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

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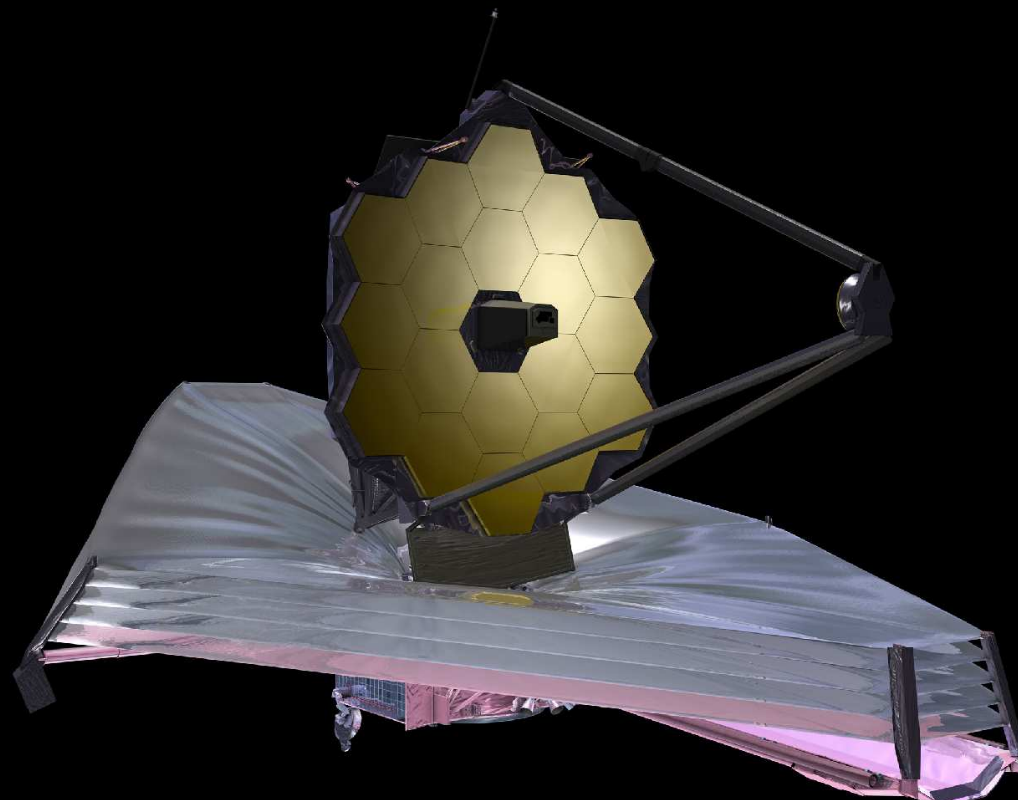


Main Message: The LF($\gtrsim$10) and difference in telescope architecture drives how to best use lensing to find the most First Light objects at z$\gtrsim$10.

Invited Talk & Panel Discussion at the "HST Frontier Fields Workshop", Nov. 13, 2014; Yale University, New Haven (CT).

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

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

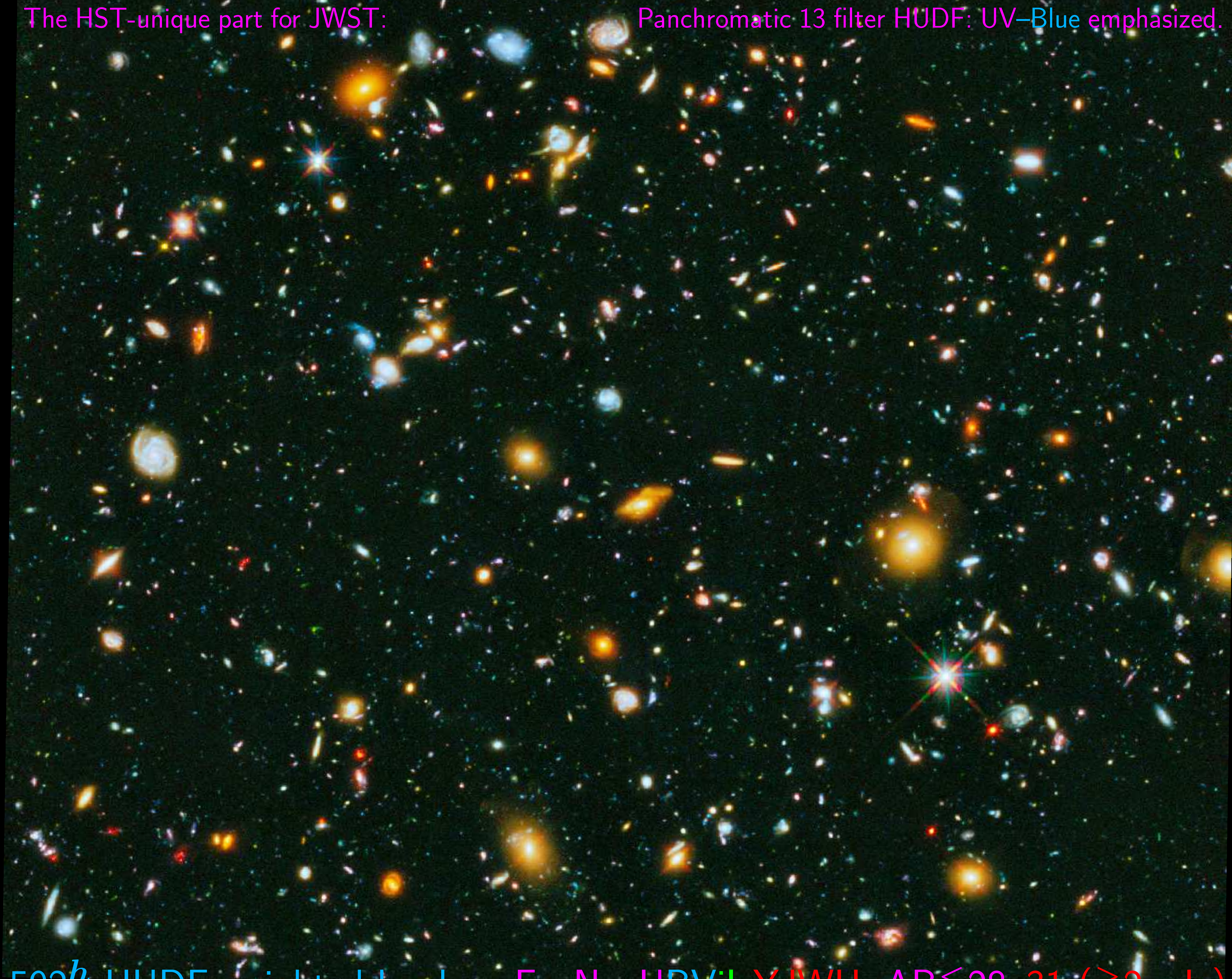
(2) JWST hardware to date, and aspects relevant to lensing.

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

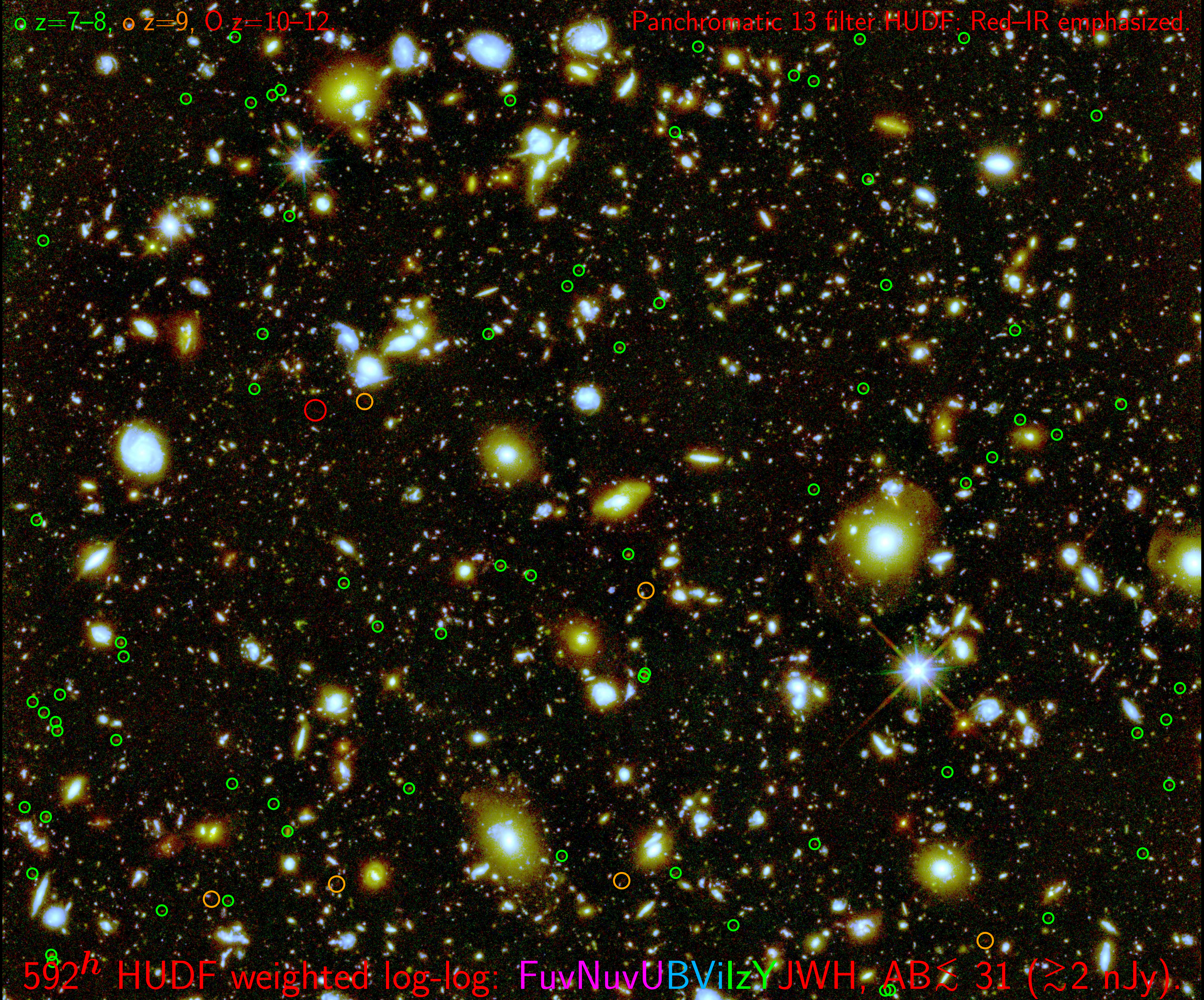
• How many random Webb Deep Fields (WDFs) compared, to the best lensing targets?

