The STRong-lensing Insights into Dark Energy Survey (STRIDES)
A Broad External Collaboration Proposal

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Background:

Strongly lensed quasars can be used to measure cosmological parameters. The time delays between the multiple images can be measured via dedicated monitoring campaigns, while the gravitational potential of the lensing galaxy and of structures along the line of sight can be modeled and measured using deep high resolution imaging and spectroscopy. The combination of these observables enables a distance, known as the time-delay distance (a combination of angular diameter distances) to be measured, which in turn can be converted into a measurement of cosmological parameters including those describing the Dark Energy equation of state (e.g. Courbin, Saha & Schechter 2002, LNP, 608, 1; Treu 2010, ARA&A, 87, 48). The constraints obtained from time delays are comparable in precision to those obtained by baryonic acoustic oscillation experiments and provide a powerful complement to other probes of dark energy (Suyu et al. 2010, ApJ, 711, 201). The power of time delays is well summarized in a recent paper by Linder (2011, PRD, 84, 12352). For a program of size comparable to the one proposed here "Adding time delay data to supernovae plus cosmic microwave background information can improve the dark energy figure of merit by almost a factor 5 and determine the matter density Ω_m to 0.004, the Hubble constant h to 0.7%, and the dark energy equation of state time variation w_a to 0.26, systematics permitting."

At the moment, the main limitation of this technique is the small sample size of lenses that have accurate time delays as well as all the other required ancillary datasets. This limitation is mostly driven by the fact that lensed quasars are rare in the sky (0.2/degree at DES depths), and *not enough suitable lenses are known at this time*.

We propose to form a collaboration with interested parties in DES to search for strongly lensed quasars. The long-term goal is to discover and follow-up ~100 previously unknown gravitationally lensed quasars. According to Oguri & Marshall (2010, MNRAS, 405, 2579) there should be approximately 120 such lenses brighter than i=21 (third faintest image), including 20 high information-content quads, to be discovered in DES. Discovering them and following them up requires a long-term investment of time and observational resources. The STRIDES team has the expertise to carry out this project, based on more than ten years of investment in search, discovery, modeling and monitoring techniques. Building on the state of the art COSMOGRAIL network (Eigenbrod et al 2005, A&A, 436, 25), our team also has the expertise and resources to carry out optimal monitoring for many years, as is required for this project. This project is, however, a big endeavor and we would welcome members of the DES Collaboration that are interested and committed to join us as part of STRIDES.

It is the assessment of the DES Strong Lensing Working Group Chairs that, while we have DES members who are interested in participating, these people do not have all the relevant expertise to carry out such an extensive program entirely within the collaboration. In addition the mix of telescope resources required is also not easily met from within the DES Collaboration. The DES Strong Lensing Working Group Chairs feel that the most effective way for DES to participate in this science is through a partnership with the STRIDES team.

In addition to the main goal of dark energy, discovery and follow-up of a large set of lenses would address many other key questions in astrophysics. This document provides an overview of this whole project, and some details on the collaboration we are proposing.

Summary of science goals:

- Primary: Dark energy from 100 gravitationally lensed quasars with time delays (distance precision and accuracy equivalent to $dH_0<1\%$).
- Secondary: Dark matter substructure from flux ratio anomalies, as measured from active galactic nuclei narrow line region, dusty tori, and radio emission

DES data requirements:

- Photometric catalogs for initial screening of lens candidates, including if possible morphological parameters (e.g. object shapes and sizes), at each epoch.
- Cutouts of lens candidates for modeling for final selection.
- Photometric catalogs (ideally with stellar masses and photometric redshifts) of fields with lenses to characterize the line of sight mass structure.

This will be the joint responsibility of the DES strong lensing working group, in collaboration with the STRIDES team.

