HOW WILL OUT-OF-FIELD STRAYLIGHT & GRAVITATIONAL LENSING BIAS AFFECT (ULTRA-)DEEP JWST SURVEYS AND THEIR PLANNING?

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ABSTRACT

We summarize the evidence from the JWST perspective why (ultra-)deep JWST surveys for First Light objects (z$\gtrsim$10) should *also* be done in random fields that are largely devoid of bright foreground objects, and not in majority around bright foreground clusters of galaxies at z$\simeq$1–2 or any other large bright foreground association, that significantly fills most of the sky pixels and that adds substantially to the sky-background and the sky-background gradients. Our arguments are:

(1) The JWST sunshield and optics design and fabrication make it very likely that the *average medium-deep to deep JWST survey field will have an out-of-field straylight component that has an amplitude of 30-50% of the Zodiacal foreground.* At the moment, we do not know the expected spatial scales of this out-of-field straylight, but the source is the Galactic plane and Galactic Center, which both will add straylight via rogue paths on top of the in-field zodiacal foreground observed in the JWST IR detectors. Since Galactic near-infrared sources show (strongly) varying structure on (sub-)arcmin scales, the JWST out-of-field straylight could have significant gradients on (sub-)armin spatial scales. The amplitude of these out-of-field straylight gradients expected in the JWST images is at the moment also unknown, but here we outline methods to estimate the out-of-field gradient-amplitude on arcmin scales. We do, however, now that the overall out-of-field straylight will add 30-50% ($\sim$0.3-0.5 mag) to the Zodiacal foreground at 1–3 μm wavelength. If the out-of-field straylight is completely flat — as the Zodiacal foreground is completely flat on arcmin scales — then the noise penalty is only $\sim\sqrt{1.4}\simeq$1.2, and therefore quite manageable. If however, the JWST out-of-field straylight has gradients that are as small as $\sim$1% of the signal itself — i.e. 0.3–0.5% of Zodiacal sky — or possibly substantially larger, then they will be quite noticeable in (ultra-)deep JWST images. In that case, every effort needs to be made to properly measure and remove these out-of-field straylight gradients. In §1 of this paper, we outline how we can best do this by planning and scheduling the (ultra-)deep JWST observations such that an optimal dithering and drizzling is possible, that will allow us to accurately measure and subtract these gradients in each location of the sky.

(2) Combined (ultra)deep HST ACS and WFC3 survey work has shown agreement between a significant number of independent groups that the evolving faint galaxy luminosity function (LF) shows a steep faint-end slope, that systematically seems to get steeper at higher redshifts, possibly as steep as Schechter $\alpha\simeq$–2.0 at z$\gtrsim$8. At the same time, the characteristic Schechter LF luminosity M^* seems to get systematically fainter from AB$\simeq$–21 mag at z$\simeq$2 at the peak of cosmic star-formation, to possibly as faint as M^* $\simeq$–19.5 mag at z$\simeq$8. If this trend continues for z$\gtrsim$10 and M^* reaches significantly fainter than AB$\simeq$–19 mag at z$\gtrsim$10, then it is possible that the majority of First Light objects will not only enter (ultra-)deep JWST images via direct lines-of-sight, but also via gravitational lensing bias (Wyithe *et al.* 2011). This lensing bias would be caused by the average galaxy foreground halo at z$\simeq$1–2. *Hence, if M^* continues to get fainter with redshift at z$\gtrsim$10, then at z$\gtrsim$12–14 it is possible that many such objects may become visible via lensing by the average foreground galaxy halo at z$\simeq$1–2, and not via straight lines of sight*. If this is true, then it may not be necessary to spend an enormous amount of HST time on foreground clusters (z$\lesssim$1–2) to obtain a large sample of z$\gtrsim$9 objects, since most z$\gtrsim$12–14 objects may be seen as lensed by random foreground objects at z$\simeq$1–2, and about half of the z$\gtrsim$10–12 objects may appear into the JWST samples that way. In summary, depending on the exact M^* (z) behavior for z$\gtrsim$10, there may not be a need to observe z$\lesssim$1–2 clusters to create an advantage in seeing z$\gtrsim$12 objects for JWST, because the average z$\simeq$1–2 foreground

galaxies may provide this gravitational bias just as well. Targeting clusters *will* allow one to peer deeper into the galaxy LF, because their gravitational magnification will be larger, but will also reduce the number of other z$\gtrsim$10–12 objects that enter the sample due to gravitational lensing bias from regular foreground galaxies, as well as the number of z$\gtrsim$10–12 objects that enter the deep field samples *unlensed* because they can be seen in between the foreground objects. This reduction in numbers is due to the fact that the extended cluster halo light will prevent the observer to see many of the other, more weakly lensed or unlensed z$\gtrsim$10–12 objects. This effect will only be compounded if the out-of-field stray-light has significant gradients (see (1)) that cannot be easy measured or removed in deep cluster images, because it may not be separable from the diffuse cluster halo light in the dithered (ultra-)deep JWST survey images.

(3) From the stray-light perspective discussed in (1), it is *may therefore not be optimal to focus future JWST (ultra-)deep fields exclusively on known foreground clusters*, because in such objects the Zodiacal sky will be swamped with the extra cluster foreground and its diffuse halo light at z=1–2. This could then prevent the JWST deep survey observer to make accurate sky-flats, and to remove any additive gradients from the (ultra-)deep JWST images in the out-of-field straylight, whose overall amplitude we know will amount to the 30–50% of the Zodiacal level. Since its these gradients could be a significant fraction of the out-of-field straylight amplitude itself (see (1)), this then may reduce the usefulness of (ultra-)deep JWST fields in those areas, since the foreground cluster and its diffuse halo light will prevent the observer from separating any additive gradients (out-of-field straylight plus the z$\simeq$1-2 cluster) from multiplicative gradients (residual flat-field errors). If on the contrary, the foreground just consists of the uniform Zodiacal light, plus the out-of-field straylight with some significant gradients — as will be the case for random “blank” deep fields — then there exists a possible path to measure and subtract these gradients through careful dithering and drizzling of the data.

In conclusion, the combination of (1) and (2) — unanticipated by many of us until we were recently confronted with these possibilities — suggests that not all (ultra-)deep JWST surveys should be done in regions with very dense foreground structures, such as clusters of galaxies or other foreground structures at z$\lesssim$1–2. On the contrary, for z$\gtrsim$12–14, a random field — which will always have gravitational lensing bias — may do as well as a foreground cluster in biasing such objects into the JWST samples (it will likely bias more visible z$\gtrsim$10–12 objects into the JWST samples than a rich cluster, but will do so with less magnification), and in any case observing random fields will provide far superior foreground gradient removal. In the real world of the JWST implemented as is, its expected out-of-field straylight and its possible gradients thus suggest to observe at least a significant number of (ultra-)deep JWST fields in random “empty” regions of sky. One should carefully study what combination of (ultra-)deep JWST fields centered on foreground clusters, plus “random” blank fields fields would be optimal in covering both the very faint-end *and* the brighter end of the z$\simeq$10–20 LF with sufficient statistics, and at the same time allow for the possibility to carefully map and subtract the out-of-field stray-light patterns in these locations of the sky.

