Career Development Plan

I. RESEARCH: A NEW FRONTIER IN DARK MATTER SUBSTRUCTURE STUDIES

A. Objectives and Significance

I propose to create the field of "time delay millilensing" as a new way to detect dark matter substructure in distant galaxies. By precisely measuring the time delays between the images in quadruple gravitational lens systems, we will be able to determine the amount of substructure in lens galaxies and probe the distribution of subhalo masses. I aim to build a theoretical framework for millilensing, apply it to good data accessible now, and guide future observations that will uncover large samples of lenses. In the near term, this program will yield constraints on the mean density in substructure and the typical subhalo mass in (lens) galaxies at redshifts $0.2 \lesssim z \lesssim 1$. With future large samples, we will be able to measure substructure as a function of galaxy mass, redshift, and environment to obtain unique constraints on the astrophysics of galaxy formation on small scales, and the fundamental nature of dark matter.

B. The Importance of Dark Matter Substructure in Galaxies

The Cold Dark Matter paradigm is justly acclaimed for its success explaining cosmological observations relating to the global geometry and expansion history of the universe, and the distribution of matter on large scales and within massive systems like clusters of galaxies [1–4]. However, there is tension between CDM predictions and observations that probe the distribution of matter inside galaxies. CDM predicts that galaxy dark matter halos should be dense and centrally concentrated, whereas many observations seem more consistent with halos that have low central densities [5–8]. Also, CDM predicts that each galaxy's halo should contain the intact remnants of hundreds of its progenitors. In the Local Group, the predicted number of dark matter subhalos significantly exceeds the observed number of dwarf galaxy satellites [9–12].

The discord shows we still have a lot to learn about galaxy formation in a dark matter universe. One thing we do not fully understand is the competition between various processes that determine the amount of substructure in galaxy halos: the accretion of new subhalos from the environment, versus the destruction of old subhalos by tidal forces [13–20]. Also, the number of subhalos that "light up" and become visible as satellite galaxies depends on whether subhalos are able to retain their gas against photoevaporation, and on the efficiency of galaxy formation in low-mass systems [21–23]. If we could measure not only the amount of substructure in galaxy halos, but also how it varies with galaxy mass, environment, and redshift, that would provide unique access to the astrophysics of galaxy formation on small scales.

Another part of our ignorance relates to the physical properties of the dark matter particle. Many models of dark matter have been proposed: it could be sterile neutrinos, or supersymmetric particles, or a manifestation of extra dimensions, or even a product from the decay of any of these particles [24–27]. All of those possibilities are compatible with observations that probe the universe on large scales. Remarkably, though, some of the models lead to different predictions about the distribution of dark matter within galaxies [13, 28, 29]. Studying galaxy substructure therefore opens the door to obtaining astrophysical evidence—circumstantial, but nonetheless important—about the fundamental nature of dark matter.

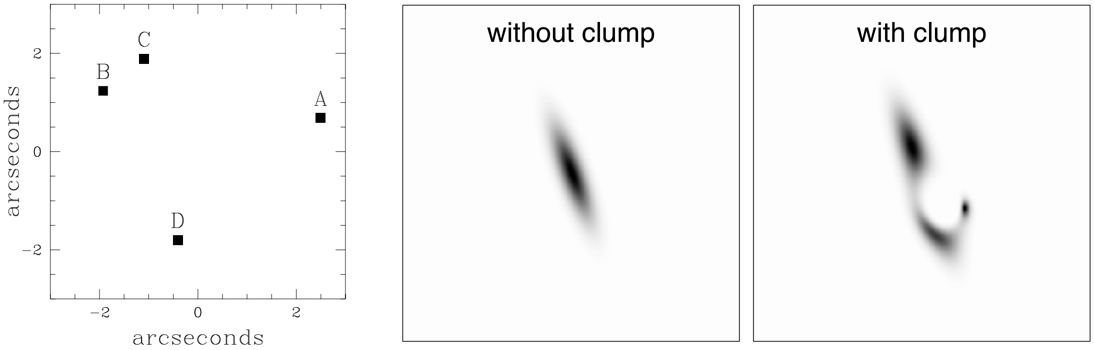

FIG. 1: A sample quad lens configuration. The middle and right panels show close-ups ($0.04''$ on a side) of image A with or without a $10^6\,M_\odot$ clump nearby. We cannot usually resolve the distortion, but we can detect the change in flux. Now I contend we should look for the change in the time delay as well.

C. Substructure and Lensing

Beyond the Local Group, strong gravitational lensing provides the only way to detect dark matter subhalos directly, by virtue of their gravity. Small mass clumps in the lens galaxy can strongly perturb lensed images, as shown in Fig. 1. If the clumps are dark matter subhalos the perturbations have angular scales of milli-arcseconds and we call the phenomenon "millilensing" [30–34]. If the clumps are stars the scales are micro-arcseconds and we call it "microlensing" [35–39]. While the spatial perturbations are too small to resolve, the flux perturbations are very apparent.

At optical and X-ray wavelengths quasar emission regions are small enough that lens flux ratios are sensitive to both dark matter subhalos and stars [40–43]; this makes it difficult to isolate millilensing and study dark matter substructure. By contrast, at radio wavelengths the quasar source is thought to be large enough to smooth over the effects of stars and be immune to microlensing. Radio flux ratios have therefore been the tool of choice for studying millilensing. The amount of substructure needed to explain radio lens flux ratios is broadly consistent with CDM predictions [32]. Unfortunately, the number of radio lenses that can be used for millilensing is currently limited to eight, and is not likely to grow substantially in the near future.

Working with Leonidas Moustakas, I have recently discovered that lens *time delays* provide an exciting new way to probe dark matter substructure, with several distinct advantages. As we shall see, time delays are not affected by microlensing, so we can use optical as well as radio data to probe dark matter substructure; this is important because the largest lens samples in the future will come from optical surveys. Time delays are sensitive to the mass function of dark matter subhalos in a way that flux ratios are not; so they offer the first real opportunity to probe the masses of subhalos in distant galaxies. By all indications the theory of time delay millilensing is very tractable; having a formal theory will provide a rigorous foundation for substructure studies, and may even allow us to do some of the statistics analytically. Appropriate time delay measurements are feasible now, and truly revolutionary datasets will become available in the foreseeable future.

D. Millilensing Calculations: Public Software

Before describing millilensing in any detail, let me explain how my calculations were done. Early millilensing studies made simple assumptions about the mass function and spatial distribution of

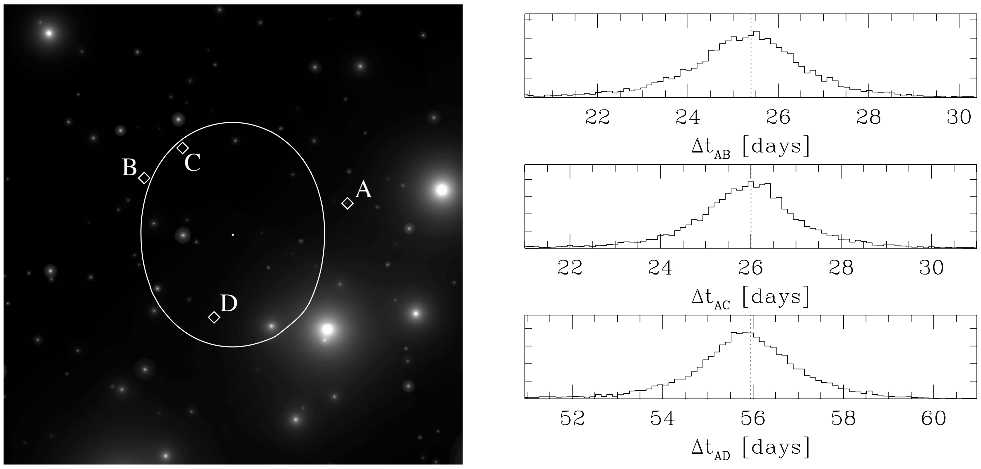

FIG. 2: **(Left)** Sample mass map of substructure from the models by Zentner & Bullock [13, 14]. The curve shows the lensing critical curve for the full lens model (including the main galaxy, which is omitted from the mass map for clarity). The points show sample lensed images. The Einstein radius is $2.2''$. **(Right)** Histograms of the time delays between the images, for 10^4 Monte Carlo simulations of substructure. (The source position is fixed, so the image configuration remains nearly fixed with only small perturbations to the image positions.) The dotted lines show what the time delays would be without substructure.

subhalos, which were inspired by CDM predictions but not precisely calibrated [31–34].[1] They did not include, for example, the fact that tidal disruption tends to reduce the amount of substructure in the inner regions of galaxy halos (where lensed images usually appear). Now it is possible to work with detailed semi-analytic models that use hierarchical structure formation theory to describe the accretion of subhalos into galaxy halos, and then track the subhalos as they evolve through dynamical friction, tidal mass loss, and heating by interactions with other structures. For illustration purposes here I use the substructure models by Zentner and Bullock and their collaborators [13–15], which produce subhalo populations similar to those of other models [16–20]. All of the models compare well with the subhalo populations seen in direct N-body simulations of galaxy formation.

