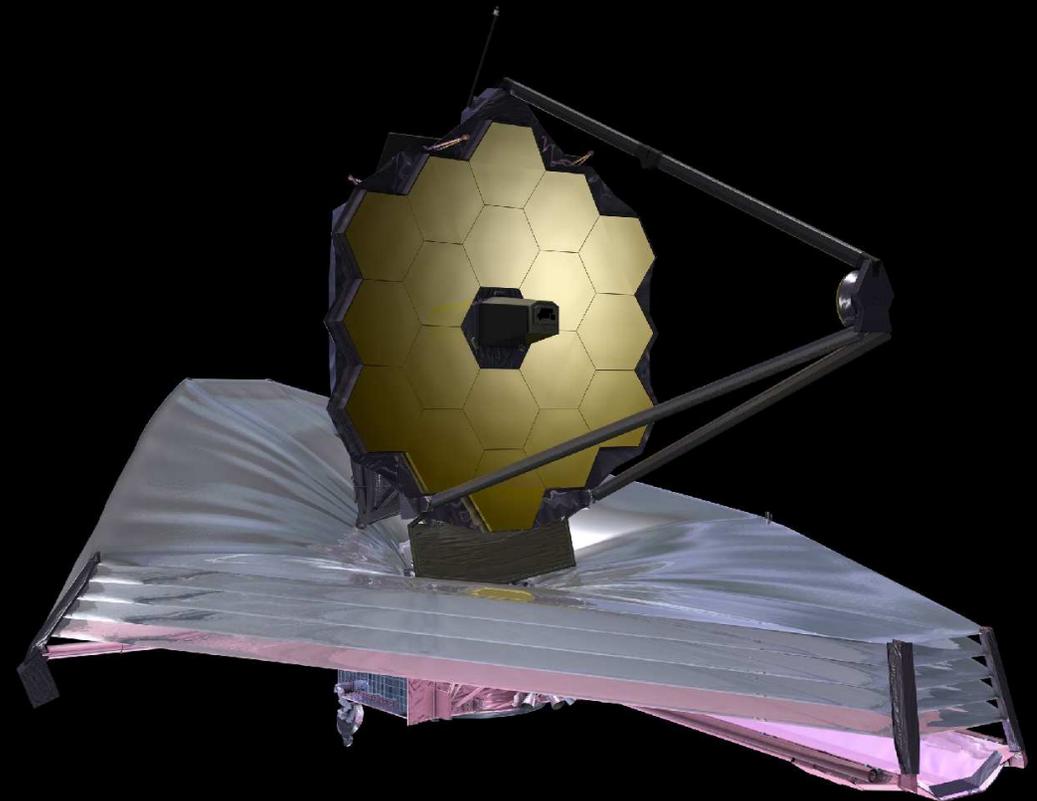# Strategies to Observe First Light with JWST: How can we best use Gravitational Lensing after 2018?

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.

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

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

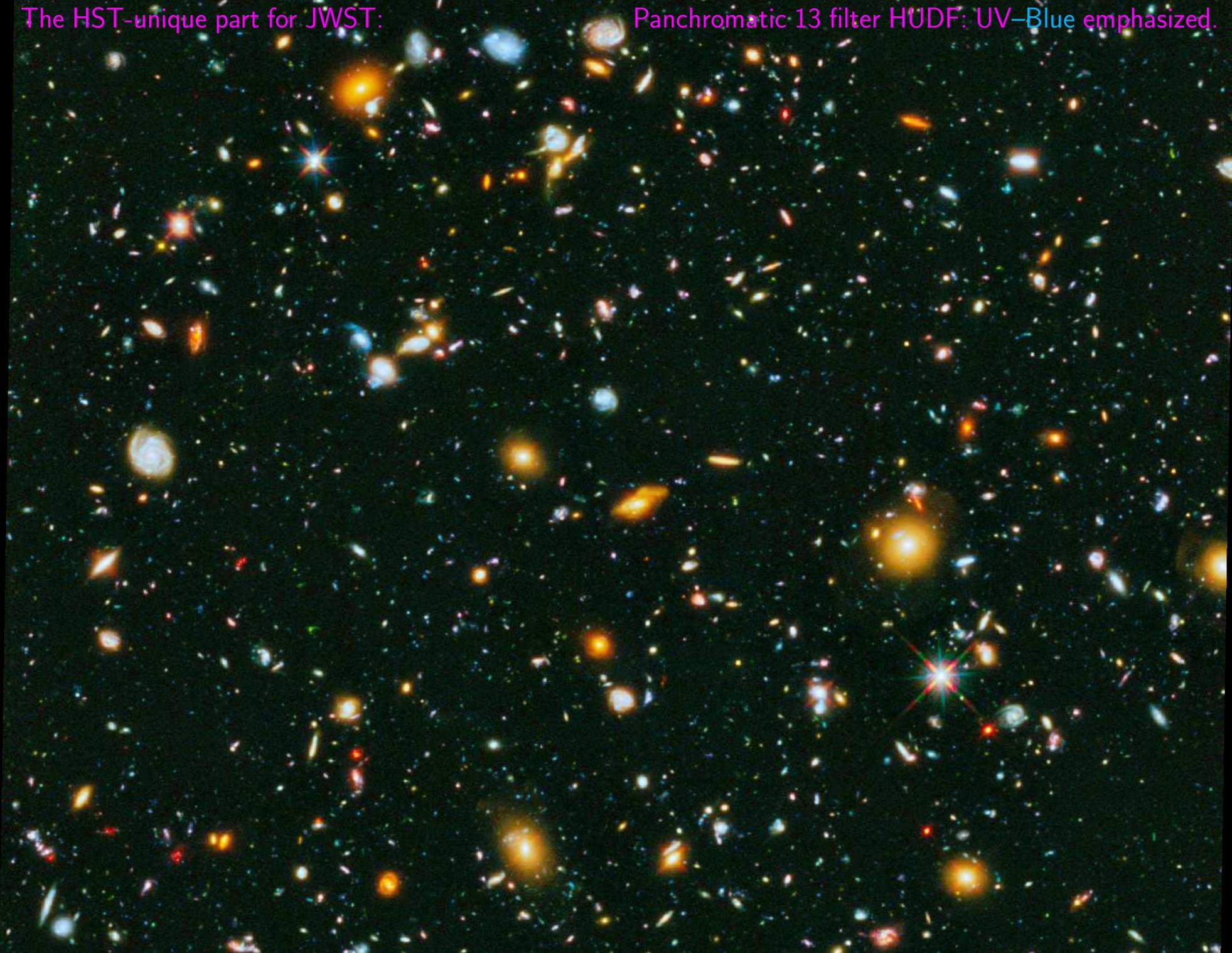(2) JWST hardware to date, and aspects relevant to lensing.

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

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

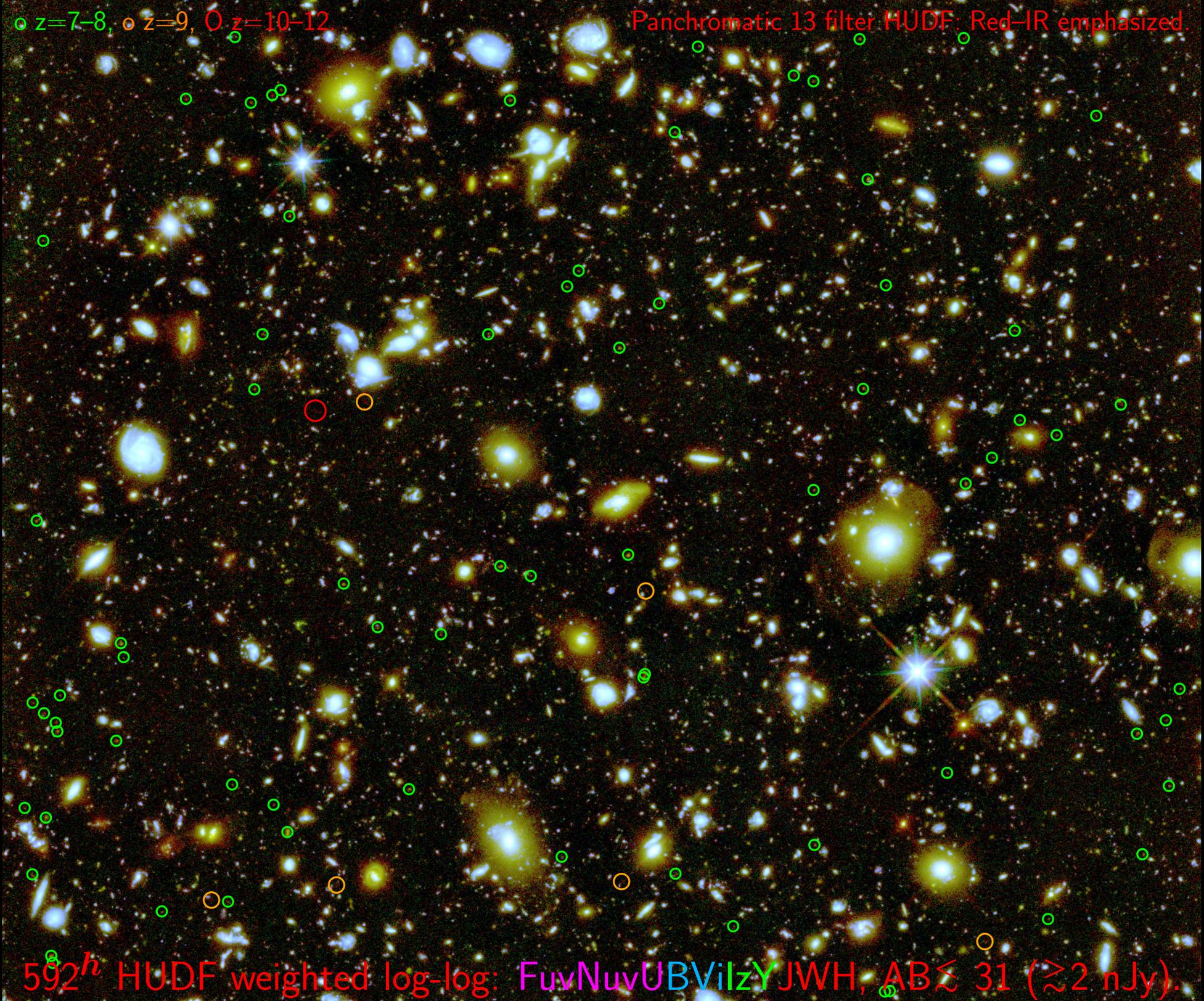(4) Recommendations and Conclusions.

