Assigned Proposal Number: SR _____

Strategic University Research Partnership Proposal for FY2015
Due Date: February 3rd, 2014, by 4 PM PST

1. Title -- Galaxy Growth at z~2-4: From Voids to Massive Proto-Clusters

2. JPL Principal Investigator
Harold W. Yorke, JPL Science Division (3200)

3. Co-Investigator(s)
Shardha Jogee, UT Austin, sj@astro.as.utexas.edu
Marco Viero, Caltech, marco.viero@caltech.edu

4. Total Budget Request for FY15: $25,000

Multi-year Student Research Initiative: [3 years]

5. Student Participants
Name: TBD, UT Austin, graduate student

6. Topic Area—

Astronomy and Fundamental Physics
[1] Origin, evolution, and structure of the universe
[ ] Gravitational astrophysics and fundamental physics
[ ] Extra-solar planets and star and planetary formation
[ ] Solar and Space Physics
[1] Formation and evolution of galaxies

Science Instruments, Observatories and Sensor Systems
[2] Advanced optics and telescopes
[ ] In-situ instruments/sensor technologies
[2] Visible/IR/submillimeter, in-situ and remote sensing instruments
[ ] Focal planes

7. Objectives— *State clearly and concisely the objectives of your work and the expected deliverables.*

The proposed SURP research program is a core part of an unprecedented study of galaxy growth at redshifts $1.9<z<3.5$ across a wide range of environments – from low-density fields to massive proto-clusters – within a huge co-moving volume of 0.5 Gpc^3 in the SHELA/HETDEX 28 deg^2 legacy field (Figure 1). This field is over ten times larger than the area mapped by other deep spectroscopic surveys at z~2-4, and consequently harbors a full range of environments at these epochs, including several tens of very massive and rare proto-clusters, which are the unambiguous progenitors of present-day Coma-type clusters (Figure 2). This study is enabled by our five deep, wide-area, photometric and spectroscopic surveys: the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX; Hill et al. 2008) blind spectroscopic survey, the SHELA *Spitzer*/IRAC survey, the *Herschel* SPIRE Stripe 82 Survey (HerS; Viero et al. 2014), the DECam *ugriz* survey, and the NEWFIRM *K*-band survey. SURP Co-Investigator Jogee is a Co-I on all five surveys, and Viero is the PI of HerS.

The SURP-funded graduate student will analyze data from the already-completed SHELA *Spitzer* and HerS *Herschel* surveys in order to explore the star formation activity, number density, and merger rate of the most massive ($M_*>10^{11}\,M_\odot$) galaxies at $1.9<z<3.5$. These results will shed light on the role of nature's assembly bias (e.g., the earlier collapse time and higher merger rates of galaxies in dense regions) and nurture (e.g., specific environmental processes) in shaping the growth of galaxies at z~2-4, the critical epoch when massive proto-clusters began to collapse, and the cosmic star formation and black hole activity peaked.

Our SURP program also promotes undergraduate research by bridging the highly successful UT Freshman Research Initiative (FRI) and the JPL summer research program. This program will strive to keep the best undergraduates engaged in research, within a collaborative peer environment, long after the three-semester FRI program ends.

8. Technical Approach— *Describe your plan to achieve your objectives. Provide specific tasks, milestones, and responsibilities.*

Understanding how galaxies in different environments form their stars and grow their dark matter halos is a fundamental goal of astronomy, as highlighted in NASA's Cosmic Origins Program. Of particular interest is the redshift range z~2-4, when massive proto-clusters begin to collapse, and the cosmic star formation (SF) and black hole accretion peak. A systematic study of galaxy growth at z~2-4 over a wide range of environments – from low-density fields to massive proto-clusters – is critical for understanding the role of nature's assembly bias (e.g., the earlier collapse time and higher merger rates of galaxies in dense regions) and nurture (e.g., environment-specific processes) in shaping the growth and activity of galaxies.

