Title: Joint Source Detection, Deblending, and Measurement for WFIRST-AFTA and LSST

PI: Robert Lupton Princeton University

Team Members: Michael Strauss, James Bosch

Summary:
In order to determine the redshifts, and therefore distances, of the galaxies detected in the High Latitude Survey of WFIRST-AFTA, we will need correspondingly deep visible light images in multiple bands from ground-based telescopes such as the Large Synoptic Survey Telescope (LSST). We will need to process the joint WFIRST-LSST data in order to obtain self-consistent photometry of galaxies. This is quite challenging for several reasons:

(a) the LSST Point Spread Function will be roughly three times larger than that of WFIRST;
(b) galaxies often exhibit “color gradients”, whereby the colors of the stellar light in a galaxy change systematically from the inner to the outer parts of the galaxy;
(c) galaxy images will often be superposed on one another at the depths of WFIRST and LSST, requiring their light to be separated before accurate and self-consistent photometry can be performed on the images.

This proposal explores this deblending problem, with an aim to determining accurate photometry of overlapping galaxy images using data from both WFIRST and the ground. A variety of different algorithms will be explored. A simple approach whereby the flux from a given pixel is assigned to a single object is clearly not adequate, especially given the very different image quality of WFIRST and ground-based data. Alternatively, the flux from a given pixel can be apportioned between distinct objects identified from peaks in the high-resolution WFIRST data, prior to measurement. Much of this proposal focuses on different ways to carry this out, testing for the robustness of the resulting photometry. A related approach is to carry out simultaneous forward-fitting, whereby the entire blended image is fit to a superposition of simple galaxy models that are convolved with the appropriate PSF model. The proposal will explore how forward modeling is affected by unmodeled substructure in the galaxy morphology.

Self-consistent photometry from the visible (ground-based) and infrared (WFIRST) images is crucial for measuring photometric redshifts for each galaxy, and thus determining its distance. Photometric redshifts are a key component in using the shapes of these galaxies as a cosmological probe. In addition, the resulting spectral energy distribution allows estimation of the stellar mass and star formation history of each galaxy, giving unprecedented insights into the growth and evolution of galaxies with cosmic time.

The algorithms developed in this proposal will be made publicly available, and will inform not only the joint analysis of WFIRST and LSST, but will be useful for a variety of future wide-field imaging surveys.

Title: Joint Analysis of Galaxy Imaging for Photometric Redshift Assignments in the WFIRST-AFTA Lensing Survey

PI: Michael Schneider Lawrence Livermore National Laboratory

Team Members: Anthony Tyson, Rachel Mandelbaum, Gregory Dubois-Felsmann, William Dawson, Samuel Schmidt, Jason Rhodes, Dustin Lang

Summary:
The weak gravitational lensing measurements in WFIRST-AFTA will combine infrared photometry with optical photometry from the ground-based Large Synoptic Survey Telescope (LSST) survey to estimate galaxy photometric redshifts (proposal category 2 in the ROSES NRA). However, the atmosphere blends galaxy images that are distinct objects as seen from space, leading to biased redshift estimates and galaxy shape measurements. Preliminary estimates indicate 30-50% of WFIRST-AFTA galaxies will be blended in LSST. To date the number density of galaxies has been small enough in shallow surveys to allow flagging and discarding blended images. Such an approach is infeasible for WFIRST and LSST due to the large blending fractions. We will develop an optimal probabilistic algorithm to utilize blended galaxies in the dark energy measurements from weak lensing in WFIRST-AFTA. Because the WFIRST-AFTA project is on a short development timescale it is crucial to identify potential changes to both WFIRST and LSST survey strategies such as depth/area tradeoffs that might improve the utilization of LSST photometric redshifts for the lensing measurements.

Title: ARCLETS for WFIRST

PI: Douglas Clowe Ohio University

Team Members: Jason Rhodes, Ian Dell'Antonio

Summary:
Weak gravitational lensing measurements of the masses of clusters of galaxies will provide a critical contribution to WFIRST s measurement of the evolution of dark energy. These measurements are complementary with those that involve large scale structure (weak lensing shear correlations, Baryon Acoustic Oscillations) or the expansion history of the Universe (Type Ia Supernovae). Exploiting the potential of cluster mass measurements with WFIRST will require very accurate calibration of the distortion of the background galaxies. Despite a decade of work on weak lensing algorithms (most of it aimed at the calibrating signal extraction for shear correlation measurements), we have not yet reached the 1% systematic uncertainty required for galaxy clusters to competitively measure dark energy. In part, this is because simulations have not been optimized to reproduce the conditions that will be encountered in a space-based weak lensing survey. We propose to undertake a series of simulations specifically designed to capture the essential features of WFIRST (the color dependence of the point spread function, the effects of diffusion, and the high resolution, background galaxy density and redshift). These simulations will allow us to improve and calibrate techniques for cluster weak lensing mass measurement, provide feedback into optimal design of the WFIRST wide survey to minimize errors in cluster mass measurement, and allow the full potential of WFIRST for cosmology to be realized.

