Monsters in the early Universe: A challenge for the LCDM paradigm?

Principal Investigator: Dr. Ben Hoyle

Institution: Institut d'Estudis Espacials de Catalunya

Electronic Mail: benhoyle1212@icc.ub.edu

Scientific Category: COSMOLOGY

Scientific Keywords: Clusters Of Galaxies, Cosmological Parameters And Distance Scale, Dark Matter, Gravitational Lensing, Groups Of Galaxies

Instruments: ACS

Proprietary Period: 12

Orbit Request	Prime	Parallel
Cycle 19	32	0

Abstract

Observations of rare, high-redshift, massive clusters over the past two years, have hinted at the possibility that there are more rare objects than naively predicted in a "vanilla" LCDM model. These exceedingly rare objects are very massive "monsters" and are already in place when the Universe was a fraction of its current age. The single most important limitation in interpreting this result is the lack of a reliable measurement of the clusters' (dark matter) halo masses. We propose to further investigate this issue by using ACS/F775W imaging in order to make the crucial mass measurement via weak gravitational lensing for 8 high-redshift clusters, which have suggestive indicators of high mass (in X-rays or Sunyaev-Zel'dovich effect) which place them in possible tension with the LCDM model.With a modest investment of 32 orbits of HST time, the weak lensing mass estimates resulting from this proposal will allow us to unlock the potential of these "monsters in the early universe" and settle the issue of whether LCDM+Gaussian initial conditions provide a good description of the observed Universe. Furthermore, rare peaks offer a direct insight into the nature of initial conditions at inflation. Thus our proposed HST project can yield significant insight into the early Universe.

Investigators:

	Investigator	Institution	Country
PI	Dr. Ben Hoyle	Institut d'Estudis Espacials de Catalunya	Spain
CoI	Prof. Licia Verde	Institut d'Estudis Espacials de Catalunya	Spain
CoI	Dr. David Bacon	ICG- Portsmouth	UK
CoI&	Dr. Aday Robaina	Institut d'Estudis Espacials de Catalunya	Spain
CoI	Prof. Raul Jimenez	Institut d'Estudis Espacials de Catalunya	Spain
CoI	Dr. Matt Hilton	University of Nottingham	UK
CoI	Dr. Ed Lloyd-Davies	University of Sussex	UK
CoI	Dr. Nicola Mehrtens	University of Sussex	UK
CoI	Prof. Kathy Romer	University of Sussex	UK
CoI	Dr. Martin Sahlen	Stockholm University	Sweden

Number of investigators: 10
& Contact CoI: Dr. Aday Robaina

Target Summary:

Target	RA	Dec	Magnitude
SPT-CLJ0102-4915	01 02 54.7200	-49 15 25.20	V = 24.5 +/- 1.5
SPT-CLJ0615-5746	06 15 49.6800	-57 46 40.80	V = 24.5 +/- 1.5
SPT-CLJ2106-5844	21 06 3.6000	-58 44 38.40	V = 24.5 +/- 1.5
SPT-CLJ0546-5345	05 46 37.2300	-53 45 25.60	V = 24.5 +/- 1.5
XMMCSJ122658+333250	12 26 58.1000	+33 32 50.90	V = 24.5 +/- 1.5
XMMCSJ105345+573514	10 53 45.9000	+57 35 14.50	V = 24.5 +/- 1.5
XMMCSJ022709-041805	02 27 9.5000	-04 18 5.00	V = 24.5 +/- 1.5
XMMCSJ083025+524128	08 30 25.9000	+52 41 28.40	V = 24.5 +/- 1.5

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
SPT-CLJ0102-4915	ACS/WFC Imaging F775W		4 (1x4)
SPT-CLJ0615-5746	ACS/WFC Imaging F775W		4 (1x4)
SPT-CLJ2106-5844	ACS/WFC Imaging F775W		4 (1x4)
SPT-CLJ0546-5345	ACS/WFC Imaging F775W		4 (1x4)
XMMCSJ122658+333250	ACS/WFC Imaging F775W		4 (1x4)
XMMCSJ105345+573514	ACS/WFC Imaging F775W		4 (1x4)

Target	Config Mode and Spectral Elements	Flags	Orbits
XMMCSJ022709-041805	ACS/WFC Imaging F775W		4 (1x4)
XMMCSJ083025+524128	ACS/WFC Imaging F775W		4 (1x4)