We are now in the unprecedented position to conduct such a study **through the powerful synergy of our five deep, wide-area, spectroscopic and photometric surveys of the 28~deg^2 HETDEX/SHELA legacy field** *(Fig. 1).* The data consist of blind spectroscopy from HETDEX (Hill et al. 2008) and photometry from the SHELA *Spitzer*/IRAC (3.6 and 4.5 μm) survey, the *Herschel* SPIRE (250, 350, and 500 μm) Stripe 82 Survey (HerS; Viero et al. 2014), the DECam *ugriz* survey, and the NEWFIRM *K*-band survey. Viero is the PI of HerS and UT investigator Jogee is a Co-I of all five surveys.

The HETDEX/SHELA field encompasses an enormous co-moving volume of 0.5 Gpc^3 at 1.9<z<3.5. This volume is **an order of magnitude larger than that of other deep spectroscopic surveys at $z>2, and contains the full range of galactic environments, from low-density voids to several tens of rare massive proto-clusters, which are the progenitors of present-day Coma-type clusters** *(Fig. 2).* In this volume, HETDEX will secure ~300,000 Lyman-α-based spectroscopic redshifts, and thereby provide accurate measurements of clustering, bias, and dark matter halo masses. We will also detect ~800,000 continuum-detected star-forming galaxies.

Our proposed SURP graduate research program is a core part of this important study and **will exploit the already completed SHELA Spitzer and HerS Herschel surveys to explore the SF activity, number density, and merger rate of the most massive ($M_*>10^{11}$ $M_\odot$) galaxies at 1.9<z<3.5, across the widely different environments within the huge 0.5 Gpc^3 co-moving volume** in the 28 deg^2 SHELA/HETDEX field.

The SHELA *Spitzer IRAC* data (5σ limit of 2.8 μJy at 3.6 μm and 4.2 μJy at 4.5 μm) detect galaxies with stellar masses as low as $10^{10}M_\odot$,at z~2 .5, nearly a full dex below the characteristic mass at that epoch. Catalogs of stellar mass, photometric redshifts, and colors are currently being derived by fitting the *Spitzer* IRAC and DECam *ugriz* data, and will be available by Fall 2014.

In the first stage (FY2015 and part of FY2016) of the project, the SURP-funded graduate student will use these catalogs to identify the most massive ($M_* > 10^{11}M_\odot$) galaxies across different environments in the 28 deg^2 HETDEX/SHELA field, and locate their *Herschel*-detected counterparts in the HerS survey. Our HerS *Herschel* SPIRE data reach 5σ depths of 64, 53, and 77 mJy at 250, 350, and 500 microns respectively. At *z* >2*,* HerS directly detects infrared-luminous galaxies (so-called ULIRGs and hyper-LIRGS) with SFRs above several hundred $M_\odot$ yr^{-1}. In order to characterize the average properties of typical galaxies with lower SFRs, we will use positional priors derived from SHELA, deblending techniques, and image stacks based on subsamples selected by stellar mass, photometric redshifts, and rest-frame colors. These infrared-based SFR measurements will complement those derived from the (extinction-corrected) rest-frame ultraviolet, thereby completing the picture of star formation at z>2. This work with be done in close collaboration with Marco Viero at Caltech/JPL.

In the second stage (FY 2016 + FY2017) of the project, the SURP-funded graduate student will explore the relation between the number density, SF activity, and merger rates of these massive ($M_* > 10^{11}$ $M_\odot$) galaxies. This part of the project would use both the photometric and the HETDEX-based spectroscopic redshifts. We will first use the large number of HETDEX spectroscopic redshifts to test some of the continuum-based photometric redshifts derived in the first stage of the project. Then, we will test the claim that most theoretical models vastly under-predict the number density of massive galaxies at z>1.5 (Guo et al. 2011). With SHELA probing stellar

masses as low as 10^{10} $M_{\odot}$, we can identify close pairs of galaxies with stellar mass ratios as small as 1:10. We will derive merger rates using the close pair method and the two-point correlation function (e.g., Bell et al. 2006; Jogee et al. 2009), while taking into account both the statistics of chance projections and visibility timescales derived from hydrodynamic simulations (e.g., Lotz et al. 2011). This will yield important constraints on the rate of major (1:1 to 1:3) and minor (1:4 to 1:10) mergers for massive galaxies at z>2.