Title: Science Yield Modeling for the WFIRST-AFTA Coronagraph

PI: Dmitry Savransky Cornell University

Team Members: Bruce Macintosh, Jeremy Kasdin

Summary:
The proposed coronagraphic instrument for WFIRST-AFTA will be an incredibly useful asset and an important step in the development and demonstration of space-based coronagraphy and high-contrast imaging. In order to produce compelling scientific results that are unattainable by other currently available instrumentation, this coronagraph and its operations must be optimized for both the WFIRST-AFTA architecture and in response to our best understanding of the distributions of orbital and physical characteristics of exoplanets. We propose to carry out a detailed study of the scientific capabilities of the WFIRST-AFTA coronagraph, including evaluations of both its ability to image known exoplanets found via doppler spectroscopy and transit photometry, as well as its ability to carry out a search for new exoplanets.

We will do so by updating an existing set of tools for the modeling of space-based exoplanet imaging missions, originally authored by the PI, to accurately describe the WFIRST-AFTA coronagraph architecture and mission. This will include detailed modeling of the effects of the observatory's geosynchronous orbit on the scheduling and execution of exoplanet observations, updated planet population models based on the latest results from Kepler and other surveys, updated target lists for both new planet searches and observations of known planets, and the incorporation of detailed optical modeling of the current coronagraph design and its impact on the detectability of exoplanets via current post-processing techniques. We will use this upgraded modeling capability to evaluate the distributions of the coronagraph's expected science yield and to answer the questions:

1) What is the optimal proportion of coronagraph time that should be devoted to searching for new planets versus attempting to image known exoplanets?
2) What are the best targets and optimal observation times for potential new detections and followup observations?
3) What are the optimal operating points in terms of detection band and permissible false positive rates and how do these affect the required integration times?

All of these investigations will be performed in collaboration with the WSO, the SDT, and the coronagraph design team to ensure that the most up to date instrument and observatory models are used in our simulations.

The result of the proposed work will be an ensemble of detailed simulations of the WFIRST-AFTA coronagraph mission portion; lists of the best available targets for imaging known exoplanets and finding new ones; the required integration time at each target; tools for dynamically scheduling coronagraph observations and followups; and recommendations for coronagraph operating parameters. A byproduct of this work will be the release of a mature, robust suite of tools for the modeling and simulation of space-based exoplanet imaging missions

to the wider community as free and open source code. These tools can be easily adapted to create optimized observing schedules for WFIRST-AFTA operations, and for use with future mission concepts and as iterative design tools for coronagraphic instruments.

This work directly addresses topic 5 (Exoplanet Coronagraphy) of the WFIRST Preparatory science call with subject matter related to modeling and simulation. Successful completion of the proposed work will build confidence in the ability of the coronagraph to fulfill the science goals set by the SDT and will produce a suite of tools of general use to the exoplanet community and for planning of the WFIRST-AFTA coronagraph operations. This work is also directly relevant to the goals of the Cosmic Origins programs as it will aide in the detection and characterization of exoplanets, improving our understanding of exoplanets at all scales of mass and semi-major axis, which is a necessary step in developing a complete understanding of planetary formation and evolution mechanisms.

Title: Inflation, Dark Energy and the AFTA: Survey Evaluation Tools

PI: Charles Bennett Johns Hopkins University

Team Members: Eiichiro Komatsu, Janet Weiland, David Larson

Summary:
We propose to address these questions about the Astrophysics Focused Telescope Assets (AFTA) implementation of the Wide-Field Infra-Red Survey Telescope (WFIRST): (1) What constraints does WFIRST/AFTA place on inflationary and dark energy cosmological parameters for a given set of nominal instrument design and observing parameters? (2) How do these constraints change with variations in mission parameters (sky area, observing duration, sensitivity, purity, astrophysical assumptions, etc.)? and (3) How should requirements or capabilities be included in the design to ensure the dark energy and inflation parameter estimates can be met? To answer these questions we propose to develop a set of simulation tools to better understand the dependencies of the cosmological results on the mission design. We emphasize that it is not our intent to argue for particular changes to the mission, but rather to provide the WFIRST/AFTA Study Office with insights, specific numbers, and functional dependencies so that the Study Office can make informed decisions.

