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PLANCK CLUSTER PAPER

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ABSTRACT

We propose to continue our program of optical imaging to unveil all of the most massive clusters in the observable Universe. We start from the all-sky Planck Sunyaev-Zeldovich (SZ) catalogs, which contain several hundred high significance (signal-to-noise ratio, SNR > 5) unconfirmed cluster candidates. Since SZ selection favors high mass clusters and the Planck confirmation process favored low redshift systems, the highest significance unconfirmed candidates are, therefore, likely massive clusters ($M_{500} > 5 \times 10^{14}$ $M_{\odot}$) at relatively high redshift ($z > 0.5$). Our proposed observations, using MOSAIC-3 on Mayall, are designed to confirm the presence of a brightest cluster galaxy (to $z \sim 1$) and red sequence of accompanying cluster members (to $z \sim 0.7$). Preliminary results from our observations over the past two years have validated our approach by the detection of optical clusters in a number of Planck candidates, including the discovery of rich systems at $z = 0.553$ and $z = 0.830$ that rival the most massive clusters known. The proposed observations represent the first step required to provide a complete all-sky census throughout the observable Universe of the most massive, high redshift clusters. Their expected high redshift and high mass make the unconfirmed Planck clusters, arguably, the most important available sample for probing deviations from ΛCDM and defining the high-mass end of the cluster mass function.

Subject headings:

1. INTRODUCTION

Throughout this paper, we adopt the following cosmological model from the Buzzard simulations: $\Omega_{\Lambda} = 0.714$, $\Omega_M = 0.286$, and $H_0 = 70$ km s^{-1}Mpc^{-1}, assume a Chabrier initial mass function (IMF; Chabrier 2003), and use AB magnitudes (Oke 1974).

2. DESIGN

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2.1. *Observations*

All observations were conducted at the Kitt Peak National Observatory (KPNO) Mayall/4m telescope. The optical observations were made with the Mosaic camera mounted at the prime focus. Two detector packages were used for the observations. The earlier Mosaic1.1 instrument consisted of eight 2048×4096 SITe CCDs, arranged 2×4, separated by a ~ 50 pixels gap with a pixel scale of $0.''26$ pixel^{-1}. Mosaic1.1 was replaced with Mosaic3, in year?, and consists of four new 4k×4k, 15 micron pixel, 500-micron thick LBNL deep-depletion CCDs. Because the only change from Mosaic1.1 to Mosaic3 are the CCDs and controllers the both versions have a $36' \times 36'$ field-of-view.

The near-IR observations utilized the National Optical Astronomy Observatory (NOAO) Extremely Wide-Field Infrared Imager (NEWFIRM; Probst et al. 2004). The instrument consists of four InSb 2048×2048 pixel arrays arranged in 2×2 with approximately $1'$ gaps between each of the CCDs. The detector has a plate scale of $0.''4$ pixel^{-1} and a $28' \times 28'$ field-of-view.

need to talk about the dithering

The optical observing strategy consists of targeted *griz* observations of individual candidates with exposure times of 350 s, 350 s, 1100 s and 1100 s (assuming dark conditions) to provide 5σ detections limits of $g = ??$, $r = 24.5$, $i = 24.5$, $z = 24.2$ ensuring the unambiguous detection of the faint (i.e., 0.4L⋆) galaxies in the red cluster sequence up to $z \sim 1.0$ (citation?) and of brightest cluster galaxies (BCGs) to higher redshifts. The choice of filters in our program is driven by the need to segregate early-type galaxies in the cluster through their colors (or photometric redshifts) by sampling blueward and red-ward of the 4000Å break.

For the NEWFIRM observations, we obtained 3600 s of Ks band imaging using 60 s exposures (5 coadded 12 s exposures) taken at 60 different dither positions distributed quasi-randomly over a square $100'' \times 100''$ region. This produced reduced images with uniform exposure and sky level. The final dithered images cover approximately $28' \times 28'$ which comfortably matches the MOSAIC observations.

A NEWFIRM integration of 3600 s allows us to reach a limiting Ks magnitude of ~ 22.0 (AB, 3σ). This magnitude limit corresponds to $\sim M_{\star} + 2$ in the cluster luminosity function at $z = 1.0$ as measured by De Propris et al. (1999), and assuming Ks AB = Ks Vega +1.86. This surface brightness limit corresponds to $\sim M_{\star} + 1.0$ at $z = 1.5$, sufficient for detecting sub $L_{\star}$ at this limit, allowing for confident detection of the BCG and associated red cluster sequence.

