Scientific Justification *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

Measuring the Hubble Constant (H_0) is crucial to understanding the age, size and critical density of the Universe. Recent direct measurements of H_0 using late time probes such Type Ia Supernovae (SNe) calibrated by Cepheid variables [2], and early time probes such as Planck's measurements of anisotropies in the Cosmic Microwave Background (CMB), are in 5-σ tension [1]. The tension could be a result of systematics involved in either probe's measurements or new physics. Using alternate methods to calibrate H_0 measurements from Type Ia SNe, i.e calibrating the distances using the tip of the red giant branch (TRGB), yields consistent results with early and late time probes [4]. In this conjecture, it is crucial to test the systematics of different probes using independent competitive and complementary methods. Strong Lensing Time Delay Cosmography (TDC) is an emerging solution that provides an independent and direct measurement of H_0, and dark energy parameters ω_0, ω_a[5]. Differences in light travel time from a strongly lensed variable source, and the deflection of light from the source due to the intervening lensing galaxy's mass distribution leads to an absolute distance measurement with 5-10% precision per lens [6].

Currently, TDC has measured H_0 with 2.4% uncertainty using 7 lensed quasars [7]. TDC requires the following 4 measurements: a lens mass model to constrain the Fermat potential of the deflector galaxy, spectroscopic redshifts of the source (z_s) and lens (z_d), line-of-sight (LOS) calibration and most importantly, measured time delays. It has been shown that H_0 measurement uncertainty can be brought down to 1% with 40 systems that have well-measured delays and 200 systems with well measured mass and radial profiles [6]. We are leveraging spectroscopic redshift surveys (e.g: 4SLSLS [8]) for required redshift precision, Keck and VLT AO observations to constrain radial profiles [6]. Using a power-law elliptical mass distribution or Navarro–Frenk–White (NFW) mass profile mitigates bias arising from mass modeling. The remaining and most important ingredient remains the measured difference in arrival time of each image.

H_0 precision is a direct product time delay measurement precision since $H_0 = H_{0,model} \times \frac{\Delta t_{model}}{\Delta t_{measured}}$. In order to measure H_0 with the desired precision, we need to observe lensed light curved from multiple images with $\sim$ 1 mmag photometric accuracy and daily cadence [9]. There have been systematic ground based efforts, of which COSMOGRAIL uses a global network of telescopes to monitor time delay lenses for 1-2 observing periods in the Northern and Southern Hemisphere. This has yielded $\sim$ 50 well measured time delays, contributing to a growing sample that can be used for TDC. Vera Rubin Observatory's Legacy Survey of Space and Time (LSST) will contain O(1000) time delay lenses that can be used for TDC [11]. LSST will have the desired photometric precision and cadence when multiple-band light curve data are combined. LSST can yield 1 - 3 day cadence on average with multi-band light curves, and 10 - 15 day cadence on average with single-band light curves which cannot be used for TDC.

This brings up a crucial need in our modeling and analysis work of lensed quasar time delays. In order to measure time delays using multi-band light curves, we need to jointly model the AGN transfer function and the lensing time delays. We are currently building tools to do this and validating our joint modeling results on simulated data. In order to prepare our time-delay measurement pipeline for LSST, we need to verify our methods on real data. The brightest targets already known in LSST have been discovered by DECam in the Dark Energy Survey (DES) [7] - these are the best targets to monitor to build up the sample of time-delay lenses for TDC. **By monitoring a sample of $\sim$ 10 lenses using DECam, we will be constructing an important benchmark dataset that will contribute directly to high precision cosmology results and enable future cosmology measurements with LSST forecasted in Figure 3** Our proposal seeks to acquire this crucial dataset required to measure any time delay from LSST, and use the TDC probe with LSST. Multi-band lensed quasar light curves from DECam will also shed light on important effects in time delay measurements including modeling extrinsic variability in quasar light curves [9] and measuring chromatic microlensing time delays [10].

Experimental Design *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification?*

We propose to observe a sample of 10 lenses shown in Figure 1. We divide this sample into two subsamples: (i) lensed quasars that have been extensively monitored in the r-band using ground based 2-m telescopes and have measured time delays and (ii) lensed quasars for which we do not have any time delays. All systems are brighter than 20 mag, with an average mag of 18.85 mag across the objects. They all have wide separations at greater than 1.15 ", making the light curve extraction and deblending easier. We have also chosen a range of image configurations with 2 doubles, 2 3-image systems (a double with a central image), 5 quads and 1 5-image system (a quad with a central image) to analyze how different image configurations can help with light curve extraction.

In order to reach the time delay precision we require for cosmology and observing microlensing effects, we require atleast an SNR of 500 and daily cadence [17]. In order to meet this need and imitate LSST observing cadence we propose to observe these objects in g, r, i bands requiring exposure times of 20 - 25 minutes per object, per night, every 3 nights. This exposure time varies due to contamination from the Moon. On nights where we are 14 days away from New Moon, we propose to schedule r-band observations only to maximize the SNR we can expect from a 25-minute exposure window. This will add up to a maximum of 4.5 hours of observation time, including slewing time, every 3 nights. We are in ongoing alliance with the DECam Alliance for Transients Program (DECAT) and plan to pool our time together.