Early time accelerated expansion (inflation) and late time accelerated expansion (from dark energy) have physical similarities and differences. They are both, in their simplest form, exponential expansions with the equation of state parameter $w = -1$, yet they appear unrelated in the sense that they occur on vastly different energy scales. Neither is well understood, hence the strong desire for improved measurements. In a practical sense, the interpretation of future measurements are interdependent. Flatness ($\Omega_k=0$) is often assumed to deduce limits on w, or alternatively $w = -1$ is assumed to deduce limits on flatness. Baryon acoustic oscillations (BAO) are effectively differential and hence approximately independent of the detailed shape of the power spectrum, $P(k)$, but if the AFTA galaxy redshift survey is used to deduce $P(k)$, then there is a strong interaction between the interpretation of $P(k)$ and inflation, including its assumptions and parameters. We propose to explore this interaction, and the mission's ability to place constraints for a range of instrumental, astrophysical, and observational conditions.

The Science Definition Team's AFTA report (Spergel et al. 2013) states, "The broad-band shape of the galaxy power spectrum $P(k)$ provides a second 'standard ruler' for geometrical measurements via the turnover scale imprinted by the transition from radiation to matter domination in the early universe, as well as a diagnostic for neutrino masses, extra radiation components, and the physics of inflation." It further notes that to constrain dark energy it is necessary to also constrain other cosmological parameters such as the Hubble constant and the matter density (both values were recently reported by Bennett et al. (2014)), as well as "the curvature Ω_k, and the amplitude and spectral index of the inflationary fluctuation spectrum." Rather than only treating these latter parameters as uncertainties to marginalize over to get dark energy constraints, we seek to study the constraints AFTA places on these inflationary parameters, both separately and jointly with dark energy constraints.

Fortunately the AFTA survey design does not require a strong trade-off between achieving dark energy and inflation constraints; both tend to be strengthened or weakened together by varying survey parameters. We begin with tools we have already developed and propose to build increasingly detailed simulation and analysis tools to evaluate the AFTA galaxy redshift survey cosmological results as a function of mission specific input parameters.

Title: Extracting distances from WFIRST/AFTA light curves and spectra

PI: Robert Kirshner Harvard-Smithsonian Center for Astrophysics

Team Members: Kaisey Mandel, Arturo Avelino

Summary:
RAISINS (GO-13046; PI: Kirshner) is an ongoing Hubble Space Telescope observing program that exploits measurements made with a 2.4m telescope in space using a near-IR detector to observe Type Ia supernovae (SN Ia) to constrain dark energy properties. This existing program has many similarities with the proposed WFIRST/AFTA supernova survey sketched by the Science Definition Team and the WFIRST Project. The RAISIN (an anagram for SN IA in the IR) program is also aimed at the same cosmological goal. Although RAISIN is modest in scope compared to the WFIRST mission (only 100 orbits), it is being done now (the most recent images were taken on June 17, 2014) and produces real data for analysis, not simulations. Our aim in the next two years is, with support from the WFIRST Preparatory Science program, to apply the data we have and the methods we have developed to analyze RAISIN data to help the SDT and WFIRST Project sharpen their plan for supernova cosmology with WFIRST/AFTA. We will also adapt our methods to the new types of data that WFIRST will obtain. As the SDT report states, The 2010 Decadal Survey, New Worlds, New Horizons, sought to advance two of the highest priority astrophysics programs the quest to understand the acceleration of the universe, and the search for other worlds. Our proposed work is perfectly aligned with the first of those goals.

Title: Sub-pixel calibration for Weak Lensing and Astrometry

PI: Michael Shao JPL

Team Members: Slava Turyshev, Mark Swain, Robert Green, Chengxing Zhai

Summary:
We have recently developed and demonstrated a new method of sub-pixel detector calibration that offers orders of magnitude improvement in astrometry with CCD focal planes. Using this technique we have demonstrated centroiding of images to 10^{-5} λ/D in laboratory conditions. Our method allows reconstructing the true optical point spread function (PSF) of a telescope from pixelated stellar images. Although this technique was originally developed for centroiding of images across a large focal plane, it can also be applied to weak lensing program on WFIRST.

We use a laser metrology technique to measure geometric imperfections in the focal plane array from pixel placement errors to non-uniform quantum efficiency (QE) within every pixel. With precise sub-pixel calibration one can use dithered images (e.g., a 2×2 dither) to derive Nyquist-sampled image of stars. The WFIRST telescope has a large 0.28 sq.deg field of view (FOV) with theoretical PSF varying considerably over that FOV. However, even at high galactic latitude there will be over 1,000 stars brighter than 16 mag and, with Nyquist-sampled images, it should be possible to calculate the spatially varying PSF at 1,000 locations in the focal plane. With knowledge of the optical PSF and sub-pixel calibration of the detector, one can remove biases in the shapes of galaxies introduced by the spatially varying PSF.