1a: Sky-Gradients Expected in JWST (Ultra-)Deep Surveys from Out-of-Field Straylight Sources

Fig. 1a. shows the 128-hr HST/WFC3 IR-mosaic in the HUDF at 1–1.6μm (YJH filters; Bouwens et al 2010, Yan *et al.* 2010; 85 additional hours by R. Ellis *et al.* have been observed in fall 2012, but are not yet added here). Fig. 1b shows the same WFC3 IR-mosaic, but stretched to $\lesssim 10^{-3}$ of Zodiacal sky. The *closed-tube* HST has residual low-level systematics, which are due to, e.g.: imperfect removal of detector artifacts such as persistence and dark-current gradients, residual flat-fielding errors, and/or faint straylight from out-of-field sources. Some of these features have improved or disappeared with the v2.0 of the WFC3 IR calibrations available as of early 2012, but those are not included here, since *the point of this study is to show what would happen if the JWST near-IR out-of-field straylight gradients are* 10^{-3} *of the Zodiacal sky — as shown here in Fig. 1b — or substantially larger.* The open JWST architecture needs very good baffling, straylight and rogue path mitigation to do ultradeep JWST fields (JUDF's) to 10^{-4} of sky, which is essential to make complete object catalogs to AB=31–32 mag. We do, however, not know at the moment if (ultra-)deep JWST images can reach that kind of surface-brightness (SB) sensitivity, and if they will allow us to subtract the local sky that accurately around these very faint objects. The reason is the following.

We do know that JWST at 1–3μm will — in addition to the regular Zodiacal background — have at least a $\sim$30–50% (of Zodi) straylight contribution that comes from out-of-field sources (specked at 2.0μm; see P. Lightsey, 2010, JWST Mission CDR). Even if this out-of-field straylight has only a 1-10% amplitude variation across the NIRCam FOV, this can still cause sky-background gradients of $\sim$0.4–4.0% of Zodi, or 10–100$\times$ larger than those seen here in the HST WFC3/ACS HUDF images in Fig. 1b! **If their possible amplitude and spatial scales are not carefully modeled and properly understood, these out-of-field straylight patterns could thus become the dominant limitation of ultradeep JWST images in going as deep as they need to go, assuming every other component in JWST works as designed.**

In Fig. 2 we show the median sky surface brightness (SB) in *all* Archival HST WFPC2 F606W images observed with the DARK-SKY or LOW-SKY option (Windhorst *et al.* 2012, in prep). This median sky-SB was measured away from all known objects in each WFPC2 image, and is usually dominated by the Zodiacal background. The observed F606W sky-SB is plotted versus ecliptic longitude l^{Ecl} (2a; top panel) and latitude b^{Ecl} (2b; bottom panel). The ecliptic latitude dependence is most pronounced, and shows the usual *vertical* sech(b^{Ecl}) dependence on latitude, as expected for an observer that resides inside the (exponential) Zodiacal disk (Windhorst *et al.* 2012). Since the Zodiacal spectrum is caused by scattered sunlight, and slightly redder than the solar spectrum, we expect a similar Zodiacal sky-SB(b^{Ecl}) behavior for JWST in the near-IR in L2, reaching a minimum Zodiacal background in H-band of AB$\simeq$22.7 mag at the Ecliptic poles. Most LOW-SKY WFPC2 sky-SB observations are within $\sim$0.3 mag from the minimum Zodiacal level in the optical (indicated by the upper ridge-line of data in Fig. 2b), except for a few significant outliers, which in the case of HST almost always occur because the sky-SB became unmeasurable, since the HST target of interest (usually a globular cluster, a nearby galaxy, or a rich galaxy cluster) overfilled the WFPC2 FOV.

For the closed tube HST, *most* occurrences of excess sky-SB in LOW-SKY WFPC2 images are modest, and occur due to a small amount ($\sim$ 0.3 mag) Earthshine leaking into the WFPC2 sky-background, which manifests itself as a constant — or at most a very slightly sloped — structureless plane across the WFPC2 image on top of the expected Zodiacal sky-SB (see Fig. 1b), which can be easily removed during the sky-background subtraction procedure that is applied during the faint object detection and photometry phase.

For JWST, the out-of-field straylight will likely be of order *30–50% of the Zodiacal background*, i.e., be $\sim$0.3–0.5 mag brighter than the Zodiacal sky (see P. Lightsey 2010, JWST Mission CDR). *It may carry spatial patterns that are at the moment unknown, but that could be significant on spatial scales contained within NIRCam images*. The brightest IR sources in the sky — the Galactic Plane and Galactic Center — are expected to contribute most of this 30-50% out-of-field straylight. Since their spatial structure is highly variable in the near-IR on arcmin–degree scales, it is not clear what their out-of-focus *spatial* contribution and *amplitude* will be in deep NIRCam and FGS images on arcmin scales. Such structures could have a 10–100×larger amplitude on arcmin scales than those seen in the the HST WFC3 HUDF near-IR images in Fig. 1b, which were few$\times 10^{-3}$ of the Zodiacal sky-SB in amplitude (see also Windhorst *et al.* 2011 for a discussion of similar gradients in the WFC3 ERS images). **If so, such out-of-field straylight patterns could become a significant limitation to JWST's ability to image clean ultradeep fields, unless careful measures are take to accurately map and remove these spatial patterns. Hence, my JWST team plans to carefully model the spatial scale and amplitude of these out-of-field straylight sources for JWST, and outline the best strategies to mitigate the impact of this straylight: how many dithers with how large of a range in dither steps are needed to optimally map and subtract such straylight patterns at the (RA, DEC) locations most visited by JWST in the sky?**

1b. Strategies to Estimate & Remove Out-of-Field Straylight Gradients in JWST (Ultra-)Deep surveys

At the moment, we suggest to proceed as following to best estimate and subtract any out-of-field straylight gradients that may be seen in JWST (Ultra-)Deep survey images. As we learn more about the completed JWST OTE, its actual instrument optics, and its flight detectors from the JSC thermal vacuum tests, this strategy will be modified and improved in the next several years:

• **(1)** Based on the WFC3 IR detector experience, we will outline the most likely *detector* causes for low-level gradients in the processed WFC3 images, and identify and test their best possible corrections. Among these are, in no particular order, and not part of a complete list: a) time-dependent dark-current variations and irregular patterns; b) persistence and imperfect persistence corrections; c) time-dependent and color- or SED-dependent flat-field errors; and d) faint sources of internal or external straylight. All of these are *additive corrections, except for c), which is multiplicative.* We will investigate the best available WFC3 on-orbit calibrations and the best recipe to optimally separate and remove all additive and multiplicative errors, and test this on the ACS+WFC3 HUDF images in Fig. 1b (including the new 2012 HUDF IR data and v2.0 of all the WFC3 calibration files).

