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Chilean AGN/Galaxy Extragalactic Survey (ChANGES)

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4MOST-ChANGES will target a legacy sample of active galactic nuclei (AGN), based on optical continuum variability and spectral energy distribution (SED) selection from several existing surveys, and ultimately complemented by Rubin LSST to: 1) constrain the low-M_{BH}, low-L/L_{Edd} end of the accretion and black hole (BH) density functions to $z \sim 1$, and, by extension, BH seed models; 2) investigate correlations among AGN (M_{BH}, L/L_{Edd}, ultraviolet slope, outflows, variability) and host properties (stellar age, metallicity, kinematics); 3) confirm/characterise rare BH subsamples (extreme variability, tidal disruption events, lensed, intervening absorption line systems) for detailed multi-wavelength follow-up studies.

Scientific context

The last ~ 60 years have seen us go from discovering the first black hole (BH) in Cygnus X-1 to detecting ≳ 10^6 supermassive BHs (SMBHs, ≳ 10^5 $M_\odot$) and hundreds of intermediate-mass BH (IMBHs, ~ 10–10^5 $M_\odot$) candidates across the Universe (for example, Greene, Strader & Ho, 2020; Flesch, 2021). Nevertheless, critical portions of the active galactic nuclei (AGN) discovery space remain poorly explored. The overwhelming majority of published AGN optical spectra (≳ 600 000; for example, Pâris et al., 2018) stem from the galaxy ($z \lesssim 0.1$) or quasi-stellar object (QSO, $M_B < -23$; blue-colour-selected) samples of the Sloan Digital Sky Survey (SDSS), and hence have poor overlap with key southern hemisphere observatories (for example, the Very Large Telescope [VLT] and the Atacama Large Millimeter/submillimeter Array). And while SDSS has likely discovered ~ 80% of bright type 1 QSOs with $i_{AB} < 19$ out to $z \sim 2$ (where the BH accretion density peaks; for example, Aird et al., 2015), fainter and/or redder AGN (g–r > 0.6; for example due to weaker accretion, lower AGN-to-host light ratios, broad absorption lines and modest dust obscuration) have yet to be systematically targeted in large numbers beyond $z \sim 0.1$. More inclusive selection techniques based on variability and/or ultraviolet–mid-infrared (UV–MIR) spectral energy distributions (SEDs) have been shown to be more effective than optical colours alone (for example, Peters et al., 2015; Tie et al., 2017; Sánchez-Sáez et al., 2019) in selecting such ignored AGN populations. Yet the largest spectroscopically confirmed variability-selected samples number ~ 13 000 AGN from SDSS Stripe 82 (~ 14% reddened fraction; Peters et al., 2015) and 1263 AGN from the Dark Energy Survey (DES) supernova fields (6% reddened fraction; Tie et al., 2017), probing a tiny fraction of the parent population. More recent studies with La Silla-QUEST (LSQ) and the Zwicky Transient Facility (ZTF) to $r_{AB} \sim 20$–21 recover reddened fractions of 10–15% (for example, Sánchez-Sáez et al., 2019), while deeper high-cadence VLT Survey Telescope (VST) imaging in COSMOS and CDF-S to $r_{AB} \sim 23.5$ (for example, De Cicco et al., 2021) identify ~ 300 variability-selected AGN deg^{-2}, with reddened AGN fractions of ~ 30% (the majority of which notably have X-ray fluxes below the eROSITA all-sky survey limit). The latter studies imply that the SDSS and DES variability samples still suffer strong biases and represent just the tip of the iceberg of a much larger population awaiting confirmation with 4MOST.

Among upcoming surveys, the Vera C. Rubin Observatory (Rubin) Legacy Survey of Space and Time (LSST) is expected to have a truly profound impact on AGN science. With its ~ 18 000-deg^2 footprint, *ugrizy* coverage (0.4–1 μm), ~ 1–3-day temporal sampling, and $r_{AB} \sim 24.5$ single-epoch 5σ-depth, the LSST will produce a high-purity sample of > 2 × 10^7 AGNs between $z = 0$ and $z = 7$, with > 50% identified in the first 1–2 years. Such numbers will quickly surpass past/current AGN samples, extending to lower luminosities, higher extinction E(B-V) ~ 0.3-1, and higher z, and enlarging rare AGN samples. Each AGN will ultimately have ≳ 800 visits (≳ 130 per filter) over the 10-year survey, enabling unique analyses. Deep LSST *ugrizy* imaging, particularly in concert with Euclid *YJHK* imaging, will