The technique of sub-pixel calibration has so far only been demonstrated in with visible CCD detectors and applied to achieve ultra-precise image centroiding. The purpose of this proposal is to extend the technique of removing biases in the shape of galaxies due to pixilation and spatially varying PSF and to extend the calibration of visible detectors to NIR detectors.

The new technique could be used to enable 4 10 microarcsecond (μas) astrometry within the 0.28 sq.deg FOV of the WFIRST telescope. Using the upcoming Gaia catalogue accurate to ~10 μas, we will be able to stitch the HgCdTe arrays on WFIRST together. Specifically, we propose to develop a pre-flight ground-based characterization of the detector arrays on WIRST using our laser metrology technique. As such, the new technique offers unique capabilities for investigation of exoplanets with WFIRST. We plan to study these exciting science possibilities.

We propose a 3-year program focused on the improvement, development, and application of our new technique of sub-pixel detector calibration. This proposal has several major objectives:

1. To extend our work on ultra-precise centroiding of images to the removal of image shape bias that is relevant to the weak lensing campaign on WFIRST. Ultra-precise sub-pixel calibration also enables very high photometric accuracy, similar to that on Kepler mission. We also intend to

expand beyond astrometric application of sub-pixel characterization to shape bias removal and precise photometry. Much of this work can proceed using our data from CCDs.

2. To extend the applicability of our technique from optical to NIR detectors and demonstrate this new technique to the H2RG detectors. The results of this work will be directly applicable to H4RG-10 detectors, which we wish to calibrate, once they will become available. We will develop data analysis methods relevant to weak lensing surveys on WFIRST by providing a proper account for the detector systematics, essentially eliminating their contribution.

3. To explore the science implication of the high-precision astrometric measurements on WFIRST that may be possible at the level of 4 μas. To investigate the science possibilities of ultra-precise astrometry and/or photometry on WFIRST, including exoplanet astrometry of super Earths, exoplanet transit observations, determination of masses of binary stars where one component is a neutron star or black hole.

Title: Precision Photometric Redshifts for Cosmology

PI: Peter Capak Caltech

Team Members: Daniel Masters, Jason Rhodes, Daniel Stern, Simon Lilly, Olivier Ilbert, Hendrik Hildebrandt, Jean Coupon, Charles Steinhardt

Summary:
The growth of structure as measured by weak lensing has been identified as one of the most sensitive probes of dark energy and dark matter, and is one of the three key dark energy experiments proposed for WFIRST. However, the weak lensing measurement depends strongly on robust photometric redshifts, and is highly sensitive to systematic biases in these redshift estimates. Several methods have been proposed to remove systematic biases based on spectroscopic samples and spatial clustering, but none has been demonstrated to perform at the level required for WFIRST. Making the problem more challenging, at least two independent methods must be developed: one to correct the systematic errors, and another to verify the correction and quantify residual error. Here we propose to develop an informed calibration of the color-redshift relation that will minimize the number of spectroscopic redshifts needed for machine learning algorithms and produce accurate Bayesian priors for template fitting algorithms.

The proposed method uses our current knowledge of galaxies and galaxy evolution from existing deep surveys to parameterize where in the WFIRST color space the photometric redshifts are well understood, and where they are not. First, we will develop a method to map from the WFIRST N-dimensional color space to redshift. This will determine which regions of color space map to redshift in a well-behaved way, and which have a more complex behavior. We will make use of the fact that higher-dimensional data (narrower band passes, more sensitive data, and larger spectral coverage) are available in select areas of the sky to determine how much uncertainty exists in WFIRST color regions. Finally, we will develop a statistical method to determine how many spectroscopic redshifts are needed in each cell of WFIRST color space to accurately map from color to redshift, and which color space cells should be excised from the weak lensing analysis due to redshift degeneracy. In addition to providing an optimal training set for machine learning, this method will be inverted to provide Bayesian priors for template fitting algorithms, which typically use either no prior, or ad hoc ones. This will provide an alternative path to obtaining the required photometric redshifts, and may also shed light on galaxy evolution. Moreover, the color space mapping provides a means to automatically identify rare and interesting Rosetta Stone objects in the WFIRST data.