• **(2)** From the first or most recent NIRCam thermal vacuum tests, we will collect where possible and where available, the best set of JWST NIRCam bias frames, darks, linearity corrections, persistence corrections, and internal flat-fields. Then we will split this data in two independent halves, and use these to repeat the analysis that was done for WFC3 above and in Windhorst *et al.* (2011). The end-product here is a first order assessment of the *internal detector* contributions to the residual *additive* (bias, dark, persistence) and *multiplicative* (flat-field) errors for the NIRCam detectors. While not directly valid for the exact on-orbit L2 NIRCam performance, this exercise should give us a good idea of the *residual intrinsic* gradients that the NIRCam detectors will produce when they are pointed at the sky in L2, even before any out-of-field straylight gets added.

• **(3)** We plan to work with with Mark Clampin, Chuck Bowers, Kong Ha at GSFC, and Paul Lightsey at Ball Aerospace to see if the (GSFC or Ball) version of the out-of-field straylight software can be run *specifically* to predict the *in-field* NIRCam variations of the out-of-field straylight, that we know will be seen by JWST once it is in L2. We know the out-of-field straylight will have an amplitude of 30–50% of Zodi (P. Lightsey, 2010, JWST Mission CDR). What we don't know is *how constant* this extra sky-SB is: will it likely be say, +40%±0.01%, or +40%±10%?. If the former could always be guaranteed, it will just result in a fairly harmless noise penalty of $\sim\sqrt{1.40}\simeq 1.2$. But if the sky-ray tracing in a realistic situation shows that the sky-SB gradients are *always 40%±10%, then we have a serious issue.* The next question to address then will be: can the *spatial scale of the 40%±10% amplitude variation be predicted by these estimates?* If the answer is yes, and the *spatial scales* are always large (i.e., $>>$ many degrees), then the harm done to ultradeep JWST images may only be adding of a 40% sky-amplitude with a very mild low-frequency gradient, which can likely be removed with a tilted plane. If the answer is, say, *40%±10% on arcmin scales, then we have a more serious issue for JWST (ultra-)deep fields, that we need to learn how to optimally correct for, and* *certainly plan for in the deep-field selection and the scheduling stage of these observations.*

• **(4)** Outline the best JWST dither and drizzle strategy that helps correct for +40%±0.1% to +40%±10% sky-gradients on arcmin scales in the processed NIRCam images (remember that we need to remove the Zodiacal + out-of-field straylight sky locally to within 0.01% to reach AB=31–32 mag!). With the spatial scale bounded from the exercise in (3) above, we will:

(a) Outline the best strategy to plan and take the NIRCam images, and then:

(b) Simulate some of the actual on-orbit NIRCam images, starting with the initial product from (2) the thermal vacuum NIRCam images to provide the NIRCam bias, dark-current and flat-field pattern.

(c) Add the observed (AB$\lesssim$29 mag) and simulated galaxies to AB$\lesssim$31–32 mag, that have been made as much as possible noiseless with the SHAPELET algorithm, and convolved with the actual JWST PSF (after removing the ACS or WFC PSF in quadrature).

(d) Add the estimated +40%±0.1% to +40%±10% out-of-field sky-gradients on arcmin scales *on a fixed sky-grid* to the simulated NIRCam JUDF images from (c).

(e) Then drizzle and stack this data, and see if the known input out-of-field straylight pattern can be isolated from the crowded ultradeep JWST galaxy images, so that it can be accurately subtracted from all the individual NIRCam exposures. If so, then subtract this localized straylight pattern in the best possible way.

(f) Then re-drizzle the stray-light corrected NIRCam images to the final (simulated) JUDF product. See how much the stray-light corrected end-product has improved over the stray-light rich original, and identify which part(s) of the above strategy and procedures can be improved.

One outcome of this exercise will be an answer to the following question: When NIRSpec or MIRI or FGS take ∼30 hour integrations on very faint JWST targets, can NIRCam usefully do calibration parallels in terms of sky-flats, so that when it observes that same target next (or previously), any out-of-field straylight patterns in this particular field can be optimally mapped and removed from the JWST images? Note this requires that the primary observations do regular field offsets or dithers — e.g. to get their targets in different MEMS slits in different exposures to optimize their own faint-object sky-subtraction, but it is expected that this will be a common observing modes when doing spectroscopy on faint objects. If not, this should be considered in the observing modes of these instruments. The goal of the above procedure is to constrain and estimate the spatial scale and amplitude of the out-of-field stray-light gradients that may be present in (ultra-)deep JWST images, and the best strategy to map and remove these.

2a. How may Gravitational Lensing Bias Affect (Ultra-)Deep JWST Surveys for z$\gtrsim$10 objects?

This section describes JWST related work in collaboration between IDS Rogier Windhorst (ASU) and collaborators Prof. J. Stuart B. Wyithe (Univ. of Melbourne, Parkville, Victoria, Australia), and Dr. Haojing Yan, (Ohio State Univ., Columbus, OH). In Wyithe *et al.* (2011), we suggested that gravitational (galaxy-galaxy) lensing may lead to a correlation between the sky positions of high redshift candidates and bright foreground galaxies, and presented some evidence for this correlation among a sample tentatively identified at z$\simeq$10.6. By extrapolating the evolution of the galaxy LF-slope and amplitude to z$\gtrsim$8, it is possible that gravitational lensing may dominate the observed properties of galaxies at z$\gtrsim$10 discovered by JWST. The observed surface density of galaxies at z$\simeq$12–15 may be boosted by an order of magnitude, and most z$\gtrsim$12-15 galaxies may be part of a multiply-imaged system, located less than ∼1 arc-second from a brighter foreground galaxy (see Fig. 4–5 here).

Recent deep HST WFC3 near-IR surveys have been used to identify hundreds of candidate high redshift galaxies, providing the most direct observations of galaxies that reionized the Universe at z$\gtrsim$7 (e.g., Bouwens *et al.* 2010, 2011; Oesch *et al.* 2012; Yan *et al.* 2010). Standard models predict that a high incidence of gravitational lensing will likely distort measurements of flux and number of these earliest galaxies. We suggest that gravitational lensing could dominate the observed properties of the most distant galaxies at z$\gtrsim$12 discovered with JWST. The possibility of large lensing biases in high redshift samples is of crucial importance to the optimal design of surveys for the first galaxies, part of the central mission of JWST.

