Large scale structure in the epoch of reionization

Until around 400 million years after the Big Bang, the Universe was a very dark place. There were no stars, and there were no galaxies. Astrophysicists need to unravel the story of exactly what happened after the Big Bang. DECam and HST (and eventually JWST) will pierce this veil of mystery and reveal the story of the formation of the first stars and galaxies in the Universe. Study of Lyman-break (LBG) galaxies during the epoch of reionization has already seen significant progress with observations using the Hubble Space Telescope. However, the Ultra Deep Field (e.g. Bouwens et al. 2010, 2011, Bunker et al 2010) is very modest in size. Reionizing galaxies, discovered out to z ~10 lie at luminosities below the break of the luminosity function. Reionization by protogalactic shocks was considered and found wanting by Wyithe, Mould & Loeb (2011). There are three reasons why an order of magnitude larger area should be surveyed for redshift 6 galaxies.

- <u>LSS</u> Our first DECam Deep Field shows structure in z = 6 candidate galaxies on ~10 Mpc comoving scales.
- <u>LF</u> The shape of the luminosity function for rarer, brighter galaxies at luminosities above L_* cannot be addressed using the HUDF owing to its small survey volume.
- <u>SNe</u> Two nights a semester is a good cadence for finding z = 6 superluminous supernovae (SLSN).

Large Scale Structure: Our first two nights yielded data on the Prime field summarized in the 2012B columns (night 1 & night 2) of Table 1. Candidate *i* band dropouts have z $\gtrsim$ 6 and their structure across the 3 square degree field is far from uniform (Figure 1). This was presented at the annual CAASTRO scientific meeting (Mould 2013b). The colour magnitude diagram (Figure 2) was published earlier by Mould (2013a). The highest scientific priority for a 2014A run is to obtain *g* and *r* images of the Prime Field to veto galactic low mass dwarfs from the dropout candidates and to raise the S/N cutoff on the present *i*, *z*,Y data. The scale on which reionization lights up the gas is accessible to the DECam Deep Field project. There are some predictions from theory by Crosby et al (2013). Primordial non-Gaussianity is a crucial test of inflationary cosmology. Following Joudaki+ 2011 and Dalal et al 2008 (http://arxiv.org/abs/0710.4560) for the non-Gaussianity calculation, for a single field, we can constrain f_{NL} (non-Gaussianity) to ±70 when marginalizing over the Gaussian bias, and to ±30 when assuming that the bias is known. For 3 disjoint fields, these f_{NL} constraints would improve to ±40 and ±17, respectively. While these constraints aren't competitive with Planck or DES, they are affected by different systematics and therefore complementary. The TAC was not convinced that the distribution seen in Figure 1 was a real effect and could have been caused by varying image quality. Indeed, we need higher S/N and refined data reduction. We'll add a 2nd reduction pipeline using SExtractor and a larger team. The scale on which reionization lights up the gas *is* accessible to this DECam Deep Field project.

Luminosity function: The number-densities of rare galaxies require wide-field observations. Space based observations have focused on higher redshifts. For example, Trenti et al. (2010, 2011) initiated the Brightest of Reionizing Galaxies (BoRG) Survey, a large program aimed at candidates at redshift z ∼ 8, when the Universe was about 650 million years old. The BoRG survey used Hubble's Wide Field Camera 3 in a pure-parallel survey, discovering galaxies that are 1–2 mags brighter than those found in the HUDF over an effective area of 100 square arc minutes. For even rarer galaxies at even brighter luminosities, wide-field cameras on large ground-based telescopes must be used. Ouchi et al. (2009, 2010) have used Suprime-cam on Subaru to study dropout galaxies at z $\sim 6-7$, identifying 22 candidates down to fluxes of Y = 26 over a 1500 arc-minute field. These candidates are up to 1 magnitude brighter than $M_\star$, but their small numbers makes the detailed shape of the luminosity function uncertain. Investigating whether the luminosity function is declining exponentially at the bright end will allow us to elucidate the fundamental relation between dark matter halos and their galaxies, and in doing so we will will contribute to understanding the role of AGN feedback and gas accretion in the most massive halos. Currently, the functional form of the luminosity function during the epoch of reionization is debated, since there might not enough time for feedback to efficiently suppress star formation in halos with $M > 10^{12} M_\odot$ (McLure et. al. 2009; Finlator et al. 2011). Other large area surveys for high z include Bowler et al (2012) [z ~ 7 galaxies over 1.5deg^2 in the UltraVISTA survey], McLure et al (2009) [z ~ 4.7–6.3 from the UKIRT Infrared Deep Sky Survey Ultra Deep Survey over 0.63deg^2] and Gabasch et al (2008) [$z \lesssim 3$ in the COSMOS survey]. ATAC has questioned whether DECameron is competitive with UltraVISTA. We submit that they are complementary: DECameron has 6× the UltraVISTA area; UltraVISTA has JHK magnitudes. We agree that JHK is an advantage for photo-z; we intend to pursue our candidate dropouts with Gemini Flamingos when the Prime field has twice the S/N that it currently has.