Title: Planet Detection and Orbit Tracing by the WFIRST Coronagraph

PI: Geoffrey Bryden JPL

Team Members: Tom Greene, John Krist, Karl Stapelfeldt, Chas Beichman, Rachel Akeson

Summary:
While the WFIRST SDT has made preliminary estimates of the number and type of planets that WFIRST will image with its coronagraph, many details still need to be addressed in order to prepare for the eventual mission. Whether a known planet is actually visible during WFIRST's mission lifetime has not been considered, nor has the planet detection phase space ruled out by current radial velocity (RV) measurements. We propose to update a set of tools developed for the Exo-C mission study to include detailed simulations of WFIRST's coronagraph performance. These tools will not only improve on earlier estimates of expected planet detection rates, but will branch into two new subjects not previously considered for WFIRST - the ability of WFIRST images to trace each planet's orbit and the potential contributions of pre- and post-mission RV measurements.
Specifically, we will calculate:
1) the probability of WFIRST detecting each known RV planet,
2) the expected number of new planet discoveries and the corresponding list of target stars,
3) the number of observations required to constrain each planet's orbital properties and (if it has measured RV signal) its mass,
4) the optimal RV measurements needed to improve the orbit determination and to predict when WFIRST should observe each planet, and
5) the number of post-mission RV observations that will be required to measure the masses of newly discovered planets.
Overall, we will determine not just the number of planet detections, but also how well each planet will be characterized.

The results from this proposal will have a clear impact on mission formulation and the eventual mission operations. Most immediately, the simulations of planet detection rates provide a straightforward metric for evaluating instrument trade studies, such as the trade between photometric bandwidth and speckle contrast level. The optimized target list and recommended number of repeat observations will provide a needed input for scheduling telescope time within a design reference mission. Identification of the precursor observations most critical for enhancing WFIRST's science return will meanwhile motivate ground-based observations over the next decade and the requirements for follow-up RV observations will help anticipate the demand for future ground-based resources.

Title: Spectral and Polarimetric Signatures of WFIRST-AFTA Exoplanet Coronagraphy Targets

PI: Nikole Lewis STScI

Team Members: Tom Greene, Wes Traub, Mark Marley, Channon Visscher, Jonathan Fortney, Michael Line, Roxana Lupu, Richard Freedman

Summary:
A key component of the current WFIRST-AFTA mission is high contrast imaging of planets and debris disks around nearby stars. It is expected that the WFIRST-AFTA mission will be able to characterize more than twenty giant planets, many of which are already known to exist from current radial velocity surveys. These giant planets will possess a broad range of atmospheric properties, including a number of possible cloud species and atmospheric compositions. The goal of the work proposed here is explore the potential diversity in the atmospheric composition, clouds, and spectra of these directly imaged planets and identify spectral signatures that could be robustly detected by the WFIRST-AFTA mission
with a detailed spectral retrieval analysis.

The proposed team will first construct one-dimensional (1D) radiative-convective atmospheric models that include the possibility of cloud formation for both known radial velocity (RV) targets and theoretical planets potentially detectable with WFIRST-AFTA. The models will be constructed assuming a broad range of atmospheric abundances, C/O ratios, and cloud/haze properties. For the twenty or so known RV planets that have been identified as targets for the WFIRST-AFTA mission, the models will incorporate available information about the system such as host spectral type, age, and planetary orbit. For unknown planets, a broad range of masses and radii that are consistent with non-detection by RV observations to date will be considered.

With the suite of 1D exoplanet model atmospheres in place, albedo spectra in the 400-1000 nm wavelength range will be computed. Additionally, we will estimate the degree of polarization as a function of orbital phase given the scattering properties of our model atmospheres. A WFIRST-AFTA exoplanet coronagraphy simulator will be constructed and utilized to produce synthetic spectra that incorporate relevant spectral resolution and noise levels. The proposed team will then apply inverse methods to the synthetic datasets to determine the accuracy with which atmospheric abundances and cloud properties can be retrieved under a specific instrument design. This will allow for the identification of the minimum spectral range and resolution needed to answer fundamental questions regarding the composition and formation history of directly imaged planets targeted by WFIRST-AFTA.

Title: An Open-Source Galaxy Redshift Survey Simulator for next-generation Large Scale Structure Surveys

PI: Beth Reid Lawrence Berkeley National Lab

Team Members: Uros Seljak

Summary:
Galaxy redshift surveys produce three-dimensional maps of the galaxy distribution. On large scales these maps trace the underlying matter fluctuations in a relatively simple manner, so that the properties of the primordial fluctuations along with the overall expansion history and growth of perturbations can be extracted. The BAO standard ruler method to measure the expansion history of the universe using galaxy redshift surveys is thought to be robust to observational artifacts and understood theoretically with high precision. These same surveys can offer a host of additional information, including a measurement of the growth rate of large scale structure through redshift space distortions, the possibility of measuring the sum of neutrino masses, tighter constraints on the expansion history through the Alcock-Paczynski effect, and constraints on the scale-dependence and non-Gaussianity of the primordial fluctuations.