(4) Recommendations and Conclusions.

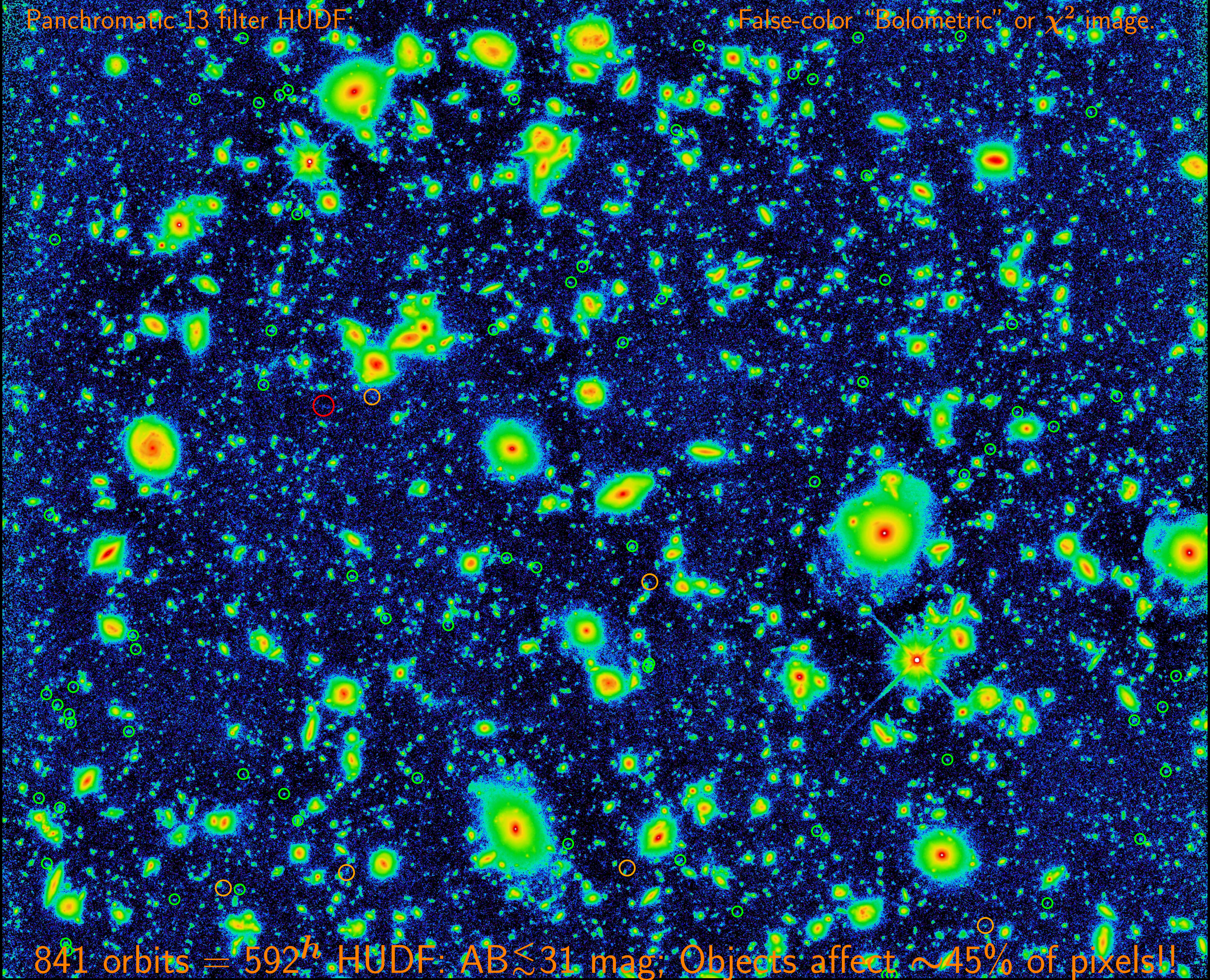
The HST-unique part for JWST: Panchromatic 13 filter HUDF: UV–Blue emphasized.



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

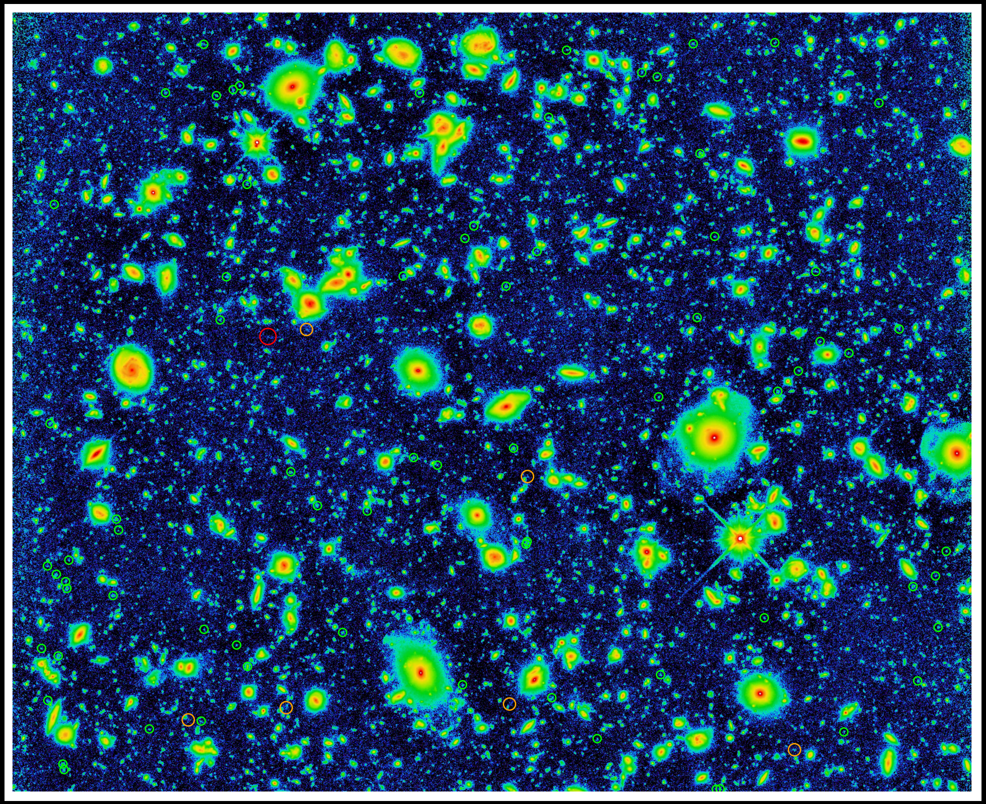


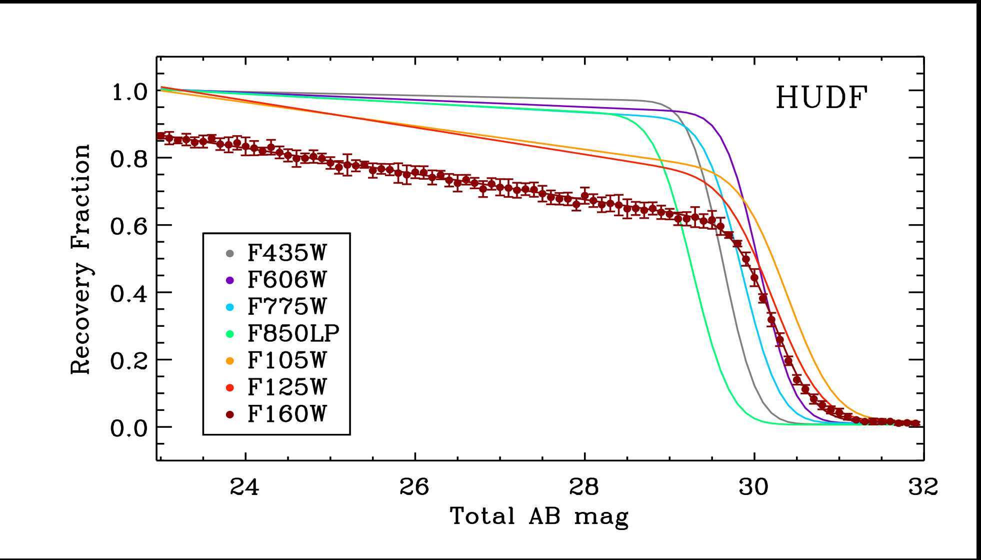
o z=7–8, o z=9, O z=10–12.
Panchromatic 13 filter HUDF: Red–IR emphasized.
592^h HUDF weighted log-log: FuvNuvUBViIzYJWH, AB≲ 31 (≳2 nJy).



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!!

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





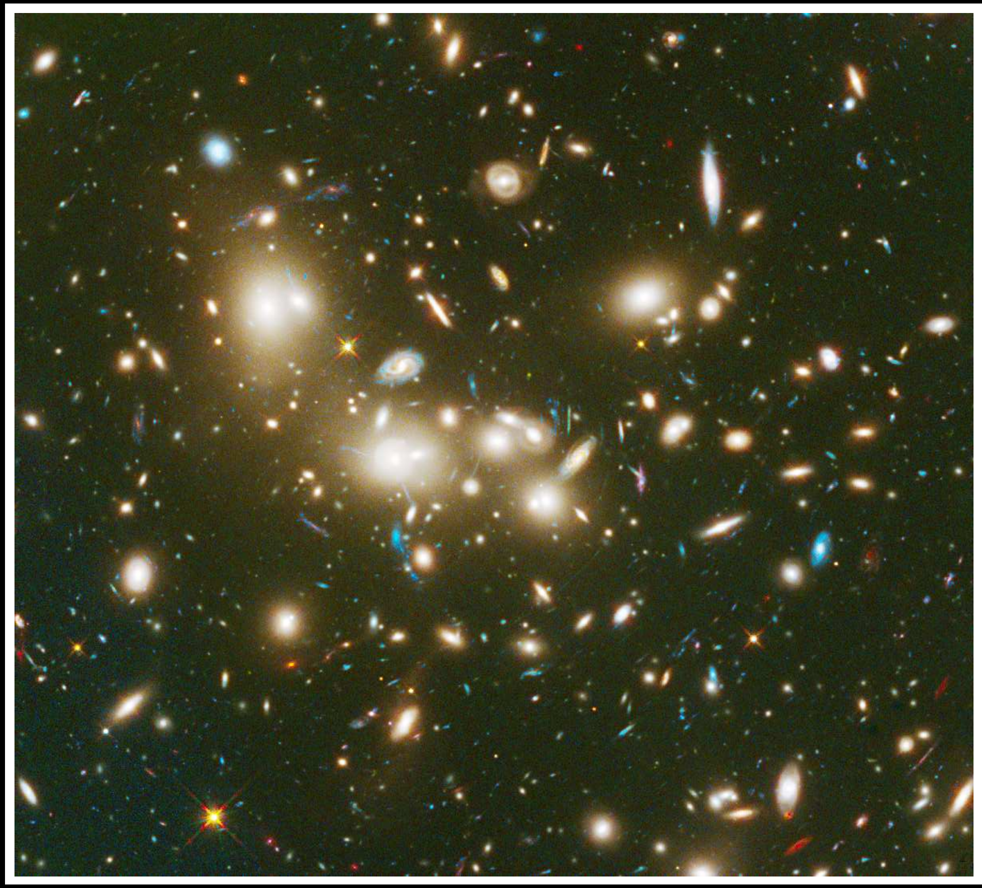
[LEFT]: HUDF bolometric or χ^2-image (false-color log-log stretch): weighted average of 841 orbits (592 hr) in 13 filters reaching AB$\lesssim$31 mag.