I recently upgraded my public lensing software *gravlens* and *lensmodel* [48] to do lensing calculations with substructure, using a tree algorithm [49] to handle thousands of subhalos quickly and efficiently. My software is widely used, so the new capabilities will be a valuable public resource.

E. Introducing Time Delay Millilensing

To examine how substructure affects lens time delays, I create a galaxy with substructure from the Zentner & Bullock models, then place a source behind it and find the lensed images. Fig. 2 shows a sample substructure mass map and lens image configuration, plus histograms of the lens time delays for 10^4 Monte Carlo simulations of substructure. Even though substructure accounts for just 0.15% of the mass projected within the galaxy's Einstein radius, it has a substantial effect: the time delays clearly differ from what they would have been without substructure, with a typical scatter of more than a day.

---

[1] A few millilensing studies have worked directly with N-body simulations [44–47], but both the original simulations and the lensing calculations are very time consuming.

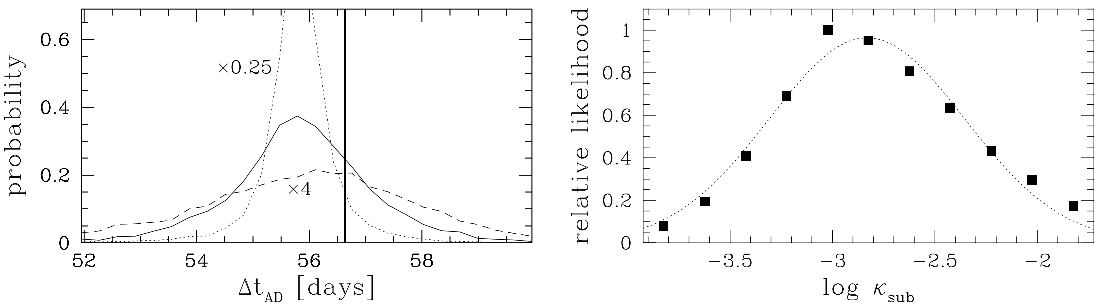

FIG. 3: **(Left)** Time delay distributions for models with different amounts of substructure. The image configuration is the same as in Fig. 2. The solid curve shows the reference model, with $\log \kappa_{\rm sub} = -2.82$ (this is the same as the bottom histogram in Fig. 2). The dashed and dotted curves have a factor of 4 more or less substructure, as indicated. The vertical line shows a sample value drawn from the reference model. The value of the probability at the "observed" time delay gives the likelihood of each model. The models with too little or too much substructure are disfavored in this likelihood sense. **(Right)** Repeating the analysis for more models, we can trace the likelihood as a function of $\kappa_{\rm sub}$ (points). I have assumed we know all three time delays to $\pm$0.3 days. The likelihood function is approximately Gaussian in $\log \kappa_{\rm sub}$ (dotted curve), with mean $\log \kappa_{\rm sub} = -2.83$ and dispersion 0.47 dex. In other words, from these (mock) data for one lens we correctly recover the amount of substructure, with an uncertainty of a factor of 3.

To detect substructure effects we therefore need to measure lens time delays with uncertainties at the level of $\pm$0.3 days or better. This is a factor of $\gtrsim$2 more precise than most time delays known today (see [50] for a compilation), but feasible in the near term for $\gtrsim$6 quad lenses; and the sample will increase to hundreds or thousands over the next five years or so (see Secs. I G and I H).

Given good time delays, the first question is whether they require substructure. Working with Scott Gaudi and Arlie Petters, I created a model-independent method to analyze lens flux ratios and determine whether the lens galaxy contains substructure [51, 52]. The method relies on mathematical relations between the magnifications of images in quad lenses that are *universal* for smooth mass distributions. The universal magnification relations can be violated only if the lens galaxy contains significant substructure. I strongly suspect we can find analogous universal relations for time delays. They have not been found yet only because no one has looked; the analysis is a straightforward extension of what we did for magnifications. Assuming we find them, the universal time delay relations will provide a powerful way to know whether observed time delays are "anomalous" in the sense that they cannot be explained by a smooth mass distribution.

We can then measure the amount of substructure. Heuristically, we get a lower bound because when there is too little substructure the observed time delay anomalies are statistically unlikely, and an upper bound because when there is too much substructure the anomalies should (statistically speaking) be even bigger than observed. We can formalize this idea with a likelihood analysis, as illustrated in Fig. 3. For a mock quad lens with time delay uncertainties of $\pm$0.3 days, the maximum likelihood method yields $\log \kappa_{\rm sub} = -2.8 \pm 0.5$, where $\kappa_{\rm sub}$ is the mean surface mass density in substructure at the positions of the images, in units of the critical density for lensing. (Since the images lie at similar distances from the center of the lens galaxy, they have very similar values of $\kappa_{\rm sub}$.) This is in excellent agreement with the amount of substructure used to generate the mock data. The uncertainty of 0.5 dex (a factor of 3) is admittedly idealized, but as we shall see there are no obvious effects that would make real lenses substantially worse. The promising conclusion is we can reliably measure substructure from individual lenses with reasonable time delay data.

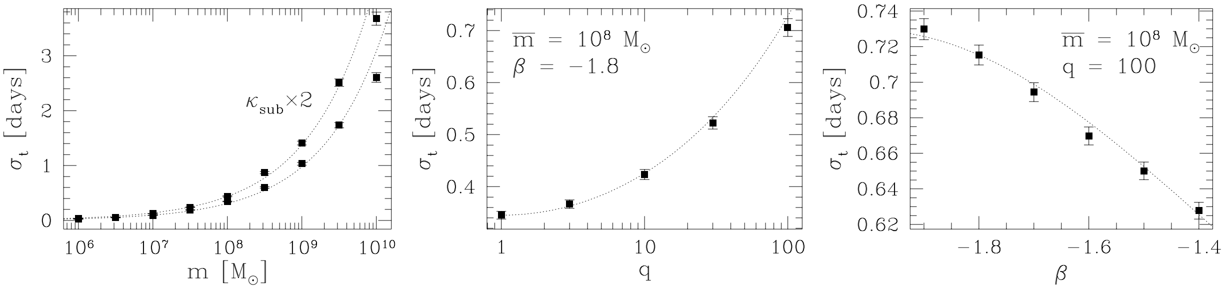

FIG. 4: Understanding how the scatter in time delays depends on the distribution of subhalo masses. **(Left)** All subhalos have a fixed mass m. The upper set of points are generated with twice the fiducial amount of substructure. **(Middle and Right)** The subhalo mass function is a power law, $dn/dm \propto m^{\beta}$, over the range $m_1 \leq m \leq m_2$. The two panels show the time delay scatter as a function of the dynamic range $q = m_2/m_1$ and the power law slope β. The dotted lines show the scaling predicted by my analytic toy model of time delay millilensing (eq. 1). The errorbars indicate statistical fluctuations.

F. Millilensing Theory

Now that we understand the basics of time delay millilensing, there are a number of interesting theoretical issues I am studying to build a rigorous framework for substructure studies.