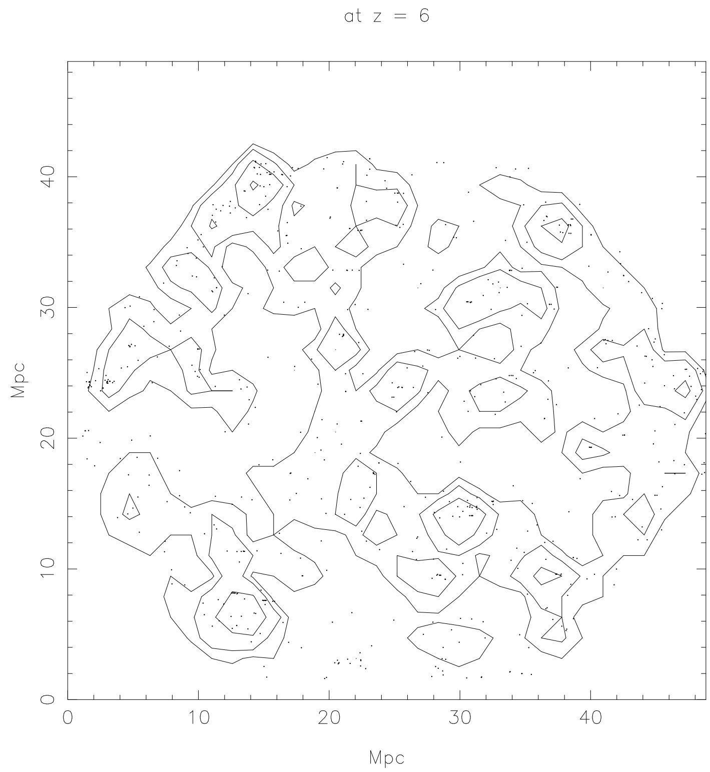

Figure 1: *i* band dropouts in the Prime Field. Contours follow the density of z ~ 6 objects. A correlation length of order k = 0.15 Mpc^{-1} is predicted by Joudaki et al (2011).

High redshift supernovae: It is believed that the collapse of pristine gas in the early Universe promoted the formation of very massive stars and potentially a different IMF than observed today (Larson 1998; Heger & Woosley 2002; O'Shea & Norman 2007, 2008). Over the last few years, wide-area, deep surveys have uncovered a rare class of "super- luminous supernovae" (SLSNe) that are 10 – 100× more luminous than typical supernovae (Quimby et al. 2011; Gal-Yam 2012) Most SLSN events are believed to be core-collapse deaths of very massive stars, ~30 - 100 $M_\odot$, with some resulting from supernova interaction with circumstellar material (Smith et al. 2007; Gal-Yam & Leonard 2009). To date, only ~15 SLSNe have been detected at low redshift (Smith et al. 2007; Gal-Yam & Leonard 2009; Pastorello et al. 2010; Gal-Yam et al. 2009; Gezari et al. 2009), with one event exhibiting a slow fade powered by the radiative decay of a large amount of ^{56}Ni (Gal-Yam et al. 2009). The single event is believed to be the first detection of a third type of supernova explosion, termed a "pair-instability supernova" (PISN). PISNe have been theorized since the 1960s (Rakavy & Shaviv 1967; Barkat et al 1967) and are the result of the deaths of stars with progenitor masses of 140–260 $M_\odot$ (Heger & Woosley 2002; Kasen et al 2011). Stars this massive generate conditions in their cores that enable the efficient conversion of gamma-ray photons into electron-positron pairs. The rapid conversion of pressure-supporting radiation into rest mass causes a violent contraction, triggering a run-away thermonuclear explosion that obliterates the star. Recently, two spectroscopically identified SLSNe were discovered at high redshift, z = 2.05 and z = 3.90, and found to be consistent with PISNe (Cooke et al. 2012) (Figure 3). The peak magnitudes of SLSNe (MUV ~ –21.5; m ~ 25 at z ~ 6) enable their detection in deep multi-epoch images using DECam. In addition, the high redshift SLSN rate has been found to be more than 10× higher than at low redshift (Cooke et al. 2012). SLSN and PISN detections at z ~ 6–7 will provide crucial data to progress stellar evolutionary models (Moriya et al. 2013; Moriya & Maeda 2012; Whalen et al. 2012, 2013; Hegar & Woosley