Keeping Undergraduates Engaged in Research: A key goal of our SURP initiative is to promote the long-term engagement of undergraduates in research by bridging the highly successful University of Texas (UT) Freshman Research Initiative and the JPL summer research program. Currently, undergraduates at UT take the Research Methods Course (AST 376) created by Dr. Jogee in order to learn practical research skills, such as navigating the Linux/Mac OSX operating system, using astronomy softwares (e.g., IRAF), writing computer programs with IDL, learning techniques for effective oral presentations, and using LaTeX to write scientific papers. After completing the class, many Freshmen join the UT Freshman Research Initiative (FRI), where they perform research in groups for up to two semesters. At the end of the FRI program, we have a large cohort of highly skilled and motivated undergraduates who are ready to take on more individual research challenges. We propose to have the SURP-funded graduate student train undergraduates in the FRI and post-FRI phases, and encourage the best ones to apply to JPL's summer research program. The latter would greatly complement the limited number of internships currently available through the NSF Research Experience for Undergraduates (REU) program.

9. Renewal Proposal— *If this is a renewal proposal, describe the accomplishments of the previous year's work: N/A*

10. Multi-Year Rationale— *If you are proposing a multi-year Student Research Initiative, please describe the benefits of an extended award.*

The proposed three-year period (FY2015 to FY2017) is appropriate for the research component of our proposal because of the large datasets involved and the schedule of the surveys. As outlined in item 8, the first stage of the research project (FY2015 + part of FY2016) relies on three already-completed large photometric surveys of the SHELA/HETDEX 28 deg^2 field, conducted with *Spitzer* IRAC, *Herschel* SPIRE and DECam. The second stage (FY2016 + FY2017) of the program requires the spectroscopic redshifts from HETDEX, which will finish covering our 28 deg^2 field with the standard fill factor by early 2016.

11. Innovative Features— *Describe any new and original features of the proposed work.*

a) The proposed SURP research program is an integral part of an unprecedented study of galaxy growth at z~2-4, over a wide range of environments, within a humongous co-moving volume of 0.5 Gpc^3 in the SHELA/HETDEX 28 deg^2 legacy field. This volume is an order of magnitude larger than that covered at z~2-4 by all existing deep spectroscopic surveys to date, and it therefore contains the full range of environments, from low density voids to several tens of rare massive proto-clusters. Our study powerfully combines data from our five deep, wide-area, spectroscopic and photometric surveys, allowing nearly a million galaxies to be studied at z~2-4 in this legacy field.

b) The SURP-funded graduate student will explore traditional and novel stacking techniques (e.g., Moncelsi 2013) to characterize the average obscured SFR of galaxies not individually detected by Herschel at z~2-4. Prior to the advent of far-IR instruments vastly more sensitive than Herschel, these techniques are key for exploring the obscured SFR in typical galaxies at z>2.

c) The plan outlined for undergraduate research in our SURP proposal will bridge the pioneering and successful UT Freshman Research Initiative (FRI) to the JPL summer research program. Our goal is to keep the best undergraduates engaged in research over a long time and within a collaborative peer environment.

12. Team Strengths— *Describe the strengths each member of the team brings to the proposed effort.*

a) JPL PI Harold Yorke's current research focuses on massive star formation in the early universe. He has significant expertise in Herschel (for which he was formerly a Project Scientist) and the design of future space-based and suborbital far infrared and submillimeter observatories.

b) UT investigator Jogee is a co-investigator of the HETDEX spectroscopic survey, and the four photometric surveys (SHELA *Spitzer*/IRAC, HerS *Herschel* SPIRE, DECam *ugriz*, and NEWFIRM K-band) relevant for this proposal. Her group is working on deriving photometric redshfits and stellar masses from the *Spitzer* and DECam data. She has expertise in characterizing the structure, star formation, and merger rate of galaxies (e.g. Jogee et al. 2009, Weinzirl et al. 2011).

c) Marco Viero (Caltech) works in the group of Professor Jamie Block who is affiliated with JPL. Viero is the PI of the HerS *Herschel* SPIRE survey (Viero et al. 2014) and has significant expertise in the use of different stacking techniques on the Herschel data.