In order to measure time delays with multi-band light curves, we need to be able to measure the transfer function that characterizes the temporal shift and distortion of light received from quasar accretion disks in different bands as shown in Figure 2. Reconstructing this function simultaneously with the lensing time delay will allow us to combine the multiple band data for each image, and then use the combined data to characterize the time delay between each pair of images.

With our observations, we will be able to model and separate extrinsic variations that are present in almost every lensed quasar known to date [12, 16] - this is crucial to understanding the intrinsic variability of lensed quasars. By extracting the external signal, we will also study the impact that microlensing has on different bands - since microlensing caustics overlap with different regions of the accretion disk emitting in different wavelengths. We can also measure the microlensing time delays and assess their impact on the lensing time delay [10].

We currently have in place software that can deconvolve and extract light curves (`STARRED` [20]) by characterizing the environment (i.e obtaining PSF from nearby stars) around a lensed quasar for multi-epoch wide-field ground based images (`lightcurver` [21]). We are currently in the process of simulating the multi-band data we expect to see with LSST and constructing the method to jointly model the AGN transfer function and lensing time delay. This method will be validated against simulation in the upcoming 8 months. We expect to receive year-1 of LSST data in 2 years. Using this DECam data before LSST DR1, we will have unlocked the potential to do cosmology forecasted in Figure 3, and we will extend the baseline observations for these targets by 1-year, leading to more precise time delays, and better characterization of the light curve variability [9].

Given the recent development of software infrastructure that can be used to extract and model the time delays, and the imminent launch of LSST-Camera, **this is the best time to observe these objects**, and DECam is the best facility to observe them with. With 1 year of DECam data, apart from cosmology results, we will be able to extract AGN physics of measuring the size of accretion disks [22], characterizing impact of microlensing time delays on time delays [14], characterizing the average time lag in emission from different passbands and the size of the regions reprocessing the X-ray corona emission in different optical/near-UV passbands.

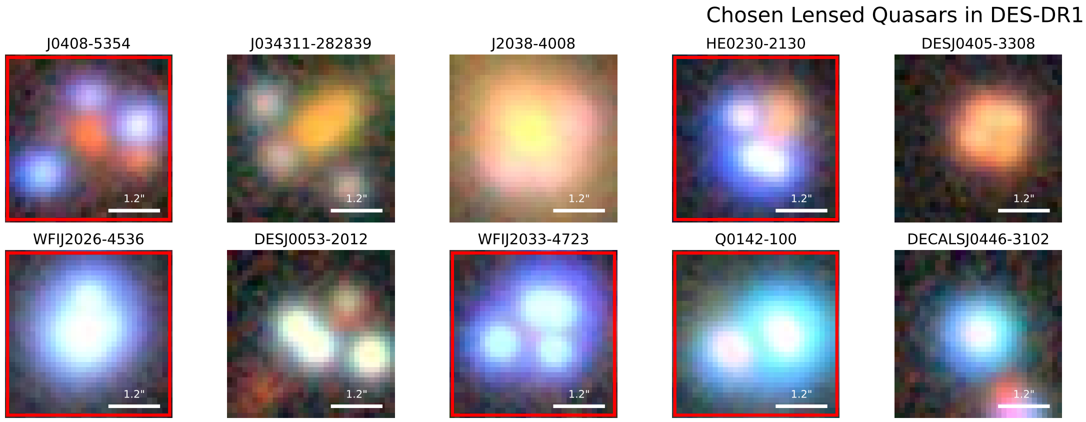

Figure 1: Selected targets for monitoring program. Lensed quasars with well measured time-delays are highlighted in red. This will act as our control sample that we can verify our multi-band time delays against. This sample will also provide guidance on how much we can trust our time delay estimates for the new objects.

References

[1] Verde, L. et al 2019 Nature, 3, 891 [2] Adam G. Riess et al 2022 ApJ934 L7 [3] DESI Collaboration 2024, arXiv:2404.03002 [4] Wendy L. Freedman et al 2019 ApJ882 34 [5] Refsdal 1964, MNRAS, 128, 307 [6] Treu, T. et al (2022), A&A Rev., 30, 8 [7] Millon M. et al 2020a A&A639, [8] Collett, T. E., et al 2023 The Messenger, 190, 49 [9] Courbin F. et al 2018 A&A609, A71 [10] S. S. Tie et al 2018 MNRAS473 1 [11] Oguri et al 2010 MNRAS405 4 [12] Mosquera, A.M. 2011 ApJ96 738 [13] Taak, Y. C. et al 2023 MNRAS524 5446 [14] Vernardos, G. et. al 2024 SSRv 220 14 [15] Tewes M. et al 2013 A&A553 A120 [16] Millon M. et al 2020c A&A642 A193 [17] Suyu, S.H. et al 2018 Space Sci. Rev.214, 91 [18] Shajib J.A. 2024, arXiv:2406.08919 [19] Chan J. H.-H. et al 2020 A&A636, A52 [20] Millon, M. et al 2024 ApJ168, 55 [21] Dux, F., 2024 JOSS 9(102), 6775 [22] Chan J. H.-H. et al 2021 A&A647, A115