2010) and their measured ultraviolet flux and rate will provide a means to estimate the ionizing contribution from supernovae and massive stars.

Super-luminous supernova rates: The redshift interval probed by the *z* filter is $6.0 < z < 7.2$ and ∼465 Mpc, comoving. Given the field of view of DECam, our LBG selection criteria probe roughly 1×10^8 Mpc. Observationally, Cooke et al. have found the z ∼ 2-4 super-luminous supernova rate to be $\sim 4 \times 10^{-7}$ Mpc/yr. This is higher than at low-z, and is expected to continue to increase with redshift. Using a detection window simulation at our proposed magnitude sensitivity and the z ∼ 2-4 rate, we expect to discover 4+ super-luminous supernovae at z ∼ 6-7 in the 14A semester.

In response to ATAC comments: (1) our detection technique first color-selects LBGs at the desired redshifts, thus the low redshift "contaminant" transients are efficiently eliminated, (2) our proven light curve analysis removes essentially all AGN and, (3) we will follow up candidates with deep Keck spectroscopy to eliminate AGN and confirm the SN redshifts. Because SLSNe are UV-luminous, the deep Keck observations will get near peak spectra of z ∼ 6 sources more luminous than M ∼ –21.5. In addition to getting the host spectrum and redshift, such deep spectra can reveal SN emission features for SLSN-II confirmed by our work at z ∼ 2 and, when compared to later host spectra, reveal Lyman continuum (< 912Å) UV leakage caused by the supernovae which is extremely valuable to reionization. DES has a weekly cadence over 5 months (August to Feb.) SUDSS also plan to look for SLSNe, also use DECam with a 2 week cadence and monitor over 9 months. Both DES & SUDSS search for SNe in *griz*, but not in Y. Neither have the length of cadence for ∼3.5 year evolution of z ∼ 6 PISNe.

Lensing: In addition to measuring the shape of the luminosity function for the brightest galaxies, studies of these objects at the extreme of the luminosity function provide a high likelihood for gravitational lensing in the sample (e.g. Wyithe et al. 2011). Along random lines-of-sight, the raw probability for multiple imaging of objects at high redshifts — because of gravitational lensing by individual foreground field galaxies — is ∼0.5%. However, the potential for gravitational lensing to modify the observed statistics can increases dramatically, owing to the magnification of numerous, intrinsically faint galaxies to observed fluxes that are above a particular survey limit. This effect, which is known as magnification bias, leads to an excess of gravitationally lensed galaxies among flux-limited samples. For example, Wyithe, Yan, Windhorst & Mao (2011) showed that a survey at $z > 6$ which reaches only 1 magnitude brighter than the characteristic luminosity of galaxies would have a lens fraction as high as 10%. Thus a survey like BoRG is expected to have a lens fraction of 10%. Indeed, among the 8 brightest candidates in BoRG, there is 1 system that is very likely multiply imaged (Barone-Nugent et al 2013). The brighter flux limit and wider area for DECam implies an even larger gravitationally lensed fraction.

The discovery of high redshift gravitational lenses provide several important avenues to open astrophysical problems. First, the magnification of a gravitationally lensed source provides an opportunity to perform spectroscopic follow-up on an intrinsically faint source, typical of galaxies at the epoch or reionization, which would be beyond the reach of spectrographs without lensing. Additionally gravitational lenses typically lie at half the angular diameter distance to the source, placing the lenses at z ∼ 1.5–2. Observations of these galactic lenses provide an opportunity to make direct measurements of the total mass of massive galaxies at z ∼1.5–2 where this is not otherwise possible.