JWST will use the number counts of high redshift galaxies to build up a statistical description of early star-forming activity. All galaxy populations are observed to have a characteristic luminosity (L^*), brighter than which galaxy numbers drop exponentially (Fig. 4a). This characteristic luminosity L^* (or M^*) is measured to be smaller at earlier times (Fig. 3b). We suggest that if the survey limit is shallower than the characteristic luminosity L^* — as expected for very high redshift galaxy samples — then the potential for gravitational lensing to modify the observed statistics increases dramatically (Fig. 5a–5d). Indeed, multiply imaged candidates at z$\gtrsim$7–9 have already been discovered behind foreground clusters via targeted searches (CLASH, e.g., Zheng *et al.* 2012), suggesting that this may also be a viable and efficient method for finding faint high redshift galaxies.

With JWST, galaxy surveys will be undertaken out to even higher redshifts well into the epoch of First Light. Following the argument above, the gravitational lens fraction, F_{lens} , as a function of M^* for z$\gtrsim$6 is shown in Fig. 5a–5b (Wyithe *et al.* 2011). The flux limits correspond to an ultra-deep JWST survey ($m_{lim}\simeq$31.4 mag), and a medium-deep survey ($m_{lim}\simeq$29.4 mag). The evolution of the characteristic luminosity is currently unknown at z$\gtrsim$10. For comparison, we therefore plotted the data corresponding to estimates of M^* based on an extrapolation from lower redshift HUDF data (Fig. 3b). Fig. 5a suggests that in ultra-deep JWST surveys for First Light objects at z$\gtrsim$10–14, more than F_{lens} $\simeq$10% of the candidates could be lensed (Wyithe *et al.* 2011). In much shallower JWST surveys that only sample the exponential tail of the Schechter LF, a lensed object fraction of F_{lens} $\simeq$10% could be seen at redshifts as low as z$\simeq$8–10. However at z$\gtrsim$12–14, the lensed fraction in such surveys could be much higher, and may affect the majority of observed galaxies. Surveys with JWST therefore need to be carefully planned and analyzed, in order to obtain a true sampling of very high redshift objects, as seen through the foreground of lensing galaxies.

As in the case of the HUDF, many of the gravitationally lensed systems will not be identified via a detected second image. The fraction of galaxies that are detected as multiply imaged systems by JWST is again significantly lower than the true multiply imaged fraction. However, as the multiple image fraction becomes very large at high redshifts (z$\gtrsim$12), observed doubles could become common (Fig. 5b). For example, the fraction of galaxies that would be observed as doubles could be larger than F_{mult} $\simeq$10% at redshifts z$\gtrsim$12 in a medium-deep JWST survey, and z$\gtrsim$16 in an ultra-deep (m_{AB} $\lesssim$31.4 mag) JWST survey. Fig. 5c also shows the predicted distributions of separation for galaxies discovered by JWST from bright foreground galaxies (Wyithe *et al.* 2011).

If the observed evolution in M^* (Fig. 3b) continues to higher redshift, then the spatial distribution of high redshift galaxies relative to foreground galaxies will depart from random at redshifts z$\gtrsim$14 for ultra-deep surveys, and at z$\gtrsim$10 for medium-deep surveys with JWST. The majority of very high redshift galaxies discovered with JWST may then be located less than 1” from a foreground galaxy, and may have been gravitationally magnified into the sample.

Of importance are the potential implications of lensing bias for the number of high redshift galaxies detected in deep JWST surveys. A key goal for JWST will be to measure the number counts of high redshift candidates, and to use these to construct luminosity functions (LF) in order to build up a statistical description of star-forming activity in galaxies. LFs describing the density of sources per unit luminosity are parametrized by a Schechter function, including free parameters for the power-law slope at low luminosities (alpha), and the characteristic absolute AB-magnitude [M_{AB} –M^* $\simeq$–2.5 log(L/L^*)] brighter than which galaxy numbers drop exponentially (Fig. 4a). Gravitational lensing has the potential to significantly modify the observed LF from its intrinsic shape. In particular, at very high luminosities on the exponential tail of the Schechter function, the LF shape can be modified from exponential to a power-law, since gravitational lensing magnifies numerous faint sources to apparently higher luminosities. This effect is shown in Fig. 5d (Wyithe *et al.* 2011), where the intrinsic and the gravitationally biased LFs are presented. Since the high redshift LF is unknown, we assume an extrapolation of the fitting formulae based on candidates discovered in and around the HUDF. Fig. 5d shows that the shape of LFs near the flux limit are not affected by gravitational lensing at z$\lesssim$6–7. However, Fig. 5d suggests that planned surveys with JWST will measure

LFs that may be significantly modified by lensing at redshifts above z$\simeq$14 and z$\simeq$10 in ultra-deep and medium-deep surveys, respectively. In conclusion, this means that deep JWST surveys of the First Light epoch at z$\gtrsim$10 may be limited by "gravitational" confusion, where a good part of the First Light "forest" may be gravitationally amplified by the foreground galaxy "trees". Lensing bias will therefore need to be carefully considered for First Light studies with JWST at z$\gtrsim$10–12.

2b. Strategies to Plan and Execute (Ultra-)Deep JWST Surveys for z$\gtrsim$10 objects in the context of Possible Gravitational Lensing Bias

In the context of the possible effects of Gravitational Lensing Bias as described in §2a, we outline in this section possible strategies how to best plan and execute (Ultra-)Deep JWST Surveys for First Light objects at z$\gtrsim$10. We recognize here too that these strategies will evolve as well between now and JWST's launch, especially when we learn more about the faint galaxy LF at z$\simeq$8–10 from current deep HST programs, and those that are planned for the near future as long as we still have HST/WFC3. Windhorst and his JWST collaborators at ASU and elsewhere plan to proceed as following to quantify in more detail the potential affects of gravitational lensing bias in deep JWST images at redshifts z$\gtrsim$8–10 — and at z$\gtrsim$10–12 in particular in the next few years:

• **(1)** Using hierarchical models available to a group of hierarchical simulators at Supercomputer group at ASU and elsewhere, we will investigate *if and how* the L^* /M^* star values continue to decrease towards higher redshifts (which is expected in hierarchical formation scenarios), as the current WFC3 surveys now suggests for z$\gtrsim$3 (Fig. 3b). We will quantify more precisely to what extent it is *unavoidable* in "shallower" HST and JWST surveys (i.e. those only reaching AB$\simeq$29–30 mag) that a significant fraction of the z$\gtrsim$8-10 objects will enter the JWST samples through gravitational lensing bias, and *not* via straight lines of sight (Fig. 4bcd). Preliminary results of such hierarchical simulations (Morgan *et al.* 2012) seem to indicate a smooth continuation of the α(z) and M^* (z) trend in Fig. 3a–3b, respectively, at z$\gtrsim$8–10 with possibly a stabilizing of the faint-end slope value around $\alpha$$\simeq$2.0 at z$\gtrsim$10. If this is indeed confirmed with more and deeper HUDF data and higher dynamic-range hierarchical simulations, and if indeed M^* continues to get fainter with redshift at z$\gtrsim$8–10 as Fig. 3b implies, then the gravitational lensing bias from the *average foreground field galaxy population at z$\simeq$1–2* may be as large as indicated in Fig. 4–5, with as main result that *the z$\sim$1–2 foreground galaxies in random deep JWST fields will gravitationally lens a significant fraction of the z$\gtrsim$12 objects to appear above the JWST detection thresholds. In other words, no special fields with rich foreground clusters may be needed, but instead the average foreground galaxies at z$\simeq$1–2 may gravitationally lens much of the average background at z$\gtrsim$10–12 into the JWST samples.*

• **(2)** In the context of gravitational lensing bias, we will carefully investigate what fraction the objects in "ultradeep" JWST surveys (i.e. those reaching AB$\gtrsim$31 mag) may become visible in between the brighter foreground (z$\simeq$1–2) objects via straight lines-of-sight, i.e. *without* lensing bias. It is possible that in the shallower JWST surveys (AB$\lesssim$29), many z$\gtrsim$10–12 objects may become visible via lensing bias (Fig. 5d).

• **(3)** We will outline the optimal JWST observing strategies, so that gravitational lensing bias by the average foreground field galaxies at z$\simeq$1–2 of First Light objects at z$\gtrsim$10–12 can be measured optimally, so that gravitational lensing bias can be properly addressed. For this, we will investigate the following aspects:

• **(3a)** How can medium-deep JWST surveys (to AB$\lesssim$29–30 mag) effectively map the expected gravitational lensing bias, and what is a sufficient number of filters (i.e., using the normal JWST observing mode) that accurate photometric redshifts of all the foreground lensing objects can be made. We must plan to make a complete mass vs. redshift map of all foreground lensing halos (at z$\simeq$1–2), to properly analyze the bright-end of the LF in shallower surveys, and to correct for gravitational lensing bias.

• **(3b)** We must incorporate the strategies outlined in §1a–1b to assure that (ultra-)deep JWST surveys can carefully map and subtract out their out-of-field straylight. This includes the requirement that all such surveys *optimally take their own sky-flats in their own direction of the sky* to obtain the best possible sensitivity, so that we can map the faint-end of the LF at z$\gtrsim$10–14 right around and in between the z$\simeq$1–2 foreground galaxies. We will investigate to what extent these may be the only locations where this part of the LF can be directly measured without lensing bias.

• **(4)** We will also outline the requirements for a new generation object finding algorithms (a new Source Extractor etc.), that will allow to find faint background objects *in the halos of brighter foreground objects at z$\simeq$1–2 will will do most of the lensing.* This will include the requirements of a multi-color pixel-to-pixel decomposition of each foreground galaxy, so that its dust extinction A_V at every pixel can be estimated and corrected for in the selection of background objects at z$\gtrsim$10, that may be lensed into the sample.

3. DISCUSSION AND CONCLUSIONS (see also Abstract)

In this paper, we summarized the evidence from the JWST perspective why (ultra-)deep JWST surveys for First Light objects (z$\gtrsim$10) should *also* be done in random fields that are largely devoid of bright foreground objects, and not in majority around bright foreground clusters of galaxies at z$\simeq$1–2 or any other large bright foreground association, that significantly fills most of the sky pixels and that adds substantially to the sky-background and the sky-background gradients. Our conclusions are:

(1) The JWST sunshield and optics design and fabrication make it very likely that the *average medium-deep to deep JWST survey field will have an out-of-field straylight component that has an amplitude of 30-50% of the Zodiacal foreground.* At the moment, we do not know the expected spatial scales of this out-of-field straylight, but the source is the Galactic plane and Galactic Center, which both will add straylight via rogue paths on top of the in-field zodiacal foreground observed in the JWST IR detectors. Since Galactic near-infrared sources show (strongly) varying structure on (sub-)arcmin scales, the JWST out-of-field straylight could have significant gradients on (sub-)armin spatial scales. The amplitude of these out-of-field straylight gradients expected in the JWST images is at the moment also unknown, but here we outline methods to estimate the out-of-field gradient-amplitude on arcmin scales. We do, however, now that the overall out-of-field straylight will add 30-50% ($\sim$0.3-0.5 mag) to the Zodiacal foreground at 1–3 μm wavelength. If the out-of-field straylight is completely flat — as the Zodiacal foreground is completely flat on arcmin scales — then the noise penalty is only $\sim\sqrt{1.4}\simeq$1.2, and therefore quite manageable. If however, the JWST out-of-field straylight has gradients that are as small as $\sim$1% of the signal itself — i.e. 0.3–0.5% of the Zodiacal sky — or possibly substantially larger, then they will be quite noticeable in (ultra-)deep JWST images. In that case, every effort needs to be made to properly measure and remove these out-of-field straylight gradients. In §1 of this paper, we outline how we can best do this by planning and scheduling the (ultra-)deep JWST observations such that an optimal dithering and drizzling is possible, that will allow us to accurately measure and subtract these gradients in each location of the sky.

(2) Combined (ultra)deep HST ACS and WFC3 survey work has shown agreement between a significant number of independent groups that the evolving faint galaxy luminosity function (LF) shows a steep faint-end slope, that systematically seems to get steeper at higher redshifts, possibly as steep as Schechter $\alpha\simeq$–2.0 at z$\gtrsim$8. At the same time, the characteristic Schechter LF luminosity M^* seems to get systematically fainter from AB$\simeq$–21 mag at z$\simeq$2 at the peak of cosmic star-formation, to possibly as faint as M^* $\simeq$–19.5 mag at z$\simeq$8. If this trend continues for z$\gtrsim$10 and M^* reaches significantly fainter than AB$\simeq$–19 mag at z$\gtrsim$10, then it is possible that the majority of First Light objects will not only enter (ultra-)deep JWST images via direct lines-of-sight, but also via gravitational lensing bias (Wyithe *et al.* 2011). This lensing bias would be caused by the average galaxy foreground halo at z$\simeq$1–2. *Hence, if M^* continues to get fainter with redshift at z$\gtrsim$10, then at z$\gtrsim$12–14 it is possible that many such objects may become visible through lensing by the average foreground galaxy halo at z$\simeq$1–2, and not via straight lines of sight*. If this is true, then it may not be necessary to spend an enormous amount of HST time on foreground clusters (z$\lesssim$1–2) to obtain a large sample of z$\gtrsim$9 objects, since most z$\gtrsim$12–14 objects may be seen as lensed by random foreground objects at z$\simeq$1–2, and about half of the z$\gtrsim$10–12 objects may appear into the JWST samples that way. In