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

592^{h} HUDF weighted log-log: FuvNuvUBVilzYJWH, AB$\lesssim$28–31 ($\gtrsim$2 nJy).
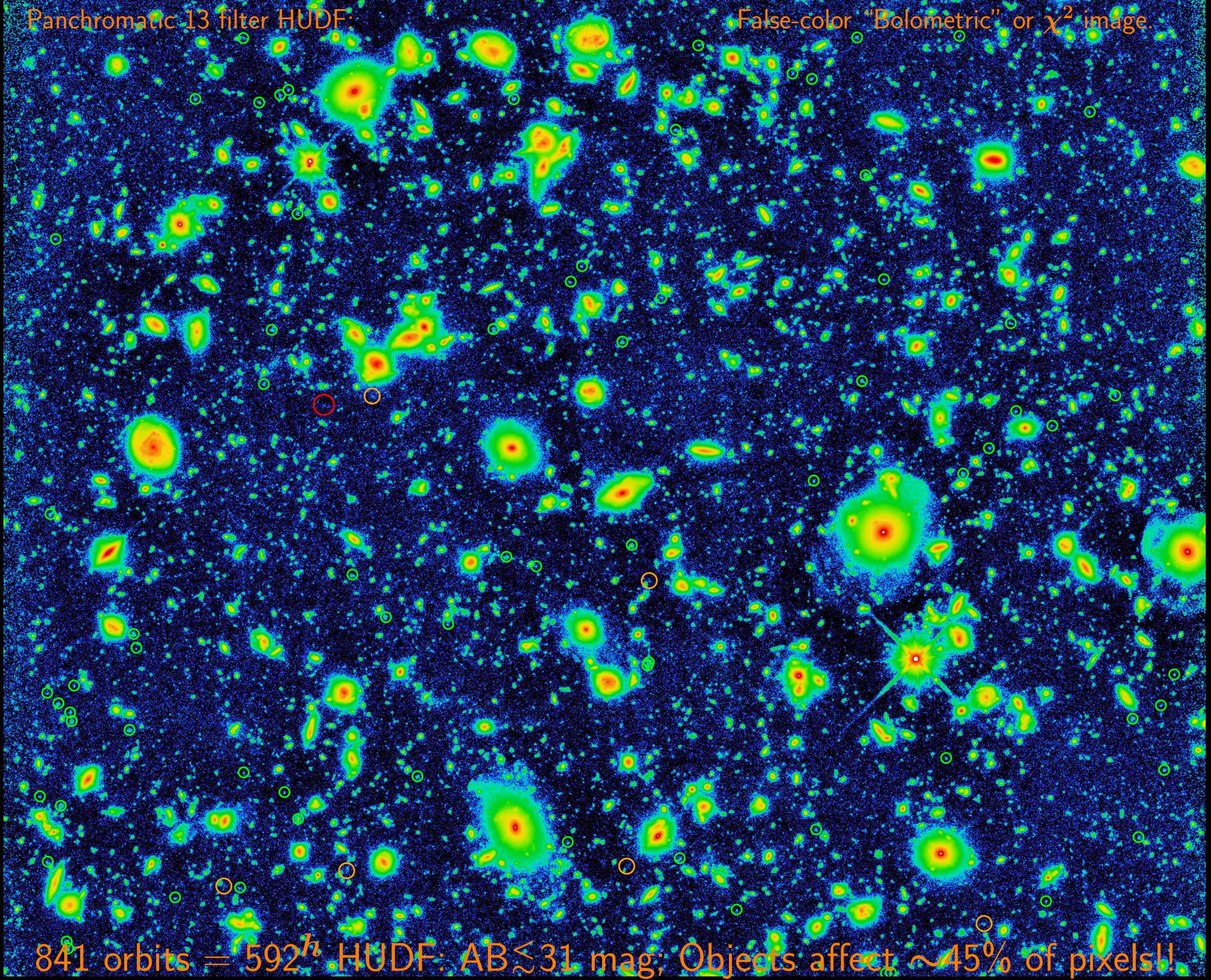
○ z=7–8, ○ z=9, ○ z=10–12   Panchromatic 13 filter HUDF: Red–IR emphasized.

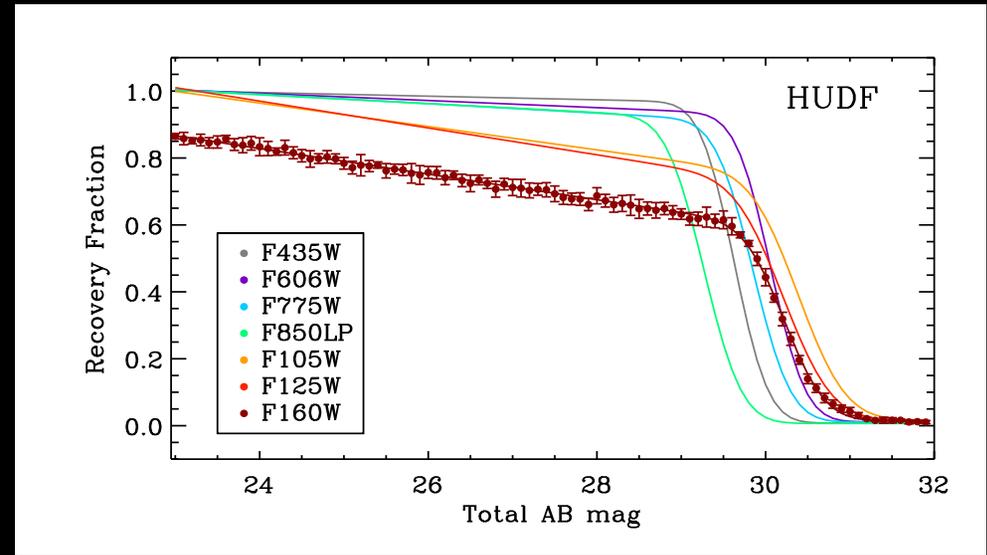592^h HUDF weighted log-log: FuvNuvUBVilzYJWH, AB≳ 31 (≳2 nJy).
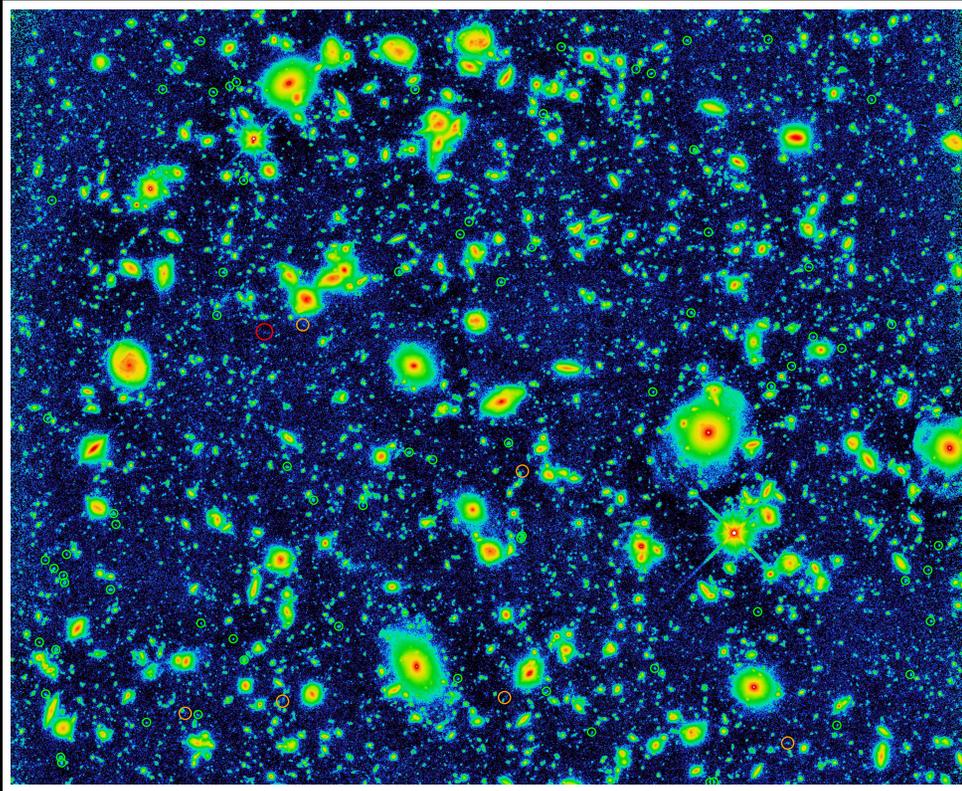
Panchromatic 13 filter HUDF:

False-color "Bolometric" or χ^2 image.

841 orbits = 592^h HUDF: AB$\lesssim$31 mag; Objects affect $\sim$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≃23 AB-mag is ∼15% incomplete!

(1) Cluster-Position Dependence of Deep-Field Completeness limits
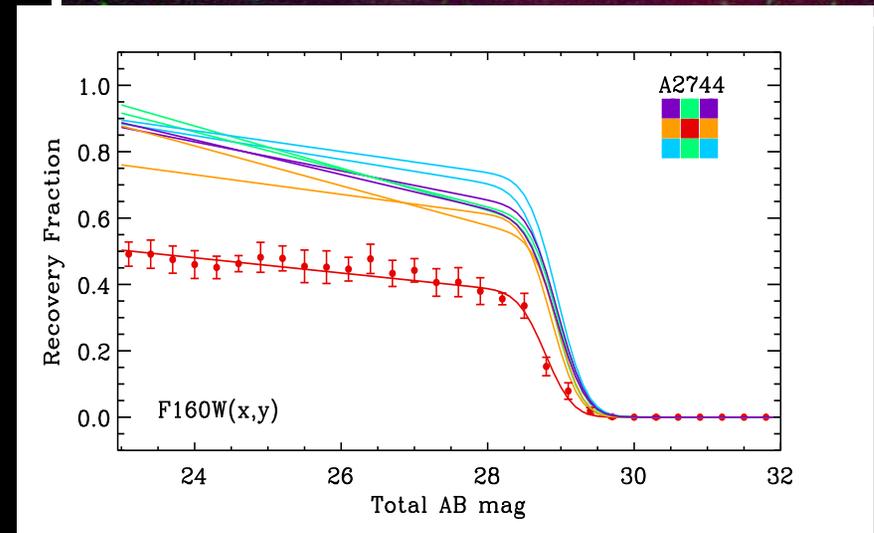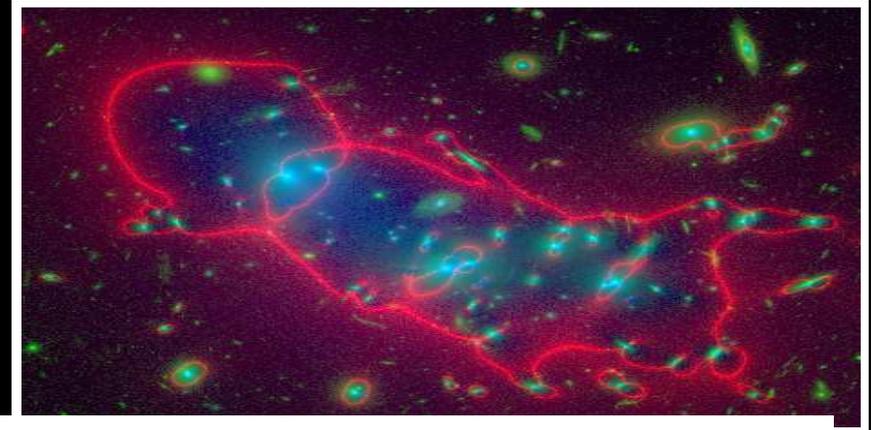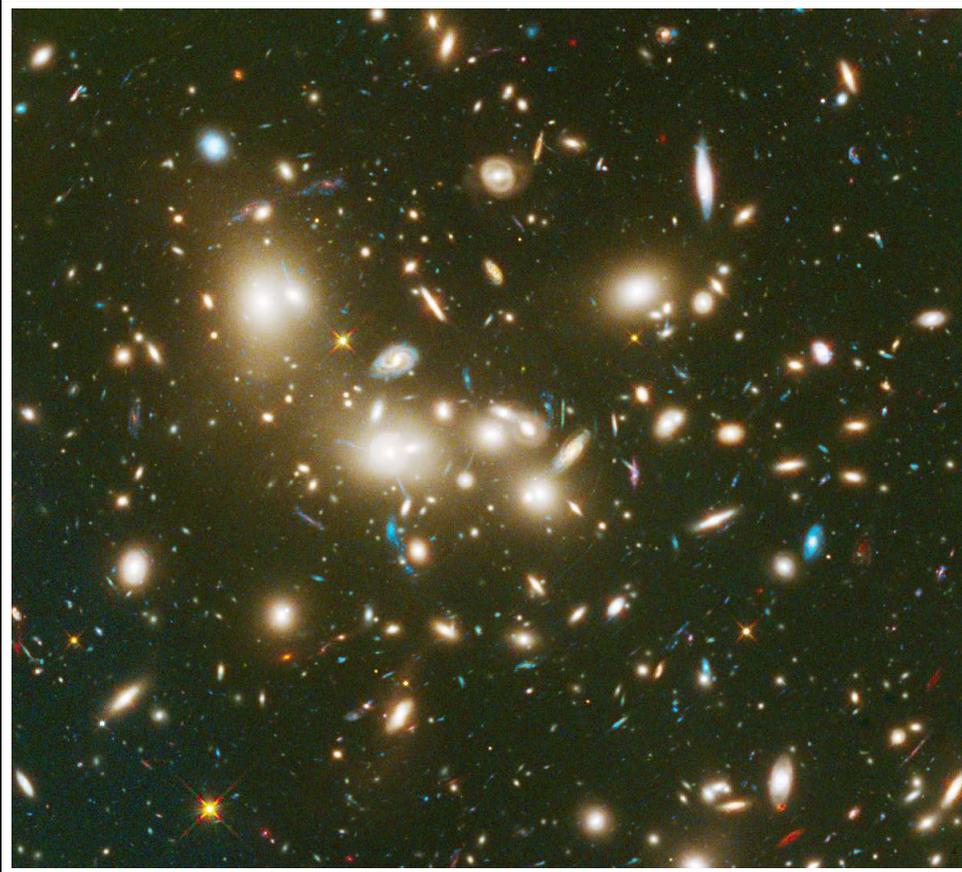
[LEFT]: HFF cluster A2744 in: F435W+F606W, F814W+F105W, F125W+F140W+F160W.