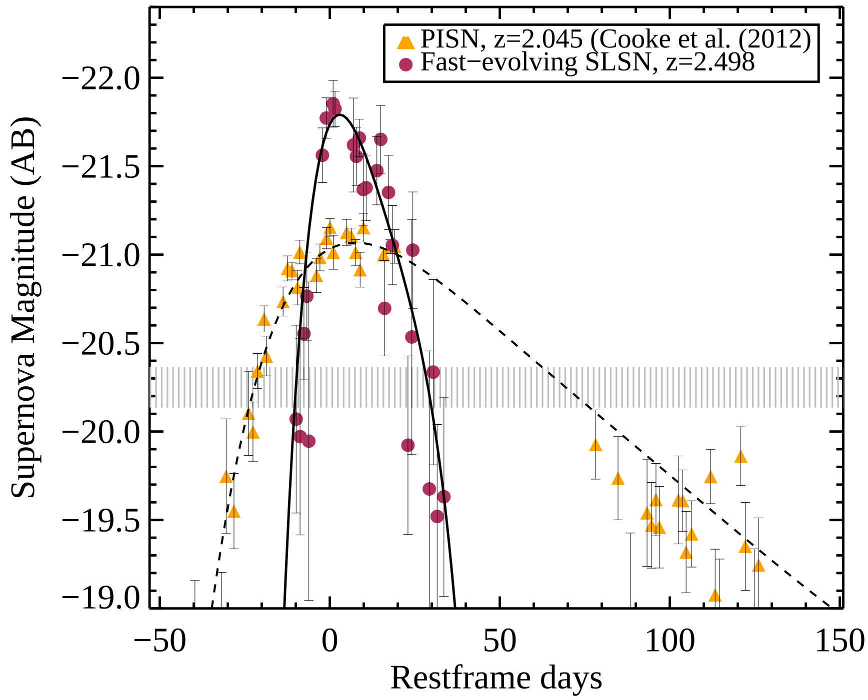

Figure 2: High redshift super-luminous supernova light curves. Two super-luminous supernovae at z ~ 2 are shown. The slow evolving PISN event is one of two PISNe discovered in Cooke et al. (2012) and the quick evolving SLSN-I type event is from Cooke et al. (2013, in prep.). The ultraviolet data probe similar wavelengths as the proposed DECam observations. The two supernovae bracket the extremes of high redshift super-luminous supernova light curve breadth and peak magnitude. The z ~ 6–7 supernova detection sensitivity of this DECam proposal is shown as the gray horizontal bar; the lower bound reflects z ~ 6 sensitivity and the upper bound, z ~ 7. The characteristic slow decay of pair-instability supernovae, resulting from the production of a large amount of ^{56}Ni, can be confirmed with future observations, given the time-dilation for z ~ 6–7 sources.

TECHNICAL JUSTIFICATION:

Our deep fields take advantage of the extraordinary red sensitivity of DECam, a 4m telescope development which the principal investigator has been following to fruition for almost 10 years. Note that Y band has rest wavelength 1050Å at z = 6. We need to sample the Balmer continuum at the longest wavelength possible for useful photometric redshifts. According to our 2012B data, calibrated using E-region standards, we estimate:

• 100 ks gives S/N = 5 at Y = 26 • 50 ks gives S/N = 5 at *z* = 26.85 • 50 ks gives S/N = 5 at *i* = 27.6

This is 1.5 mag deeper at Y than the VISTA, UltraVISTA and VIDEO infrared surveys. Hickey et al (2010) have surveyed the GOODS-South field to Y = 26 (50% completeness point) but covered only 119 arcsec^2.

Our first goal is to achieve a 36 ksec deep DECam field centred on the Hubble Deep Field. Our 2012B data gave us only a brief glimpse of this field. Next, we'll be able to raise the 2012B accumulation in the Prime field from 18ksec to 36 ksec. This will raise the S/N of our *i*-dropout galaxies from 2 to 5. Our third goal for 2014 is to spot supernovae in the Prime field at z $\gtrsim$ 2. The observed SN decline rate is 3 times slower at this redshift. We request 2 nights per semester 2014–2016A. Supernova discovery in the Prime field should be aided by the 2012B data. We'll also obtain deep g, r, i, z band images to provide colour information. Deep data at wavelengths shorter than the break is really key to reducing contamination, which can be particularly severe for the brightest LBG galaxies. This is evident from the red contours in Figure 3. Half the candidates at $1 < z{-}Y < 2$ and $z > 25$ may be galactic stars at the end of the main sequence, until $r, i > 27$ mag data are obtained to filter them out.