A summary of our observations is given in Table 1.

3. DATA REDUCTION AND CALIBRATION

Standard image reductions including subtraction of dark frames, flat fielding, sky-subtraction, and bad pixel masking was performed by the NOAO virtual observatory using the MOSAIC (Valdes & Swaters 2007) and NEWFIRM (Swaters et al. 2009) science pipelines. The resultant FITS files consist of fully reduced images with

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TABLE 1
BASIC PROPERTIES OF THE TEN GALAXY CLUSTERS TARGETED WITH THE MS: COLUMN 1: OUR INTERNAL CLUSTER NAME; COLUMN 2: ABELL CATALOG ID; COLUMN 3: THE RIGHT ASCENSION OF THE CLUSTER; COLUMN 4: THE DECLINATION OF THE CLUSTER; COLUMN 5: THE NOMINAL (OFTEN PHOTOMETRIC) CLUSTER REDSHIFT; COLUMN 6: THE MEASURED RICHNESS FROM RYKOFF ET AL. (2012); COLUMN 7: THE DATE OF OUR OBSERVATIONS.

Cluster (1)	RA (J2000) (2)	DEC (J2000) (3)	Optical Obs. (4)	NIR Obs. (5)	Filters (6)
MSJ010455.4+000336.3	...	01:04:55.369	+00:03:36.28	0.277	129.7 ± 4.9
MSJ133520.1+410004.1	Abell 1763	13:35:20.092	+41:00:04.12	0.223	191.0 ± 5.7
MSJ140102.0+025242.6	Abell 1835	14:01:01.965	+02:52:42.63	0.252	135.6 ± 5.2
MSJ153656.3+242431.6	...	15:36:56.253	+24:24:31.60	0.226	70.1 ± 4.4
MSJ164019.8+464241.5	Abell 2219	16:40:19.812	+46:42:41.51	0.225	202.6 ± 5.4
MSJ172227.2+320757.2	Abell 2261	17:22:27.182	+32:07:57.24	0.224	185.8 ± 7.4
MSJ211849.1+003337.3	...	21:18:49.069	+00:33:37.33	0.270	121.0 ± 4.6
MSJ215422.9+003723.5	Abell 2392	21:54:22.936	+00:37:23.48	0.223	87.2 ± 4.8
XMMXCSJ124425.9+164758.0	...	12:44:25.203	+16:47:48.00	0.235	11.4 ± 1.7
XMMXCSJ125650.2+254803.2	...	12:56:49.999	+25:48:02.99	0.280	8.2 ± 1.8

either all single exposure CCDs mosaicked into a single image extension (as in the case of Mosaic1.1 and NEWFIRM) or as a multi-extension FITS file with each single exposure CCD occupying a separate extension.

We then mosaic each separate exposure into a master mosaic as described in the following section.

3.1. *Mosaicking*

Combined mosaics are created with SWARP (Bertin et al. 2002). The individual dither frames are stacked and then median combined to produce the final completed mosaic. The final mosaic retains the native plate scale, and header information. The final exposure time is calculated as the median exposure time of the combined images, and similarly the final airmass is median of the individual air masses. need to talk about the weight images

The full parameter file used while creating the mosaics is given in Appendix A.

3.2. *Astrometric Calibration*

Each of the final mosaics produced in the previous section are first astrometrically aligned with *Gaia* (Gaia Collaboration et al. 2016b) Data Release 1 (Gaia Collaboration et al. 2016a) using SCAMP (Bertin 2006) as a part of PHOTOMETRYPIPELINE (PP; Mommert & M. 2017).

Sources are extracted from the mosaics with a signal-to-noise ratio (SNR) of at least ten and with a minimum area of at least 12 pixels. The extracted sources are then matched to the *Gaia* data and a new astrometric solution is calculated. Because the initial astrometric solution from the VO is quite accurate, the resultant corrections are less than $1''$.

3.3. *Photometric Calibration*

After the mosaics have been astrometrically aligned, we use PP to produce a photometric solution. PP calculates a photometric zero-point in each of our observed bands by comparing field stars located throughout the mosaic to known photometry from large-area sky surveys. Because our sources are spread across the entire northern sky, and because we prefer to minimize the number of differences between photometric solutions we are limited to two surveys. We first seek photometric data from the *Sloan Digital Sky Survey* (SDSS; York et al. 2000) Data Release 13 (Alam et al. 2015) get a new citation for dr13 this is for dr12. When our target does not lie within the SDSS footprint we utilize the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Chambers et al. 2016) Data Release 1 (hereafter PS1; Flewelling et al. 2016). Both surveys provide accurate *griz* magnitudes and large on-line queriable databases for rapid automated calibration.