Follow-up data requirements:

We anticipate that completion of the project will require:

- Hundreds of deep HST and Keck/VLT AO images for confirmation of lenses discovered in DES images and for precise Einstein ring modeling.
- Several years of monitoring of the lenses on 1-2m class telescopes to measure accurate image time delays
- Dozens of nights on Keck, VLT and other large telescopes to obtain spectroscopic redshifts, lens galaxy stellar kinematics, AGN line fluxes etc

This will be the responsibility of the STRIDES team using their expertise and their access to the COSMOGRAIL network (Courbin & Meylan) and Las Cumbres Global Telescope Network (Treu) for monitoring and the Keck (Fassnacht & Treu) and VLT (Courbin & Meylan) Telescopes.

Personnel requirements:

Senior Personnel. This will be the main science project of the PI, who will be an active participant of the DES strong lensing working group. We anticipate that the Co-PIs will devote a substantial fraction of their research time to the project (or project pathfinders) to develop tools**.** When appropriate, they will also participate in the DES strong lensing

working group. In addition, it is expected that members of the DES collaboration will want to participate actively in the STRIDES project. Some are already Co-PIs and Co-Is in the current proposal and others may join on the course of the project. If additional non-DES CoIs join STRIDES and need to work directly with DES data, we would request the approval of DES before sharing proprietary data with them. Members of the DES collaboration may join at any time as CoIs as per the DES policy for participating in DES analysis projects.

Junior Personnel. We anticipate that over the course of the project we will involve at least 10-11 junior investigators, postdocs and students distributed amongst the PI and Co-PI institutions. The PI and each non-DES Co-PI will be limited to 1 Post-doc, 1 PhD student and 1 undergraduate student working on DES data at any one time. The majority of them would be working on algorithms, modeling, or follow-up projects. The junior investigators working with DES data will be identified, and their names submitted for approval as addenda to this broad scope external collaboration proposal, or in future, to the DES collaboration on a case by case basis. Participation from junior investigators at other DES institutions is encouraged. Extended visits of suitable junior personnel from DES institutions to STRIDES institutions and vice versa is also encouraged.

Duration of the collaboration:

Owing to the long-term nature of the project and the commitment required for monitoring work we have given some thought as to what would be an appropriate duration for the initial collaboration. We are proposing that the initial collaboration would look for and follow-up lens candidates in the first 2500 square degrees of the survey area. We anticipate that this will take 2-3 years from candidate confirmation to publication. At this time we would revisit the agreement and if all parties are in agreement we would propose a collaboration for the remaining 2500 square degrees.

Publication Policy:

Papers that include DES data that are not public or papers that were initiated before the data became public are subject to the DES publication policy. This includes, for example, papers that describe the discovery of lens candidates. Authorship will be offered to DES builders for papers that describe only follow-up non-DES data but make use of information obtained from non-public DES data, such as lens candidate coordinates, provided the elapsed time between the publication of the information or the release of the relevant DES data, and the submission of the subsequent paper is less than 18 months. Papers that are based on public data (and were initiated after the data became public) or papers that are based only on follow-up non-DES data and only make use of information obtained from public or published DES data will not be subject to the DES authorship policy. Naturally, the expectation is that those members of DES who have contributed actively to STRIDES will be become an integral part of the STRIDES collaboration (as CoIs or Co-PIs) and therefore acquire authorship rights, according to STRIDES publication policy to be decided by the STRIDES PI and Co-PIs.

Expected Timeline:

- 2012
  - DES starts
  - Lens finding algorithms improvement and testing
- 2013
  - DES lensed QSO discovery and confirmation begins
- 2014
  - Confirmation begins
  - Monitoring begins
  - Line of sight work begins
- 2015
  - Confirmation continues
  - Monitoring continues
  - Line of sight work continues
  - Deep imaging and spectroscopic follow-up begins
  - Detailed modeling begins
- 2016
  - Confirmation continues
  - Monitoring continues
  - Deep imaging and spectroscopic follow-up continues
  - Detailed modeling continues
  - Line of sight work ends
- 2017
  - Confirmation ends
  - Monitoring continues
  - Deep imaging and spectroscopic follow-up continues
  - Detailed modeling continues
  - Flux ratio radio begins
  - Flux ratio IR begins
- 2018
  - Monitoring continues
  - Deep imaging and spectroscopic follow-up ends
  - Detailed modeling continues
  - Flux ratio radio continues
  - Flux ratio IR continues
- 2019
  - Monitoring ends
  - Detailed modeling ends
  - Flux ratio radio ends
  - Flux ratio IR ends
- 2020
  - Publication of final results

Management plan and short description of the PI/CoPIs expertise.