Our 3 fields are the Prime field 0555-6130, the 16hr field 1640-75 & HDFS 2233-606. Two of these are high galactic latitude DES (Dark Energy Survey) fields.

• HDFS has a large heritage of observations, see http://www.stsci.edu/ftp/science/hdfsouth/hdfs.html;

The Prime field is a new complementary field without HST coverage, yet.

- All fields are circumpolar allowing all night to be used efficiently.
- We exploit the moon tolerance of 1 μm observations to minimize conflict with other DECam programs.

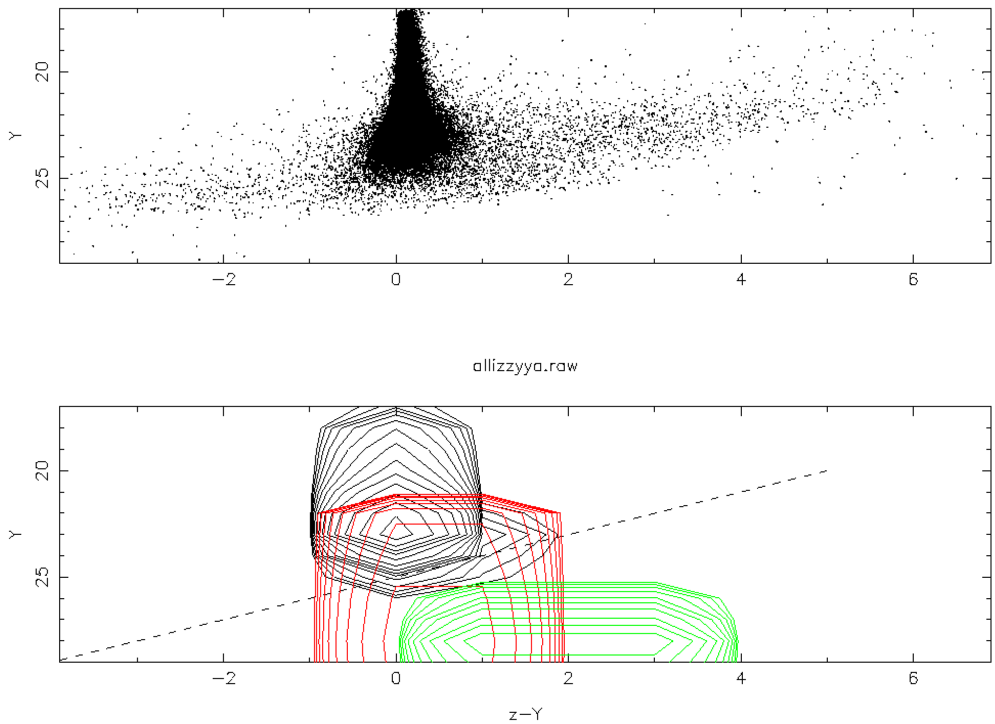

Figure 3: CMD in the Prime field from our 2012B nights. The red contours are star counts from the Bahcall-Soneira model of the Galaxy. The spacing is factors of $\sqrt{2}$. The green contours are galaxy counts at z = 5.5–6.5 from the Hubble UDF. The black contours are our counts. The dashed line is a completeness line at z = 25 mag. We need to go deeper to better overlap the high redshift galaxy contours.

Table 1: Past and proposed exposure distribution

Band	2012B1	2012B2	2014	2015	2016A
g	–	–	140m	140m	70m
r	–	–	140m	140m	70m
i	–	130m	140m	140m	70m
z	140m	130m	560m	560m	280m
Y	140m	130m	600m	600m	300m

DES itself is carrying out a 4000 Type Ia supernovae survey in the redshift range $0.05 < z < 1.2$ (Bernstein et al 2012). The OzDES collaboration is supporting that project with AAOmega redshifts (Lidman et al 2013). Followup of DECameron *i*-band dropouts and high redshift SNe would be with Gemini S, as soon as increased S/N on dropouts and discovery of SN candidates makes it appropriate to propose.

The Large Scale Structure in our results to date is particularly interesting. We now request time to make these results secure, define the bright end of the luminosity function, and find the highest redshift supernovae. This needs long term status from ATAC.

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