Mass function of subhalos. In Fig. 3 I kept the mass function of subhalos fixed as given by the Zentner & Bullock models, and adjusted the overall amount of substructure. We can also consider Monte Carlo simulations with different distributions of subhalo masses: either a δ-function, or a power law over some finite range. Fig. 4 shows that the scatter in the time delays is very sensitive to the mean subhalo mass, reasonably sensitive to the dynamic range of the mass function, and mildly dependent upon the mass function slope. This means time delays (unlike flux ratios [30–32]) offer a real opportunity to probe the distribution of dark matter subhalo masses in distant galaxies.

Note that the effect of substructure on time delays decreases as the clump mass decreases. This has an important corollary: there is no measurable effect on time delays from stars. (See Sec. I G for a discussion of microlensing "noise" in light curves.) As a result, we can study millilensing at all wavelengths without worrying about contamination from microlensing.

Analytic theory. Large-scale Monte Carlo simulations are unavoidable when studying flux ratios, but time delays look to be different. Guided by the probability theory behind Monte Carlo techniques, I have developed an analytic toy model to explain the scalings in Fig. 4. It predicts

$$\sigma_t \propto \left(\kappa_{\rm sub}\, \frac{\langle m^2 \rangle}{\langle m \rangle} \right)^{1/2} , \qquad (1)$$

where $\langle \cdots \rangle$ denotes an average over the mass function. The success of the toy model gives a strong indication that I can develop a full formal theory of time delay millilensing. This theory will yield deep insights into time delay millilensing, and will also strengthen and accelerate the likelihood analysis to constrain substructure. These benefits are unique to time delay millilensing; analytic results for flux ratio millilensing are elusive because flux ratios are highly nonlinear and substructure effects lie well outside the perturbative regime.

Model uncertainties. The predicted time delay distributions in Fig. 3 depend on the overall mass distribution, or "macromodel," in addition to the substructure. We must concede that there are uncertainties in the macromodel, and ascertain whether we can control them well enough to

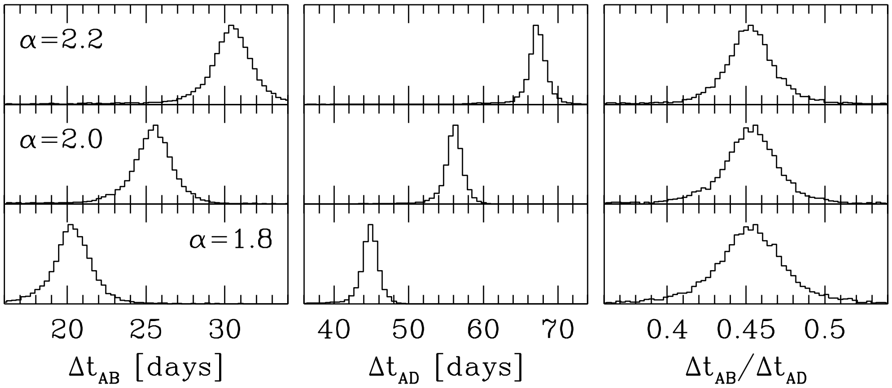

FIG. 5: Examining the radial profile degeneracy. The main lens galaxy has a power law density profile $\rho \propto r^{-\alpha}$, or equivalently a surface density profile $\kappa \propto R^{1-\alpha}$, while the substructure is given by the models by Zentner & Bullock [13, 14]. Varying the galaxy's profile rescales the time delays (left and middle columns). However, the time delay *ratio* (right column) is largely unaffected: the mean ratio stays the same, while there is a small change in the scatter. (The time delays between images A, B, and D are used for illustration; time delays involving image C could be used as well.) Time delay ratios therefore allow us to probe dark matter substructure without worrying about the radial profile degeneracy.

derive useful constraints on substructure. In quad lenses the angular structure of the macromodel is well constrained, so the key concern is the radial profile degeneracy: varying the radial density profile of the main lens galaxy rescales the time delays but leaves other observables unchanged [53–56]. This would seem to make changes induced by substructure degenerate with changes in the radial profile. However, the radial profile rescaling affects all images in the *same* way, while substructure affects each image *independently*. So with more than one time delay (as in a quad lens), we can take *ratios* of the delays to cancel the rescaling and isolate substructure effects (see Fig. 5). This very promising inference is currently empirical, but I expect it can be made rigorous with the formal theory of time delay millilensing. Since radial profile effects do not cancel perfectly (there are small differences in the widths of the time delay ratio histograms in Fig. 5), the full theory will also be useful in understanding and correcting for these residual effects.

Other modeling concerns include departures from elliptical symmetry [57–59], and the environment of the lens galaxy [60]. With these we can again rely on the fact that any non-local feature in the lens potential will affect all images in some coordinated way, whereas substructure affects the images independently. This has already allowed me to eliminate departures from elliptical symmetry as an explanation for flux ratio anomalies [51, 52, 58]. Now I plan to extend the analysis to time delays, and to consider effects of lens environments as well. Once we fully understand how to distinguish between global macromodel systematics and local substructure effects, we can build a Bayesian maximum likelihood framework (see [32]) to control the modeling systematics and derive valuable constraints on substructure.

Combining time delays and flux ratios. As we explore new science enabled by time delays, we should not forget the value of flux ratios as well. Monitoring programs must account for microlensing in order to measure time delays (e.g., [61–64]), so in principle they yield microlensing-corrected flux ratios. I plan to study whether these corrected flux ratios are sufficiently precise and robust to constrain substructure. If so, I will study how much more we can learn about substructure with both time delays and flux ratios as complementary probes.

Astrophysical scalings. Using the semi-analytic substructure models, I will be able to run extensive Monte Carlo simulations of different scenarios and demonstrate lensing's unique ability to measure substructure as a function of galaxy mass, redshift, and environment. This will provide strong motivation to measure large samples of lens time delays in upcoming surveys.

Subhalo structure. My preliminary simulations suggest that millilensing is not much affected by the choice of density profile for the subhalos. This makes sense in that a subhalo's profile ought to matter only if the light ray's trajectory passes well within the subhalo's tidal radius. I will determine how often a light ray actually pierces a subhalo, and then examine how different subhalo radial profiles affect the lensing results. If the subhalo profile is unimportant that simplifies the lensing theory and analysis. Conversely, if the subhalo profile is important that opens the possibility that we can actually probe *inside* dark matter subhalos in distant galaxies.

Biases. We need to consider whether there are any issues that would cause lens galaxies to be biased in terms of the amount of substructure they contain. It seems unlikely that substructure directly affects lensing cross sections enough to create a bias, but there might be an indirect effect. For example, since lensing depends on the projected surface mass density, it tends to favor oblate galaxies seen edge-on rather than face-on, or prolate galaxies viewed along their long axes. Depending on how substructure traces the overall mass, this could bias lensing toward higher than average amounts of projected substructure. If we want to draw conclusions about universal substructure statistics with lensing, we must understand any biases in the sample.

Line of sight. Light rays are influenced by matter all along the line of sight from the source to the observer, so low-mass halos fore or aft of the lens galaxy could contribute to millilensing [65–67]. Lieu [68] recently introduced a formalism to compute fluctuations in time delays induced by point masses along the line of sight (although in examples he overestimated the abundance of free-floating compact objects in the universe). Chen et al. [69] have argued that, due to clustering, the halos most important for millilensing are likely to be in or associated with the lens galaxy. While low-mass halos along the line of sight are also interesting, they raise slightly different science questions, so we need to understand what population we are probing.

The Hubble Constant. Since substructure produces scatter in time delays, it contributes random noise to lensing measurements of H_0. Even if substructure noise is not significant compared with other uncertainties in current H_0 constraints (cf. [50]), it will become more important as lens data improve, so we need to examine it carefully. Empirically, substructure noise appears to be unbiased; there is no obvious systematic offset in the time delay histograms (see Fig. 2), and hence no systematic shift in recovered H_0 values. The scatter looks to be quasi-Gaussian; if so, the noise in H_0 can be reduced by averaging over a lens ensemble. While these conclusions seem promising, they are currently just empirical inferences from simulations. With the formal theory of time delay millilensing I will rigorously determine whether substructure noise in H_0 is indeed unbiased, and study how lens ensembles can be used to improve the accuracy of the H_0 constraints.