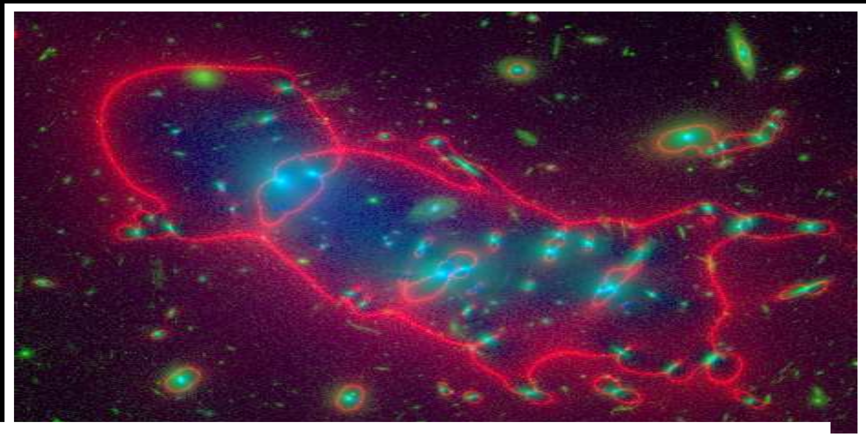
- Faint object wings cover ∼45% of all pixels (Koekemoer et al. 2013)!

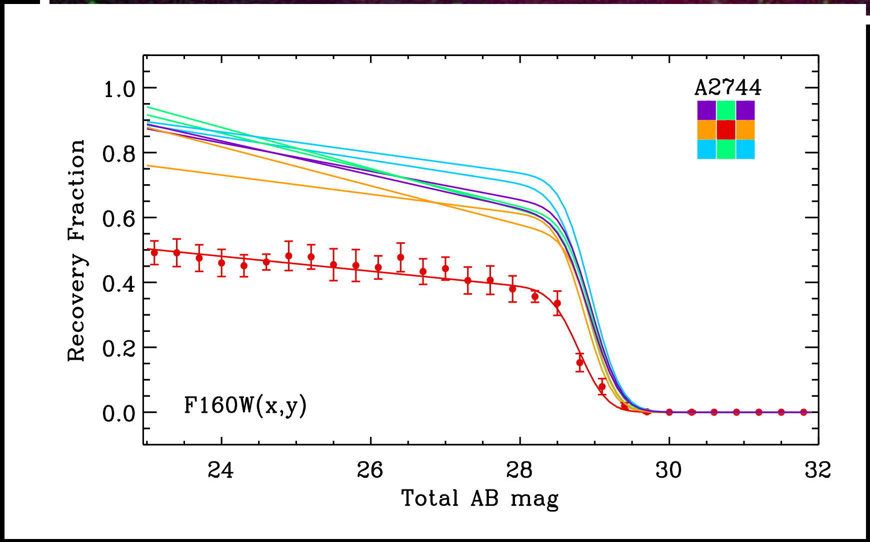
[RIGHT]: HUDF *wavelength-dependent* completeness functions from Monte Carlo (MC) insertions:

- 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.

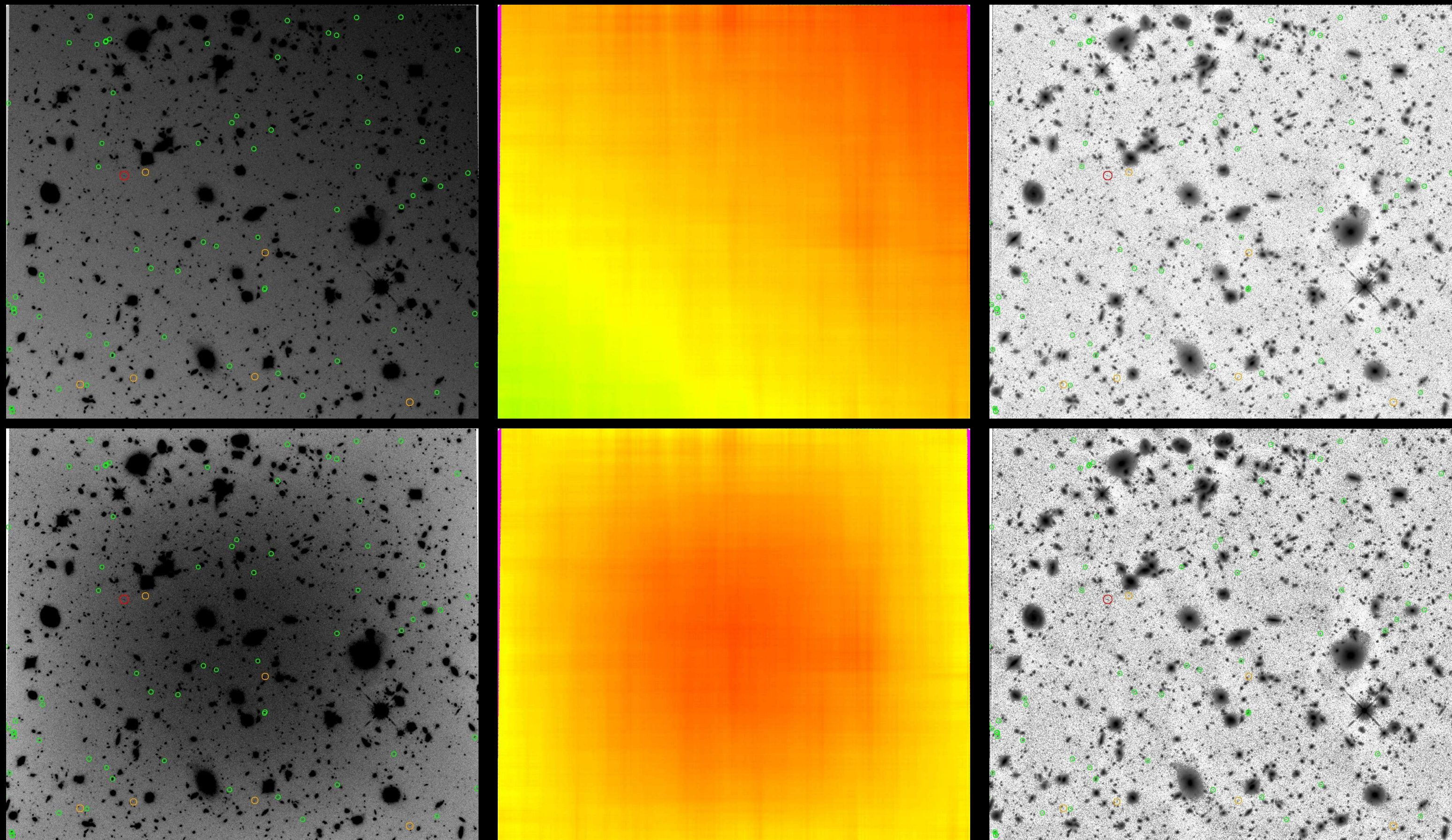
(2) JWST hardware to date, and how to best use it for high redshift lensing.

[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?



[TOP]: [Left] HUDF F160W image with *worst case* (95% of Zodi) rogue-path amplitude imposed

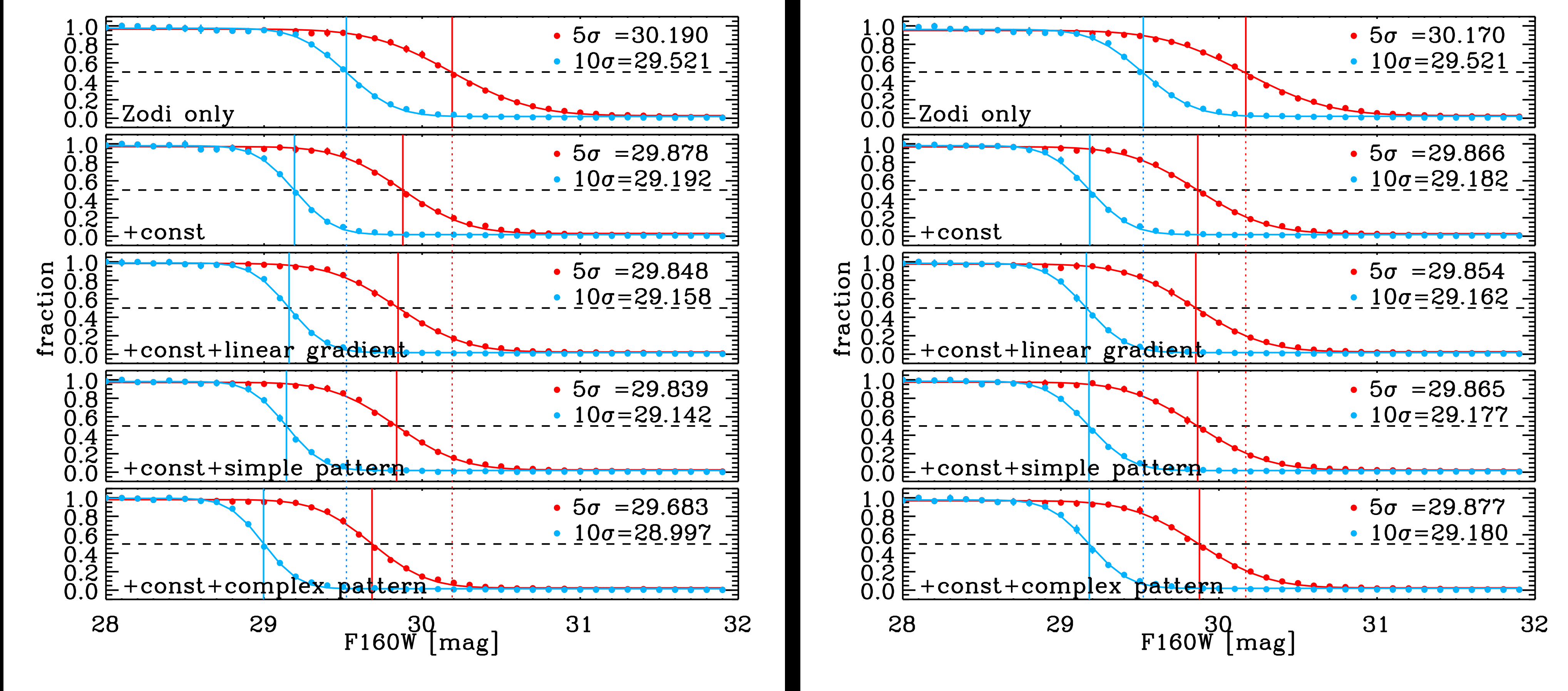
± a 4% *linear gradient* from corner-to-corner.