Sources are extracted from the combined mosaics with a $3''$ diameter aperture; sources with a SNR$\geq$ 10 are matched to a survey catalog and a photometric zero-point is determined. We use half of the available stars (with accurate catalog photometry) to derive the zero-point resulting in zero-points calculated from approximately $10 - 500$ stars and with typical uncertainties of give zp errors in the different bands.

4. ANALYSIS

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4.1. *Source Extraction and Photometry*

For source extraction and photometry estimation we use Source Extractor (hereafter SExtractor; Bertin & Arnouts 1996) run dual image mode where the i' image serves as a detection image. See Appendix B for a complete parameter listing.

4.2. *Photometric Redshifts*

We determine photometric redshifts from the four-band optical images using BPZ (Benitez 2000) following the same procedure as in Menanteau et al. (2008).

4.3. *Cluster Finding*

We create RGB images using STIFF (Bertin & Emmanuel 2011). We use MAXBCG (Koester et al. 2007).

5. RESULTS AND DISCUSSION

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6. SUMMARY

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github.com; the IPython package (Perez & Granger 2007); matplotlib, a Python library for publication quality graphics (Hunter 2007). iraf is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy under cooperative agreement with the National Science Foundation (Tody 1993). PyRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

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APPENDIX

SWARP

```
#----------------------------------- Output -----------------------------------
IMAGEOUT_NAME          coadd.fits      # Output filename
WEIGHTOUT_NAME       coadd.weight.fits # Output weight-map filename

HEADER_ONLY            N               # Only a header as an output file (Y/N)?
HEADER_SUFFIX          .head           # Filename extension for additional headers

#------------------------------- Input Weights --------------------------------

WEIGHT_TYPE            NONE            # BACKGROUND,MAP_RMS,MAP_VARIANCE
# or MAP_WEIGHT
WEIGHT_SUFFIX          .weight.fits    # Suffix to use for weight-maps
WEIGHT_IMAGE                           # Weightmap filename if suffix not used
# (all or for each weight-map)

#------------------------------- Co-addition ----------------------------------

COMBINE                Y               # Combine resampled images (Y/N)?
COMBINE_TYPE           MEDIAN          # MEDIAN,AVERAGE,MIN,MAX,WEIGHTED,CHI2
# or SUM

#-------------------------------- Astrometry ----------------------------------
```

```
CELESTIAL_TYPE         NATIVE          # NATIVE, PIXEL, EQUATORIAL,
# GALACTIC,ECLIPTIC, or SUPERGALACTIC
PROJECTION_TYPE        TAN             # Any WCS projection code or NONE
PROJECTION_ERR         0.001           # Maximum projection error (in output
# pixels), or 0 for no approximation
CENTER_TYPE            MANUAL             # MANUAL, ALL or MOST
CENTER         00:00:00.0, +00:00:00.0 # Coordinates of the image center
PIXELSCALE_TYPE        MANUAL          # MANUAL,FIT,MIN,MAX or MEDIAN
PIXEL_SCALE            0.2666          # Pixel scale
IMAGE_SIZE             0               # Image size (0 = AUTOMATIC)

#-------------------------------- Resampling ----------------------------------

RESAMPLE               Y               # Resample input images (Y/N)?
RESAMPLE_DIR           .               # Directory path for resampled images
RESAMPLE_SUFFIX        .resamp.fits    # filename extension for resampled images

RESAMPLING_TYPE        LANCZOS3        # NEAREST,BILINEAR,LANCZOS2,LANCZOS3
# or LANCZOS4 (1 per axis)
OVERSAMPLING           0               # Oversampling in each dimension
# (0 = automatic)
INTERPOLATE            N               # Interpolate bad input pixels (Y/N)?
# (all or for each image)

FSCALASTRO_TYPE        FIXED           # NONE or FIXED
FSCALE_KEYWORD         FLXSCALE        # FITS keyword for the multiplicative
# factor applied to each input image
FSCALE_DEFAULT         1.0             # Default FSCALE value if not in header

GAIN_KEYWORD           GAIN            # FITS keyword for effect. gain (e-/ADU)
GAIN_DEFAULT           0.0             # Default gain if no FITS keyword found
# 0 = infinity (all or for each image)

#--------------------------- Background subtraction ---------------------------

SUBTRACT_BACK          Y               # Subtraction sky background (Y/N)?
# (all or for each image)

BACK_TYPE              AUTO            # AUTO or MANUAL
# (all or for each image)
BACK_DEFAULT           0.0             # Default background value in MANUAL
# (all or for each image)
BACK_SIZE              128             # Background mesh size (pixels)
# (all or for each image)
BACK_FILTERSIZE        3               # Background map filter range (meshes)
# (all or for each image)

#------------------------------ Memory management -----------------------------

VMEM_DIR               .               # Directory path for swap files
VMEM_MAX               2047            # Maximum amount of virtual memory (MB)
MEM_MAX                128             # Maximum amount of usable RAM (MB)
COMBINE_BUFSIZE        64              # RAM dedicated to co-addition(MB)

#------------------------------ Miscellaneous ---------------------------------

DELETE_TMPFILES        Y               # Delete temporary resampled FITS files
# (Y/N)?
COPY_KEYWORDS          OBJECT          # List of FITS keywords to propagate
# from the input to the output headers
WRITE_FILEINFO         N               # Write information about each input
# file in the output image header?
WRITE_XML              N               # Write XML file (Y/N)?
```

```
XML_NAME               swarp.xml       # Filename for XML output
VERBOSE_TYPE           NORMAL          # QUIET,NORMAL or FULL

NTHREADS               0               # Number of simultaneous threads for
# the SMP version of SWarp
# 0 = automatic
```