Subsurvey Name	Area (deg^2)	Parent sample (Completeness)	Limiting magnitude	Selection notes
W_VARZ+W_VARG+W_VARL	$> 10^4$	$\sim 1.5 \times 10^6$ (60%)	$r \sim 21$	Variability from ZTF, Gaia, LSQ
W_SED	$> 10^4$	$\sim 1.8 \times 10^8$ (35%)	$r \sim 22.5$	DELVE+VHS+WISE
W_MUL	$> 10^4$	$\sim 4 \times 10^5$ (50%)	$r \sim 20.5$	2+ visits, > 6 months apart
W_HIZ	$> 10^4$	$\sim 3 \times 10^4$ (75%)	$i, z \sim 22.5$	$z > 4$
D_ALL	16	$\sim 1 \times 10^4$ (90%)	$r \sim 23$	X-ray, MIR, radio, optical
T_TDE + T_TDEHOST	$> 10^4$	$\sim 3 \times 10^4$ (3%/50%)	$r \sim 21$	TDEs + Hosts
T_LST	$> 10^4$	$\sim 2 \times 10^5$ (25%)	$r \sim 22.5$	EVAGN, LLAGN
T_LEN	$> 10^4$	$\sim 3 \times 10^3$ (75%)	$r \sim 22.5$	QSO + lens galaxy

Table 1. Properties and selection criteria of the ChANGES subsurveys.

offer relatively accurate photometric redshifts and spatially resolved SEDs for a substantial fraction of its anticipated $\sim 2 \times 10^9$ extragalactic detections. This will ultimately allow statistical comparisons between AGN and inactive galaxies across redshift, environment, luminosity, and some (deblended) host properties. However, in order to extract detailed physical constraints (for example precise stellar properties, BH masses, accretion rates, line kinematics), and to study accretion physics and address fundamental evolutionary questions, spectroscopy is required. To this end, the Chilean AGN/Galaxy Extragalactic Survey (ChANGES) will acquire ≈ 1.79 Mhrs of 4MOST low-resolution spectroscopy for a large, representative sample of AGN within the LSST footprint (≳ 10 000 deg^2), selected primarily via variability and optical/NIR/MIR SEDs from existing imaging data within the LSST's footprint.

Target selection and survey area

Table 1 specifies our current survey design, indicating the survey regions and input catalogues. The selection functions for our two primary samples are driven by variability features and full optical-MIR SED modelling, respectively, allowing us to overcome past optical colour selection biases. Target completeness is further weighted by the relative number of targets across bins of colour, estimated redshift/luminosity, and variability timescale and amplitude. The variability sample is based on ZTF-DR11, Gaia-DR3, and LSQ data using machine-learning selection (for example, Sánchez-Sáez et al., 2021), aiming to observe ~ 60% of sources from a sample of $\sim 1.5 \times 10^6$ AGN with $r_{AB} \lesssim 21$. Our SED selection derives from DELVE-DR2, VHS-DR6, VIKING-DR2, and catWISE2020 data using SED-fitting techniques (for example, Assef et al., 2010; Boquien et al., 2019), aiming for ~ 30% coverage from a target pool of $\sim 1.8 \times 10^6$ AGN with $r_{AB} \lesssim 23$. We augment these samples with ~ 10 000 multiwavelength selected AGN in four 4MOST/LSST deep-drilling fields (DDFs) and ~ 150 000 host-dominated AGN or unique BH-related phenomena selected using the LSST's unparalleled variability constraints during its first few years of operation (see below). The resulting spectroscopic observations will characterise a large, representative population of relatively unobscured (i.e., potentially reddened), lower-M_{BH}, low-M_{BH}/M_{host}-ratio, and/or lower-L/L_{Edd} AGN out to $z \sim 0.5$–1, that have yet to be well sampled by any other method, owing to weaker emission and host domination.

Specific scientific goals

BH accretion rate (BHAR) and M_{BH} densities, evolution and host synergies. The moderately accreting AGN sample to be probed by ChANGES ($10^{-4} < L/L_{Edd} < 10^{-1}$; see Figure 1) comprises ~ 50–80% of the estimated total mass accretion onto BHs in type 1 and mildly obscured AGN and strongly complements other 4MOST AGN samples. The sample will be used to characterise the low-L/L_{Edd} and low-mass contributions to the BHAR and M_{BH} density distributions and push several landmark $z \lesssim 0.1$ constraints out to $z \sim 0.5$–1, as functions of several, potentially interdependent, driving parameters (for example redshift, M_{BH}, L/L_{Edd}, M_*, SFR, morphology, gas content, M_{halo}, and environment). We aim to assess in better detail where and how lower-mass BH growth occurs (as input for the next-generation Event Horizon Telescope, Athena, and LISA), and quantify the role of downsizing and feedback processes in the establishment of AGN scaling relations.