[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.



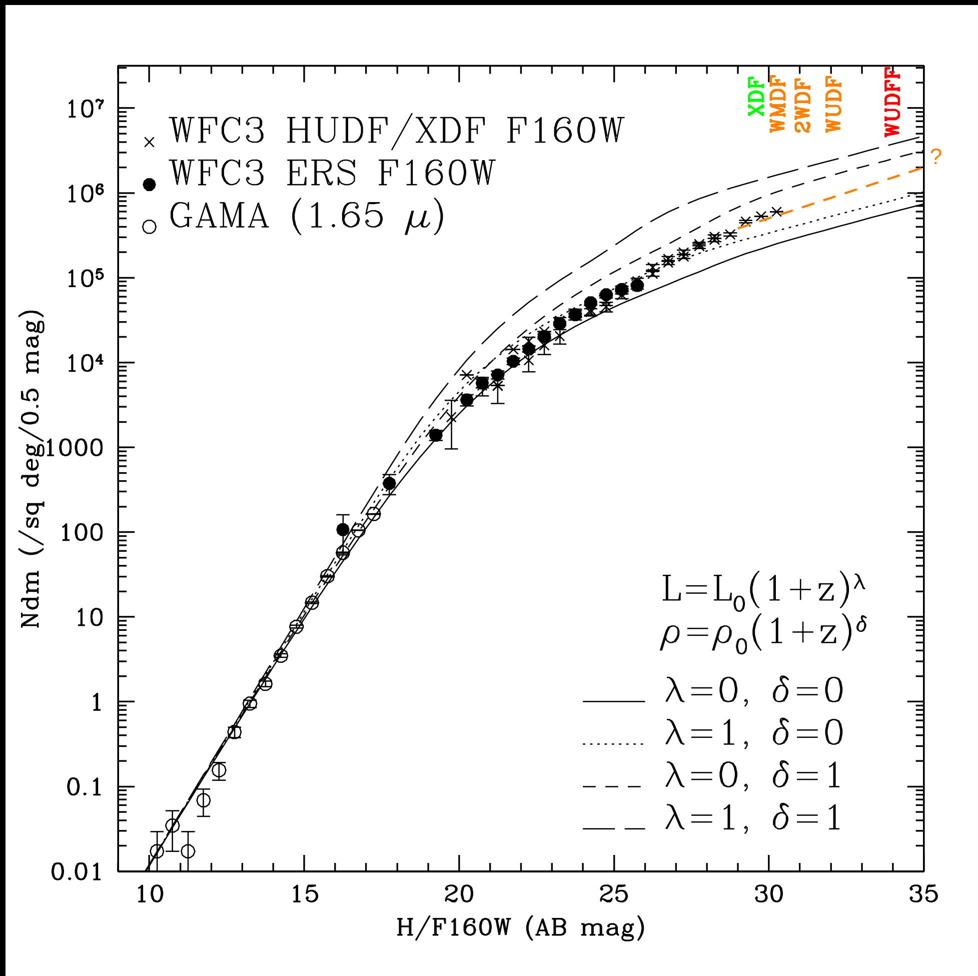
[LEFT]: Completeness tests in HUDF F160W image *before* imposing on top of Zodi (=22.70 H-mag arcsec^{-2}; Petro 2001) [2nd–5th row]: *Constant 95% of Zodi amplitude*; *+ a ±4% linear gradient*; or *simple 2D pattern of ±4%*; or *a more complex pattern*.

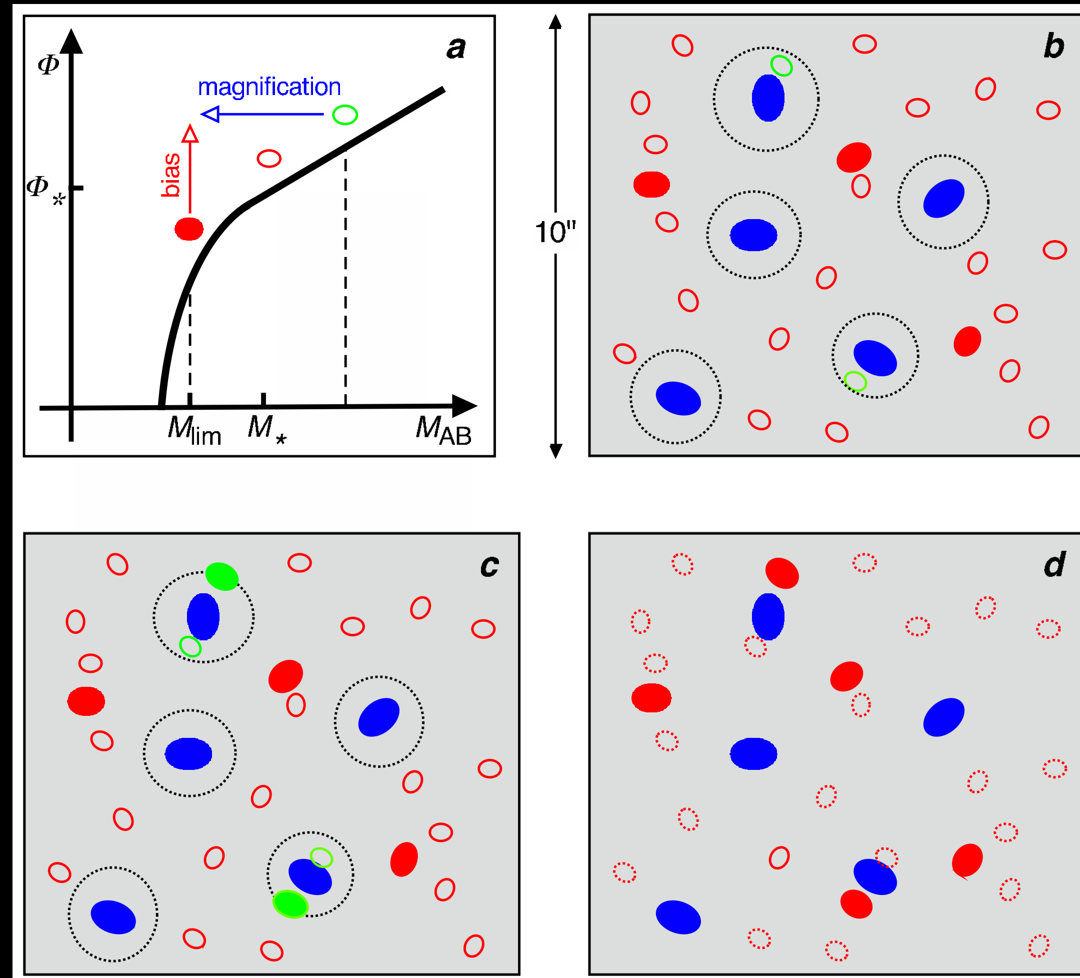
[RIGHT]: Same as left *after* best fit to + removal of image sky-background.

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.