PI:

- Tommaso Treu (UCSB, USA): overall coordination; discovery and confirmation with Keck; confirmation and follow-up with HST and Keck spectroscopy; flux ratios with adaptive optics spectroscopy and JWST; access to LCOGT for monitoring.

Co-PIs (builders):

- Matthew Auger (IOA, UK): liaison with DES quasar group, spectroscopy follow-up.
- Liz Buckley-Geer (FNAL, USA): DES collaboration strong lensing working group co-chair; interface with DES data products, discovery algorithms, lens modeling.
- Frederic Courbin (Lausanne, Switzerland): monitoring via the COSMOGRAIL network; confirmation and follow-up with VLT; deconvolution; microlensing.
- Chris Fassnacht (UCD, USA): confirmation and follow-up with AO imaging and Keck spectroscopy; line of sight characterization; monitoring with radio; flux ratios with radio.
- Josh Frieman (FNAL, USA): DES; cosmography.
- Phil Marshall (Oxford, UK): discovery and confirmation algorithms; coordination with SpaceWarps; lens modeling support.
- Richard McMahon (IOA, Cambridge, UK): Co-chair of the DES Quasar working group, discovery algorithms
- Georges Meylan (Lausanne, Switzerland): monitoring via the COSMOGRAIL network; confirmation and follow-up with VLT imaging and spectroscopy; microlensing.
- Sherry Suyu (ASIAA, Taiwan): lens modeling lead.

CoIs:

- Adriano Agnello (UCSB, USA): discovery algorithms, follow-up, confirmation and modeling
- Adam Amara (ETH-Zurich, Switzerland) – VLT follow-up, lens modeling, time domain analysis
- Francisco Castander (IEEC, Spain): GTC and VLT follow-up.
- David Finley (FNAL, USA): coordination with SpaceWarps.
- Andy Howell (LCOGT, USA): LCOGT follow-up
- Chris Kochanek (OSU, USA) - monitoring via the COSMOGRAIL network
- Huan Lin (FNAL, USA): strong lens searches, interface with DES data products, and lens modeling, image simulations, cosmography.
- Martin Makler (CBPF, Brazil): DES collaboration strong lensing working group co-chair, lens modeling, follow-ups

- Paul Martini (OSU, USA): Co-chair of the DES Quasar working group, discovery algorithms
- Anupreeta More (IPMU, Tokyo, Japan; DES External Collaborator application pending): strong lens searches.
- Brian Nord (FNAL, USA): discovery algorithms, lens modeling, cosmography.
- Douglas Tucker (FNAL, USA): follow-up observing
- Risa Wechsler (Stanford, USA): lens modeling

The initial PI and Co-PIs are considered STRIDES "builders". Additional non-DES CoIs might be invited by the PI and Co-PIs, once the collaboration is established. The name of candidate non-DES CoIs will be submitted for approval to the DES collaboration as addenda to this proposal. Members of the DES collaboration (and their associated postdocs and students) may join at any time as CoIs as per the DES policy for participating in DES analysis projects. STRIDES CoIs can become Co-PIs and "builders" if they spend more than one year full time equivalent working on the project, according to the following procedure. A CoI wishing to obtain Co-PI status should submit a request to the PI and Co-PIs detailing the work carried out for the project. The PI and Co-PIs will review the request and award Co-PI status if the workload meets the criterion.