G. Near-Term Data

The discussion so far makes the data requirements clear: we need to measure multiple time delays in quad lenses, with uncertainties of 0.3 days or so. Quasars certainly vary enough to make precise measurements feasible. Optical and radio monitoring campaigns routinely yield time delays with uncertainties of $\sim$1 day or better (see [50] for a compilation); this includes six quad lenses, with more being monitored. The precision is limited mainly by the fact that—until now—there has been little motivation to do better. At X-ray wavelengths, quasars vary rapidly enough to enable remarkable measurements: Chandra and XMM observations of the quad lens PG 1115+080 yielded a time delay between the two closest images of 3.58 ± 0.14 hours [70].

Strategy. With Leonidas Moustakas, I am studying how to refine time delay measurements. We expect the most efficient use of resources is to take lenses with known delays and plan periods of intensive follow-up monitoring at intervals separated by the delays. Key questions are how long each epoch should last, what cadence should be used during each epoch, what photometric precision is required, and how many epochs are needed. We will examine these issues by creating mock light curves, "observing" them with different strategies, and recovering the time delays to compare with the input values. This approach will allow us to evaluate different strategies quantitatively and in detail. Different lens systems will probably have different requirements, depending on the time delays and image brightnesses, so we will create a pipeline that will allow us to do a custom analysis for each lens.

Facilities. Once we develop a strategy for each lens, we will identify appropriate facilities for carrying out the observations. The known time delays have been obtained with a wide variety of ground-based optical and radio telescopes (e.g., [61–64]), so the observing requirements are not specific to any one facility. Good ground-based seeing is often adequate, since we already have precise astrometry of nearly all lenses from Hubble Space Telescope observations and/or radio interferometry. The aperture and exposure time requirements are modest (because the lenses whose time delays have been measured already are the ones that are easiest to observe). All but one of the time delays in quad lenses are less than 100 days (and most are much less), so we will be able to obtain multiple epochs of monitoring in a single observing season.

The precision of the one available X-ray time delay measurement raises the question of whether we should pursue systematic X-ray monitoring. It is not feasible to do blind X-ray monitoring to measure initial time delays. But once the delays are reasonably well known, it may be practical to use X-ray monitoring to refine the measurements. An important technical question we will seek to answer is whether instrumental calibrations are stable enough to compare light curves taken months apart. If so, we will certainly pursue more X-ray measurements of time delays.

Microlensing? It is important to consider whether there will be any problems due to microlensing when we observe at optical and X-ray wavelengths. When stars move in front of the images, they do not modify the time delays (see Sec. I F), but they do change the image brightnesses. Since microlensing affects each image independently, it constitutes a sort of noise when we are looking for the correlated variations that reveal the time delays between images. Fortunately, the time scale for microlensing variability is years, which is longer than the time delays we are interested in, and much longer than the precision we seek. Consequently, it is quite feasible to account for microlensing when analyzing light curves and still measure time delays well [61–64].

H. Looking to the Future

The next five years will see the dawn of a new era in strong lensing, because new surveys are poised to discover thousands of lenses [71–75]. Some of the projects being discussed are the Panoramic Survey Telescope And Rapid Response System (Pan-STARRS) [76], the Large Synoptic Survey Telescope (LSST) [77], the Dark Universe Explorer (DUNE) [78], the Joint Dark Energy Mission (JDEM) [79], and the Square-Kilometer Array (SKA) [80]. I seek not to become committed to any specific project(s), but to lay the groundwork to enable any large-scale, time-domain survey to become a powerful tool for studying millilensing and dark matter substructure.

Working with large samples will create both opportunities and challenges that we need to plan for. With hundreds or thousands of lenses, we probably cannot afford individual follow-up of each one, so we will need to extract as much as we can from the original survey. Fortunately, many of the projects explicitly contain a program to monitor a portion of the sky for variability. The time sampling may not let us measure time delays in individual lenses with exquisite precision, but there are two things to be said. First, having a large sample will allow us to combine many lenses to beat down shot noise, even if we divide the lenses into subsamples first (by, e.g., galaxy mass, redshift, and/or environment). Second, all the projects are still in planning stages, and would be receptive to reasonable suggestions about sampling strategies that could yield lens time delays without compromising other science goals. I therefore plan to study different sampling patterns to derive general guidelines for time-domain surveys that wish to enable lensing science. This work will have broad applicability as we enter the era of time-domain astronomy.

I. Work Plan

This work is being carried out in collaboration with Leonidas Moustakas. I am leading the theoretical program, and we are working together on the observational program. I request funding to support one graduate student per year to work full-time on this project. This project will provide excellent training in methodology, combining theory, observations, and data analysis. It will also allow the student to study important problems in lensing, dark matter, and substructure. The work for this project can be divided into four phases.

Year 1: Groundwork. The first phase centers on three issues that drive our observing plans. First, we must predict the amplitude of millilensing in real lenses to set data requirements. Using existing Monte Carlo techniques, we will study how substructure and millilensing scale with galaxy mass, redshift, and environment, in order to make specific predictions for each lens. With my supervision, the graduate student will take charge of running the simulations and interpreting the results. Second, I will establish a framework for modeling time delay millilensing in my *lensmodel* software. The student and I will "observe" and model simulated data, giving careful attention to understanding and controlling modeling uncertainties. This will allow us to carefully forecast our ability to constrain substructure with realistic measurements. Third, we must develop observing strategies to measure time delays with sufficient precision to probe substructure. Leonidas Moustakas has already begun to build a pipeline to simulate different observing strategies and generate mock lens light curves. We will combine this pipeline with millilensing forecasts to select optimal strategies and create a custom observing plan for each lens. The results from this work will have broad relevance beyond our specific planning goals, and will lead to at least three papers.

Years 2–4: Observations. We will begin to implement our observing plans as they are completed. Until we have the detailed plans it is difficult to anticipate the precise mix of facilities, but we will consider all possibilities: ground-based optical and radio telescope, the Hubble Space Telescope, and the Chandra and XMM X-ray observatories. We will look to obtain several epochs of data on each of six quad lenses. Most of the lens time delays are short enough that we can obtain multiple epochs within a single observing season, so the three-year span will be more than adequate. We will all collaborate on writing observing proposals and carrying out the observations.

We do not anticipate that new time-domain surveys will produce a large sample of new lenses with good time delays during the period of this grant. However, the work done here will enable those surveys to become valuable tools for millilensing studies of dark matter substructure.

Years 2–4: Theory. In parallel with the observations, we will address theoretical issues related to the analysis and interpretation of millilensing data. We will examine how millilensing depends on the mass function and internal structure of subhalos. We will study lensing biases and line of sight effects to make sure we know what subhalo populations we are probing. We will use the formal theory of millilensing to develop fast and robust data analysis methods. This work will involve both Monte Carlo simulations and analytic theory, and will lead to a number of theory papers.

Years 4–5: Analysis. We will of course begin analyzing the data as soon as they become available. The low-level data product will be light curves, the mid-level product will be new, precise time delays, and the high-level product will be constraints on dark matter substructure. We will analyze each lens individually, and then do a joint analysis to derive the best possible constraints on the mean density of substructure and typical subhalo mass in lens galaxies. We will also reexamine lensing constraints on the Hubble constant with the new time delays. To culminate the project, we will consider the implications of our work for understanding the astrophysics of galaxy formation on small scales, and the fundamental nature of dark matter.

I seek to have one undergraduate student work on this project each year, with the incoming and outgoing students overlapping in the summer. (Hence the budget includes funding for two undergraduates each summer.) The undergraduates will be able to participate in any aspect of the program. My astrophysics learning community is intended to prepare the students so they can design their own specific project within the context of the full program (see Sec. II E).

II. EDUCATION: READING, WRITING, AND CRITICAL THINKING FOR RESEARCH

A. Objectives and Significance

I propose to create a vibrant astrophysics learning community to make research an integral part of undergraduate science education. I will create a coherent program to carry students from a first introduction to astrophysics research, through the development of critical thinking skills (reading and writing, evaluating evidence, and analyzing arguments), to the practice of research itself. Above all, the students will deepen their understanding of science as a dynamic process of discovery and analysis. The astrophysics learning community will engage in outreach activities including creating "science reader's guides" for many topics in astrophysics, and hosting a research lecture each semester aimed at undergraduates. I will use established assessment tools to evaluate my new pedagogical methods, and make the methods available to other instructors.

