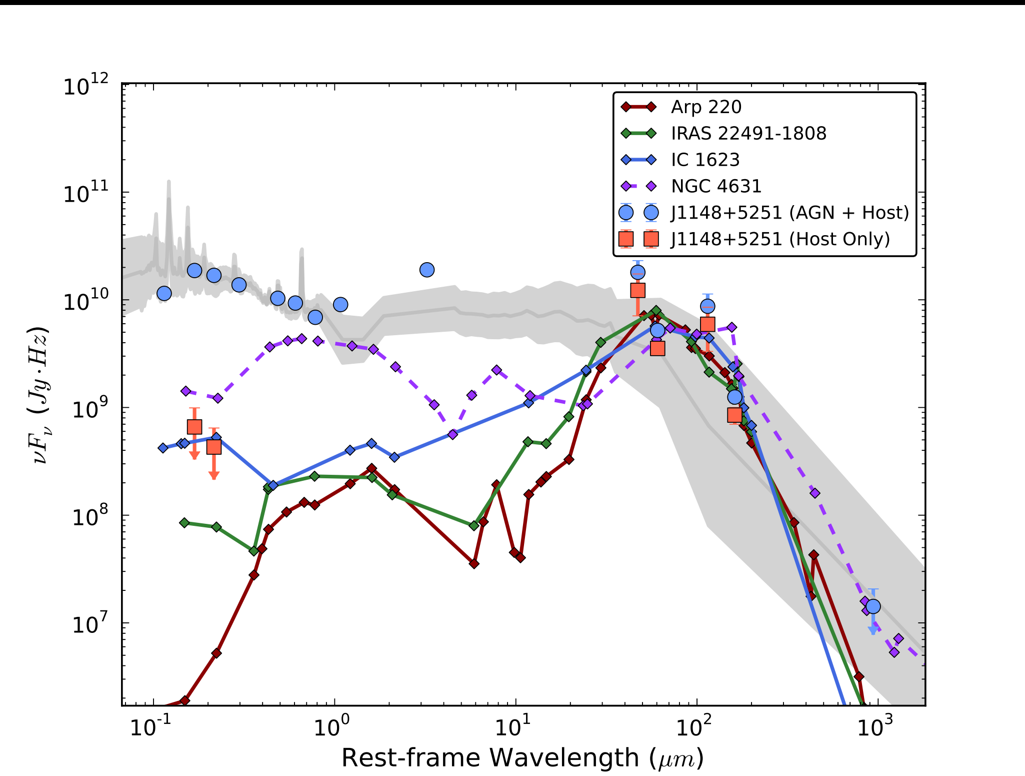
- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile. Gemini AO images to pre-select PSF stars (Mechtley^{+} 2014).
- First detection out of four z≃6 QSOs [2 more to be observed].
- One z≃6 QSO host galaxy: Giant merger morphology + tidal structure??