13. Exchange of personnel— *Describe any plans to have work performed at JPL by university personnel or at the university by JPL personnel*.

The SURP-supported graduate student will travel to Pasadena to work with the PI and members of Jamie Bock's group. This work will focus on the use of the *SHELA* Spitzer survey and the HerS *Herschel* SPIRE survey, and the interpretation of the results of the proposed study.

14. Significance and Impact of Results on JPL Missions and Programs—*Indicate specific missions/programs or types of missions*

Our SURP research program focuses on the huge datasets from two large-area surveys (the *SHELA* Spitzer survey and the HerS *Herschel* SPIRE survey) of the SHELA/HETDEX 28 deg^2 legacy field, conducted with the current JPL *Spitzer* and *Herschel* missions. The results of this project will help inform future/proposed JPL missions, such as MIRI and SAFIR/CALISTO, to push the stellar mass and obscured SFR limits well below those of *Spitzer* and *Herschel* at z>2. This study is an important step towards a focused *JWST* key project involving JPL personnel.

15. JPL Principal Investigator Signature *(an original signature is required)*

Name: Harold W. Yorke Signature: Date:

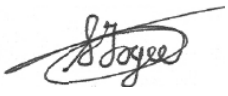
16. Document Reviewer Signature *(Line organization's export document reviewer - an original signature is required)*

Name: Signature: Date:

17. JPL PI Division Manager (or designee) Signature *(an original signature is required)*

Name: Signature: Date:

18. University Lead Co-Investigator Signature

Name: Shardha Jogee Signature:  Date: Jan 24, 2014

19. University Authorizing Signature *(this signature may also be provided instead on a letter attached with university budget): See attached letter from UT OSP*