B. Motivation

Since physics is a quantitative and mathematically sophisticated science, physics education naturally involves a lot of technical training. We can often use the excitement of research to motivate students to learn technical calculations. My fear as an instructor, though, is that students will only learn to follow recipes, without truly understanding the concepts and thinking scientifically [81]. I strive to employ a variety of skills—such as estimation, detailed calculation, toy models, scaling relations, and graphical analysis—and to phrase questions so that students must synthesize concepts and figure out what calculations to do. My students seem to recognize this, as indicated by comments on course evaluations: "[Professor Keeton] encourages thinking about how to solve a problem rather than the usual plug and chug physics questions." "Homework assignments were challenging but instructive." "Homework was actually almost fun."

Still, I wish to convey more fully the nature of scientific inquiry. Practicing scientists do not just make some measurement or calculation and immediately understand everything. We assume and approximate. We evaluate imperfect data, and probe for uncertainties and errors. We form ideas and interpretations, try them on our colleagues, and discard most of them. When we think we have something useful to say, we construct an argument that we hope will be clear and convincing. Then, often, we debate. We are called upon to defend our statements. We make more measurements or calculations, and refine our thinking. Collectively, and over time, we gain some new understanding of the world we live in.

In other words, we practice critical thinking of the sort that is supposed to be the heart of a liberal education [82]. Unfortunately, these skills are under-emphasized in traditional undergraduate science education. I propose to fill this neglected niche by introducing reading, writing, and critical thinking right from the start, as a complement to technical coursework. I will create an astrophysics learning community designed (1) to introduce freshmen to astrophysics research, (2) to teach sophomores about reading and writing for research, (3) to create a reading group for all students but particularly juniors to practice their critical thinking skills, and (4) to guide seniors into research projects. This will provide a coherent program for students who participate all four years, although it will be possible for students to join or leave at any stage. The community (especially the reading group) will be vertically integrated so younger students can learn alongside and be mentored by their more experienced colleagues.

Based on my experience teaching the junior-level astrophysics survey course at Rutgers, which attracts a broad spectrum of science and engineering students (and even one Classics major), I expect this program will have broad appeal. While the content of my program will focus on astrophysics, the critical thinking skills will be applicable across the sciences. I will therefore make the program structure available to other science instructors using established channels online.

C. Special Topics Seminar

The first element of my program is a seminar for freshmen to read about and discuss recent research in astrophysics. This will be part of a new program at Rutgers to introduce beginning students to the excitement of research in small, interactive one-credit courses. My specific goal is for students to learn to look beyond stated research results (as reported in popular media, for example) and understand how the researchers reached their conclusions, what aspects of the research are uncertain and why, and what questions remain open. My broader goal is to introduce students to the scientific critical thinking skills they will be developing throughout their education.

The Rutgers first-year seminars are intended to be venues of collaborative learning, and need to be assessed accordingly. These one-credit courses are to be graded pass/fail, based on preparation, attendance, and participation since those are crucial elements of a discussion course. In assessing the effectiveness of the course itself, I have two interests:

- *Evaluating the quality of the discussion in each class period.* Brief daily evaluations, developed by the Learning Communities National Resource Center, will help students assess their own learning, and provide me with immediate and valuable feedback [83, 84].
- *Assessing whether the course as a whole achieves my learning goals.* A pair of pre- and post-term surveys, developed by the Science Education for New Civic Engagements and

> Responsibilities (SENCER) project, will help me understand whether the course enhances students' confidence and interest in science and science learning [85–87].

A third tool I will use to gauge whether the course is raises interest in science and research is the rate at which students from the course join the astrophysics learning community.

D. New Course: "Reading and Writing for Research"

The second element of my program is a new course in which 15–20 students will learn about astrophysics by reading and discussing works of science journalism and literature. The course will target sophomores in order to give them a "big picture" view of scientific research before they delve into advanced coursework. The students will learn about the nature of scientific inquiry by examining the evidence presented in the papers we read, discussing its interpretation, and critiquing the way the scientific arguments are presented. They will hone their critical thinking and writing skills by composing four papers; the projects will have different styles but will all demonstrate quantitative, evidence-based reasoning. Above all, the students will discover for themselves that science is an active process of discovery, analysis, and understanding.

Format and content. Students learn critical thinking best while working on authentic tasks they find fascinating [88]. Therefore we will engage scientific literature directly through reading, discussing, and writing. We will read pieces from popular science publications (such as Scientific American and Science News) to set the background and context, and give the students a familiar starting point. We will read research literature to examine first-hand how new results are obtained and presented, and see how they work their way into a general understanding of the universe. Reading original works will also help the students realize (perhaps to their surprise) that science is primarily about what we do not know, and how we discover.

I will use a mix of classic and current literature. The classic literature provides the benefit of hindsight. For example, it is commonly said that Edwin Hubble discovered the expanding universe. Yet his discovery paper made no mention of such a concept; it simply reported "a relation between distance and radial velocity among extra-galactic nebulae" [89]. The interpretation came later [90]. Hubble's paper actually provides a beautiful example of analyzing imperfect data, taking care to address the limitations and uncertainties, and still coming away with a firm (and correct) conclusion. With more recent discoveries, such as the accelerated expansion of the universe [91, 92], we can study the evolving arguments and interpretations.

Assessing student learning. I want the students to use writing as a tool for learning, and to gain experience evaluating evidence and constructing scientific arguments. During the semester I will ask the students to create a portfolio containing four significant works representing different styles of scientific communication: (1) News item in the style of Science News, written for an educated but general audience. (2) Commentary in the style of Nature News & Views, written for scientists but not astronomers. (3) Conference presentation. (4) Mock research paper. The assignments are designed to become increasingly sophisticated, to take students from the level of pieces they are already familiar with, to the level of a professional publication.

In each project I will play the role of editor. I will give detailed comments on the strength and clarity of the argument, the depth of the analysis, and whether the paper hits its target audience, and then return the paper for revision. The mock research paper will also include (anonymous) peer review. The freedom to make mistakes, receive comments, and make improvements is central to effective learning [93]. Plus, revision is essential to good writing, and a very real part of writing in science. I will assign grades only to the final papers.

Assessing course effectiveness. I will use two different tools to assess whether the course affects the way students think about science. First, as in the freshman seminar, I will use the pre- and post-term surveys from the SENCER project to evaluate students' learning gains [85]. These surveys provide important information about students' attitudes toward science that are particularly valuable when developing new pedagogical methods [86, 87].

Second, I will ask the students to conclude their portfolios with an essay reflecting on what they have learned and how they have (or have not) changed their thinking about science. I will also invite the students to write comments or recommendations about the course, to be given to the next year's students. (To encourage frankness, these comments will be anonymous.) Such reflective writing pieces provide unique insight into how students actually learn, and how they think about their learning [94], so they will help me adjust the course to meet my goals.

Sustainability. The course will initially be offered through the Rutgers College Honors Program [95], which provides guidance and support for new course development. In creating new pedagogical methods related to reading and writing in physics, I will receive support from the Rutgers Writing Program [96] and Center for Teaching Advancement and Assessment Research [97]. Once I demonstrate student success, I will seek to have the course adopted as a regular course in the Physics department. I will continue teaching the course for several years, but the same structure could be used with content from any area of physics, so the course will be a versatile offering for many years to come.

Rutgers is considering introducing a new Core curriculum to replace the current set of distribution requirements. If adopted, the Core curriculum will include a new requirement for a course on writing in a discipline [98]. My new course would qualify for this requirement, so I will propose to have it recognized as part of the Core.

Dissemination. The SENCER project provides an established infrastructure for disseminating new pedagogical methods in science education [85]. The project maintains a set of model courses available for use in a variety of disciplines. I will nominate my course as a SENCER model course, with the support of two Rutgers faculty members who have already created SENCER models.

E. Astrophysics Reading Group

The third element of my program is an astrophysics reading group designed to carry learning out of the classroom and engage students more fully in reading and critical thinking about research. Each semester students in the group will pick a research topic of interest to them and identify relevant readings ranging from popular publications to research articles. The students and I will gather informally but regularly each week, in what I intend to be a non-graded but strongly intellectual environment, to discuss the articles they have read. I will provide guidance, especially in selecting appropriate readings, but will encourage students to lead discussions analyzing the evidence and arguments in the readings.