Extracting this broadband clustering information hinges on both our ability to minimize and subtract observational systematics to the observed galaxy power spectrum, and our ability to model the broadband behavior of the observed galaxy power spectrum with exquisite precision. Rapid development on both fronts is required to capitalize on WFIRST's data set. We propose to develop an open-source computational toolbox that will propel development in both areas by connecting large scale structure modeling and instrument and survey modeling with the statistical inference process.

We will use the proposed simulator to both tailor perturbation theory and fully non-linear models of the broadband clustering of WFIRST galaxies and discover novel observables in the non-linear regime that are robust to observational systematics and able to distinguish between a wide range of spatial and dynamic biasing models for the WFIRST galaxy redshift survey sources. We have demonstrated the utility of this approach in a pilot study of the SDSS-III BOSS galaxies, in which we improved the redshift space distortion growth rate measurement precision by a factor of 2.5 using customized clustering statistics in the non-linear regime that were immunized against observational systematics. We look forward to addressing the unique challenges of modeling and empirically characterizing the WFIRST galaxies and observational systematics.

Title: WFIRST Exoplanet Microlensing Survey Simulation

PI: David Bennett University of Notre Dame

Team Members:

Summary:
We propose to update the space-based exoplanet survey simulation code that was responsible for the selection of such a survey as a part of the WFIRST mission. The primary focus of this upgrade will be to include all the effects that can be used to make direct mass measurements and distance estimates of the planetary systems found by the survey. These effects include microlensing parallax and direct measurement of the relative proper motion between the source and planet host star. The simulations will also include fully realistic simulated images with all known noise sources and systematic errors. This will allow the simulation to be used to help develop the WFIRST exoplanet microlensing survey photometry and astrometry pipeline.

Title: The Circumstellar Environments of Exoplanet Host Stars

PI: Christine Chen STScI

Team Members: Dean Hines, Bertrand Mennesson, John Krist, Remi Soummer, Colin Norman, Chris Stark

Summary:
The WFIRST-AFTA mission currently includes the provision for a high contrast imaging instrument with a primary goal of discovering new, low mass exoplanets and characterizing their atmospheres. To date, eight exoplanetary systems have been discovered via direct imaging using the current generation of ground-based high-contrast facilities. Five of those systems, including the iconic beta Pictoris and HR 8799 systems, possess infrared excesses, indicative of the presence of circumstellar dust. Detailed studies of dust and gas morphology in the beta Pictoris disk provided the impetus for searching for, and eventually imaging the planet. These studies further suggest that additional planets orbit the star, but are below current detection thresholds. Such systems will be prime targets for WFIRST-AFTA, which will obtain visual spectroscopy of several spectral features from molecules in the exoplanet atmospheres including CH_4, H_2O, and CO_2. We propose to: (1) model the dust in exoplanetary systems with well characterized planets and infrared excesses to better constrain the dust geometry and particle properties; (2) generate synthetic WFIRST-AFTA images of these disks with embedded known and putative planets using point-spread-functions generated by JPL, and run our simulations though a WFIRST-AFTA pipeline; and (3) evaluate the sensitivity of WFIRST-AFTA to known and putative planets that have a range of masses and distances from their host stars. The proposed simulations will also assist the community in understanding how WFIRST-AFTA will contribute to our knowledge of debris disks and the role that minor bodies play in the delivery of water into the terrestrial planet zone. The proposed project is complementary to the efforts currently being carried out by the Science Definition Team (SDT), which focus on simulating planets embedded in tenuous disks, analogous to the Zodiacal dust system in our Solar System, the Earth s resonant dust ring, and the HR 4796 dust ring (that contains no known planets).

Title: Colorful Investigations of Supernovae for WFIRST-AFTA

PI: Ryan Foley UIUC

Team Members: Dan Scolnic

Summary:
Type Ia supernovae (SNe Ia) are extremely good probes of dark energy, and WFIRST-AFTA is particularly well suited to make the best SN distance measurements possible. For conservative assumptions, the WFIRST SN survey is projected to have twice the impact as its other probes. Considering that Euclid will only have a minimal SN survey, but strong programs for other dark energy probes, the WFIRST SN survey is especially unique and important.

With an initial simulation of the WFIRST-AFTA survey, we have determined that the largest statistical and systematic uncertainties are related to SN color. SN distances strongly depend on the precise measurement of SN colors since we must make a dust extinction correction that depends on the observed color. The details of how the correction is applied and the possibility that the correction evolves with redshift combine with potential calibration systematics to limit the current effectiveness of the SN component of WFIRST-AFTA.

Here, we propose to support two graduate students to (1) investigate how intrinsic color variations will impact WFIRST-AFTA systematic uncertainties, (2) determine improved methods for reducing the systematic uncertainties related to SN color, and (3) simulate survey strategies incorporating our results to obtain the highest dark energy figure of merit (DE-FoM).