Novel time-domain spectral synergies. AGN vary on nearly all timescales. Our experimental design will yield 4MOST spectra for up to $\sim 1.2 \times 10^6$ AGN, which when combined with intensively sampled LSST multi-colour light curves will: 1) relate their variability and SED/spectral properties; 2) enable precision measurement of continuum lags for type 1 AGN; 3) gain insight into the unobservable far-UV regime based on the emission-line strengths of high ionisation species; and 4) extend our database of labelled systems to optimise the LSST's photometric classification and redshifts. We seek to observe ~ 20% of the variability-selected AGN sample (all with $r_{AB} < 19$ and 50% with $19 < r_{AB} < 20$) at least twice, to systematically study spectral variations in tandem with the LSST's unprecedented optical monitoring. Our large samples will cover a broad span of AGN physical (z, M_{BH}, L/L_{Edd}) and variability (amplitude and characteristic timescale of their light curves) parameter spaces, allowing examination of how AGN spectral properties vary across these parameters and how they comply with standard accretion disc predictions. Differences for low-M_{BH} vs. low-L/L_{Edd} AGN may probe when and how AGN transition to advection-dominated accretion flows.

Completeness and obscured fraction corrections. Although the optical–MIR selection of ChANGES will cover a wide parameter space, it will still suffer from various forms of incompleteness (for example, ability to recover redshifts,