Initially I expect the reading group will draw heavily from my seminar and writing course, but it will be open to everyone. Students of all years will participate together in a vertically integrated community. Nevertheless, I expect juniors to play particularly prominent roles, because they will have had time to develop their critical thinking skills, and will want to use the opportunity to learn more about certain topics before selecting their senior research projects. In this way the reading group will build a bridge from classroom learning to the practice of research. Extrapolating from the level of interest I have encountered in my junior-level astrophysics course, I anticipate the founding group would contain roughly a dozen members and grow from there.

The reading group will engage in two outreach activities. First, to culminate each semester students in the group will invite an astronomer to visit Rutgers and give a research lecture aimed at them, the undergraduates. This idea emanates from the experience of spring 2005 and spring 2006, when the Rutgers Astronomy group was interviewing candidates for faculty positions. We asked each candidate not only to give a technical research seminar, but also to speak about research to our undergraduate students. The request was unusual, but both the students and the faculty candidates thoroughly enjoyed the experience. (In spring 2007 when we were not interviewing, students in my course complained that there were no more student-level research talks.) Now I would like to make this a regular event each semester, hosted by the astrophysics research group. I will still provide guidance but let the students exert leadership in selecting and inviting the speaker, arranging the event, and publicizing it to the broader university community.

As the second outreach activity, at the end of each semester the reading group will distill the semester's experience into what I call a "science reader's guide" that we will make available online. This will be an annotated bibliography of the materials the group read during the semester, together with a set of questions that other groups—high school classes, amateur astronomy clubs, or other interested groups—can use to generate discussion. Creating the reader's guide will give the students a tangible accomplishment and pride of authorship. Over time, the reading group will generate a significant online resource for those who want to learn more about astrophysics research.

The Rutgers administration strongly supports the creation of such organized cocurricular learning activities, and is working to create a mechanism by which student participation is officially recognized [98]. Nevertheless, the reading group will be voluntary, which means I can use the level of participation to assess its effectiveness. Participation will be high if students find that it enhances their confidence and interest in science.

F. Research Projects

The fourth element of my program is research projects for students during their senior year. Science departments at Rutgers already provide opportunities for undergraduate research, but do not usually offer any preparation before the start of the project itself. My goals in giving students more background in the nature of research are: (1) to enable students to play a more active role in defining their own research projects; (2) to help students appreciate how technical and critical thinking skills come together to drive scientific inquiry; and (3) ultimately to encourage more students to undertake research projects, whether in Physics or another department. To that end, I will use the rate at which students from the astrophysics learning community take on research projects as one way to assess the effectiveness of the program as a whole.

I plan to involve undergraduate students in my own research group on a regular basis. My goal is to have one student do a senior project with me each year. (I already have students lined up for the next two years.) Ideally, a student will join my research group during the summer before his or her senior year, and remain through the following summer. That way I will have two undergraduates in my group each summer, so the incoming student can learn from the graduating student. I will hold regular meetings involving my whole group, so the undergraduate students can learn from my graduate students (typically two at any time) as well as from me.

G. Mentorship

I have already mentored two undergraduate students on summer research projects. In particular, Jennifer van Saders worked with me the summer after her freshman year, and her work yielded a paper that we submitted to The Astrophysical Journal. It also led to a Hubble Space Telescope archive/theory proposal we wrote together, which was recently approved. This summer Ms. van Saders is participating in a Research Experience for Undergraduates program at the Very Large Array, but next summer she will work with me again on the HST program, and then write her senior honors thesis with me in 2008–2009. In 2007–2008 I will supervise Jonathan Faiwiszewski for his senior honors thesis. These experiences motivate my desire to include undergraduate students in my group for the duration of the grant (and beyond).

H. Diversity

One metric I will use to assess the effectiveness of my teaching/training program is gender diversity. Already I have mentored one woman on a research project (Ms. van Saders), and helped a woman from my class find a project with another professor. I hope to recruit women from my seminar and writing course into the astrophysics learning community, and even into research projects. The Rutgers astrophysics group provides a supportive environment for women in research, with roughly equal numbers of male and female graduate and undergraduate students.

One of my current Ph.D. students, Arthur Congdon, is quadriplegic and visually impaired. Despite his disabilities, he and I have already published two research papers together and submitted a third to Physical Review D. I welcome opportunities to work with other disabled students.

I recently joined the Research In Science and Engineering (RISE) program at Rutgers as a faculty mentor. RISE supports undergraduate students from groups that are traditionally underrepresented in science and engineering, including minority students and those from economically disadvantaged backgrounds, to come to Rutgers for summer research projects. I will invite students from the RISE program to participate fully in my own research group and the astrophysics learning community, as a way to broaden their research experience at Rutgers.

III. RESULTS FROM PRIOR NSF SUPPORT

I was an unfunded collaborator on NSF grant AST-0206084 titled “Discovering Poor Groups with Strong Lenses” (PI Ann Zabludoff), which received $290,849 for the period 5/1/2002–4/30/2005. We used theoretical studies to identify biases in lensing analyses related to the environments of lens galaxies [60]. We also carried out a systematic observational survey of lens galaxy environments. We found that $\sim$70% of all lens galaxies lie in groups of galaxies and/or have complex structures along the line of sight that significantly affect the lensing, and we characterized the newly-discovered groups in detail [99, 100]. Using the new data, we have begun to make the first sophisticated lens models that properly treat lens environments. The new models clearly demonstrate that there is a common dark matter halo enveloping the group of galaxies around the lens PG 1115+080, constrain the halo’s physical properties, and reveal a surprising connection between lens environments and lensing constraints on the Hubble constant [101].

---

[1] Tonry, J. L., et al., “Cosmological Results From High-z Supernovae,” Astrophys. J. **594**, 1 (2003).

[2] Spergel, D. N., et al., “Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results: Implications for Cosmology,” Astrophys. J. Supp. **170**, 377 (2007).

[3] McDonald, P., Miralda-Escudé, J., Rauch, M., Sargent, W. L. W., Barlow, T. A., Cen, R., & Ostriker, J. P., “The Observed Probability Distribution Function, Power Spectrum, and Correlation Function of the Transmitted Flux in the Lyα Forest,” Astrophys. J. **543**, 1 (2000).

[4] Clowe, D., Bradač, M., Gonzalez, A. H., Markevitch, M., Randall, S. W., Jones, C., & Zaritsky, D., “A Direct Empirical Proof of the Existence of Dark Matter,” Astrophys. J. Lett. **648**, L109 (2006).

[5] Binney, J. J., & Evans, N. W., “Cuspy dark matter haloes and the Galaxy,” Mon. Not. R. Astron. Soc. **327**, L27 (2001).

[6] Debattista, V. P., & Sellwood, J. A., “Constraints from Dynamical Friction on the Dark Matter Content of Barred Galaxies,” Astrophys. J. **543**, 704 (2000).

[7] Weiner, B. J., Sellwood, J. A., & Williams, T. B., “The Disk and Dark Halo Mass of the Barred Galaxy NGC 4123. II. Fluid-Dynamical Models,” Astrophys. J. **546**, 931 (2001).

[8] Spekkens, K., Giovanelli, R., & Haynes, M. P., “The cusp/core problem in galactic halos: Long-slit spectra for a large dwarf galaxy sample,” Astron. J. **129**, 2119 (2005).

[9] Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P., “Dark matter substructure within galactic halos,” Astrophys. J. Lett. **524**, L19 (1999).

[10] Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F., “Where are the missing Galactic satellites?” Astrophys. J. **522**, 82 (1999).

[11] Strigari, L. E., Bullock, J. S., Kaplinghat, M., Diemand, J., Kuhlen, M., & Madau, P., “Redefining the Missing Satellites Problem,” ArXiv e-prints arXiv:0704.1817 (2007).

[12] Koposov, S., et al., “The Luminosity Function of the Milky Way Satellites,” ArXiv e-prints arXiv:0706.2687 (2007).

[13] Zentner, A. R., & Bullock, J. S., “Halo Substructure and the Power Spectrum,” Astrophys. J. **598**, 49 (2003).