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



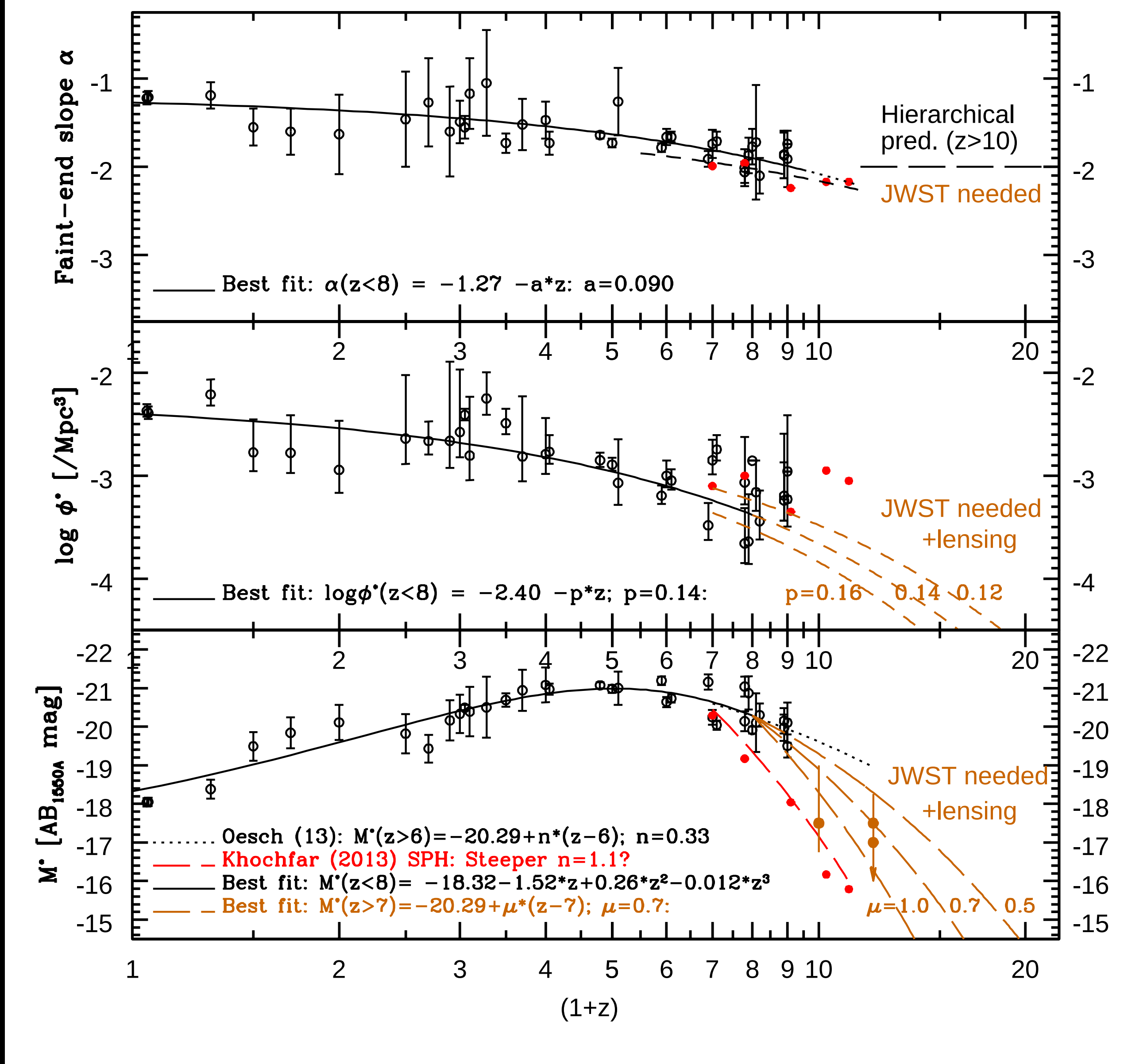


1.6μm counts (Windhorst+2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

• Faint-end near-IR count-slope≃0.16±0.02 dex/mag ⟺
Faint-end LF-slope $\alpha(z_{med}$ ∼1.6)≃–1.4 ⇒ reach M_{AB}≃–14 mag.

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

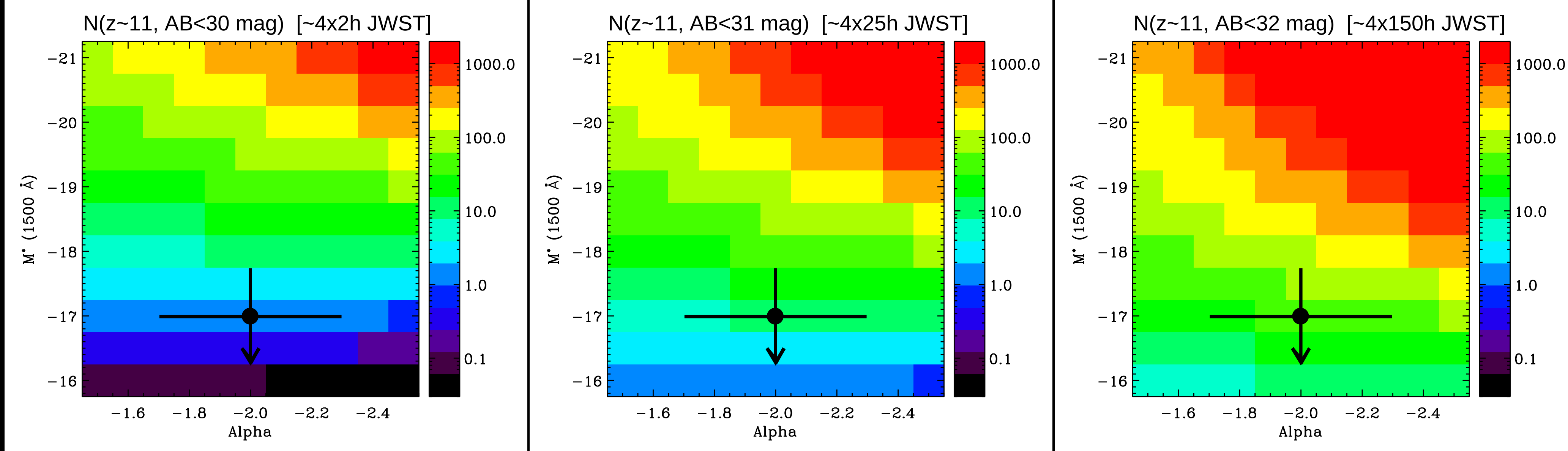
• Lensing will change the landscape for JWST observing strategies (WUDFF).



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.

$\Rightarrow$ Will have significant consequences for JWST survey strategy.



What do the 6 possible z$\simeq$9 and single z$\gtrsim$10 HUDF candidate mean?

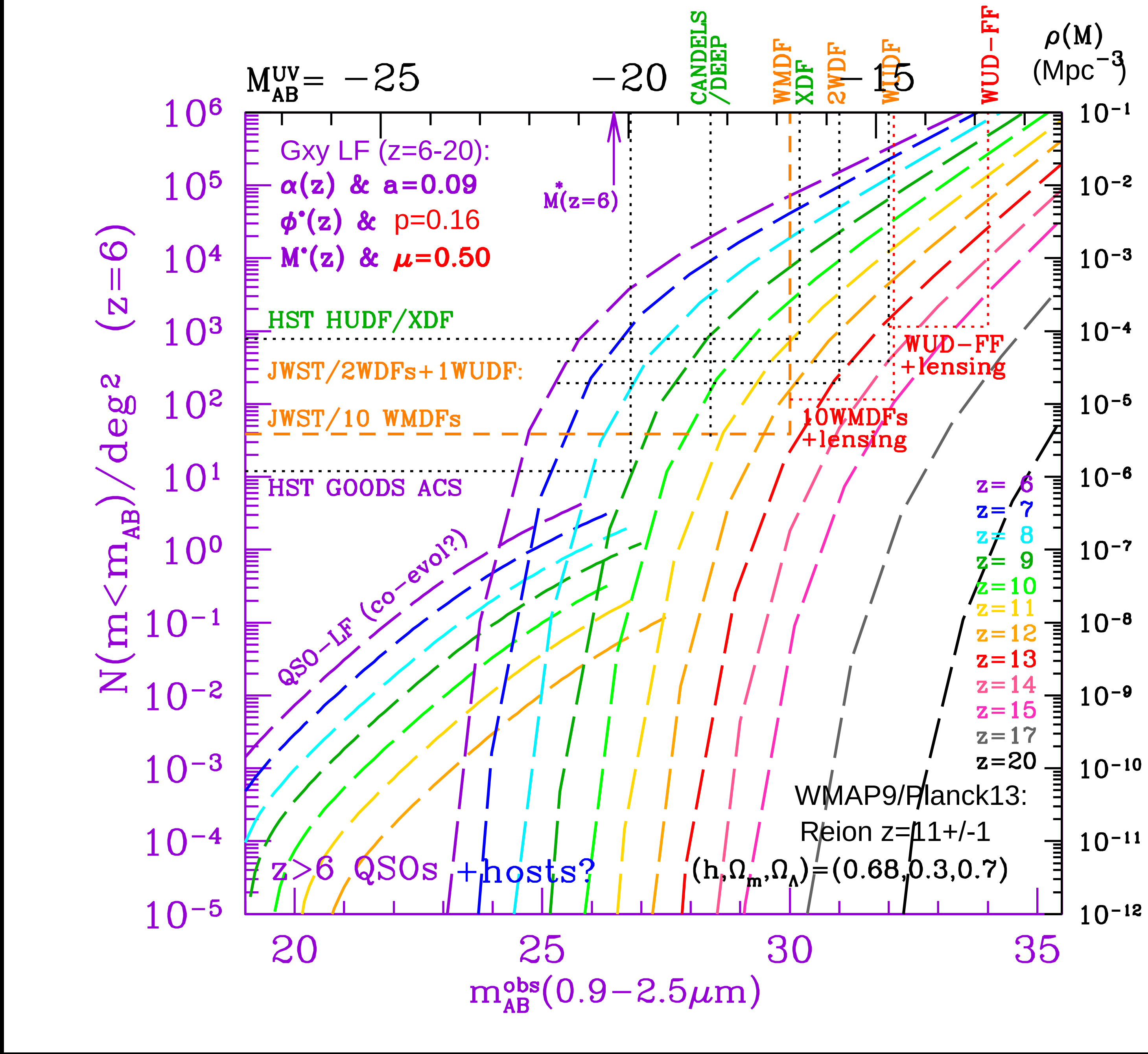
Integrate Schechter LFs with α(z), Φ^* (z) and M^* (z): $\lesssim$45% sky-coverage by AB$\lesssim$30 objects (Koekemoer+13). Cosmic Variance $\gtrsim$30%.