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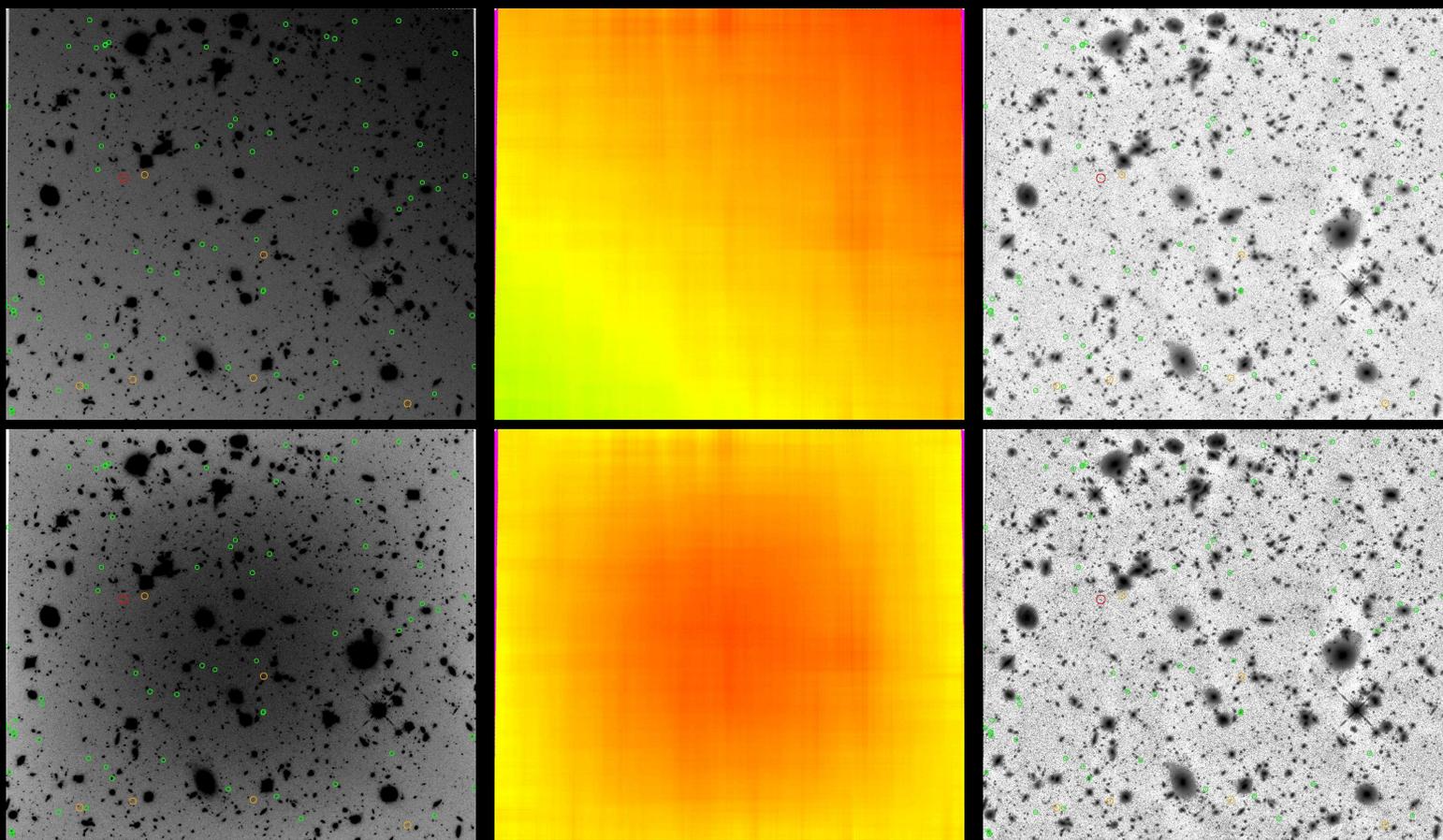
[TOP]: [Left] HUDF F160W image with *worst case* (95% of Zodi) rogue-path amplitude imposed $\pm$ a 4% *linear gradient* from corner-to-corner.

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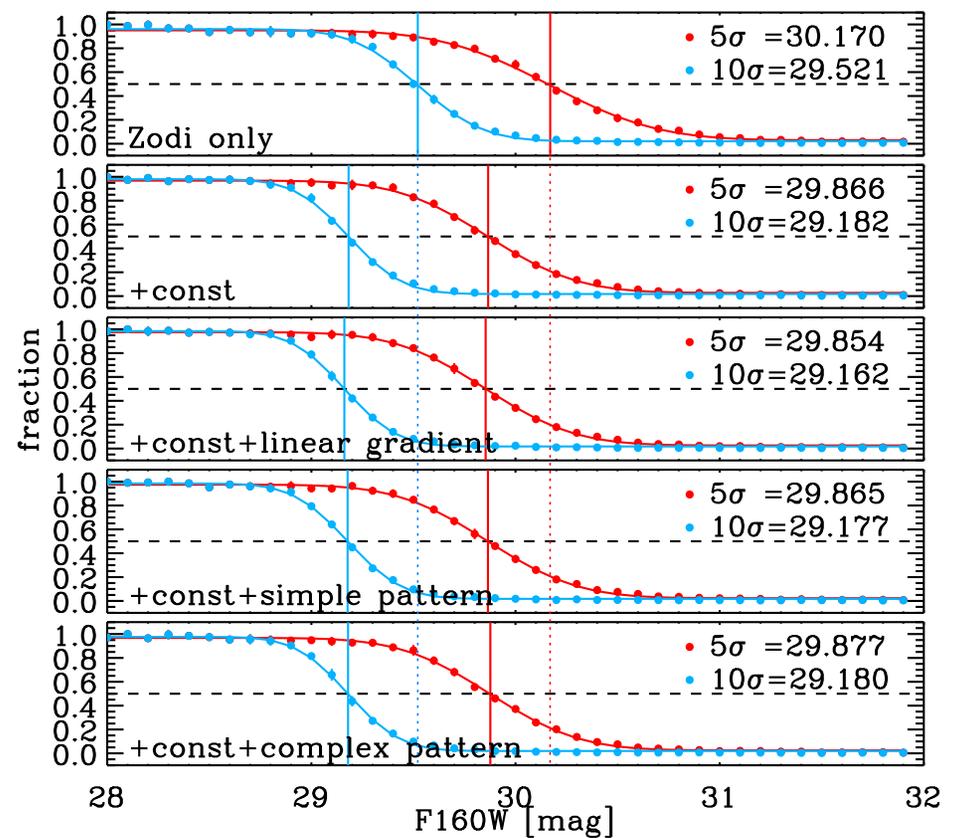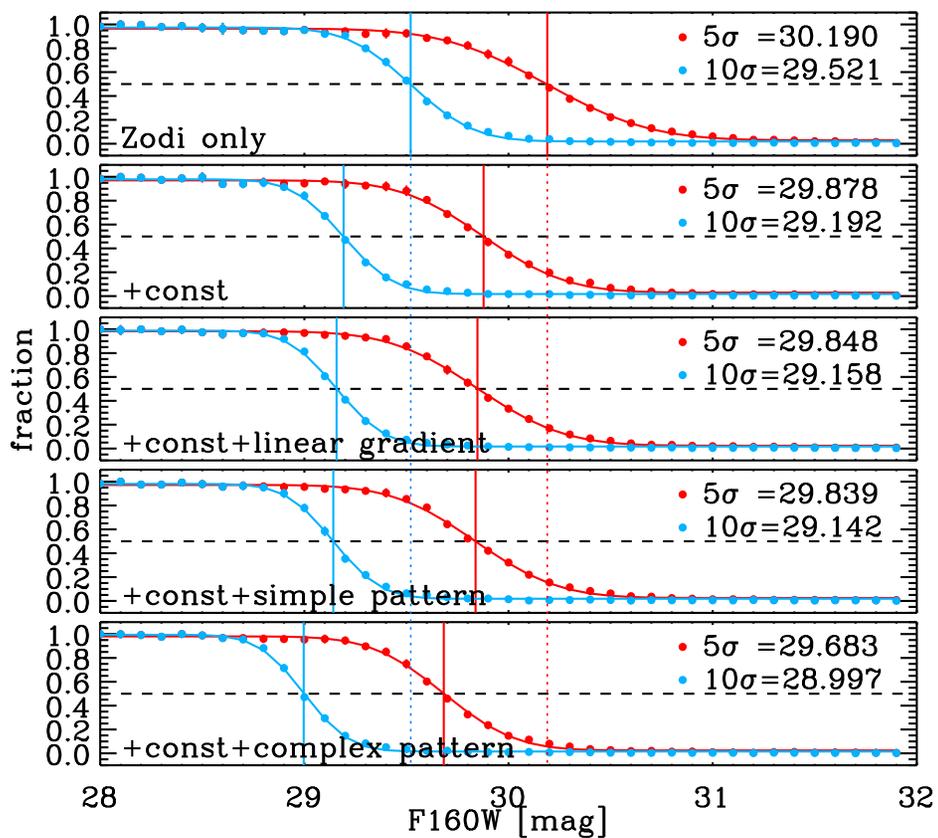
[LEFT]: Completeness tests in HUDF F160W image *before* imposing on top of Zodi (=22.70 H-mag arcsec^{-2}; Petro 2001) [2nd–5th row]:
Constant 95% of Zodi amplitude; + *a ±4% linear gradient*; or *simple 2D pattern of ±4%*; or *a more complex pattern*.