summary, depending on the exact M^* (z) behavior for z$\gtrsim$10, there may not be a need to observe z$\lesssim$1–2 clusters to create an advantage in seeing z$\gtrsim$12 objects for JWST, because the average z$\simeq$1–2 foreground galaxies may provide this gravitational bias just as well. Targeting clusters *will* allow one to peer deeper into the galaxy LF, because their gravitational magnification will be larger, but will also reduce the number of other z$\gtrsim$10–12 objects that enter the sample due to gravitational lensing bias from regular foreground galaxies, as well as the number of z$\gtrsim$10–12 objects that enter the deep field samples *unlensed* because they can be seen in between the foreground objects. This reduction in numbers is due to the fact that the extended cluster halo light will prevent the observer to see many of the other, more weakly lensed or unlensed z$\gtrsim$10–12 objects. This effect will only be compounded if the out-of-field stray-light has significant gradients (see (1)) that cannot be easy measured or removed in deep cluster images, because it may not be separable from the diffuse cluster halo light in the dithered (ultra-)deep JWST survey images.

(3) From the stray-light perspective discussed in (1), it is *may therefore not be optimal to focus future JWST (ultra-)deep fields exclusively on known foreground clusters,* because in such objects the Zodiacal sky will be swamped with the extra cluster foreground and its diffuse halo light at z=1–2. This could then prevent the JWST deep survey observer to make accurate sky-flats, and to remove any additive gradients from the (ultra-)deep JWST images in the out-of-field straylight, whose overall amplitude we know will amount to the 30–50% of the Zodiacal level. Since its these gradients could be a significant fraction of the out-of-field straylight amplitude itself (see (1)), this then may reduce the usefulness of (ultra-)deep JWST fields in those areas, since the foreground cluster and its diffuse halo light will prevent the observer from separating any additive gradients (out-of-field straylight plus the z$\simeq$1-2 cluster) from multiplicative gradients (residual flat-field errors). If on the contrary, the foreground just consists of the uniform Zodiacal light, plus the out-of-field straylight with some significant gradients — as will be the case for random "blank" deep fields — then there exists a possible path to measure and subtract these gradients through careful dithering and drizzling of the data.

In conclusion, the combination of (1) and (2) — unanticipated by many of us until we were recently confronted with these possibilities — suggests that not all (ultra-)deep JWST surveys should be done in regions with very dense foreground structures, such as clusters of galaxies or other foreground structures at z$\lesssim$1–2. On the contrary, for z$\gtrsim$12–14, a random field — which will always have gravitational lensing bias — may do as well as a foreground cluster in biasing such objects into the JWST samples (it will likely bias more visible z$\gtrsim$10–12 objects into the JWST samples than a rich cluster, but will do so with less magnification), and in any case observing random fields will provide far superior foreground gradient removal. In the real world of the JWST implemented as is, its expected out-of-field straylight and its possible gradients thus suggest to observe at least a significant number of (ultra-)deep JWST fields in random "empty" regions of sky. One should carefully study what combination of (ultra-)deep JWST fields centered on foreground clusters, plus "random" blank fields fields would be optimal in covering both the very faint-end *and* the brighter end of the z$\simeq$10–20 LF with sufficient statistics, and at the same time allow for the possibility to carefully map and subtract the out-of-field stray-light patterns in these locations of the sky.

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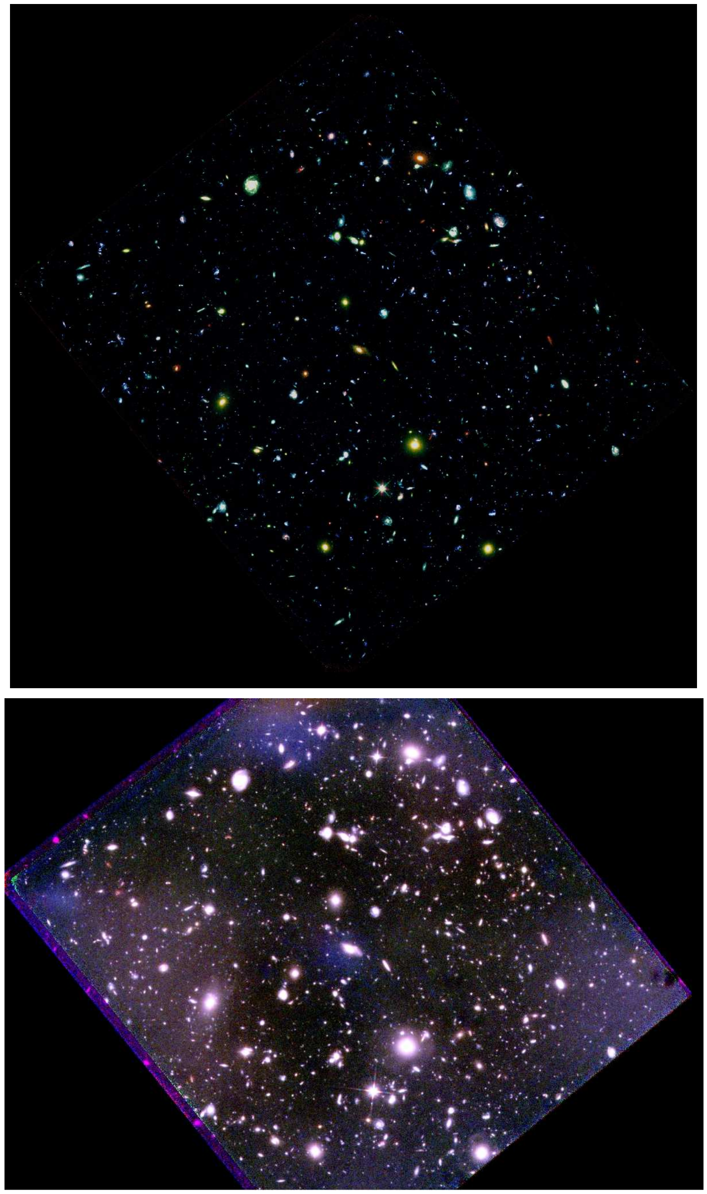