20. Figures, Graphics, Tables, etc.

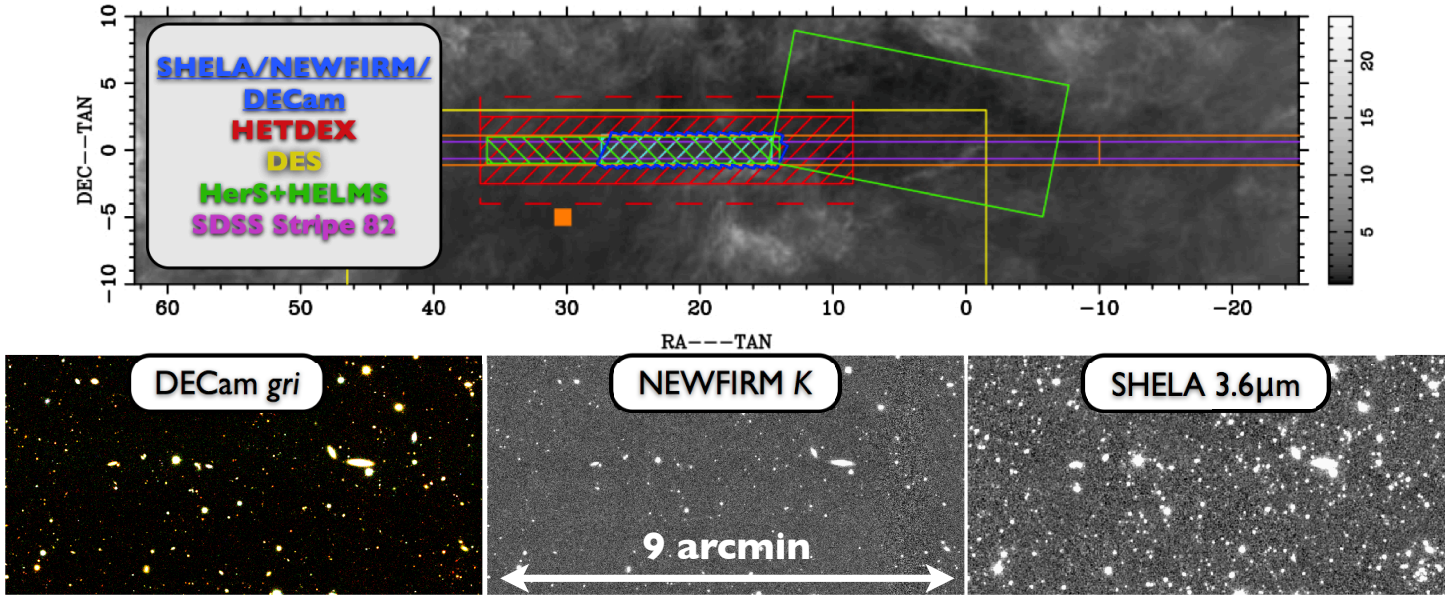


Figure 1: *Top*: The 28 deg^2 footprint of the HETDEX/SHELA field (dark blue) compared to that of SDSS Stripe 82 (purple), the full HETDEX equatorial field (red), and the survey regions of the Dark Energy Survey (DES, yellow) and the *Herschel* Stripe 82 Survey (HerS, green). *Bottom Left:* DECam three-color *gri* image of a 9' x 4.5' region of the HETDEX/SHELA field (<0.05 % of the full field). We also have *u*- and *z-band* images in our possession. *Bottom Center and Right*: Our NEWFIRM *K*-band and *Spitzer*/IRAC 3.6 μm data covering the same 9' x 4.5' region

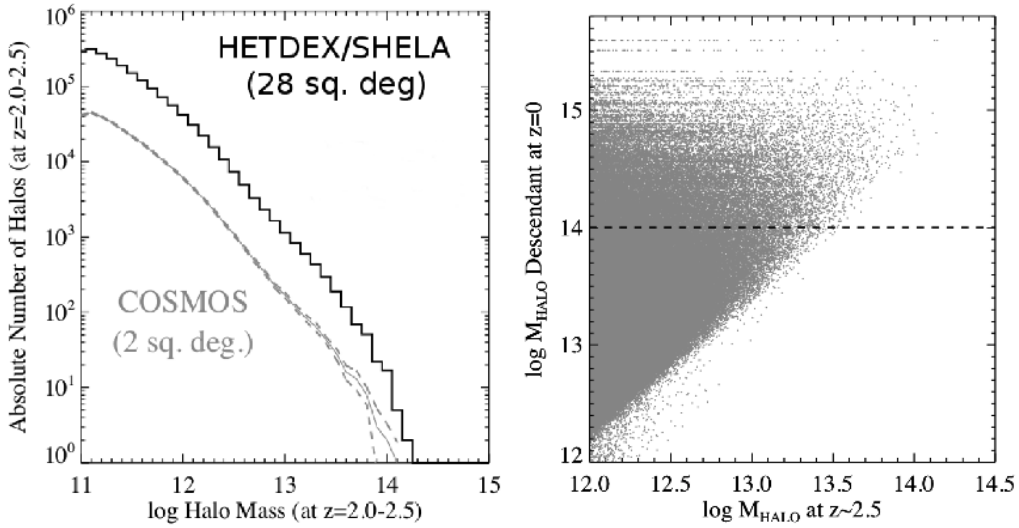


Figure 2: *Left*: We show the mass function of dark matter halos at z~2.5, based on the Millennium 1 simulations. The HETDEX/SHELA 28 deg^2 field is expected to contain over an order of magnitude more high mass (halo mass at z~2.5 >$10^{13.5}$ M_o) halos at z~2.5 than the 2 deg^2 COSMOS survey. *Right:* We show the relationship between the mass of dark matter halos at z~ 2.5 and their z~0 descendants. The rare high mass (halo mass at z~2.5 >$10^{13.5}$ $M_\odot$) halos at z~ 2.5 are of particular interest because they unambiguously evolve into present-day rich Coma-type clusters (halo mass at z~0>$10^{14.7}$ $M_\odot$). In contrast, lower mass halos at z~2.5 can evolve into present-day fields, groups, or clusters.