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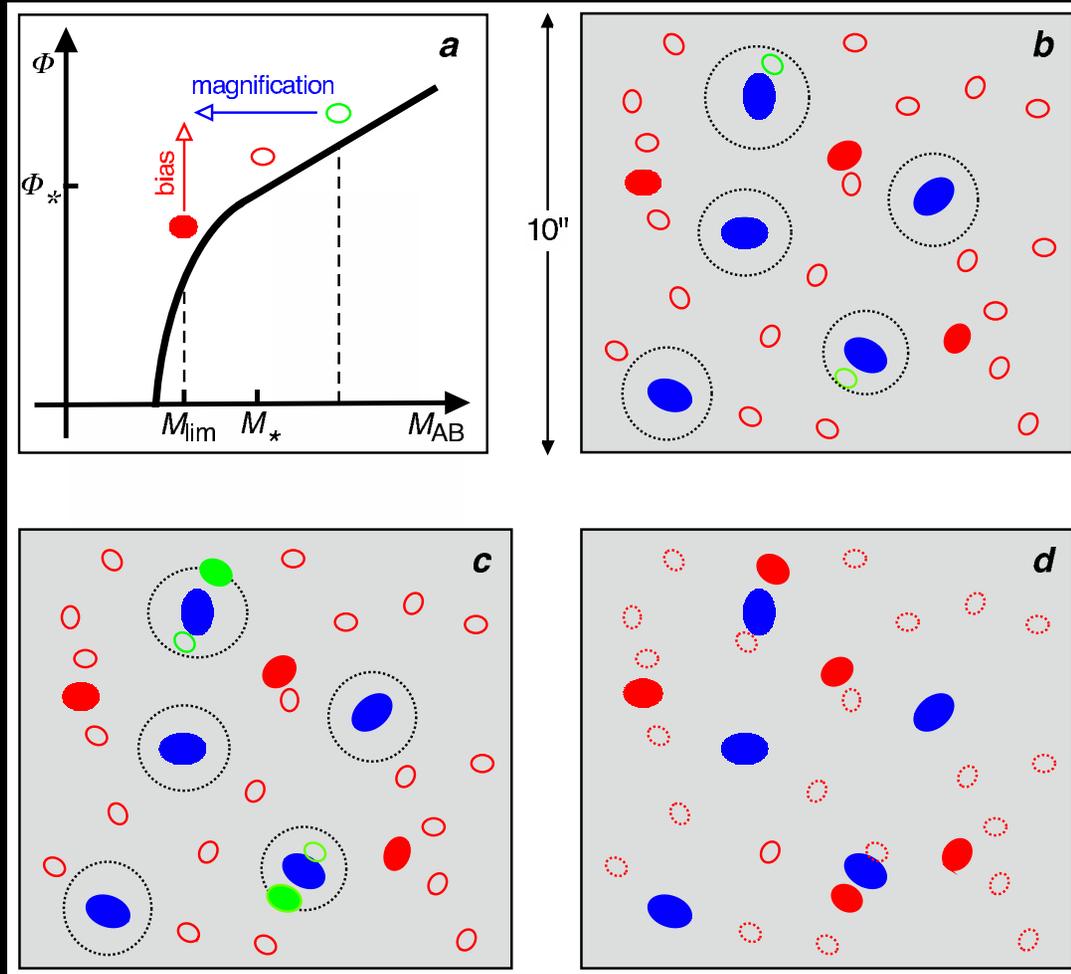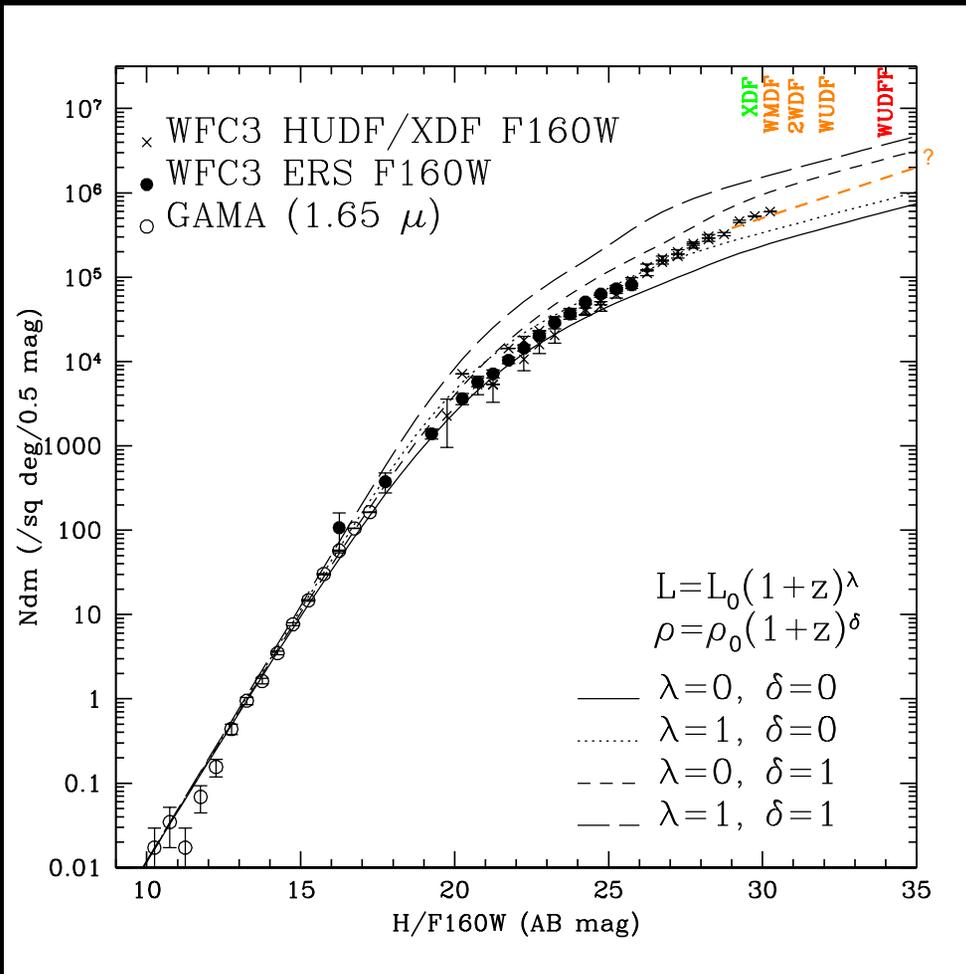
1.6μm counts (Windhorst[+]2011).   [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

● Faint-end near-IR count-slope$\simeq$0.16$\pm$0.02 dex/mag $\iff$

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$\lesssim$32 objects: $M_{AB} \simeq$−15 (LMCs) at z$\simeq$11.

● Lensing will change the landscape for JWST observing strategies (WUDFF).
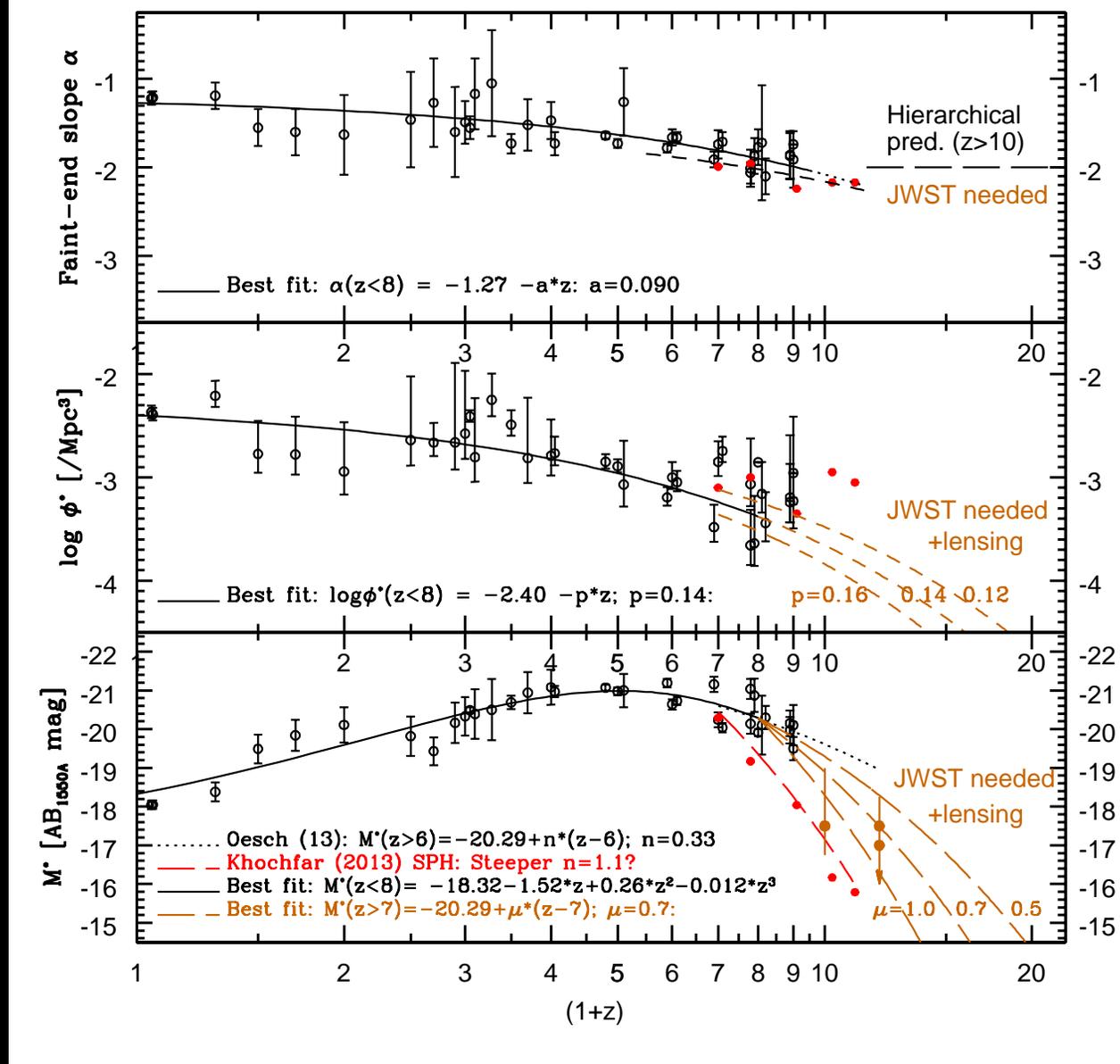
Evolution of Schechter UV-LF: faint-end LF-slope $\alpha(z)$, $\Phi^*(z)$ & $M^*(z)$:
- For JWST $z \gtrsim 8$, expect $\alpha \lesssim -2.0$; $\Phi^* \lesssim 10^{-3}$ (Mpc^{-3}) (Bouwens[+] 14).
- HUDF: Characteristic M^* may drop below -18 or -17.5 mag at $z \gtrsim 10$.