Total prime orbits: 32

■ Scientific Justification

In the past couple of years the abundance of high-redshft clusters has received renewed attention. Since the publication of the weak-lensing (WL) mass of XMMUJ2235.3-255 at $z = 1.4$ [1] the community has realized that **it is now finally possible to exploit the well-known potential of high-redshift, rare, collapsed structures to test cosmology** (e.g., [2] and references therein) . XMMUJ2235.3-255's mass and redshift makes it an exceedingly rare object: only a handful of such objects should be found in the full sky, but this object was found surveying a very small fraction of it: it has a low *"probability to be observed"*. In other words, XMMUJ2235.3-255 is a $\sim 10^{15} M_{\odot}$ monster when the Universe was still young: only ∼35% of its current age. Refs [3] showed that a moderate amount of primordial non-Gaussianity could make XMMUJ2235.3-255 less unlikely. This has attracted a lot of attention as primordial non-Gaussianity offers a new window into the mechanism that generated the primordial perturbations at the origin of structure formation. While the search for primordial gravity waves via the polarization of cosmic microwave background anisotropies can shed light on the energy scale of inflation, primordial non-Gaussianity measures the self interaction of the inflaton (or, in multi-field models, the interactions among the fields driving inflation). An exciting development of the past few years is the realization that primordial-non-Gaussianity could in principle be used to reconstruct the operators appearing in the Lagrangian describing inflation, offering a new direct link between cosmological observations and fundamental physics. This is a new development and it remains to be seen if real-world effects, systematics etc., do not spoil this possibility.

Of course, the standard ΛCDM model assumes Gaussian initial conditions, and the fact that XMMUJ2235.3-255 is such a rare event could be interpreted as a signature of tension between observations and the underlying model. Refs. [4,5] examine under what conditions a single rare event could rule out the cosmological paradigm. In particular [5] discusses possible biases in this evaluation. **The single, most important, source of systematic biases is the (dark matter) mass determination of the rare event under consideration**. Rare events are powerful probes of cosmology because the halo mass function (i.e. the theoretical prediction of their number density as a function of mass) is an extremely steep function of the mass (the mass function depends exponentially on the object mass). For the same reason any inference is strongly affected by errors on the mass determination. Consequently, as discussed at length in [5], Eddington bias also plays a significant role. **All these problems can be efficiently mitigated with good and reliable mass estimates such as weak lensing mass measurements**. One may also worry that the theory may be poorly understood and that the theoretical mass function may be affected by theoretical uncertainties, but extensive N-body simulation tests show this effect is, for now, sub-dominant.

Since XMMUJ2235.3-255, several other high-redshift massive clusters have been found, especially by the South Pole Telescope via the clusters Sunyaev-Zel'dovich (SZ) signature in the Cosmic Microwave Background sky [7]. Why should then a single, high-redshift, rare object be used when many are now available? Ref. [6] (carefully scrutinized and corroborated by [8]) represents a first attempt to do so, in the context of fitting for an additional parameter to the standard ΛCDM model, a parameter that quantifies the level of primordial non-Gaussianity. **Ref. [6], despite making conservative assumptions about the objects' mass and volume covered by the parent survey, finds that at about 2.5σ level the data favor non-zero non-Gaussianity**. This result cannot however be interpreted as "the ΛCDM paradigm is ruled out": the tolerance for ruling out a paradigm should be much greater than that used in parameter fitting. In fact, the quantitative evaluation of the *probability to be observed* of the objects considered is in full agreement between Refs [5] and [6]. Of course, other deviations from the ΛCDM model could also work in accommodating our "monsters in the early Universe" such as exotic dark energy models or modifications of gravity [10]. In any case, accurate and precise mass determinations, and in particular WL estimates, are crucial to make any further progress in interpreting this possible tension.

Using several objects contributes to making this approach more robust: a single object may appear rare because of rare, peculiar circumstances ("flukes"), not because of its high-mass. Think for example of the Bullet cluster, whose X-ray temperature is greatly enhanced by the merger. Without additional follow up observations and independent mass measurements one would infer a –fictitious– extremely high mass.

We therefore propose here to follow up 8 high-redshift clusters with suggestive indicators of high mass in X-rays or SZ and a low ***probability to be observed*****, to make the crucial (dark matter) halo mass measurements via weak gravitational lensing (WL).**