Title: Studying Cosmic Dawn and Emission Line Galaxies with WFIRST-AFTA

PI: James Rhoads Arizona State University

Team Members: Sangeeta Malhotra, Nor Pirzkal

Summary:
WFIRST-AFTA will provide a wealth of near-infrared spectra and imaging for 100s of millions of galaxies at redshifts z=1-3. While the primary aim of the WFIRST spectroscopic survey is to determine the geometry of the universe, these data will revolutionize our understanding of galaxy evolution at the peak epoch of star formation activity. Understanding the galaxy spectra will not only help us address major issues in galaxy formation and evolution, but will also reduce random and systematic errors in the redshift determination for BAO and weak lensing experiments.

We offer extensive experience of studying line emitters from z=0.3-7, using both slitless spectroscopy on HST and narrow-band imaging from the ground, together with higher resolution ground-based spectroscopic followup. The HST slitless spectrographs are the best analogs to the WFIRST-AFTA spectrograph in spectral and spatial resolution, and in operations mode. There are unique challenges in slitless spectroscopy, and our extensive experience will help to meet them.

The three top-level science goals given by the "New Worlds, New Horizons" decadal survey report are Cosmic Dawn, New Worlds, and the Physics of the Universe. WFIRST's core mission objectives explicitly include the Physics of the Universe (through dark energy surveys) and New Worlds (through microlensing and perhaps coronographic observations). WFIRST-AFTA can make equally powerful contributions to the study of Cosmic Dawn. Its sensitivity, spatial resolution, and wide field of view make it uniquely powerful for studying the first faint, highly redshifted galaxies.

We propose to:
(1) Apply this accumulated expertise, software and existing HST data to help with the predictions, simulations, and detailed planning and possible optimization of spectroscopic observations.
(2) Detail how studies of Emission Line Galaxies (ELGs) between z=1-3 will address outstanding questions in galaxy evolution and assembly at the peak of star-formation and AGN activity at z=1-3.
(3) Explore how WFIRST-AFTA can revolutionize also our understanding of Cosmic Dawn, both using the already-planned HLS and supernova survey, and through deep GO observations.

For this we will use the collective power of HST slitless grism data both with ACS and WFC3 as well as simulation packages such as aXeSIM. We have led several large grism programs, and developed software for both simulating and analysing slitless grism data (aXe and aXeSIM). We have also contributed to design and planning of JDEM/WFIRST missions and white papers. We

will adapt our software to WFIRST, and use it for end-to-end simulations of the WFIRST spectroscopic survey, to determine the expected properties of the WFIRST emission line galaxy samples.

We will summarize our results in three white papers, on (1) those properties of emission line galaxy populations most crucial to WFIRST planning; (2) the prospects for reionization tests using WFIRST-AFTA; and (3) the potential effects of changes to either instrumental paramters or observing strategy on the resulting emission line galaxy samples.

Title: Preparatory studies for the WFIRST supernova cosmology measurements

PI: Saul Perlmutter Lawrence Berkeley National Laboratory

Team Members: Davi Rubin, Greg Aldering, David Rabinowitz, Charles Baltay

Summary:
In the context of the WFIRST-AFTA Science Definition Team we developed a first version of a supernova program, described in the WFIRST-AFTA SDT report. This program uses the imager to discover supernova candidates and an Integral Field Spectrograph (IFS) to obtain spectrophotometric light curves and higher signal to noise spectra of the supernovae near peak to better characterize the supernovae and thus minimize systematic errors. While this program was judged a robust one, and the estimates of the sensitivity to the cosmological parameters were felt to be reliable, due to limitation of time the analysis was clearly limited in depth on a number of issues. The goal of this proposal is to further develop this program and refine the estimates of the sensitivities to the cosmological parameters using more sophisticated systematic uncertainty models and covariance error matrices that fold in more realistic data concerning observed populations of SNe Ia as well as more realistic instrument models. We propose to develop analysis algorithms and approaches that are needed to build, optimize, and refine the WFIRST instrument and program requirements to accomplish the best supernova cosmology measurements possible. We plan to address the following:
a) Use realistic Supernova populations, subclasses and population drift. One bothersome uncertainty with the supernova technique is the possibility of population drift with redshift. We are in a unique position to characterize and mitigate such effects using the spectrophotometric time series of real Type Ia supernovae from the Nearby Supernova Factory (SNfactory). Each supernova in this sample has global galaxy measurements as well as additional local environment information derived from the IFS spectroscopy. We plan to develop methods of coping with this issue, e.g., by selecting similar subsamples of supernovae and allowing additional model flexibility, in order to reduce systematic uncertainties. These studies will allow us to tune details, like the wavelength coverage and S/N requirements, of the WFIRST IFS to capitalize on these systematic error reduction methods.
b) Supernova extraction and host galaxy subtractions. The underlying light of the host galaxy must be subtracted from the supernova images making up the lightcurves. Using the IFS to provide the lightcurve points via spectrophotometry requires the subtraction of a reference spectrum of the galaxy taken after the supernova light has faded to a negligible level. We plan to apply the expertise obtained from the SNfactory to develop galaxy background procedures that minimize the systematic errors introduced by this step in the analysis.
c) Instrument calibration and ground to space cross calibration. Calibrating the entire supernova sample will be a challenge as no standard stars exist that span the range of magnitudes and wavelengths relevant to the WFIRST survey. Linking the supernova measurements to the relatively brighter standards will require several links. WFIRST will produce the high redshift sample, but the nearby supernova to anchor the Hubble diagram will have to come from ground based observations. Developing algorithms to carry out the cross calibration of these two