Fig. 1a (TOP): 128-hr HST/WFC3 IR-mosaic in HUDF at 1–1.6μm (YJH filters; Bouwens et al 2010, Yan *et al.* 2010; 85 additional hours will be added by R. Ellis *et al.* shortly after 09/2012).
Fig. 1b (BOTTOM): Same WFC3 IR-mosaic, but stretched to $\lesssim 10^{-3}$ of Zodiacal sky The *closed-tube* HST has residual low-level systematics: Imperfect removal of detector artifacts such as persistence and dark-current gradients, flat-fielding errors, and/or faint straylight from out-of-field sources. The open JWST architecture needs very good baffling and rogue path mitigation to do ultradeep JWST fields (JUDF's) to 10^{-4} of sky, which is essential to make complete object catalogs to AB=31–32 mag. We know that JWST at 2.0μm will — in addition to the regular Zodiacal background — have at least a $\sim$40% (of Zodi) straylight contribution that comes from out-of-field sources. Even if this out-of-field straylight has only a 1–10% amplitude variation across the NIRCam FOV, this will still cause sky-background gradients of 0.4–4.0% of Zodi, or 10–100$\times$ larger than those seen here in the HST WFC3/ACS HUDF images!

If their possible amplitude and spatial scales are not carefully modeled and properly understood, these out-of-field straylight patterns could become the dominant limitation of ultradeep JWST images in going as deep as they need to go, assuming every other component in JWST works as designed. Hence, we will carefully model the spatial scale and amplitude of these out-of-field straylight sources for JWST, and outline the best strategies to mitigate the impact of this straylight: how many dithers with how large of a range in dither steps are needed to optimally map and remove this straylight pattern at the (RA, DEC) locations most visited by JWST in the sky?

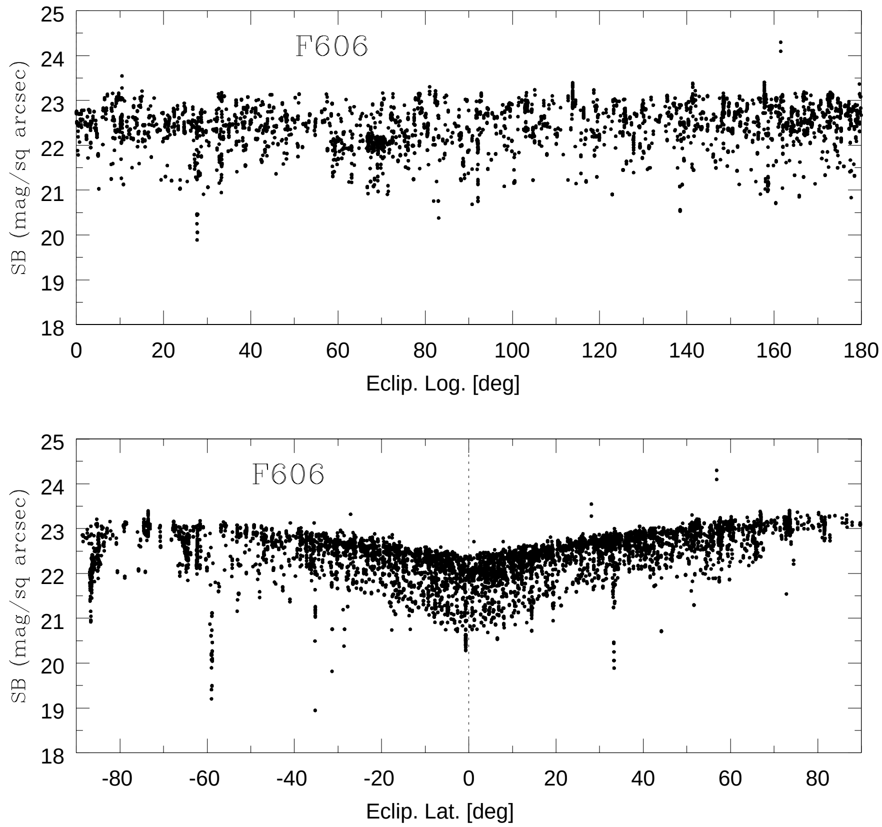
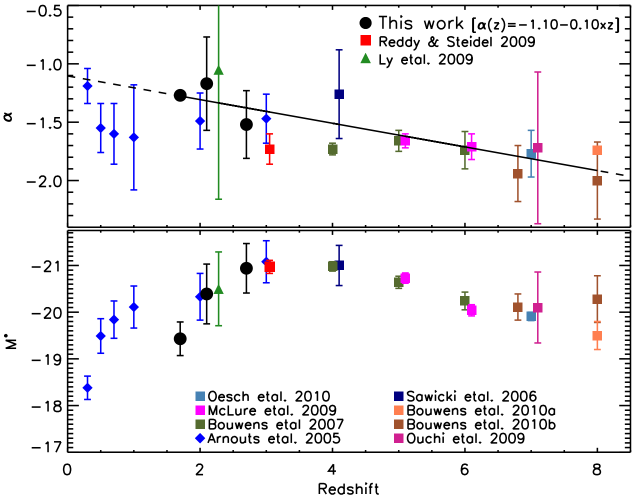


Fig. 2: Median sky surface brightness (SB) in *all* Archival HST WFPC2 F606W images observed with the DARK-SKY or LOW-SKY option (Windhorst *et al.* 2012, in prep). The median sky-SB was measured away from all known objects in each WFPC2 image, and is usually dominated by the Zodiacal background. It is plotted versus ecliptic longitude l^{Ecl} (2a; top panel) and latitude b^{Ecl} (2b; bottom panel). The ecliptic latitude dependence is most pronounced, and shows the usual *vertical* sech(b^{Ecl}) dependence on latitude, as expected for an observer that resides inside the (exponential) Zodiacal disk. We expect a similar Zodical sky-SB(b^{Ecl}) behavior for JWST in L2. Most LOW-SKY WFPC2 sky-SB observations are within $\sim$0.3 mag from the minimum Zodi, except for a few significant outliers, which in the case of HST almost always occur because the sky-SB became unmeasurable, since the HST target of interest (usually a globular cluster, a nearby galaxy, or a rich galaxy cluster) overfilled the WFPC2 FOV.

For the closed tube HST, most occurrences of excess sky-SB in LOW-SKY WFPC2 images are modest, and occur due to a small amount ($\sim$0.3 mag) Earthshine leaking into the WFPC2 sky-background, which manifests itself as a constant or at most a very slightly sloped structureless plane across the WFPC2 image on top of the expected Zodiacal sky-SB, which can be easily removed during the sky-background subtraction procedure that is applied during the faint object detection and photometry (Source-Extractor) phase.