WL estimates directly and with greatly improved precision, the dark matter halo mass, bypassing the astrophysical effects that can plague e.g., the X-ray mass determination, and greatly mitigating the Eddington/Malmquist bias that can affect SZ-selected (and X-ray selected) high-redshift clusters. In order to exclude "flukes" one would ideally need mass determinations from at least two independent techniques (X-ray, SZ, WL etc.). SZ surveys have so far produced the highest number of rare events. The next-generation of high-redshift clusters samples will be overwhelmingly found by planned X-ray surveys such as the forthcoming e-ROSITA (launch in 2012, expected 50-100$\times 10^3$ clusters), whereas current SZ surveys are near the end of operations and future surveys (e.g., ActPol) will detect relatively few ($\sim$1000) galaxy clusters. For this reason our target sample includes 4 SZ-selected clusters and 4 X-ray selected clusters. The SZ-selected clusters were found by the South Pole telescope and include the estimated rarest object so far known. The X-ray selected clusters were found or re-analysised by the XMM Cluster Survey (XCS) [9]. One X-ray cluster is as yet unpublished. The two subsets are matched in (estimated) mass range, redshift, and *probability to be observed* range. The target clusters all have a *probability to be observed* < 0.6 (with 5 out of 8 < 0.45, recall that low probability to be observed indicates tension with Gaussian ΛCDM cosmology with WMAP priors) and they are all found at high ($z \gtrsim 0.8$) redshift. Fig. 1 illustrates the current situation highlighting the possible tension with standard ΛCDM. We also show the forecasted effect of reducing the mass error with the WL measurements proposed here (should the central mass value remain unchanged).

We are aware of other seemingly related clusters proposals being submitted to this same call or recently awarded. The CLASH collaboration aims at observing a much larger sample of lower redshift objects. A cluster probability to be observed decreases with increasing mass and redshift. We concentrate on high-redshift, rare events and have thus no overlap with CLASH. The South Pole Telescope collaboration is proposing follow up of their SZ selected cluster sample: this is a much larger sample of clusters with broader scope. Our scientific goal is focussed on objects in some tension with the standard model. A proposal with Perlmutter as PI also aims at observing massive $z > 1$ objects. Our proposals are highly complementary: we focus on the weak lensing signal taking full advantage of the ACS wide field of view, they focus on photometry. We have informally agreed to share data.

We wish to measure the coherent, weak lensing distortion in the shapes of the distant galaxies in the image, which is a direct probe of the space-time metric along the line of sight to the cluster. The cluster potential generates changes in the observed ellipticities of background galaxies, so by measuring these ellipticities we can infer the cluster mass. Given the expected redshift distribution and ellipticity dispersion of the background objects, we have calculated the expected lensing shear and convergence signal-to-noise within 1-3' for each cluster, taking into account the cluster redshifts and current cluster mass indicators. From this we derive expected errors on the WL mass estimates, as seen in figure 1. **Given the high redshift of the clusters, HST is the only existing facility with the capability of observing, resolving and measuring the shapes of the background galaxies whose distortion carry the information of the dark matter halo mass**.

To conclude, in the past 2 years, observations of rare, high-redshift massive clusters have hinted at a possible indication that there are more rare objects that naively predicted in a "vanilla" ΛCDM model. While this indication is not enough to rule out the model, it highlights two important points: a) It is within our reach to fully exploit the potential of high-redshift clusters as cosmological probes b) the main limitation is imposed by the lack of a robust and accurate mass determination. WL mass estimates such as the ones we propose here will allow us to overcome this limitation and unlock the potential of these "monsters in the early Universe". **With the masses obtained from our WL measurements we could finally settle the issue of whether ΛCDM+Gaussian initial conditions and WMAP priors are a good description of the observed Universe.**

The availability of the proposed weak-lensing masses in combination with future, ground base, multi-color information can also be used to test if the stellar populations of rare peaks are different from those of normal peaks.

Our team is highly qualified to pursue this scientific program. We have significant expertise in weak-lensing studies using HST data (Bacon) as well as the study of galaxy shapes in a general context from high-resolution ACS and WFC3 data (Robaina, Hilton). We have a broad background in theoretical modeling of clusters (Romer, Verde, Sahlén, Hoyle), especially of the effects of primordial non-Gaussianity on large scale structures and number counts. Verde authored the 2 most popular non-Gaussian mass functions on the market, Verde and Jimenez first highlighted the possible tension between high-redshift clusters and the theoretical expectations and Hoyle was the first to interpret quantitatively the existence of more than one high-redshift clusters in terms of deviations from Gaussian initial conditions. Romer, Hilton, Hoyle, Lloyd-Davies, Mehrtens, Sahlén are leading the XCS.