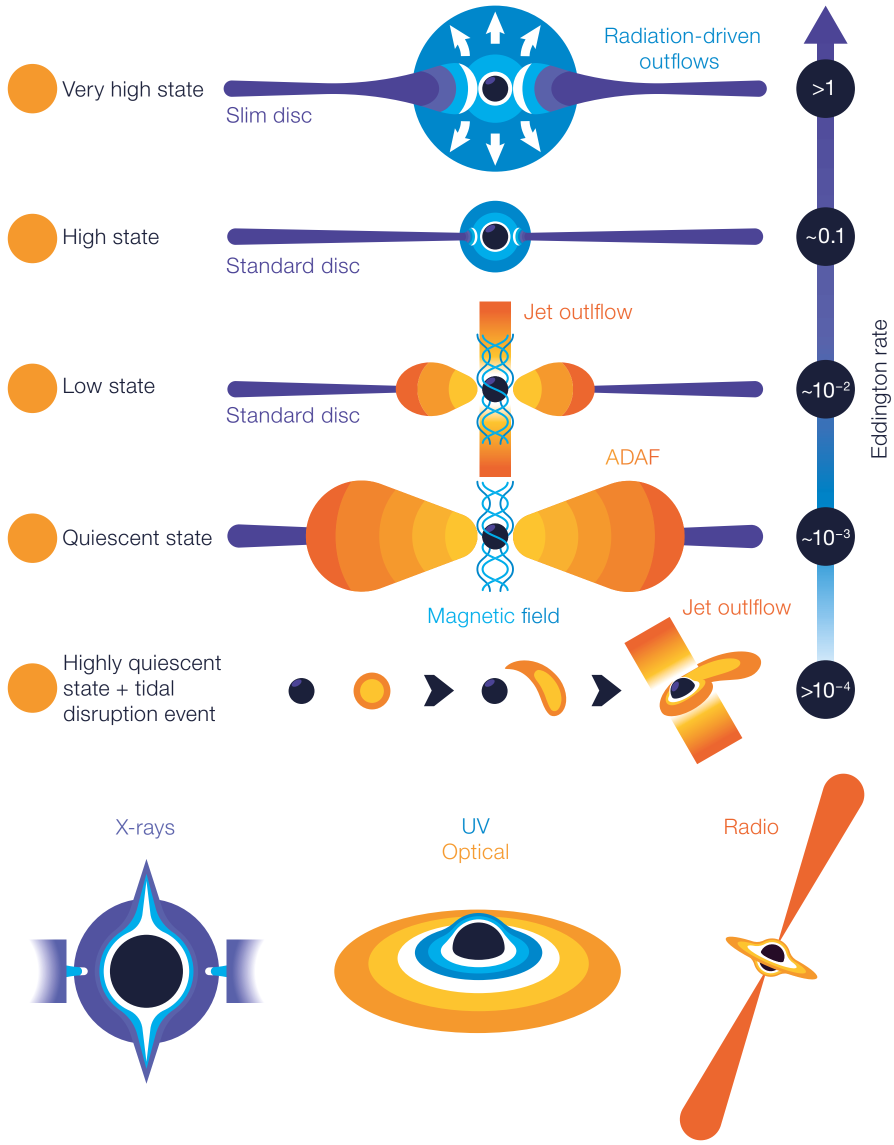

Figure 1. The distinct types of accreting SMBHs we expect to detect with 4MOST-ChANGES (super L/L_{Edd}, high-L/L_{Edd}, low-L/L_{Edd}, quiescent + TDE). Credits: J. Utreras/F. Bauer (CATA)

detect spectral features, discern AGN types in severely host-dominated sources) and be biased against heavily obscured AGN. To correct for these, ChANGES will carry out deeper observations in the DDF regions for both optical variability+SED selected AGN (HSC/VST/DES) to assess completeness and obscured AGN samples from X-rays (XMM-SERVS), MIR (SERVS) and radio (MIGHTEE/EMU) to estimate obscured fractions as functions of, for example, z, M_{BH}, L/L_{Edd}, M_*.

Changing-type/EVAGN. Current samples of extreme variability AGN (EVAGN; $\Delta m/\Delta t > 1$ mag yr^{-1}) number in the thousands (for example, Luo, Shen & Yang, 2020; López-Navas et al. 2023), with the LSST expected to uncover orders of magnitude more. ChANGES will prioritise up to ~ 100 000 such targets for single (and when feasible, multi-epoch) spectra to establish an unprecedented sample for studies of detailed accretion physics and constraints on 'changing-type' AGN (Graham et al., 2020). The latter can be compared to a well-characterised search for changing-type AGN among ≳ 200 000 targets with high-signal-to-noise multi-epoch splits from ChANGES' Time-Domain Spectral Synergy campaign to establish absolute rates.

Tidal disruption events (TDEs). TDEs provide important constraints on the physics and demographics of quiescent SMBHs and their hosts, but only ~ 60 have been well characterised to date (for example, Gezari, 2021). The LSST is expected to find ~ 6000 TDEs a year to $z \sim 0.5$ ($r_{AB} \sim 23.5$ mag), providing much larger samples with which to understand their demographics and triggering. ChANGES aims to prioritise ~ 1000 high-confidence TDEs below $z \sim 0.2$ for direct confirmation and characterise ~ 15 000 TDE hosts (measuring velocity dispersions for a brighter subset). Of particular interest will be IMBH-TDEs from compact stars and white dwarfs, which should be less luminous and shorter than TDEs from SMBHs.

High-redshift AGN. Moderate-L_{bol} AGN at $z > 4$ are a key population for constraining BH formation models and early evolution (Volonteri et al., 2017). Yet the current $z > 4$ QSO luminosity function is pinned down by just a few hundred objects at $-24 < M_{1450} < -30$ (for example, McGreer et al., 2018), leaving the faint-end slope and evolution highly uncertain; uncertainties rise further beyond $z \sim 5$, since classical colour selection techniques break down because of confusion with stars. ChANGES will target ~ 12 000 $z > 4$ candidates, selected via optical-MIR photometry and/or variability, to improve statistics particularly for fainter AGN.

Lensed AGN. The LSST will discover thousands of strongly lensed QSOs out to high redshift, enabling novel constraints on, for example, accretion processes, evolution, the initial mass function, cosmology (addressing early vs. late H_0 'tension') and the inner structure of high-z AGN. However, an essential first step for most lensed-AGN-enabled science cases is measurement of both source and lens redshifts. ChANGES aims to spectroscopically confirm ~ 1500 QSOs and lens galaxies, dramatically increasing the number of confirmed QSO lenses in the southern hemisphere.

Intervening quasar absorption-line systems (QALs). QALs are powerful probes of the neutral gas content and metal inflow–outflow in galaxies over cosmic time. Past spectroscopic surveys have provided unprecedented QAL statistics but may potentially be biased against the most gas-rich systems as a result of the blue QSO colour selection (for example, Krogager et al., 2019). The low spectral resolution has also limited the accuracy of metal column densities, which are sensitive tracers of galaxy conditions and cosmic chemical evolution. ChANGES QSOs will be much less biased, providing an unprecedented sample of QALs covering key absorption lines (HI, CIV, SiIV, SiII, CII, OI, MgII, and NaI).