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

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

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

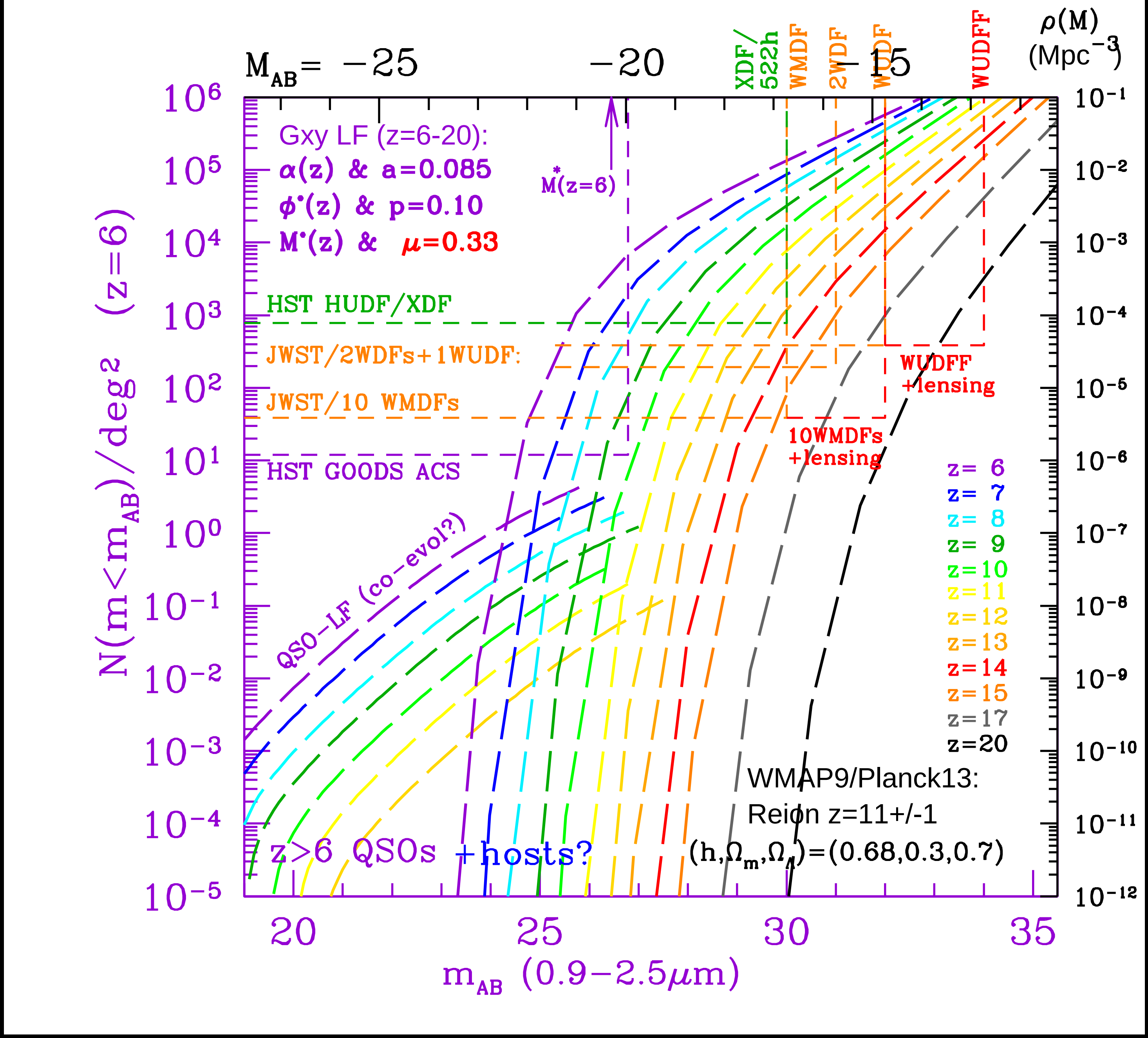
- (3) [Right] Webb UltraDeep Field (**WUDF**) (4×150h; NIRCam DD?]: Expect 30–90 objects to AB$\lesssim$32 mag, many more if lensing targets.



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

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

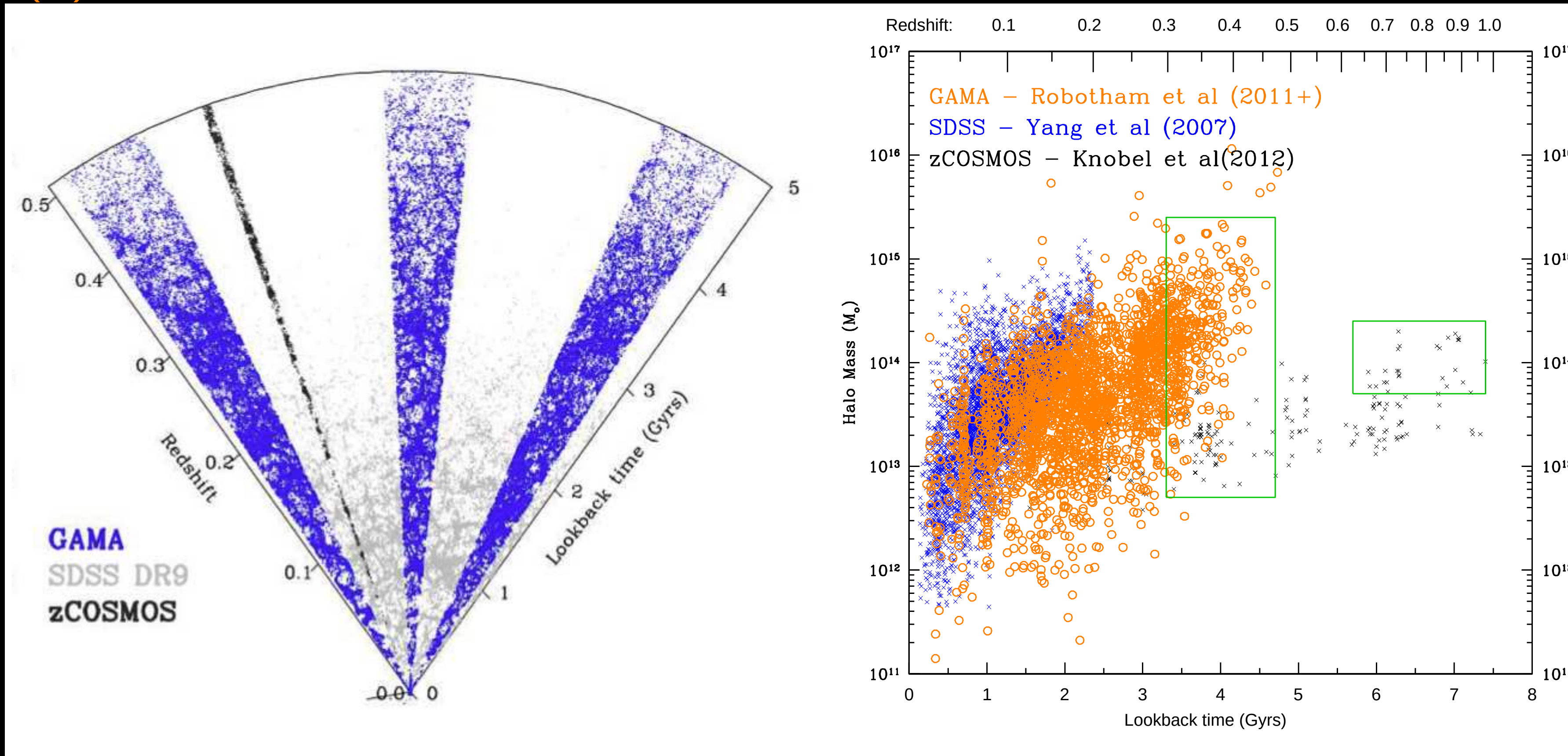
- Will need lensing targets for WMDF–WUDFF to see z≃12–15 objects.



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 $\Longleftrightarrow$ M^* (z≃11) fainter than −18±0.5 mag?

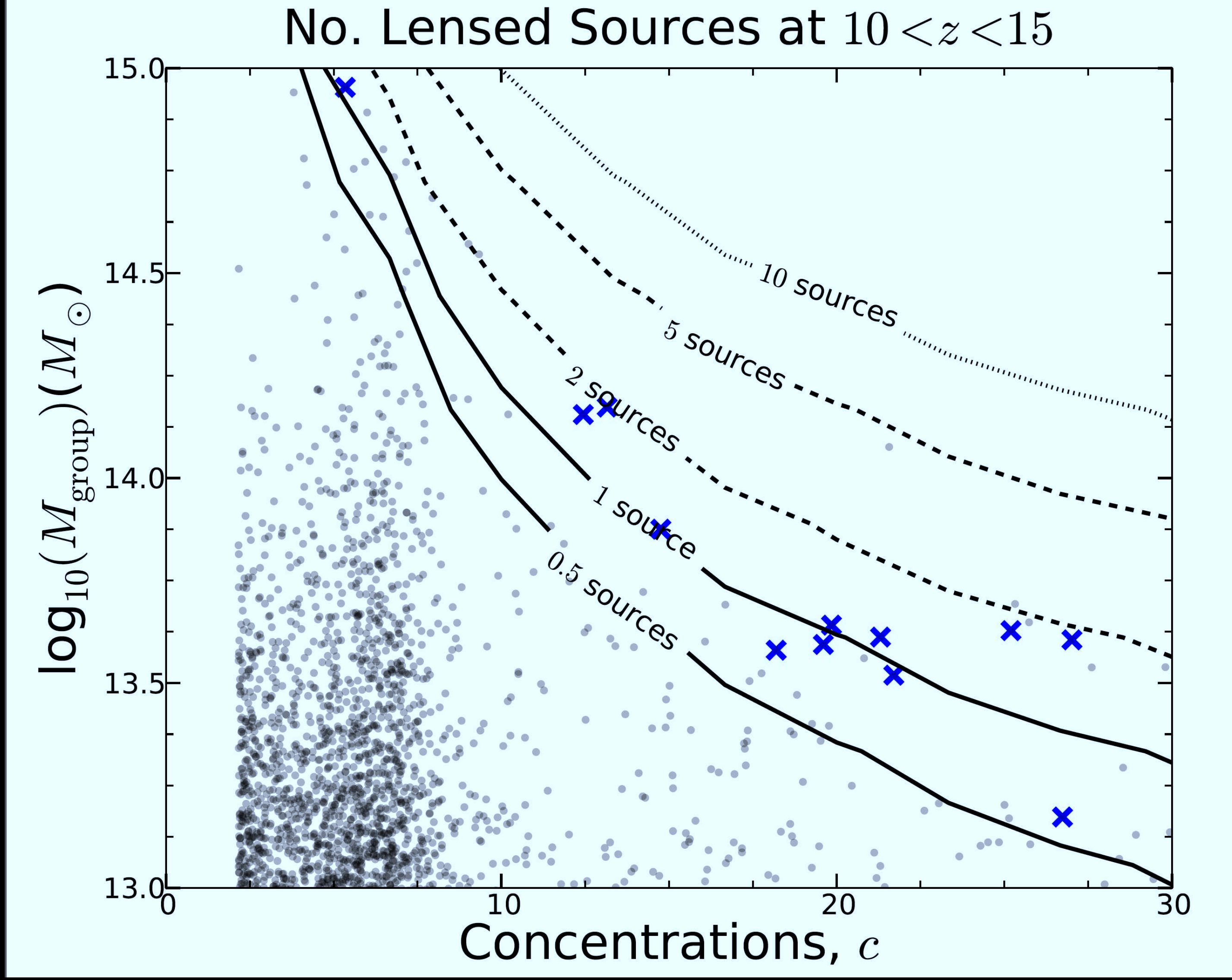
(3) What are the best lensing targets for JWST to see First Light?



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}\gtrsim$5 (Robotham$^+$ 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.



GAMA group mass versus concentration assuming NFW DM halo profiles.

Contours = Nr of expected lensed sources (Δz=1; Barone-Nugent+ 13).