[14] Zentner, A. R., Berlind, A. A., Bullock, J. S., Kravtsov, A. V., & Wechsler, R. H., “The Physics of Galaxy Clustering. I. A Model for Subhalo Populations,” Astrophys. J. **624**, 505 (2005).

[15] Koushiappas, S. M., Zentner, A. R., & Walker, T. P., “Observability of gamma rays from neutralino annihilations in the Milky Way substructure,” Phys. Rev. D **69**, 043501 (2004).

[16] Taylor, J. E., & Babul, A., “The Dynamics of Sinking Satellites around Disk Galaxies: A Poor Man’s Alternative to High-Resolution Numerical Simulations,” Astrophys. J. **559**, 716 (2001).

[17] Taylor, J. E., & Babul, A., “The evolution of substructure in galaxy, group and cluster haloes - I. Basic dynamics,” Mon. Not. R. Astron. Soc. **348**, 811 (2004).

[18] Benson, A. J., Lacey, C. G., Baugh, C. M., Cole, S., & Frenk, C. S., “The effects of photoionization on galaxy formation - I. Model and results at z=0,” Mon. Not. R. Astron. Soc. **333**, 156 (2002).

[19] Oguri, M., & Lee, J., “A realistic model for spatial and mass distributions of dark halo substructures: An analytic approach,” Mon. Not. R. Astron. Soc. **355**, 120 (2004).

[20] van den Bosch, F. C., Tormen, G., & Giocoli, C., “The mass function and average mass-loss rate of dark matter subhaloes,” Mon. Not. R. Astron. Soc. **359**, 1029 (2005).

[21] Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H., “Reionization and the Abundance of Galactic Satellites,” Astrophys. J. **539**, 517 (2000).

[22] Somerville, R. S., “Can Photoionization Squelching Resolve the Substructure Crisis?” Astrophys. J. Lett. **572**, L23 (2002).

[23] Kravtsov, A. V., Gnedin, O. Y., & Klypin, A. A., “The Tumultuous Lives of Galactic Dwarfs and the Missing Satellites Problem,” Astrophys. J. **609**, 482 (2004).

[24] Dodelson, S., & Widrow, L. M., “Sterile neutrinos as dark matter,” Phys. Rev. Lett. **72**, 17 (1994).

[25] Feng, J. L., “Supersymmetry and cosmology,” Annals of Physics **315**, 2 (2005).

[26] Cheng, H.-C., Feng, J. L., & Matchev, K. T., “Kaluza-Klein Dark Matter,” Phys. Rev. Lett. **89**, 211301

(2002).

[27] Strigari, L. E., Kaplinghat, M., & Bullock, J. S., “Dark matter halos with cores from hierarchical structure formation,” Phys. Rev. D **75**, 061303 (2007).

[28] Colín, P., Avila-Reese, V., & Valenzuela, O., “Substructure and Halo Density Profiles in a Warm Dark Matter Cosmology,” Astrophys. J. **542**, 622 (2000).

[29] Davé, R., Spergel, D. N., Steinhardt, P. J., & Wandelt, B. D., “Halo Properties in Cosmological Simulations of Self-interacting Cold Dark Matter,” Astrophys. J. **547**, 574 (2001).

[30] Mao, S., & Schneider, P., “Evidence for Substructure in Lens Galaxies?” Mon. Not. R. Astron. Soc. **295**, 587 (1998).

[31] Metcalf, R. B., & Madau, P., “Compound Gravitational Lenses as a Probe of Dark Matter Substructure within Galaxy Halos,” Astrophys. J. **563**, 9 (2001).

[32] Dalal, N., & Kochanek, C. S., “Direct Detection of Cold Dark Matter Substructure,” Astrophys. J. **572**, 25 (2002).

[33] Chiba, M., “Probing Dark Matter Substructure in Lens Galaxies,” Astrophys. J. **565**, 17 (2002).

[34] Metcalf, R. B., Moustakas, L. A., Bunker, A. J., & Parry, I. R., “Spectroscopic Gravitational Lensing and Limits on the Dark Matter Substructure in Q2237+0305,” Astrophys. J. **607**, 43 (2004).

[35] Witt, H. J., Mao, S., & Schechter, P. L., “On the universality of microlensing in quadruple gravitational lenses,” Astrophys. J. **443**, 18 (1995).

[36] Wyithe, J. S. B., Webster, R. L., Turner, E. L., & Mortlock, D. J., “A gravitational microlensing determination of continuum source size in Q2237+0305,” Mon. Not. R. Astron. Soc. **315**, 62 (2000).

[37] Schechter, P. L., & Wambsganss, J., “Quasar microlensing at high magnification and the role of dark matter: Enhanced fluctuations and suppressed saddle points,” Astrophys. J. **580**, 685 (2002).

[38] Congdon, A. B., Keeton, C. R., & Osmer, S. J., “Microlensing of an extended source by a power-law mass distribution,” Mon. Not. R. Astron. Soc. **376**, 263 (2007).

[39] Dobler, G., Keeton, C. R., & Wambsganss, J., “Microlensing of central images in strong gravitational lens systems,” Mon. Not. R. Astron. Soc. **377**, 977 (2007).

[40] Kochanek, C. S., Dai, X., Morgan, C., Morgan, N., Poindexter, S., & Chartas, G., “Turning AGN Microlensing From a Curiosity Into a Tool,” ArXiv Astrophysics e-prints arXiv:astro-ph/0609112 (2006).

[41] Keeton, C. R., Burles, S., Schechter, P. L., & Wambsganss, J., “Differential Microlensing of the Continuum and Broad Emission Lines in the Most Anomalous Lensed Quasar, SDSS 0924+0219,” Astrophys. J. **639**, 1 (2006).

[42] Blackburne, J. A., Pooley, D., & Rappaport, S., “X-Ray and Optical Flux Anomalies in the Quadruply Lensed QSO 1RXS J1131-1231,” Astrophys. J. **640**, 569 (2006).

[43] Pooley, D., Blackburne, J. A., Rappaport, S., & Schechter, P. L., “X-Ray and Optical Flux Ratio Anomalies in Quadruply Lensed Quasars. I. Zooming in on Quasar Emission Regions,” Astrophys. J. **661**, 19 (2007).

[44] Bradač, M., Schneider, P., Steinmetz, M., Lombardi, M., King, L. J., & Porcas, R., “B1422+231: The influence of mass substructure on strong lensing,” Astron. Astrophys. **388**, 373 (2002).

[45] Bradač, M., Schneider, P., Lombardi, M., Steinmetz, M., Koopmans, L. V. E., & Navarro, J. F., “The signature of substructure on gravitational lensing in the ΛCDM cosmological model,” Astron. Astrophys. **423**, 797 (2004).

[46] Amara, A., Metcalf, R. B., Cox, T. J., & Ostriker, J. P., “Simulations of strong gravitational lensing with substructure,” Mon. Not. R. Astron. Soc. **367**, 1367 (2006).

[47] Macciò, A. V., Moore, B., Stadel, J., & Diemand, J., “Radial distribution and strong lensing statistics of satellite galaxies and substructure using high-resolution ΛCDM hydrodynamical simulations,” Mon. Not. R. Astron. Soc. **366**, 1529 (2006).

[48] http://redfive.rutgers.edu/˜keeton/gravlens

[49] Barnes, J., & Hut, P., “A Hierarchical $O(N \log N)$ Force-Calculation Algorithm,” Nature (London) **324**, 446 (1986).

[50] Oguri, M., “Gravitational Lens Time Delays: A Statistical Assessment of Lens Model Dependences and Implications for the Global Hubble Constant,” Astrophys. J. **660**, 1 (2007).

[51] Keeton, C. R., Gaudi, B. S., & Petters, A. O., “Identifying Lenses With Small-Scale Structure. I. Cusp

Lenses," Astrophys. J. **598**, 138 (2003).

[52] Keeton, C. R., Gaudi, B. S., & Petters, A. O., "Identifying Lenses With Small-Scale Structure. II. Fold Lenses," Astrophys. J. **635**, 35 (2005).

[53] Falco, E. E., Gorenstein, M. V., & Shapiro, I. I., "On Model-Dependent Bounds on H_0 From Gravitational Images: Application to Q0957+561A,B," Astrophys. J. Lett. **289**, L1 (1985).