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

N(z~11, AB<30 mag) [~4x2h JWST]   N(z~11, AB<31 mag) [~4x25h JWST]   N(z~11, AB<32 mag) [~4x150h JWST]
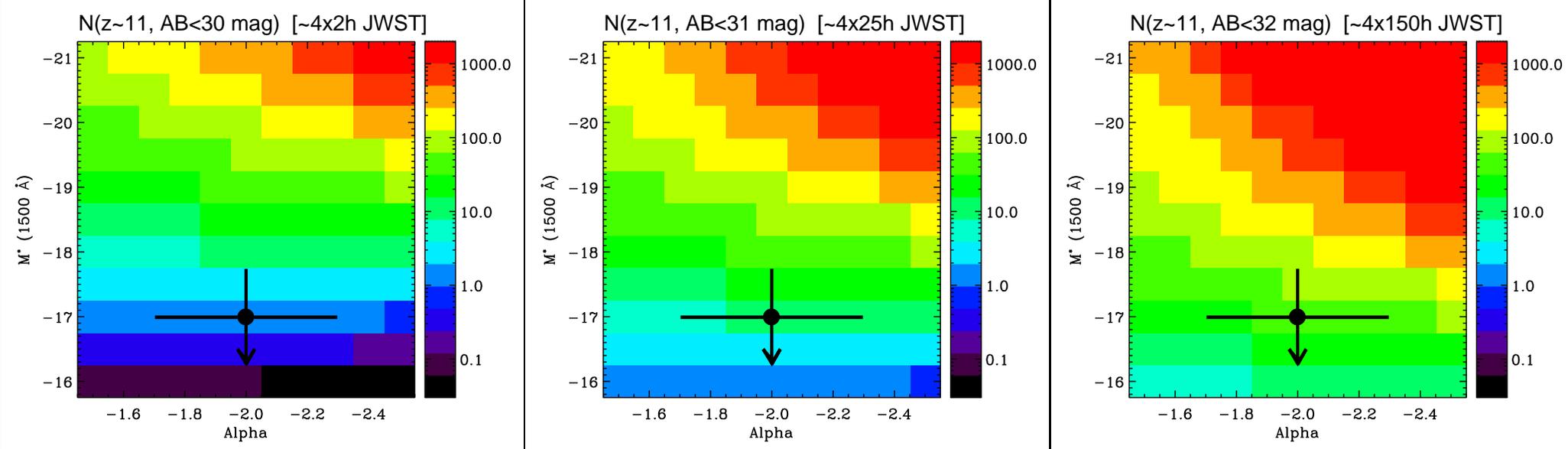
**What do the 6 possible z≃9 and single z≳10 HUDF candidate mean?**

Integrate Schechter LFs with $\alpha(z)$, $\Phi^*(z)$ and $M^*(z)$: ≲45% sky-coverage by AB≲30 objects (Koekemoer[+]13). Cosmic Variance ≳30%.

For any $\alpha(z≳10)$, implies $M^*(z≳10)≳$–18 or $\Phi^* ≲10^{-3.5}$, 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.
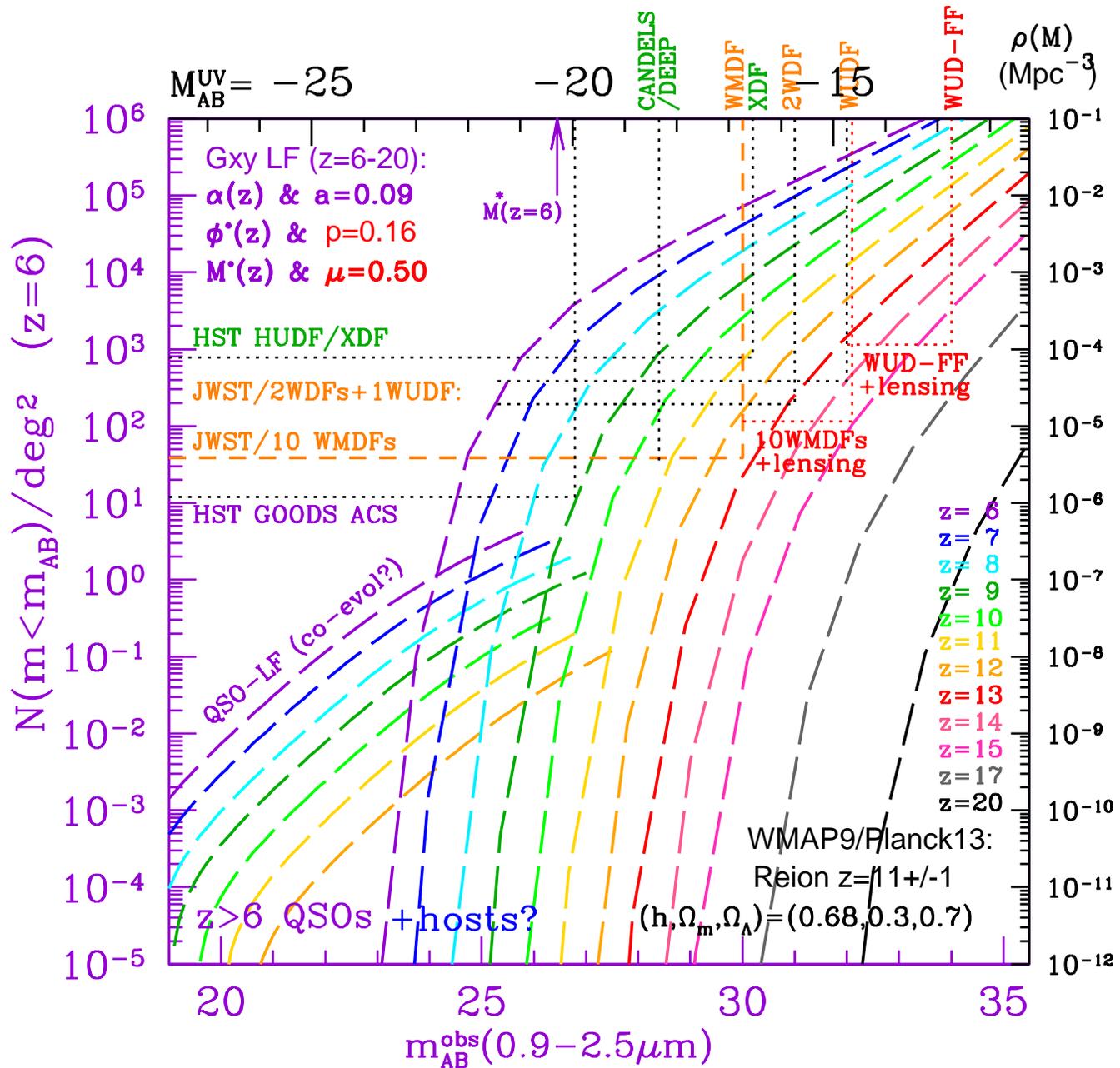
Schechter LF ($6 \lesssim z \lesssim 20$) with best-fit $\alpha(z)$, $\Phi^*(z)$, $M^*(z)$ & $\mu=0.50$.
Area/Sensitivity for: HUDF/XDF, **10 WMDFs**, 2 WDFs, & 1 WUDF.
● Will need lensing targets for WMDF–WUDFF to see $z \simeq 12$–15 objects.
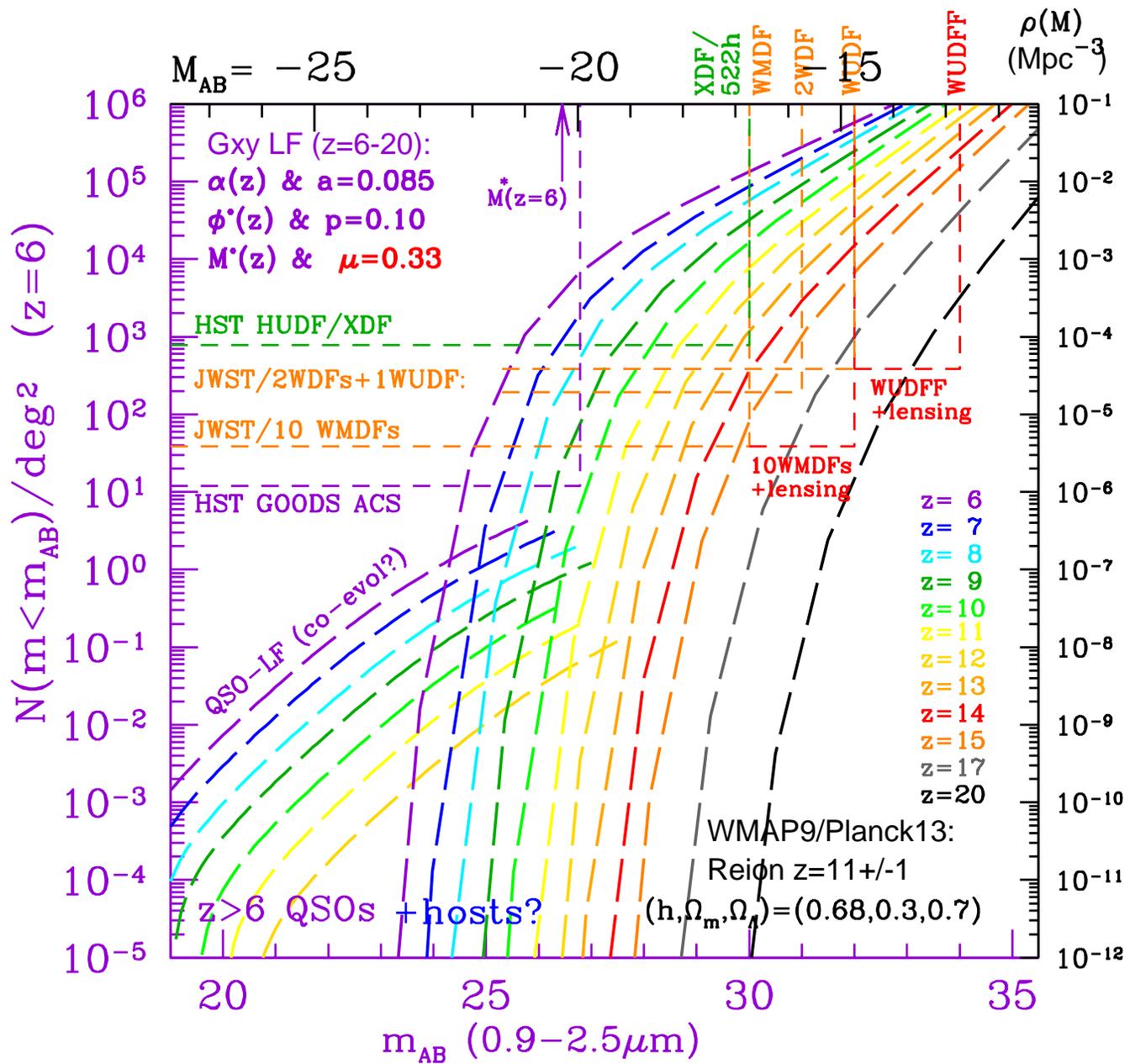
Same as p. 15, but optimistic M^*(z) drop: μ=0.33 (Oesch et al. 2013).
● If so, far more $9 \lesssim z \lesssim 12$ objects expected in XDF, even though N($6 \lesssim z \lesssim 8$) remains the same $\iff M^*$($z \simeq 11$) fainter than -18 ± 0.5 mag?