SEXTRACTOR

```
#-------------------------------- Catalog ------------------------------------

CATALOG_NAME     test.cat       # name of the output catalog
CATALOG_TYPE     ASCII_HEAD     # NONE,ASCII,ASCII_HEAD, ASCII_SKYCAT,
# ASCII_VOTABLE, FITS_1.0 or FITS_LDAC
PARAMETERS_NAME  $PIPE/confs/bcs_Catalog.param  # name of the file containing catalog contents

#------------------------------- Extraction ----------------------------------

DETECT_TYPE      CCD            # CCD (linear) or PHOTO (with gamma correction)
DETECT_MINAREA   12              # min. # of pixels above threshold
DETECT_MAXAREA   0              # max. # of pixels above threshold (0=unlimited)
THRESH_TYPE      RELATIVE       # threshold type: RELATIVE (in sigmas)
# or ABSOLUTE (in ADUs)
DETECT_THRESH    1.5            # <sigmas> or <threshold>,<ZP> in mag.arcsec-2
ANALYSIS_THRESH  1.0            # <sigmas> or <threshold>,<ZP> in mag.arcsec-2

FILTER           Y              # apply filter for detection (Y or N)?
FILTER_NAME      $PIPE/confs/configs/gauss_3.0_5x5.conv   # name of the file containing the filter
FILTER_THRESH                   # Threshold[s] for retina filtering

DEBLEND_NTHRESH  32             # Number of deblending sub-thresholds
DEBLEND_MINCONT  0.005          # Minimum contrast parameter for deblending

CLEAN            Y              # Clean spurious detections? (Y or N)?
CLEAN_PARAM      1.0            # Cleaning efficiency

MASK_TYPE        CORRECT        # type of detection MASKing: can be one of
# NONE, BLANK or CORRECT

#-------------------------------- WEIGHTing ----------------------------------

WEIGHT_TYPE      NONE           # type of WEIGHTing: NONE, BACKGROUND,
# MAP_RMS, MAP_VAR or MAP_WEIGHT
RESCALE_WEIGHTS  Y              # Rescale input weights/variances (Y/N)?
WEIGHT_IMAGE     weight.fits    # weight-map filename
WEIGHT_GAIN      Y              # modulate gain (E/ADU) with weights? (Y/N)
WEIGHT_THRESH                   # weight threshold[s] for bad pixels

#-------------------------------- FLAGging -----------------------------------

FLAG_IMAGE       flag.fits      # filename for an input FLAG-image
FLAG_TYPE        OR             # flag pixel combination: OR, AND, MIN, MAX
# or MOST

#------------------------------ Photometry -----------------------------------

PHOT_APERTURES   11.25              # MAG_APER aperture diameter(s) in pixels
PHOT_AUTOPARAMS  2.5, 3.5       # MAG_AUTO parameters: <Kron_fact>,<min_radius>
PHOT_PETROPARAMS 2.0, 3.5       # MAG_PETRO parameters: <Petrosian_fact>,
# <min_radius>
PHOT_AUTOAPERS   0.0,0.0        # <estimation>,<measurement> minimum apertures
# for MAG_AUTO and MAG_PETRO
PHOT_FLUXFRAC    0.5            # flux fraction[s] used for FLUX_RADIUS

SATUR_LEVEL      50000.0        # level (in ADUs) at which arises saturation
```

```
SATUR_KEY        SATURATE       # keyword for saturation level (in ADUs)

MAG_ZEROPOINT    0.0            # magnitude zero-point
MAG_GAMMA        4.0            # gamma of emulsion (for photographic scans)
GAIN             0.0            # detector gain in e-/ADU
GAIN_KEY         GAIN           # keyword for detector gain in e-/ADU
PIXEL_SCALE      0.0            # size of pixel in arcsec (0=use FITS WCS info)