[54] Keeton, C. R., & Kochanek, C. S., "Determining the Hubble Constant from the Gravitational Lens PG 1115+080," Astrophys. J. **487**, 42 (1997).

[55] Saha, P., "Lensing Degeneracies Revisited," Astron. J. **120**, 1654 (2000).

[56] Kochanek, C. S., "What Do Gravitational Lens Time Delays Measure?" Astrophys. J. **578**, 25 (2002).

[57] Evans, N. W., & Witt, H. J., "Fitting Gravitational Lenses: Truth or Delusion," Mon. Not. R. Astron. Soc. **345**, 1351 (2003).

[58] Congdon, A. B., & Keeton, C. R., "Multipole Models of Four-Image Gravitational Lenses With Anomalous Flux Ratios," Mon. Not. R. Astron. Soc. **364**, 1459 (2005).

[59] Saha, P., & Williams, L. L. R., "Gravitational Lensing Model Degeneracies: Is Steepness All-Important?" Astrophys. J. **653**, 936 (2006).

[60] Keeton, C. R., & Zabludoff, A. I., "The Importance of Lens Galaxy Environments," Astrophys. J. **612**, 660 (2004).

[61] Kochanek, C. S., Morgan, N. D., Falco, E. E., McLeod, B. A., Winn, J. N., Dembicky, J., & Ketzeback, B., "The Time Delays of Gravitational Lens HE 0435-1223: An Early-Type Galaxy with a Rising Rotation Curve," Astrophys. J. **640**, 47 (2006).

[62] Poindexter, S., Morgan, N., Kochanek, C. S., & Falco, E. E., "Mid-IR Observations and a Revised Time Delay for the Gravitational Lens System Quasar HE 1104-1805," Astrophys. J. **660**, 146 (2007).

[63] Vuissoz, C., et al., "COSMOGRAIL: the COSmological MOnitoring of GRAvItational Lenses. V. The time delay in SDSS J1650+4251," Astron. Astrophys. **464**, 845 (2007).

[64] Fohlmeister, J., et al., "A Time Delay for the Cluster-Lensed Quasar SDSS J1004+4112," Astrophys. J. **662**, 62 (2007).

[65] Keeton, C. R., "Analytic Cross Sections for Substructure Lensing," Astrophys. J. **584**, 664 (2003).

[66] Metcalf, R. B., "Testing ΛCDM with Gravitational Lensing Constraints on Small-Scale Structure," Astrophys. J. **622**, 72 (2005).

[67] Metcalf, R. B., "The Importance of Intergalactic Structure to Gravitationally Lensed Quasars," Astrophys. J. **629**, 673 (2005).

[68] Lieu, R., "Strong lensing time delay: a new way of measuring cosmic shear," ArXiv Astrophysics e-prints arXiv:astro-ph/0701659 (2007).

[69] Chen, J., Kravtsov, A. V., & Keeton, C. R., "Lensing Optical Depths for Substructure and Isolated Dark Matter Halos," Astrophys. J. **592**, 24 (2003).

[70] Chartas, G., Dai, X., & Garmire, G. P., "Chandra and XMM-Newton Results on the Hubble Constant from Gravitational Lensins," in Measuring and Modeling the Universe, Carnegie Astrophysics Series, Vol. 2, ed. W. L. Freedman (2004);
http://www.ociw.edu/ociw/symposia/series/symposium2/proceedings.html

[71] Kuhlen, M., Keeton, C. R., & Madau, P., "Gravitational Lensing Statistics in Universes Dominated by Dark Energy," Astrophys. J. **601**, 104 (2004).

[72] Fassnacht, C. D., Marshall, P. J., Baltz, A. E., Blandford, R. D., Schechter, P. L., & Tyson, J. A., "Strong Lensing Studies with the LSST," Bull. Amer. Astron. Soc. **36**, 1531 (2004).

[73] Marshall, P., Blandford, R., & Sako, M., "The SNAP strong lens survey," New Astron. Rev. **49**, 387 (2005).

[74] Koopmans, L. V. E., Browne, I. W. A., & Jackson, N. J., "Strong gravitational lensing with SKA," New Astron. Rev. **48**, 1085 (2004).

[75] Kochanek, C. S., Mochejska, B., Morgan, N. D., & Stanek, K. Z., "A Simple Method to Find All Lensed Quasars," Astrophys. J. Lett. **637**, L73 (2006).

[76] http://pan-starrs.ifa.hawaii.edu/public

[77] http://www.lsst.org

[78] http://www.dune-mission.net

[79] http://universe.nasa.gov/program/probes/jdem.html

[80] http://www.skatelescope.org

[81] Halloun, I., & Hestenes, D., “The Initial Knowledge State of College Physics,” American Journal of Physics **53**, 1043 (1985); —-, “Common Sense Concepts About Motion,” American Journal of Physics **53**, 1056 (1985).

[82] Arons, A., “Critical Thinking and the Baccalaureate Curriculum,” Liberal Education **71**, 141 (1985).

[83] McCartney, K. A., “Approaches to Assessment in the Collaborative Learning Seminar/Discussion,” in Assessment in and of Collaborative Learning: A Handbook of Strategies, developed and edited by the Washington Center’s Evaluation Committee;
http://www.evergreen.edu/washcenter/resources/acl/d1.html

[84] Scarborough, M., “Circumscribing Seminar Space,” in Assessment in and of Collaborative Learning: A Handbook of Strategies, developed and edited by the Washington Center’s Evaluation Committee;
http://www.evergreen.edu/washcenter/resources/acl/d2.html

[85] Science Education for New Civic Engagements and Responsibilities;
http://www.sencer.net/Assessment/assessmenttools.cfm

[86] Middlecamp, C. H., Jordan, T., Shachter, A. M., Lottridge, S., & Oates, K., “Chemistry, Society, and Civic Engagement (Part I): The SENCER Project,” J. Chem. Ed. **83**, 1301 (2006).

[87] Weston, T., Seymour, E., & Thiry, H., “Evaluation of Science Education for New Civic Engagements and Responsibilities (SENCER) Project,” report prepared for the National Center for Science and Civic Achievement (2006);
http://www.sencer.net/Assessment/pdfs/Assessment/FINAL_REPORT_SENCER_12_21_06.pdf

[88] Bain, K., What the Best College Teachers Do, Harvard University Press (2004).

[89] Hubble, E., “A relation between distance and radial velocity among extra-galactic nebulae,” Proc. Nat. Acad. Sci. **15**, 168 (1929).

[90] Robinson, H. P., “Relativistic Cosmology,” Rev. Mod. Phys. **5**, 62 (1933).

[91] Riess, A. G., et al., “Observational evidence from supernovae for an accelerating universe and a cosmological constant,” Astron. J. **116**, 1009 (1998).

[92] Perlmutter, S., et al., “Measurements of Omega and Lambda from 42 high-redshift supernovae,” Astrophys. J. **517**, 565 (1999).

[93] Light, R., The Harvard Assessment Seminars, Harvard University Graduate School of Education and Kennedy School of Government (1990).

[94] Johnson-Bogart, K., “Writing Portfolios: What Teachers Learn from Student Self-Assessment,” in Assessment in and of Collaborative Learning: A Handbook of Strategies, developed and edited by the Washington Center’s Evaluation Committee;
http://www.evergreen.edu/washcenter/resources/acl/d1.html

[95] http://rchonors.rutgers.edu/seminars.htm

[96] http://wp.rutgers.edu

[97] http://ctaar.rutgers.edu

[98] “Transforming Undergraduate Education: Report of the Task Force on Undergraduate Education at Rutgers-New Brunswick/Piscataway,” http://ur.rutgers.edu/ugtaskforce (2005).

[99] Momcheva, I., Williams, K., Keeton, C. R., & Zabludoff, A. I., “A Spectroscopic Study of the Environments of Gravitational Lens Galaxies,” Astrophys. J. **641**, 169 (2006).

[100] Williams, K., Momcheva, I., Keeton, C. R., Zabludoff, A. I., & Lehár, J., “First Results from a Photometric Survey of Strong Gravitational Lens Environments,” Astrophys. J. **646**, 85 (2006).

[101] Cangi, A., “A detailed study of the gravitational lens PG 1115+080,” Masters thesis, Rutgers University (2006).