(3) What are the best lensing targets for JWST to see First Light?
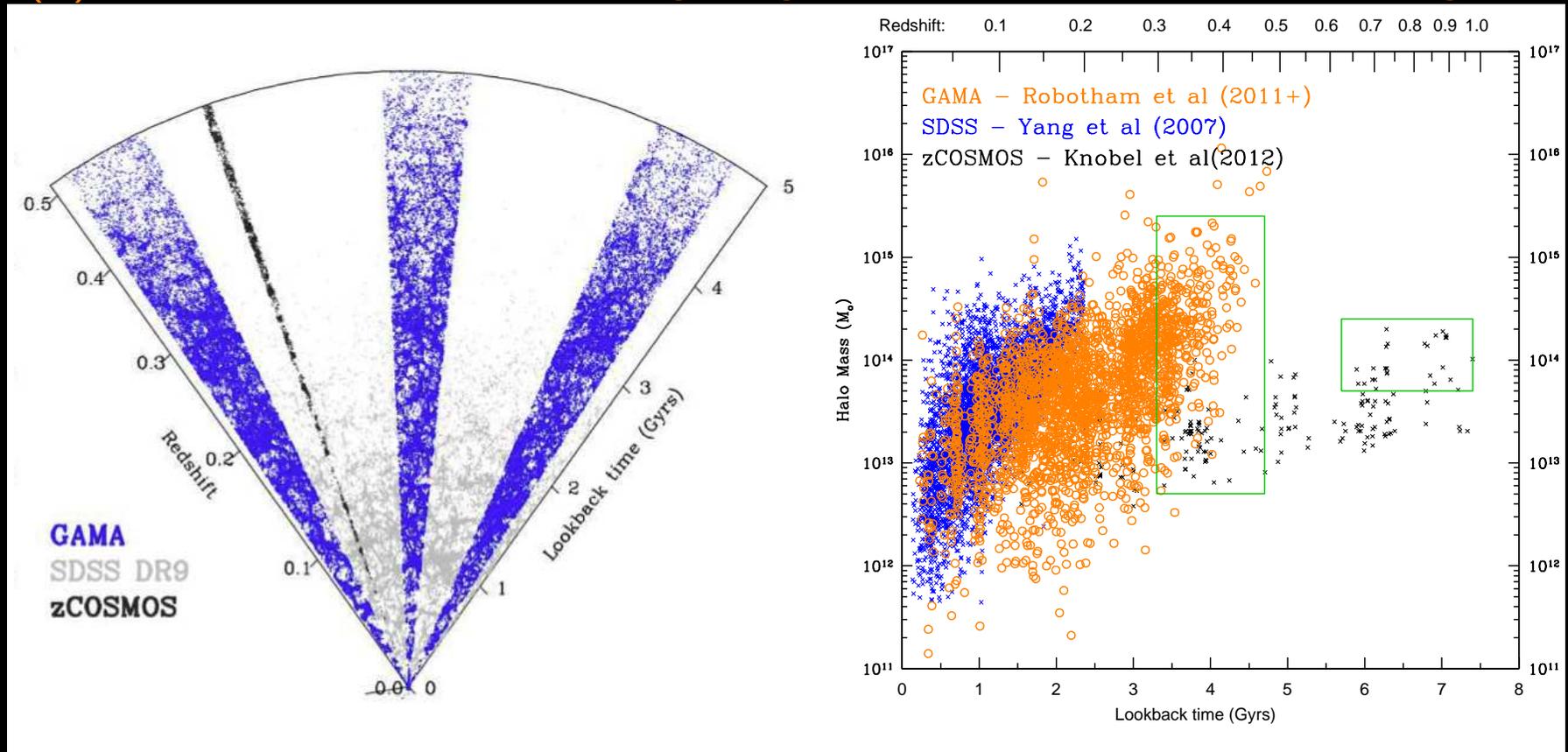
For JWST, use the best lenses in 2018: Rich clusters or (compact) groups!

[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.

No. Lensed Sources at $10 < z < 15$
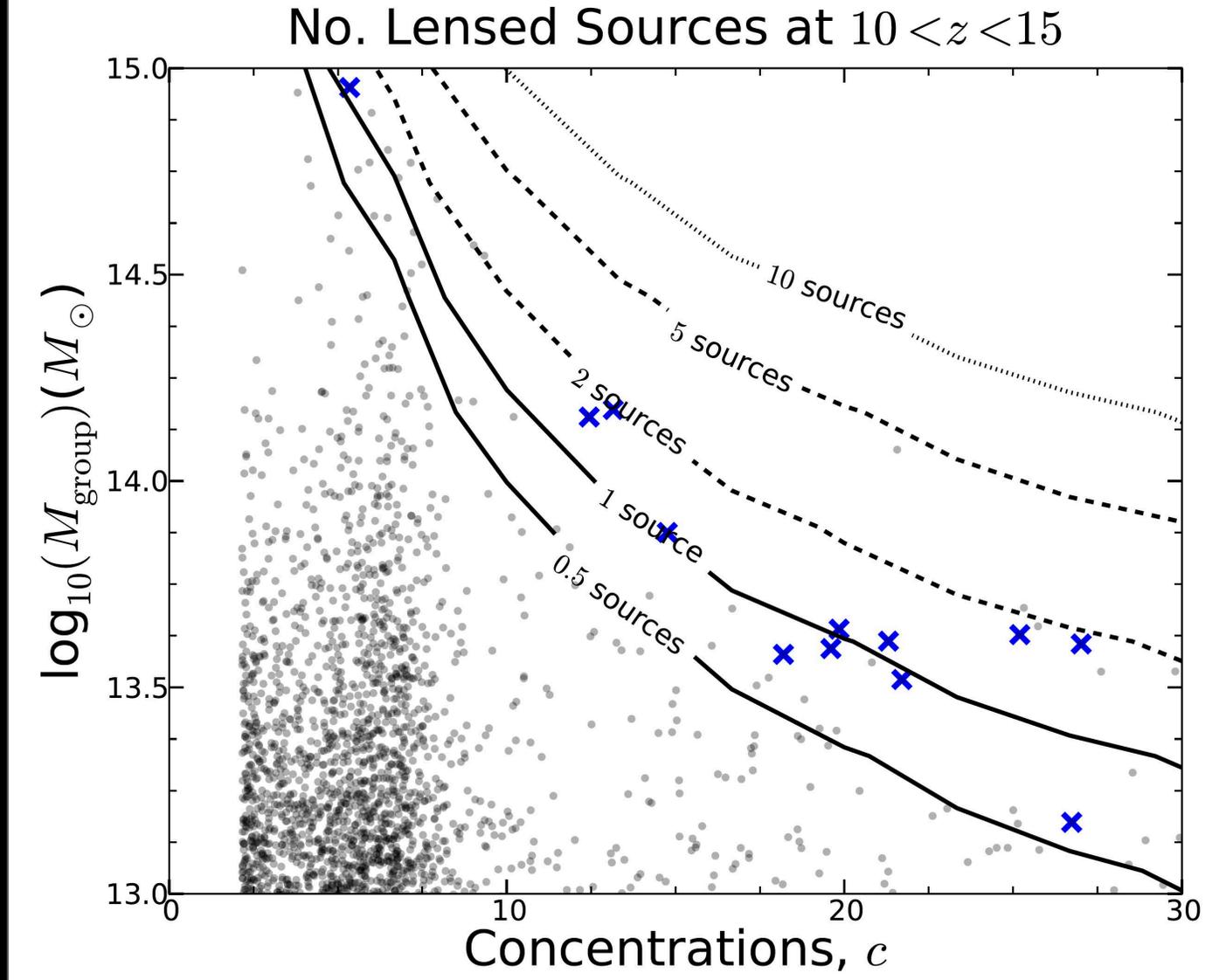
GAMA group mass versus concentration assuming NFW DM halo profiles.
Contours $=$ Nr of expected lensed sources ($\Delta z = 1$; Barone-Nugent[+] 13).
- 10 WMDFs on best GAMA groups add $\sim$50 $z \simeq$ 6–15 sources (AB$\lesssim$30).
- Get $\gtrsim$5$\times$ more ($\sim$250) lensed sources at z$\simeq$2–15; $\sim$600 at AB$\lesssim$31.
WUDFF (AB$\lesssim$32) pointed at cluster yields $\sim$300 lensed sources at 6$\lesssim$z$\lesssim$15.
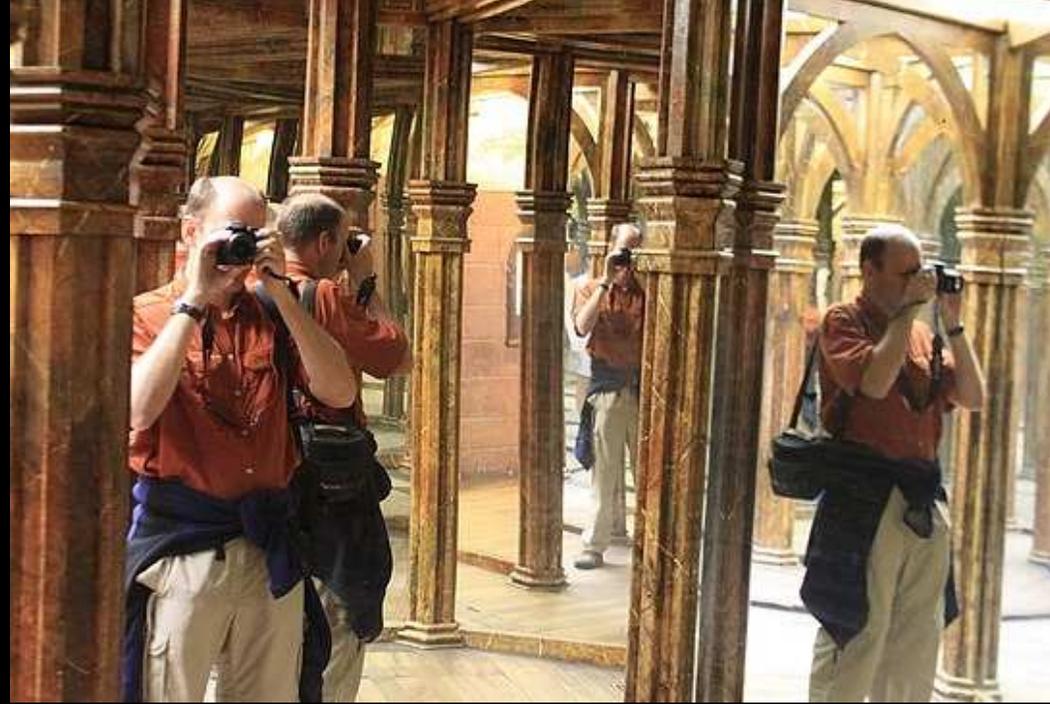
Conclusion: JWST First Light strategy must consider three aspects:

(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 $\Phi^* \lesssim 10^{-3.5}$, 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 $\sim$7 hr Webb Medium-Deep Fields (10 WMDF's), anticipating that:

- NIRCam team & GO's will do two ($\sim$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, $\sim$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
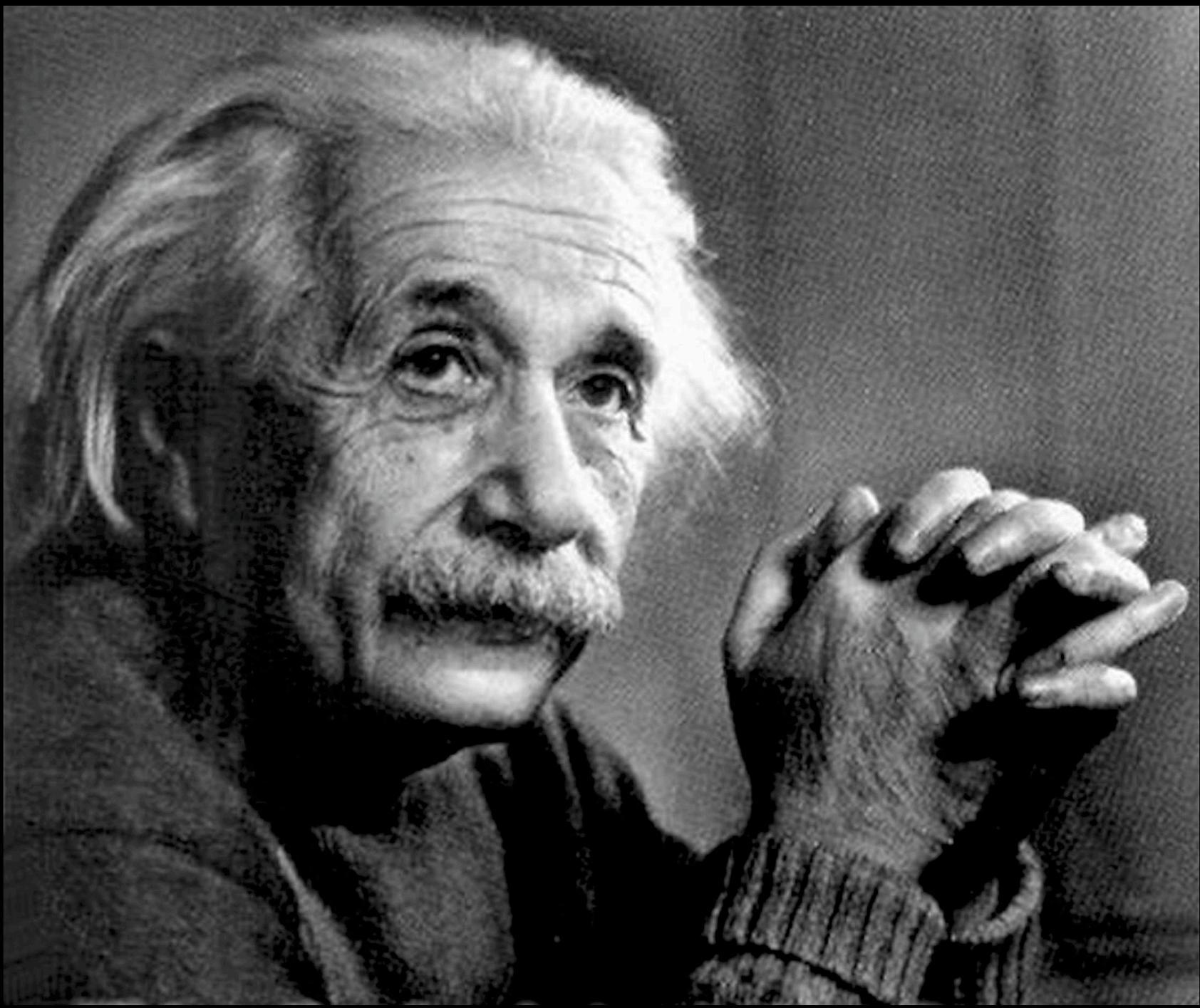
In 2016, we should hold an Einstein Centennial Workshop in Princeton on: "Gravitational Lensing in the JWST Era".

- 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/

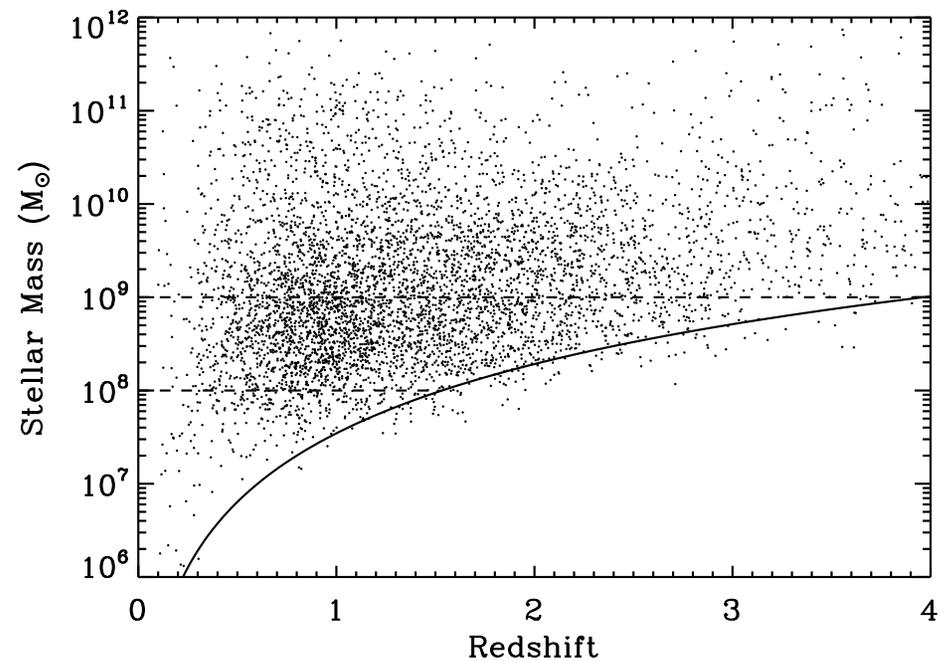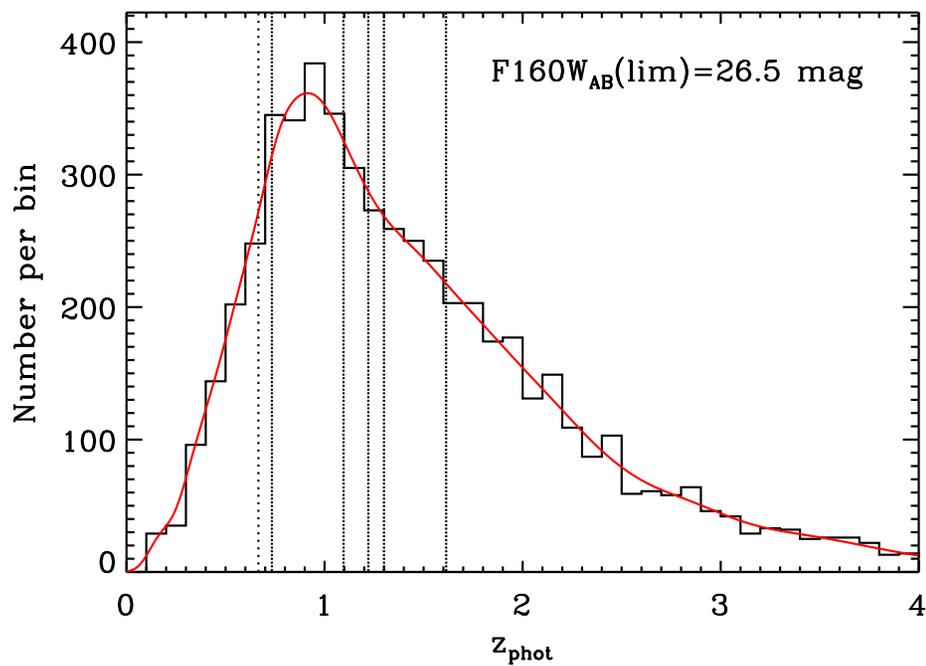http://www.stsci.edu/jwst/instruments/fgs

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?).

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

● HUDF shows WFC3 z≃7–9 capabilities (Bouwens[+] 2010; Yan[+] 2010).