Description of the Observations

We propose to obtain F775W (i-band) imaging with HST/ACS of 8 massive clusters at $0.8 \lesssim z \lesssim 1.3$. Our primary scientific goal is to estimate the total masses of the individual clusters (or "lenses") by measuring the shear distortion that their large gravitational potentials induce in the observed shape of background galaxies (or "sources"), an effect known as weak gravitational lensing. We can achieve this goal with a modest investment of 32 orbits. Our sample consists of very rare, super-massive galaxy clusters at high redshift which have mass estimates obtained either by Sunyaev-Zel'dovich telescopes such as the South Pole Telescope or via conversion between X-ray temperature and mass in objects detected in the XMM Cluster Survey [9]. These previously estimated masses suffer from strong systematic uncertainties, related to the behavior of gas in clusters, whereas the independent weak-lensing measurement proposed here, provides a direct measurement of the dark matter halo mass, greatly reducing the systematic error uncertainty, and accurate to within $\sigma(M)/M \sim 7-35\%$ for 7 out of 8 clusters and $\sim 60\%$ (which can still lead to good constraints when combined with the X-ray) for the highest redshift cluster. This level of accuracy and precision is critical when trying to determine if the existence of these monsters in the high-redshift, early Universe is at odds with the predictions of the standard ΛCDM model assuming WMAP priors on the cosmological parameters.

Given the redshift and magnitude distribution of our background sources, estimated from the Hubble Ultra Deep Field analysis provided by Coe et al. (2006)[11], we calculate that typical sources would have an effective radius $\lesssim 0.1''$ [12] in the case of the highest redshift clusters. Hence we choose to use ACS with the F775W filter as it provides an optimal combination of spatial resolution (pixel scale after drizzling will be $0.03''$), sensitivity, wavelength range and PSF stability. Moreover, this combination has been shown to provide optimal results for weak lensing studies of $z > 1$ clusters [1,13]. In order to guarantee the reliability of our measurement, we will only use sources which span at least 5 consecutive pixels on the CCD. We will observe each target in 4 different orientation angles -varying from orbit to orbit- in order to prevent possible artifacts introduced by charge transfer in the CCD. Given that we do not have the need of an specific absolute orientation angle, but only relative shifts between different exposures, this should not impose major restrictions in order to schedule our observations.

While the power of the method relies on the statistical distribution of elongations in galaxy shapes, we need a modest signal-to-noise (hereafter S/N) for galaxy images in order to perform an accurate measurement. A suitable population of background sources, which we require to lie in the redshift range $0.8-1.5$, will lie in the magnitude range $25 < i_{775} < 26.5$ (c.f. Table 9 and Fig 20 of Coe et al). We can achieve a S/N$\sim$4 per galaxy at the faintest magnitude in the i_{775} filter with an exposure time of $\simeq 9600$ seconds. We propose to observe each of our 8 fields for this exposure time; given this depth we can measure the shear and hence the mass of each cluster, to within an uncertainty in mass of between 7% and 35% for 7 out of 8 clusters and $\sim 60\%$ for the highest redshift cluster. The uniform magnitude limit will aid analysis by ensuring that we have the same source population in each case, with only the lens redshift changing from field to field. This allows uniform image processing, catalogue completeness and shear samples across all images.

We are proposing to observe every target for 4 orbits, each split into four sub-exposures. We will use a four-point, sub-pixel dither pattern. In this way, we will be able to reject cosmic rays and bad pixels, while we improve the spatial resolution. Guide star acquisition requires 6 minutes. Filter changes, readout, setup and maneuver related to dithering will take $\sim$5 minutes in every set of exposures. The total amount of overhead time is then approximately 11 minutes, leaving $\sim$40 minutes of integration time per orbit and a total exposure time of 9600s per target over the whole program.

References

[1] Jee et al. 2010, ApJ, 504,672; [2] Matarrese S., Verde L., Jimenez R., 2000, ApJ, 541, 10. [3] Jimenez R., Verde, L., 2009,Phys.Rev.D80:127302; Cayon et al. 2010, arXiv:1006.1950; [4] Holz D., Perlmutter S., 2010, arXiv:1004.5349; [5] Mortonson M., Hu W., Huterer D., 2010, Phys.Rev.D, 83, 023015; [6] Hoyle B., Jimenez R., Verde L., 2010, arXiv:1009.3884; [7] Foley R. J., et al, 2011, arXiv:1101.1286; Williamson et al 2011, arXiv:1101.1290; [8] Enqvist K., Hotchkiss S., Taanila O., 2010, arXiv:1012.2732; [9] Romer et al, 2000, ; Lloyd-Davies et al., 2011, MNRAS submitted, arXiv:1010.0677 ; [10] Sahlén et al in preparation.; Baldi M., Pettorino V., 2011, MNRAS in press. [11] Coe et al.,2006, A. J., 132, 926; [12] Haussler et al., 2007, ApJS, 172, 615; [13] Postman et al. in prep.

. . . . .