- 10 WMDFs on best GAMA groups add ∼50 z≃6–15 sources (AB≲30).
- Get ≳5× more (∼250) lensed sources at z≃2–15; ∼600 at AB≲31.

WUDFF (AB≲32) pointed at cluster yields ∼300 lensed sources at 6≲z≲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;

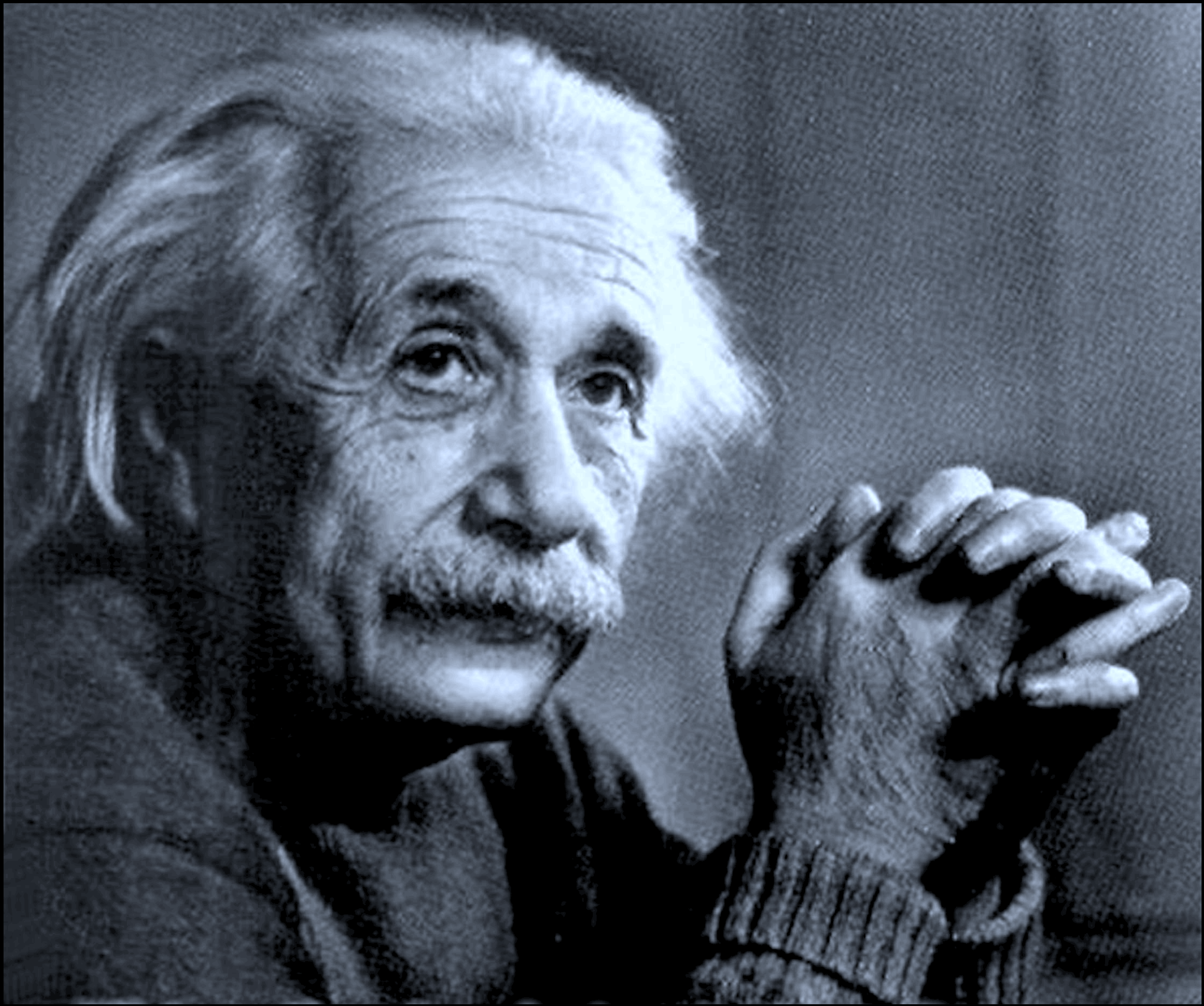
- JWST GO's will hopefully do an Webb Ultradeep Field (800 hr WUDF).

(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



In 2016, we should hold an Einstein Centennial Workshop in Princeton on:
"Gravitational Lensing in the JWST Era".

- 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/

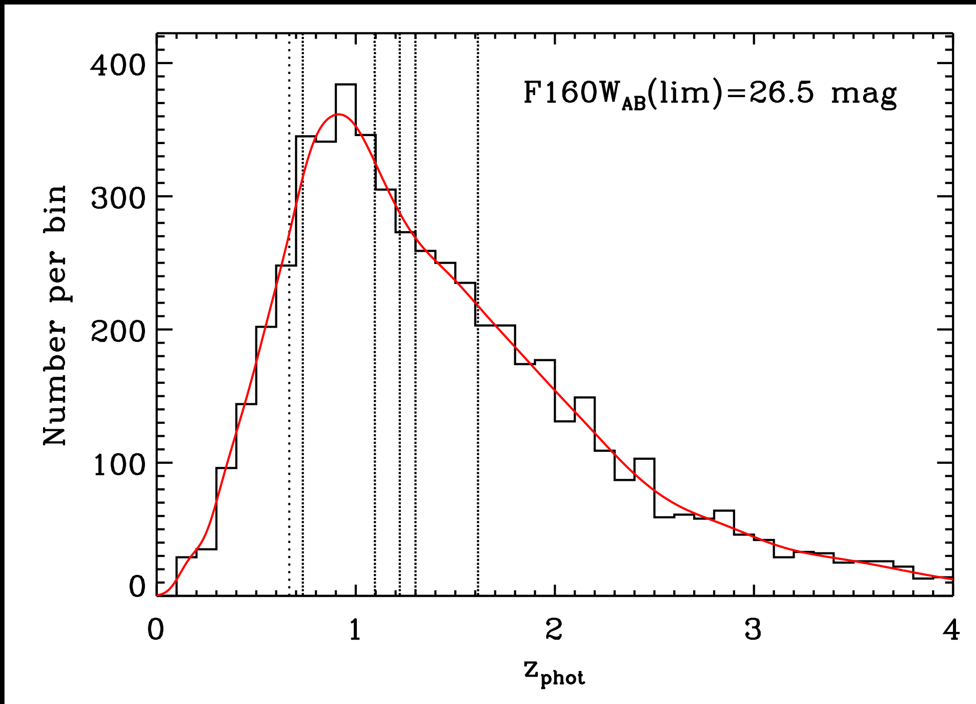
http://www.stsci.edu/jwst/instruments/fgs

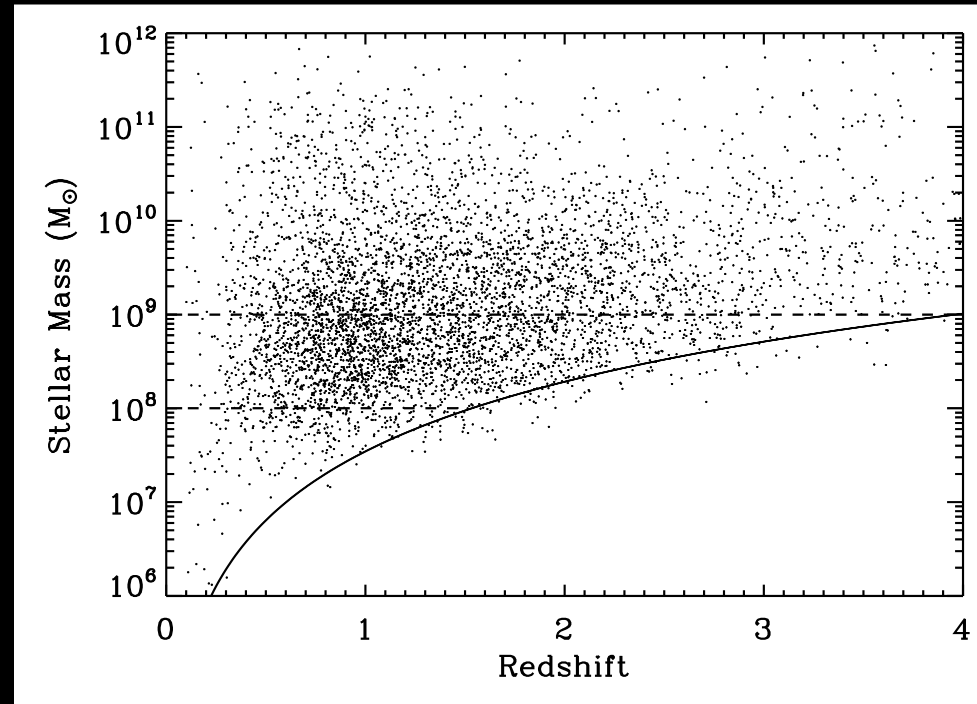
Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

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).