samples to the required one percent level will be an important goal of our proposal. An integral part of this calibration will be to remove all instrumental signatures and to develop unbiased measurement techniques starting at the pixel level.

We then plan to pull the above studies together in a synthesis to produce a correlated error matrix. We plan to develop a Fisher Matrix based model to evaluate the correlated error matrix due to the various systematic errors discussed above. A realistic error model will allow us to carry out a more reliable estimates of the eventual errors on the measurement of the cosmological parameters, as well as serve as a means of optimizing and fine tuning the requirements for the instruments and survey strategies.

Title: Detecting and Characterizing Exoplanets with the WFIRST Coronagraph: Colors of Planets in Standard and Designer Bandpasses

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Summary:
The WFIRST mission is now envisioned to include a coronagraph for the purpose of direct detection of nearby exoplanets, including planets known to exist via radial velocity detection and new discoveries. Assuming that starlight rejection sufficient for planet detection (~1e-9) can be achieved, what can be learned about these planets given a realistic spectral resolution and signal-to-noise ratio? We propose to investigate the potential for WFIRST to efficiently discriminate planets from background sources, and to characterize planets in terms of important diagnostic atmospheric features, using broad- and intermediate band color data. We will map out this capability as a function of signal-to-noise ratio, bandpass location, and bandpass width.

Our investigation will place emphasis on gas giants, ice giants, and mini-Neptunes (compatible with current AFTA-C baseline performance specifications), as well as a variety of super-Earths (an AFTA-C "stretch" goal). We will explore a variety of compositions, cloud types, phase angles, and (in the case of super-Earths with semi-transparent atmospheres) surface types. Noiseless spectra generated for these model planets will be passed through (a) standard bandpasses for comparison to prior work and (b) filter transmission curves corresponding to bandpasses of 5-20% over the full range of WFIRST's expected bandpass (400 - 1,000 nm). From this, filter combinations will be used to generate planet colors and find filter sets that most efficiently discriminate between planets and background sources, and between planets of different type. We will then repeat this exercise for S/N levels of 1-1,000 in order to (1) explore the true efficacy of broadband measurements in exoplanet studies, and (2) provide an estimate of total required integration time for a compelling WFIRST exoplanet program.

To accomplish this, we will use model spectra for mini-Neptunes, and ice and gas giants of varying composition (Hu et al. 2013), and observed spectra for Solar System objects (Jupiter, Saturn, Uranus, Neptune, and Titan; Karcoschka 1994). We will also use observed SCIAMACHY spectra for the desert, ocean, forest, and icy Earth, in order to build a diverse set of spatially integrated super-Earth spectra, plus variations in atmospheric composition. Simulated observed spectra will be generated for planets placed under the irradiance of stellar spectral types corresponding to WFIRST's highest priority targets for exoplanet imaging (approximately K5V through F5V). The colors extracted from these spectra will be compared to colors extracted from spectra for a wide range of likely extragalactic sources (Bruzual & Charlott 2003) and extincted stellar background sources.

Finally, we will assess the "background threat" for the 100 most favorable targets for exoplanet imaging with WFIRST. This flag will be assigned based on number and type of background sources expected at various galactic latitudes, and the above results indicating how readily such sources can be discriminated from exoplanets.

As a result of this intensive, three year effort, we will deliver to the community a library of planet spectra and colors in standard and proposed "designer" passbands for planets of all types under stars of varying spectral type, plus colors for a wide range of expected stellar and extragalactic background sources. These data will be available for future work in simulating images and eventual "double blind" studies in extracting planet sources and atmospheric signatures. We expect that our investigation will inform WFIRST and all future direct imaging missions of (1) how different planets will appear at "first glance" from the likely sea of background of stars and unresolved extragalactic sources, and (2) the necessary performance specifications required to characterize the most important atmospheric constituents and discriminate between planets of varying type.