● JWST will trace mass assembly and dust content $\lesssim 5$ mag deeper from z≃1–12, with nanoJy sensitivity from 0.7–5μm.
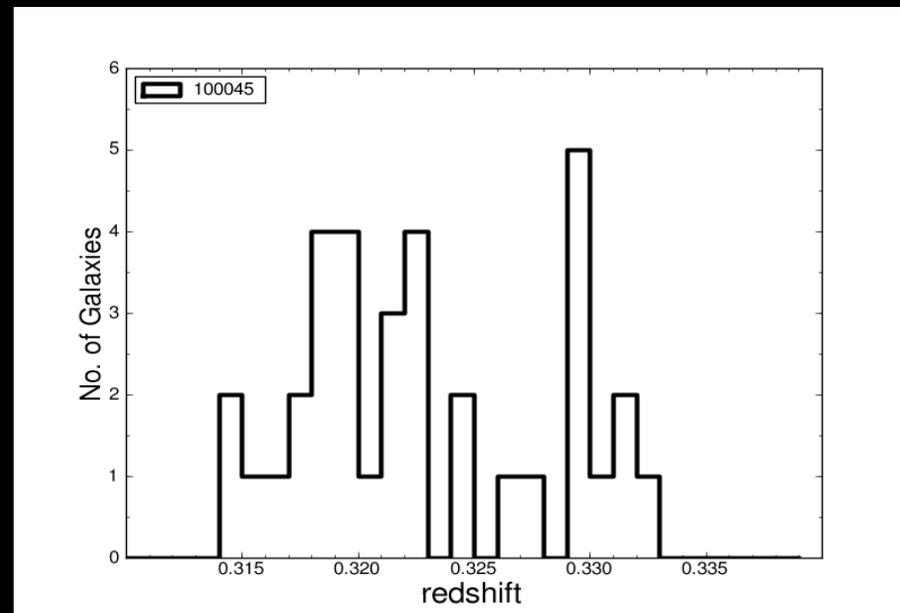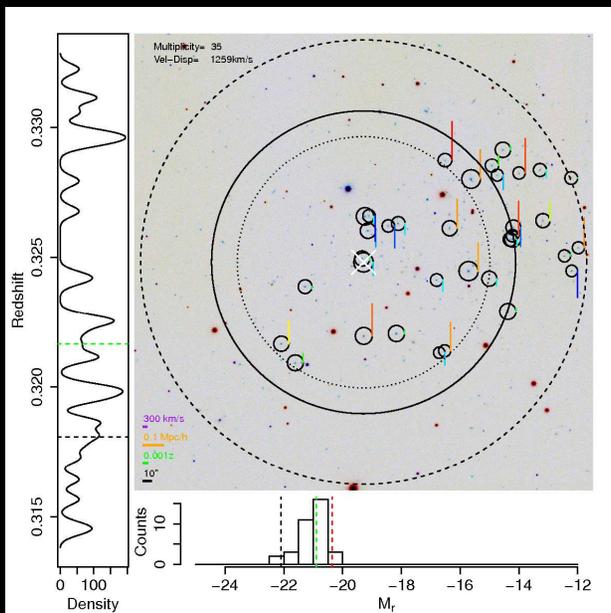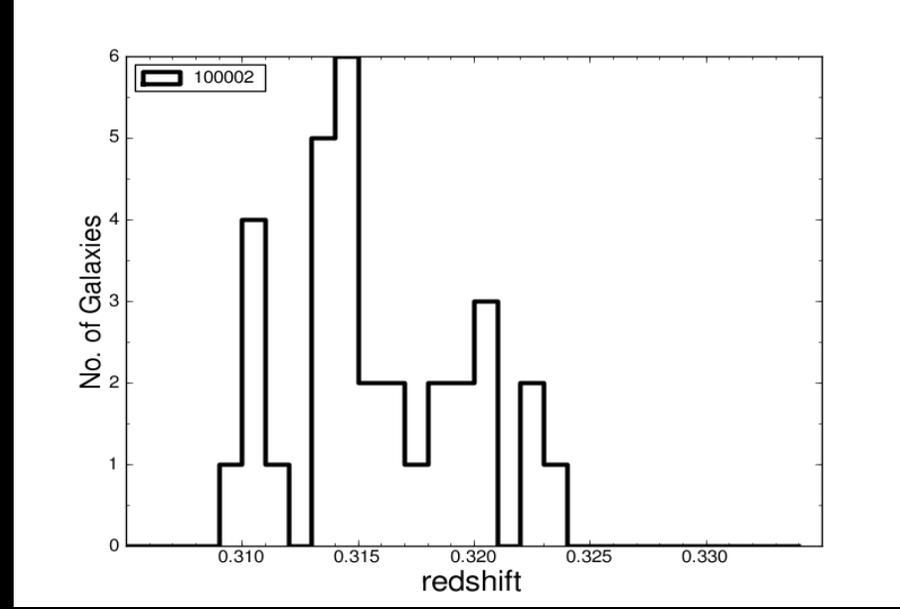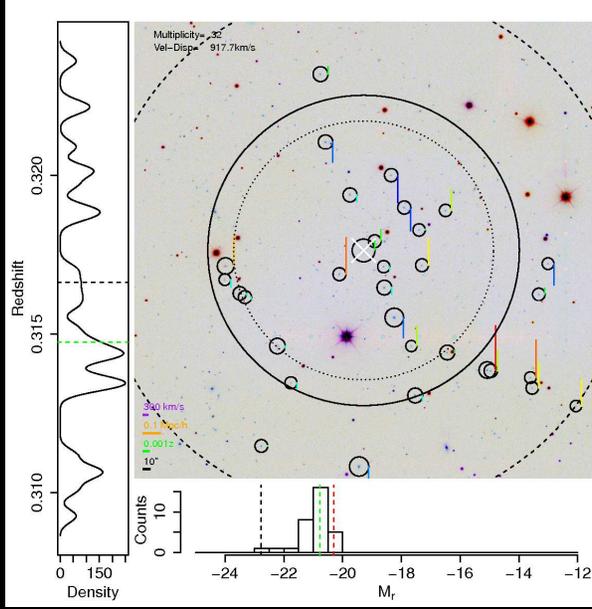
[Left] GAMA groups with secure AAT redshifts for R≲19.8 AB-mag.
Also show redshift probability and absolute magnitude (M_r) distributions.
[Right] Measured group redshift distribution for two GAMA groups.
• Will select our WMDF IDS targets on groups (+ some clusters).
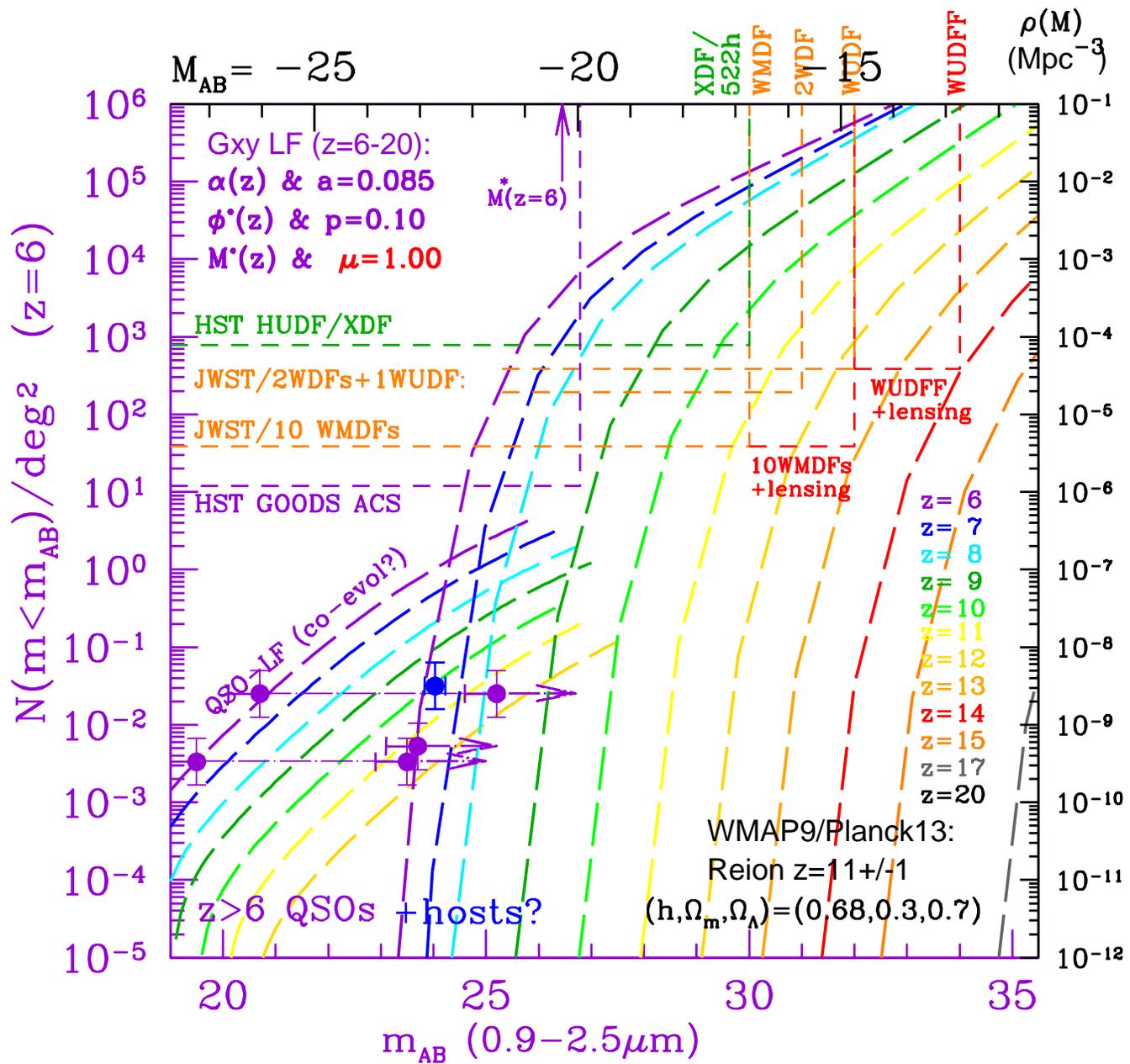
Same as before, but pessimistic M^* (z) evolution parameter: μ=1.0.

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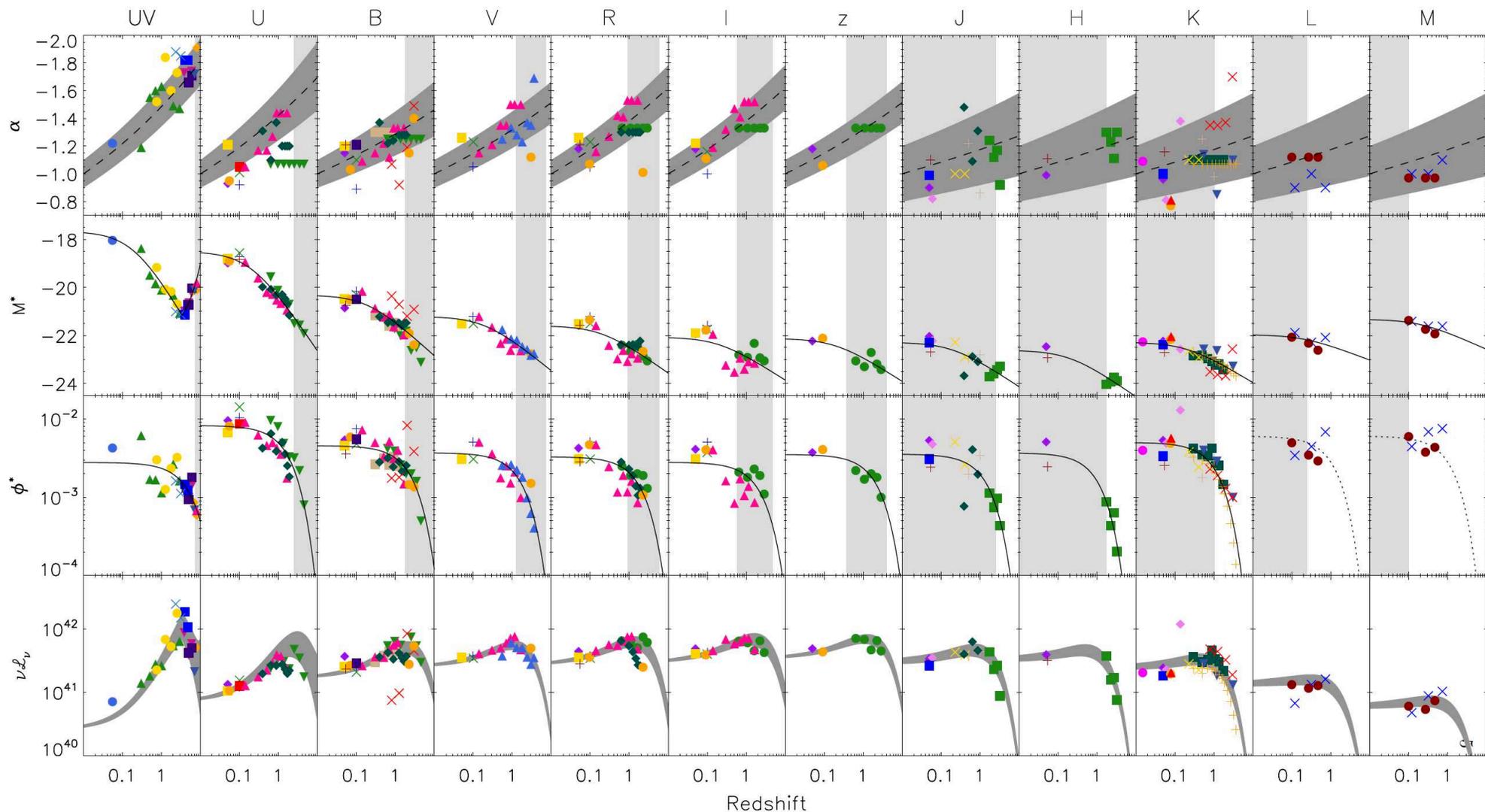
(Helgason, K., Ricotti, M., & Kashlinsky, A. 2012, ApJ, 752, 113).

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$\gtrsim$25). Will update for JWST.

Figure axes and labels:

- Y-axis (left): B_{Vega} (F450W) [total mag], values 10–37
- Y-axis (inner left): J'_{AB} (1.35 μ) [total mag], values 22–35
- X-axis: Effective Radius r_e (arcsec), values .001 to 100

Legend:
- HDF Par Type
- ● ○ E/S0
- ◆ ◇ Sabc
- ▲ △ Sd/Irr
- — E/S0 model
- — Sabc model
- ■ ■ CDM simuls

Labels in plot: RC3:, ESO –LV, MGC, G–b diffraction limit, HST I–band diffr. limit, Ground SB–limit, HST/HDF SB–limit, HUDF SB–limit, JWST 25–hr SB–limit, JWST diffr. limit, Expected sizes in Λ–CDM models, GC's z=7, M_B=–17, M_B=–20, 1000–hr JWST det. limit

Natural Conf. limits:
1/50 beams
1/10 beams
1 obj/ beam (sky is covered)