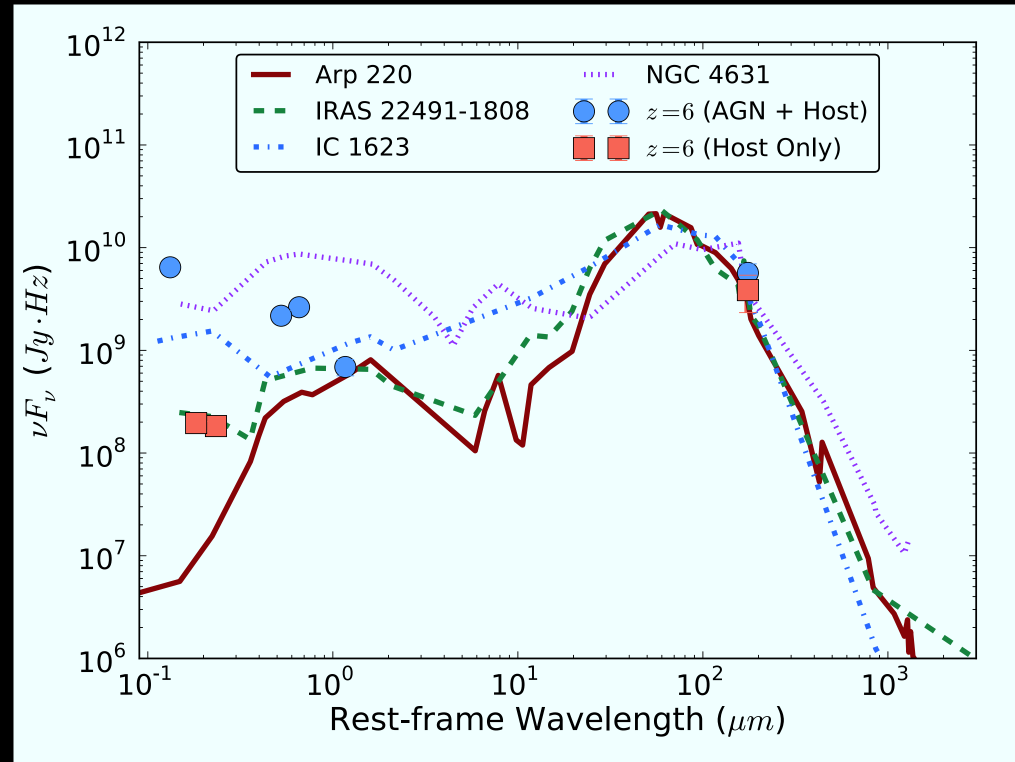
- Same J+H structure! Blue UV-SED colors: (J–H)≃0.19, constrains dust.
- M_{AB}^{host}(z≃6)$\lesssim$–23.0 mag, i.e., ∼2 mag brighter than L*(z≃6)!

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

Many more such quasars with host galaxies observed at z≃2–3.