Spectral success criteria and figure of merit

The wide-area surveys aim for signal-to-noise ≳ 10 $Å^{-1}$ in one ~ 1000-Å blue, green or red window for r_{AB} ≲ 21 targets to constrain AGN and host properties (weak lines, stellar continua, etc.), and signal-to-noise ≳ 1 $Å^{-1}$ among fainter targets to constrain redshifts only. Within the DDFs, we extend these ~ 1 mag deeper. We anticipate a spectroscopic success rate of ~ 80% for most subsurveys (dropping to ~ 50% for $z > 5$ AGN). Our overall figure of merit is a weighted combination of each subsurvey, based on achieving the specified completeness limits for the target numbers indicated.

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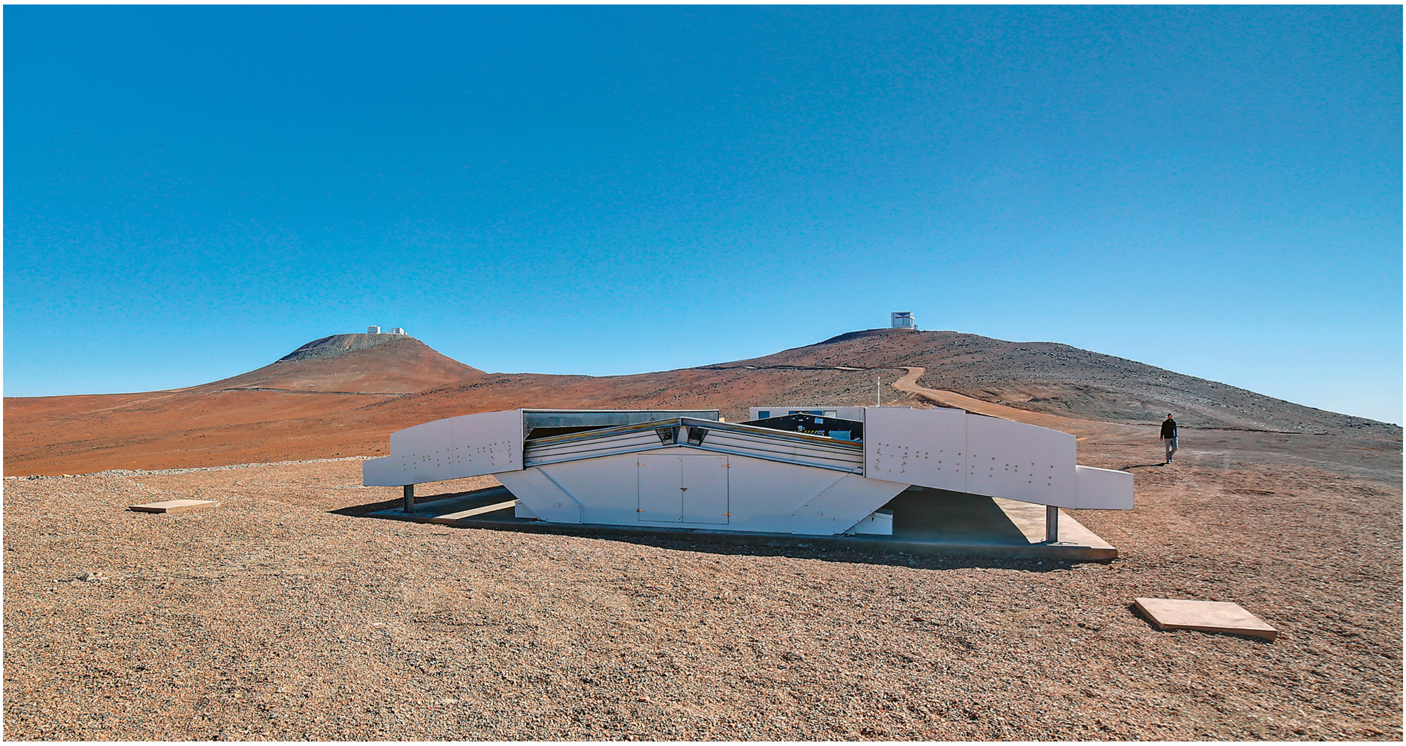

The Next-Generation Transit Survey (NGTS) is located at ESO's Paranal Observatory in northern Chile. This project is searching for transiting exoplanets — planets that pass in front of their parent star and hence produce a slight dimming of the star's light that can be detected by sensitive instruments. The telescopes focus on discovering Neptune-sized and smaller planets, with diameters between two and eight times that of Earth. This image shows the NGTS enclosure in the day. The VISTA (right) and VLT (left) domes can also be seen on the horizon.