21. SURP Budget Sheet

Category	FY'15 cost
SURP tasks are reported on a Direct Cost ("Raw Cost + Fringe Benefits") basis - no other burdens should be included.	
1. **Salaries**— *(Itemize) Only itemize the person names or job classifications and the number of hours for each. Show one total $ salary figure for labor.* Harold W. Yorke (? Hours)	$ 3416
2. **Labor Fringe** — *Employee Benefits*	$ 1742
3. **Cat A Labor**— *(Itemize) Only itemize the person names or job classifications and the number of hours for each. Show one total $ figure for labor.* *Itemize names & hours here*	$ 0
4. **Procurements–PO (Equipment, Materials and Supplies)** *(Itemize)*	$ 0
5. **Procurement–RSA (or PS) for University Subcontract(s)** *(Important! See notes #1 and #2 below)* *Itemize and indicate whether the subcontract will be a RSA or PS type.*	$19,500
6. **Procurements– PS** *(Itemize equipment subcontracts)*	$ 0
7. **Procurements– PS** *(Itemize materials and supplies subcontracts)*	$ 0
8. **Services**— (*Itemize all in-house services at JPL)*	$ 0
9. **Travel**— *(itemize by trip into the following categories):* --- Domestic Conference Travel (specify conference title, travel destination, and total budgeted cost for each conference) --- Domestic Programmatic Travel (specify travel destination and total budgeted cost for each trip) --- Foreign Conference Travel (only one foreign conference travel is allowed per year, specify conference title, travel destination, and total budgeted cost for the conference) --- Foreign Programmatic Travel (specify travel destination and total budgeted cost for each trip)	$ 0
10. **Other**—*(Chargebacks, etc.) (telephone, computer)*	$ 342
11. **TOTAL BUDGET REQUEST** *(total of dollars 1 through 10)*	$25,000

Note #1: You must attach a budget breakdown from each university partner. There is no page limit and the format is the university's choice. The budget breakdown should be adequate for reviewers to understand labor, procurements, subcontracts, services, travel, and university overhead.

Note #2: Use an "RSA" type of subcontract to send funds to your university partner, except for the following circumstances: If your proposal involves hardware or software deliveries or if government furnished property will be sent to the university, then a RSA subcontract will not be allowed. Under these circumstances, use a "PS" type of subcontract

22. Budget Details for University Partner(s)

Complete the table below for each partner. You may include your collaborator's budget details in a format of their choosing, in addition to this table - there is no page limit for this

UNIVERSITY PARTNER BUDGET SHEET	**FY'15 Cost**
a. Salaries (*Itemize*) *Only "itemize" the person names and job classifications and the number of hours for each. You can show one total $ salary figure for labor.* *Student salary (GRA III) at 50% appointment for 3.75 months* *= $1957 x 3.75= $7339*	$7,339
b. Employee Benefits - At 32%, fringe = $2348	$2348
c. Procurements –Equipment, Materials and Supplies *(Itemize).*	$0
d. Procurements – Subcontracts *(Itemize)*	$0
e. Services – *(Itemize)*	$0
f. Travel – *(Itemize)* Student will spend 14 days at JPL or JPL personel with spend time at UT Airfare $400 + 14 day lodging $1400 = $1800	$1800
g. Other - *(Itemize) (include Tuition Remission here)* *Summer tuition*	$1752
h. Overhead - external *(university or other outside organization)* Indirect cost at 54.5% on salary and travel	$6261
i. **Total Budget** *(sum of lines a. through h. - include this in your budget sheet above)*	**$19,500**

NOTE: The above table shows the UT budget only for FY 2015. If our SURP initiative is funded over three years (FY 2015, 2016, and 2017), as requested in our proposal, we expect the UT budget for FY2016 and FY2017 to be similar (~$19,500) to the above FY2015 budget . We have attached a budget justification (SURP-Jogee-budget-justif.pdf) for the UT Austin budget.