(2b) HST WFC3 observations of dusty QSO host galaxies at z≃6



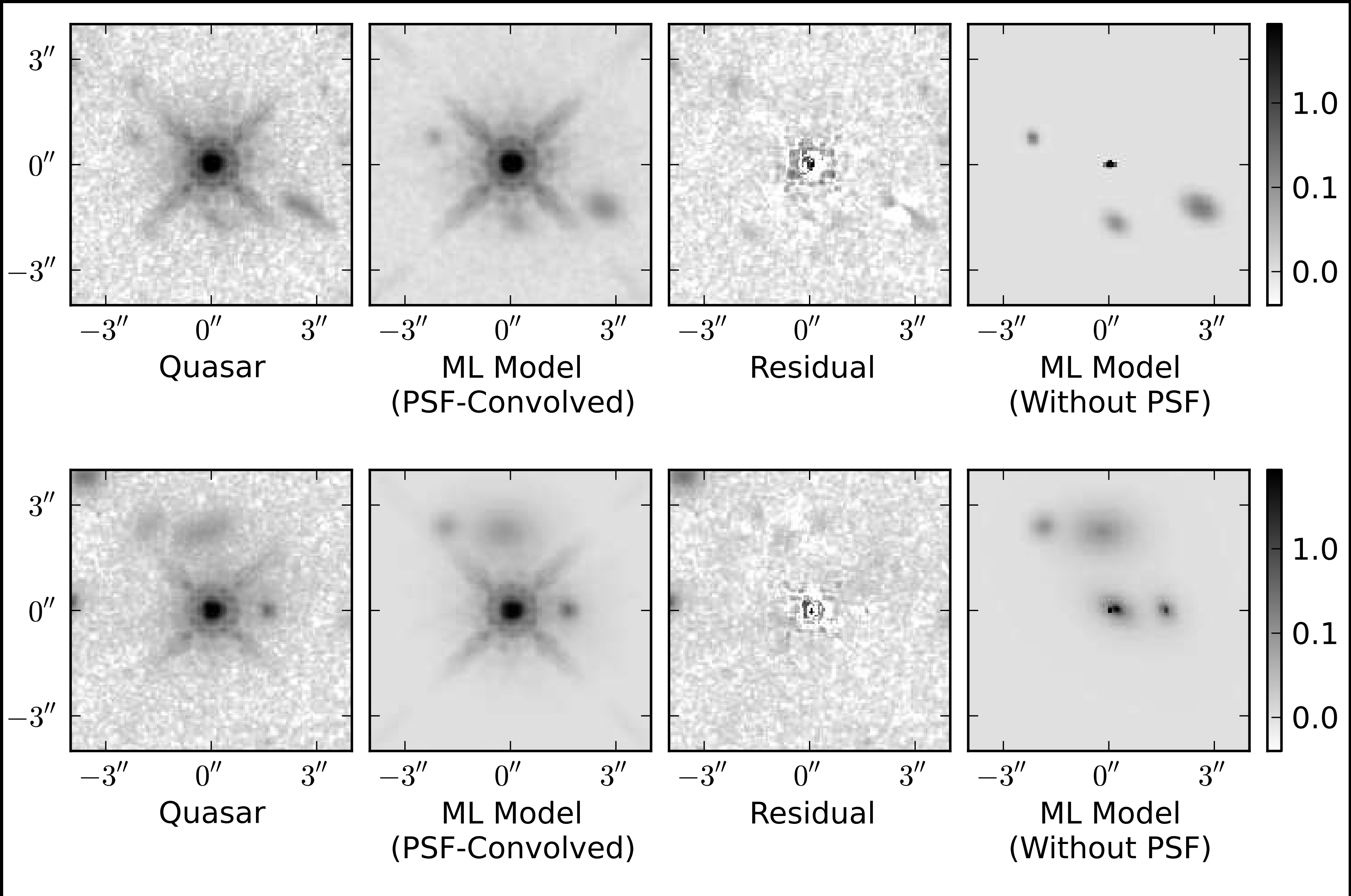


- Blue dots: z≃6 QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at z≳1 (normalized at 0.5μ). Red: z≃6 host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages≲1 Gyr) normalized at 100μm:

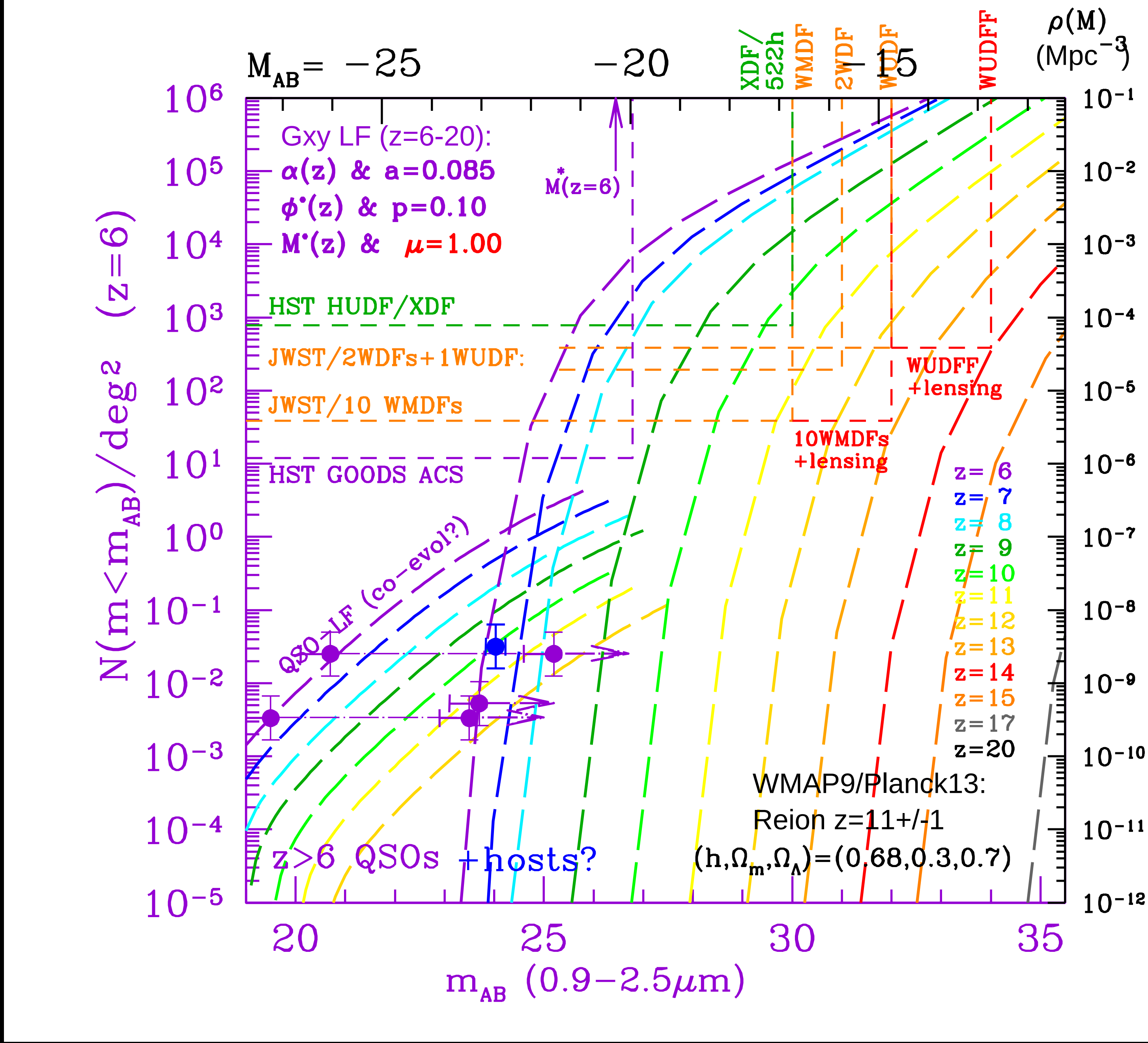
[LEFT] Rules out z=6.42 spiral or bluer host galaxy SEDs for 1148+5251. (U)LIRGs & Arp 220s permitted (Mechtley et al. 2012, ApJL, 756, L38).
[RIGHT] Detected QSO host has IRAS starburst-like SED from rest-frame UV–far-IR, A_{FUV}(host)∼1 mag (Mechtley 2013 PhD; et al. 2014).

- JWST Coronagraphs can do this 10–100× fainter (& for z≲20, λ≲28μm).