Special Requirements

Coordinated Observations

Justify Duplications

Past HST Usage and Current Commitments

Relevant past papers using HST data by coI's:

-. Bacon & Schaefer 2009, MNRAS, 396, 2167 - the first detection of the new lensing distortion 'twist', using a shapelet analysis of HST observations of A901/2 (STAGES, Gray et al 2009, MNRAS, 393, 1275)

-. Massey et al 2007, Nature, 445, 286 - Bacon was responsible for creating the 3D potential map for the COSMOS field.

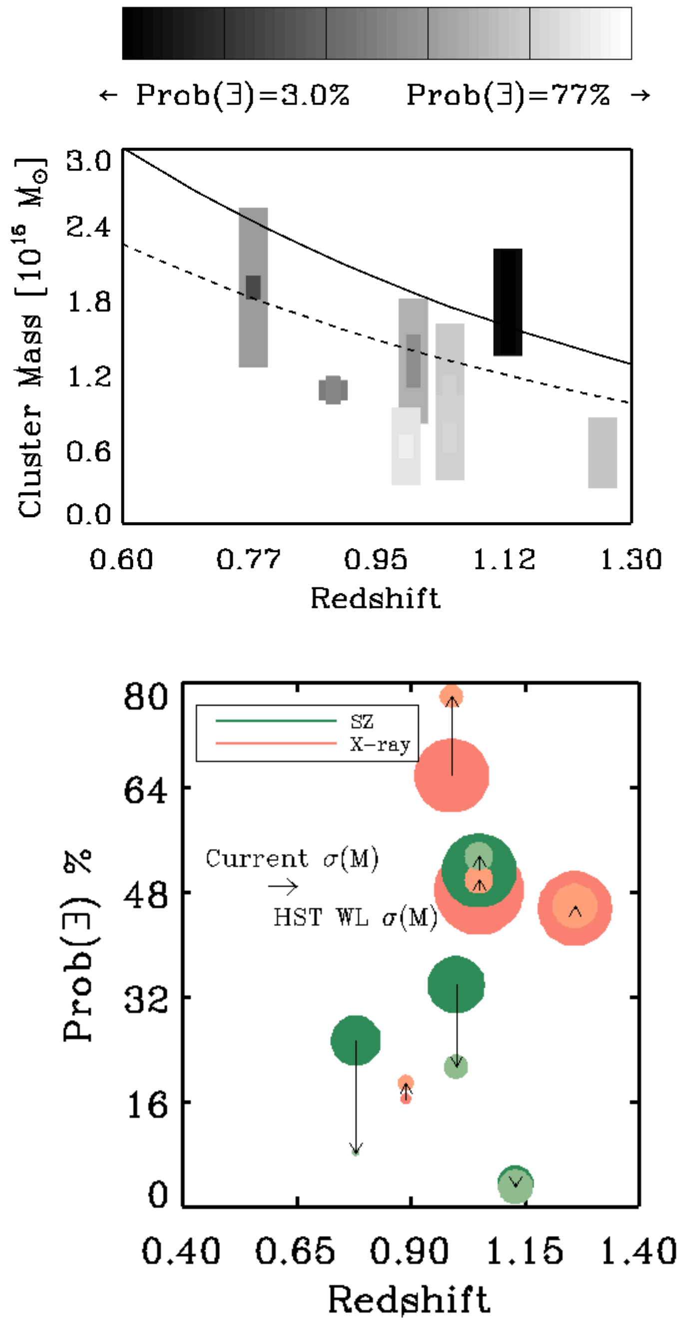

Figure 1: Left: Our targets in the redshift vs mass plane. The length of the wider bars indicate current SPT and X-ray derived $1\,\sigma$ cluster mass uncertainty (typically $\sigma(M)/M \sim 50\%$) and the thinner bars indicated the forecasted $1\,\sigma$ mass error from HST observations ($\sigma(M)/M < 35\%$, and assuming that the central value of the mass remains unchanged). The color-scheme corresponds to the probability to be observed (or how rare the object is) and quantifies the tension with ΛCDM (the lower the probability, the higher the tension). For reference, the solid (dotted) line is the threshold of Ref. [5] for ruling out the ΛCDM Universe at 95% confidence if only one massive object was observed and was located above it within the SPT (X-ray) survey footprint. Right: Our sample in the redshift vs probability plane. The size of the symbol is proportional to the mass uncertainty, the arrows indicate how this plot will change as a result of the HST observations (again assuming that the central value of the mass remains unchanged, and the different mass measurements are not combined). Note that in some cases a smaller mass error may lead to less tension with ΛCDM as e.g., for the cluster at $z = 0.99$.