#------------------------- Star/Galaxy Separation ----------------------------

SEEING_FWHM      1.2            # stellar FWHM in arcsec
STARNNW_NAME     $PIPE/confs/configs/default.nnw    # Neural-Network_Weight table filename

#------------------------------ Background -----------------------------------

BACK_TYPE        AUTO           # AUTO or MANUAL
BACK_VALUE       0.0            # Default background value in MANUAL mode
BACK_SIZE        64             # Background mesh: <size> or <width>,<height>
BACK_FILTERSIZE  3              # Background filter: <size> or <width>,<height>

BACKPHOTO_TYPE   GLOBAL         # can be GLOBAL or LOCAL
BACKPHOTO_THICK  24             # thickness of the background LOCAL annulus
BACK_FILTTHRESH  0.0            # Threshold above which the background-
# map filter operates

#------------------------------ Check Image ----------------------------------

CHECKIMAGE_TYPE  NONE           # can be NONE, BACKGROUND, BACKGROUND_RMS,
# MINIBACKGROUND, MINIBACK_RMS, -BACKGROUND,
# FILTERED, OBJECTS, -OBJECTS, SEGMENTATION,
# or APERTURES
CHECKIMAGE_NAME  check.fits     # Filename for the check-image

#--------------------- Memory (change with caution!) -------------------------

MEMORY_OBJSTACK  3000           # number of objects in stack
MEMORY_PIXSTACK  300000         # number of pixels in stack
MEMORY_BUFSIZE   1024           # number of lines in buffer

#------------------------------- ASSOCiation ---------------------------------

ASSOC_NAME       sky.list       # name of the ASCII file to ASSOCiate
ASSOC_DATA       2,3,4          # columns of the data to replicate (0=all)
ASSOC_PARAMS     2,3,4          # columns of xpos,ypos[,mag]
ASSOCCOORD_TYPE  PIXEL          # ASSOC coordinates: PIXEL or WORLD
ASSOC_RADIUS     2.0            # cross-matching radius (pixels)
ASSOC_TYPE       NEAREST        # ASSOCiation method: FIRST, NEAREST, MEAN,
# MAG_MEAN, SUM, MAG_SUM, MIN or MAX
ASSOCSELEC_TYPE  MATCHED        # ASSOC selection type: ALL, MATCHED or -MATCHED

#----------------------------- Miscellaneous ---------------------------------

VERBOSE_TYPE     NORMAL         # can be QUIET, NORMAL or FULL
HEADER_SUFFIX    .head          # Filename extension for additional headers
WRITE_XML        N              # Write XML file (Y/N)?
XML_NAME         sex.xml        # Filename for XML output
XSL_URL          file:///opt/sextractor_2.19.5/share/sextractor/sextractor.xsl
# Filename for XSL style-sheet
NTHREADS         1              # 1 single thread

FITS_UNSIGNED    N              # Treat FITS integer values as unsigned (Y/N)?
INTERP_MAXXLAG   16             # Max. lag along X for 0-weight interpolation
INTERP_MAXYLAG   16             # Max. lag along Y for 0-weight interpolation
INTERP_TYPE      ALL            # Interpolation type: NONE, VAR_ONLY or ALL
```

```
#--------------------------- Experimental Stuff -----------------------------

PSF_NAME         default.psf    # File containing the PSF model
PSF_NMAX         1              # Max.number of PSFs fitted simultaneously
PATTERN_TYPE     RINGS-HARMONIC # can RINGS-QUADPOLE, RINGS-OCTOPOLE,
# RINGS-HARMONICS or GAUSS-LAGUERRE
SOM_NAME         default.som    # File containing Self-Organizing Map weights
```