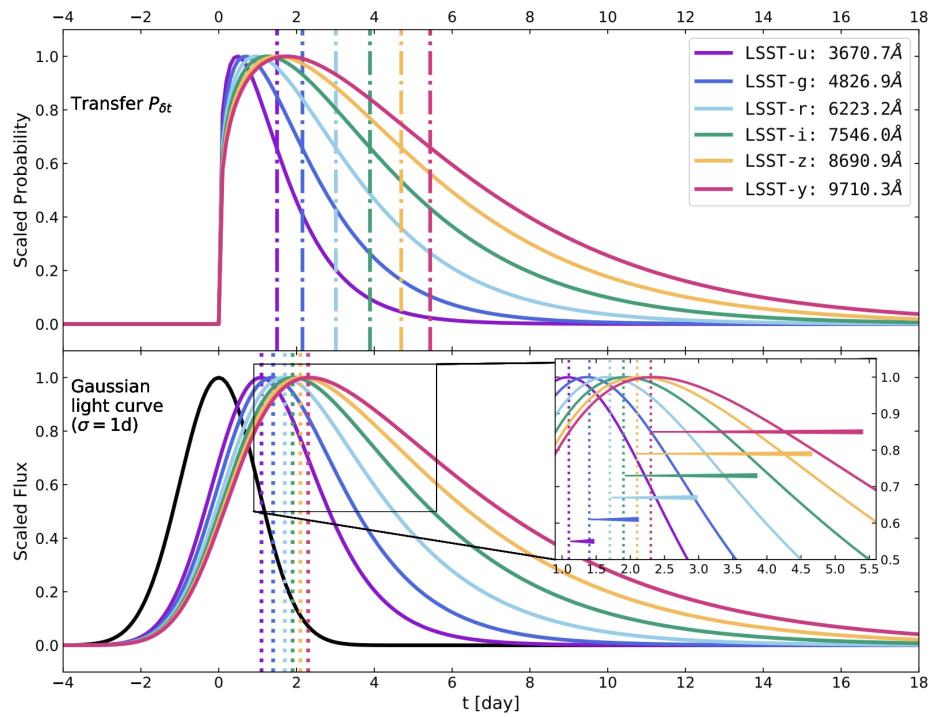

Figure 2: Transfer Function demonstrating the shift and distortion of AGN driving variability (in black) in each LSST band: u, g, r, i, z, y. Our observation are a result of this transfer function convolved with the driving variability: thus deconvolving this kernel will be essential in characterizing the driving variability, and then measuring time delays.

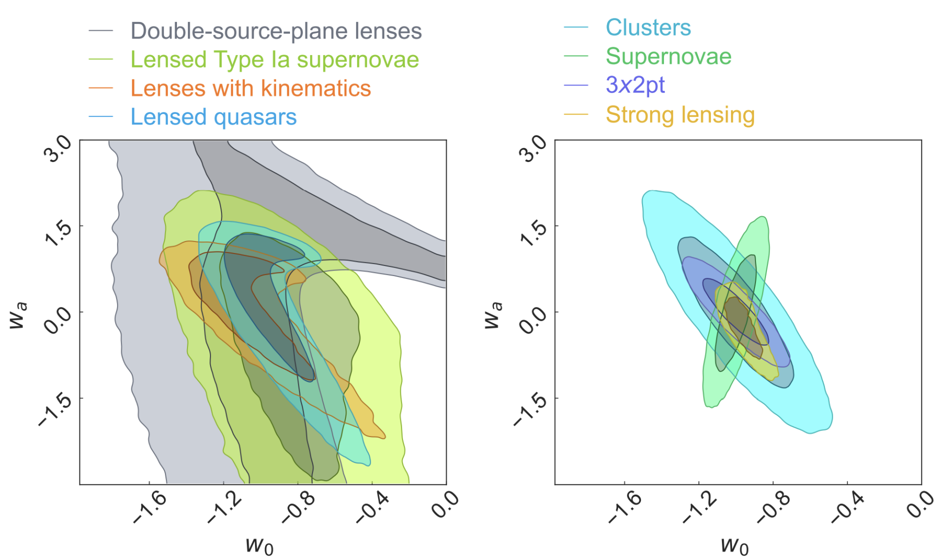

Figure 3: Left: Cosmology constraints from each strong lensing probe. In order to use the light blue contour corresponding to lensed quasars, we need to have our time-delay measurement tools tested and verified. Thus, DECam will be instrumental in helping us prepare for cosmology with LSST. Right: Forecast from the primary dark energy probes used in the Dark Energy Science Collaboration (DESC).