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



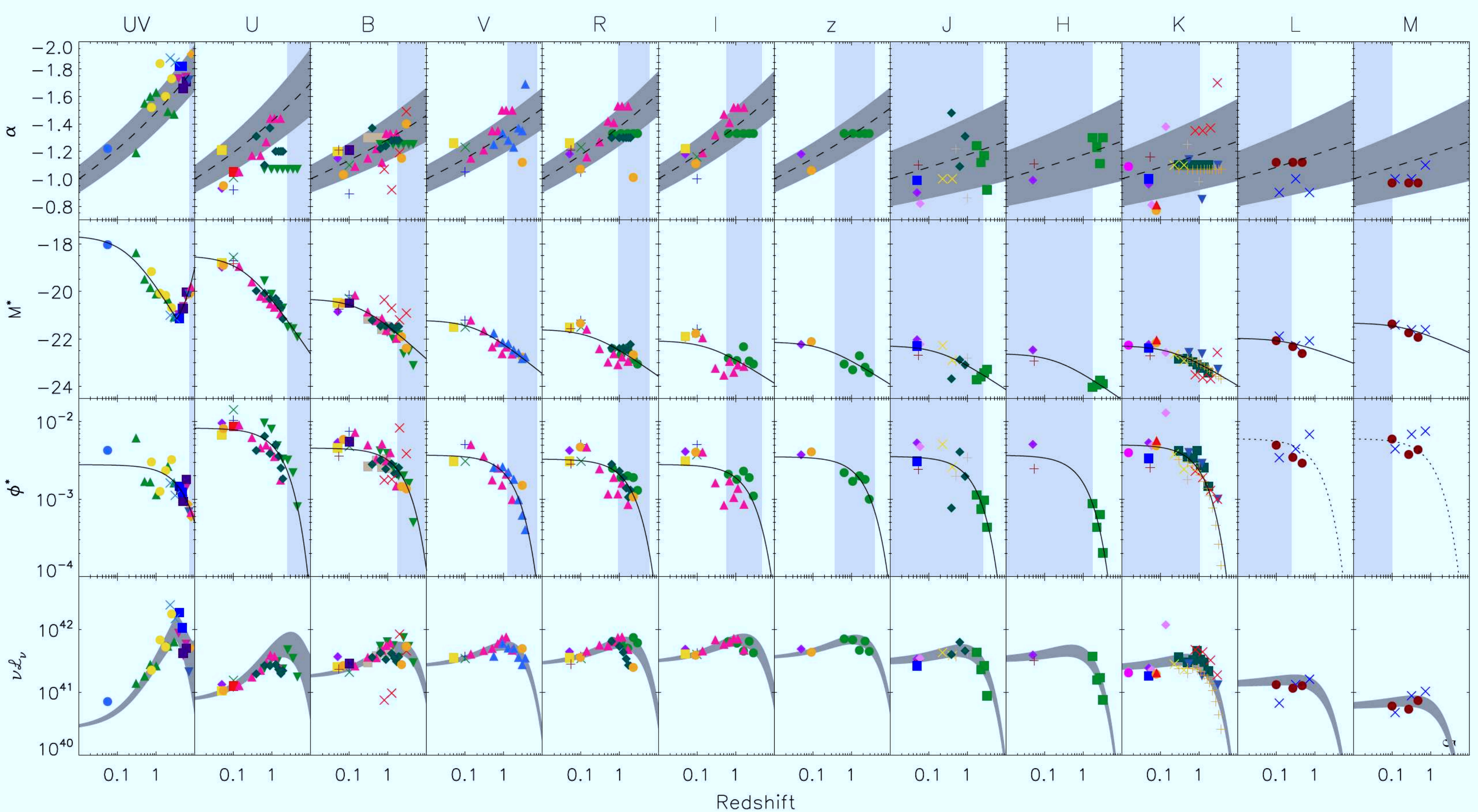
- Monte Carlo Markov-Chain runs of observed PSF-star + Sersic ML light-profile models: merging neighbors (some with tidal tails?; Mechtley, Jahnke, MPI, Koekemoer, Windhorst et al. 2014).
- JWST Coronagraphs can do this 10–100× fainter (& for z$\lesssim$20, $\lambda\lesssim 28\mu$m).



Same as before, but pessimistic M^* (z) evolution parameter: μ=1.0.

- If so, JWST surveys would need lensing to see most $\gtrsim$11 objects.
- Add z$\simeq$6 QSO host galaxy limits (or fluxes) by Mechtley$^+$ (2012, 2014).

THE ASTROPHYSICAL JOURNAL, 752:113 (18pp), 2012 June 20
HELGASON, RICOTTI, & KASHLINSKY



(Helgason, K., Ricotti, M., & Kashlinsky, A. 2012, ApJ, 752, 113).

LEFT: Rest-frame UV-LF behavior quite different from longer wavelengths:

Rest-frame UV-LF ($\lesssim$Balmer break) is what NIRCam will observe at z$\gtrsim$10!
(WMAP-9/Planck universe too young for Balmer breaks at z$\gtrsim$12!).

B, I, J AB-mag vs. half-light radii r_e from RC3 to HUDF limit are shown.

All surveys limited by by SB (+5 mag dash)

Deep surveys bounded also by object density.

Violet lines are gxy counts converted to to natural conf limits.

Natural confusion sets in for faintest surveys (AB$\gtrsim$25). Will update for JWST.