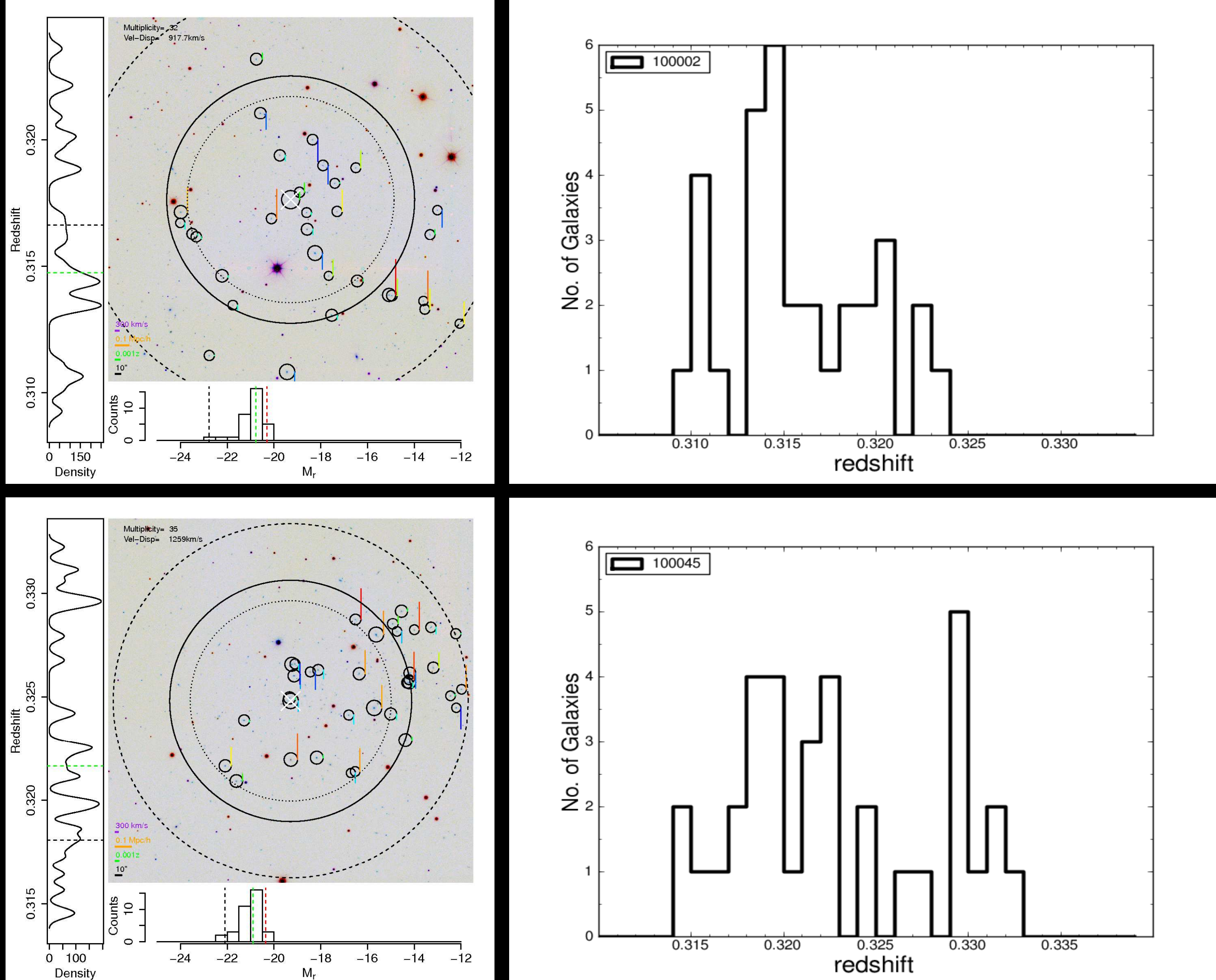
WFC3 ERS 10-band redshift estimates accurate to $\lesssim$4% with small systematic errors (Hathi et al. 2010, 2013), resulting in a reliable N(z).

• 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.

• 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.

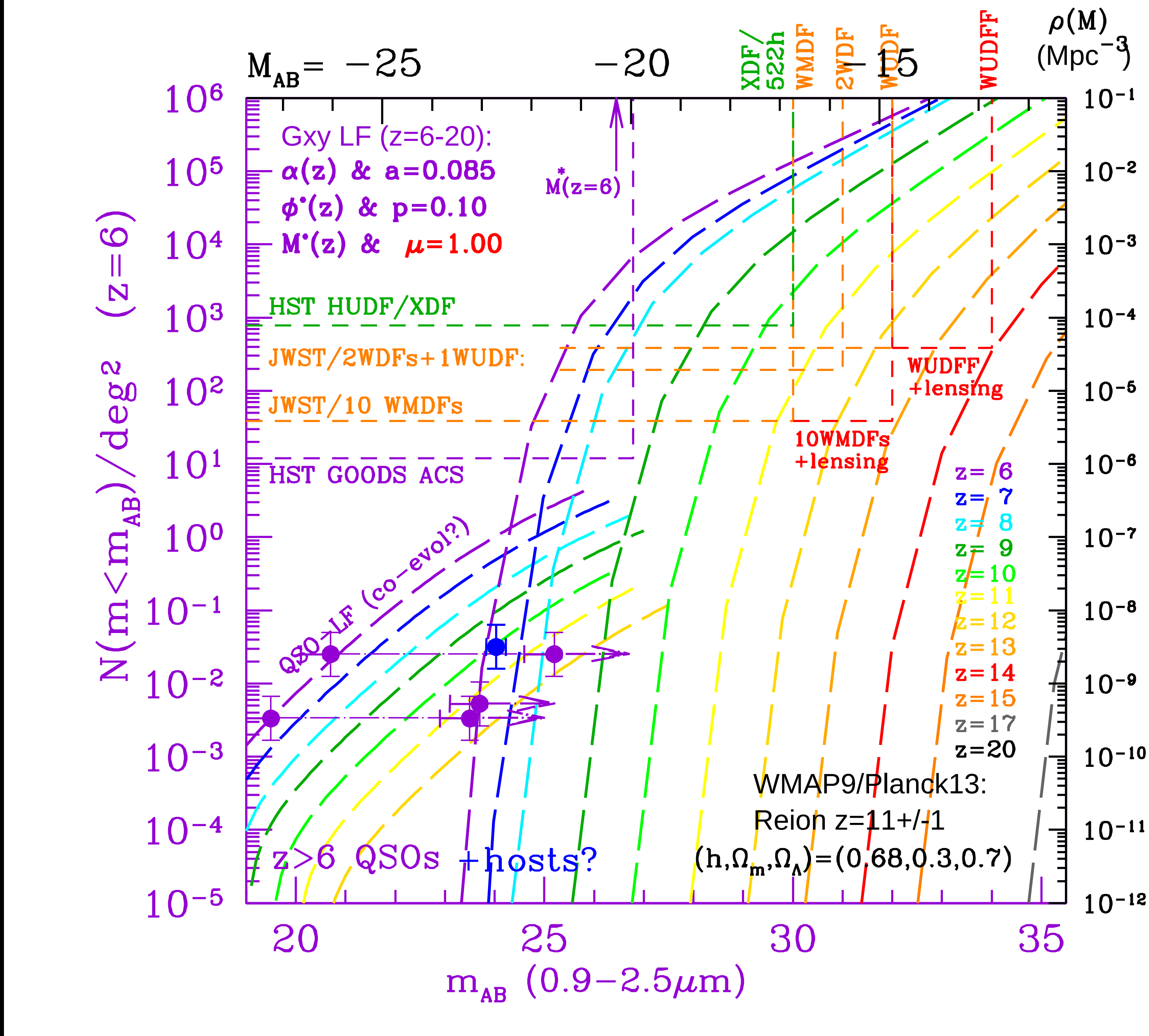


[Left] GAMA groups with secure AAT redshifts for R$\lesssim$19.8 AB-mag.

Also show redshift probability and absolute magnitude (M_r) distributions.

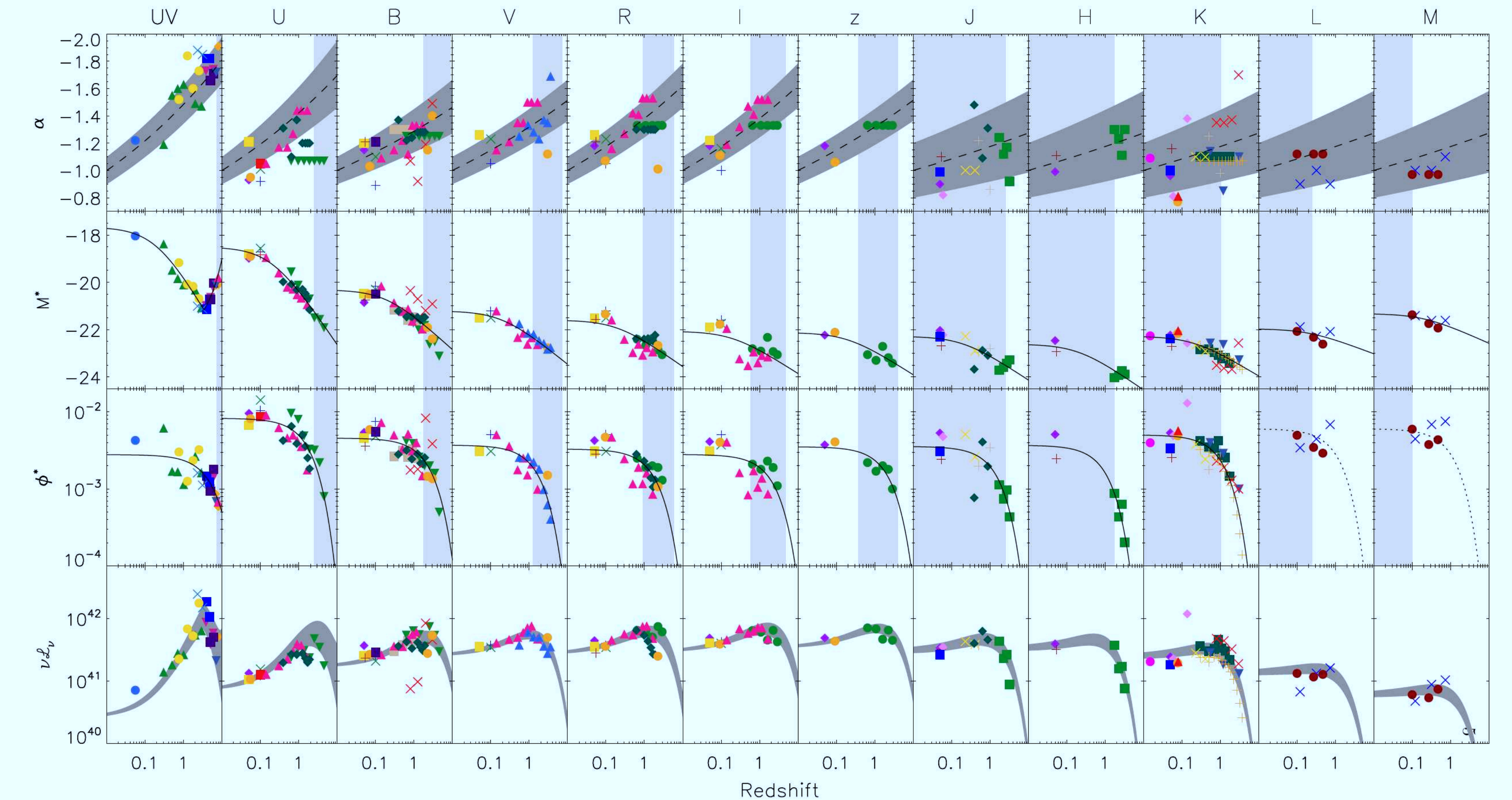
[Right] Measured group redshift distribution for two GAMA groups.

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



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).



(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≳25). Will update for JWST.