For JWST, the out-of-field straylight will likely be of order 30–50% of the Zodiacal background ($\sim$0.3–0.5 mag; P. Lightsey 2010, JWST Mission CDR), AND may carry spatial patterns that are at the moment unknown, but that could be significant on spatial scales contained within NIRCam images. The brightest IR sources in the sky — the Galactic Plane and Galactic Center — contribute most of this 30-50% out-of-field straylight. Since their spatial structure is highly variable in the near-IR on arcmin–degree scales, it is not clear what their out-of-focus SPATIAL contribution and AMPLITUDE will be in deep NIRCam and FGS images on scales of arcmin. Such structures could have a 10–100$\times$larger amplitude on arcmin scales than those seen in the the HST WFC3 HUDF near-IR images in Fig. 1ab, which were few$\times 10^{-3}$ of the Zodiacal sky-SB (see also Windhorst *et al.* 2011). If so, such out-of-field straylight patterns could become a significant limitation to JWST's ability to image clean ultradeep fields, unless careful measures are taken to accurately map and remove these spatial patterns. Hence, we must carefully model the spatial scale and amplitude of these out-of-field straylight sources for JWST, and outline the best strategies to mitigate the impact of this straylight: How many dithers with how large of a range in dither steps are needed to optimally map and remove this straylight pattern at the (RA, DEC) locations most visited by JWST in the sky?



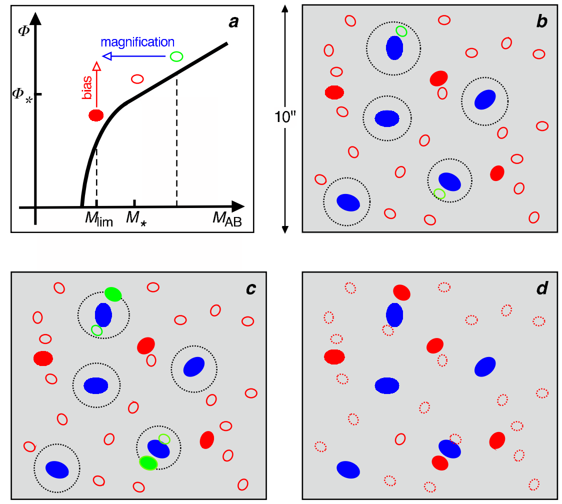


Fig. 3 (LEFT 2 PANELS): Measured faint-end LF slope evolution (3a; top panel) and characteristic luminosity evolution (3b; bottom panel) from Hathi *et al.* (2010, 2012). In the JWST regime at z$\gtrsim$8, we expect the faint-end LF-slope to be as steep as $\alpha\simeq$2.0, and the characteristic Schechter luminosity to become fainter than M^* $\gtrsim$–19 mag. This could have critical consequences for gravitational lensing bias at z$\gtrsim$10–12. **Fig. 4 (RIGHT 4 PANELS):** It may be hard to see the forest for the trees in the first 0.5 Gyrs: Foreground galaxies (in blue; z$\simeq$1–2 or age$\simeq$3–6 Gyr) may gravitationally lens or amplify background galaxies at z$\gtrsim$8–10 (in red; cosmic age$\lesssim$0.5 Gyr; Wyithe *et al.* 2011, Nature, 469, 181), thereby lifting these objects above the JWST detection thresholds (solid green). **If this is true, this could change the landscape for JWST observing strategies. We therefore plan to investigate in much greater detail all evidence we have for the LF slope and M^* value change with redshift from current, planned, and future HST/WFC3 deep surveys, and pursue hierarchical models that predict the slope and M^* behavior for z$\simeq\gtrsim$8–20. This information will be used to investigate how much lensing bias is expected in medium-deep and ultradeep JWST images at redshifts z$\simeq$8–20.**

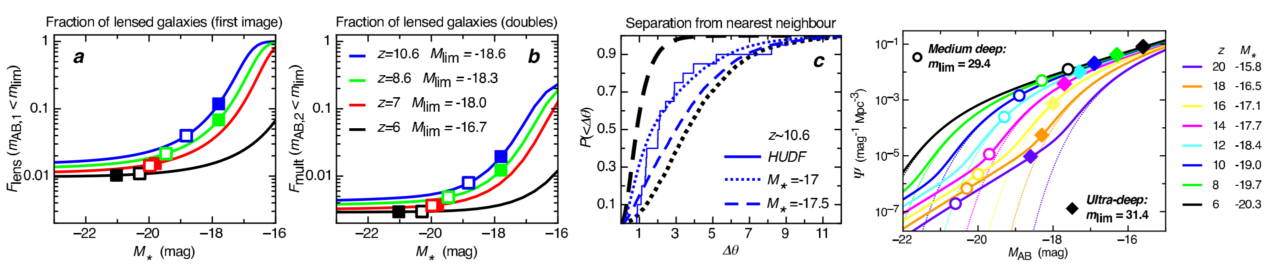


Fig. 5a [LEFT PANEL]: Fraction of candidates at z$\simeq$6–10.6 (black–blue curves) that could be lensed by average foreground objects (at z$\simeq$1–2) as present in the HUDF, following Yan *et al.* (2010) and Wyithe *et al.* (2011, Nature, 469, 181). **5b [2nd MIDDLE LEFT PANEL]:** Same, but for the much smaller fraction of objects where the second lensed image also becomes visible at AB$\lesssim$29 mag in the HUDF. **5c [MIDDLE RIGHT PANEL]:** Angular separation distribution of HUDF z$\simeq$10 candidates to the nearest lensing foreground candidate in the HUDF, suggesting that M^* (z$\simeq$10.6) could be as faint as $\simeq$–17 mag. **5d [RIGHT PANEL]:** Following Wyithe *et al.* (2011), the steep faint-end LF-slope $\alpha\gtrsim$2 expected at z$\gtrsim$8 (Fig. 3a) and a characteristic faint M^* that is considerable fainter than $\gtrsim$–19 mag (Fig. 3b), may result in the bulk of the foreground galaxies (which are at z$\simeq$1–2) to cause significant boosting by gravitational lensing of objects z$\gtrsim$8–10, as pictured schematically in Fig. 4a–4d above. **We will carefully investigate how this will specifically result in the intrinsic Schechter LF of Fig. 4a — which is an exponential at the bright-end and a power-law at the faint-end — being modified by gravitational lensing bias into a double power-law on each side of M^* , as depicted in the right panel here. We will use existing hierarchical simulations to investigate at what redshift z$\gtrsim$12 gravitational lensing bias may become the dominant mode of objects entering JWST medium-deep and deep surveys, depending on exactly how quickly M^* is expected to become fainter with redshift for z$\gtrsim$10 (see Fig. 3b). We will then design an optimal JWST survey strategy to best observe this.**