02 INFORMATION ABOUT PRINCIPAL INVESTIGATORS/PROJECT DIRECTORS(PI/PD) and co-PRINCIPAL INVESTIGATORS/co-PROJECT DIRECTORS

Submit only ONE copy of this form **for each PI/PD and co-PI/PD** identified on the proposal. The form(s) should be attached to the original proposal as specified in GPG Section II.C.a. Submission of this information is voluntary and is not a precondition of award. This information will not be disclosed to external peer reviewers. ***DO NOT INCLUDE THIS FORM WITH ANY OF THE OTHER COPIES OF YOUR PROPOSAL AS THIS MAY COMPROMISE THE CONFIDENTIALITY OF THE INFORMATION.***

PI/PD Name: Joel R Primack

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

Race:
(Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status:
(Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☒ None

Citizenship: (Choose one) ☒ U.S. Citizen ☐ Permanent Resident ☐ Other non-U.S. Citizen

Check here if you do not wish to provide any or all of the above information (excluding PI/PD name): ☐

REQUIRED: Check here if you are currently serving (or have previously served) as a PI, co-PI or PD on any federally funded project ☒

Ethnicity Definition:
Hispanic or Latino. A person of Mexican, Puerto Rican, Cuban, South or Central American, or other Spanish culture or origin, regardless of race.
Race Definitions:
American Indian or Alaska Native. A person having origins in any of the original peoples of North and South America (including Central America), and who maintains tribal affiliation or community attachment.
Asian. A person having origins in any of the original peoples of the Far East, Southeast Asia, or the Indian subcontinent including, for example, Cambodia, China, India, Japan, Korea, Malaysia, Pakistan, the Philippine Islands, Thailand, and Vietnam.
Black or African American. A person having origins in any of the black racial groups of Africa.
Native Hawaiian or Other Pacific Islander. A person having origins in any of the original peoples of Hawaii, Guam, Samoa, or other Pacific Islands.
White. A person having origins in any of the original peoples of Europe, the Middle East, or North Africa.

WHY THIS INFORMATION IS BEING REQUESTED:

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Collection of this information is authorized by the NSF Act of 1950, as amended, 42 U.S.C. 1861, et seq. Demographic data allows NSF to gauge whether our programs and other opportunities in science and technology are fairly reaching and benefiting everyone regardless of demographic category; to ensure that those in under-represented groups have the same knowledge of and access to programs and other research and educational oppurtunities; and to assess involvement of international investigators in work supported by NSF. The information may be disclosed to government contractors, experts, volunteers and researchers to complete assigned work; and to other government agencies in order to coordinate and assess programs. The information may be added to the Reviewer file and used to select potential candidates to serve as peer reviewers or advisory committee members. See Systems of Records, NSF-50, "Principal Investigator/Proposal File and Associated Records", 63 Federal Register 267 (January 5, 1998), and NSF-51, "Reviewer/Proposal File and Associated Records", 63 Federal Register 268 (January 5, 1998).

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PI/PD Name: Avishai Dekel

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

Race:
(Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status:
(Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☒ None

Citizenship: (Choose one) ☐ U.S. Citizen ☐ Permanent Resident ☒ Other non-U.S. Citizen

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Black or African American. A person having origins in any of the black racial groups of Africa.
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PI/PD Name: Anatoly A Klypin

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

Race:
(Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status:
(Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☒ None

Citizenship: (Choose one) ☒ U.S. Citizen ☐ Permanent Resident ☐ Other non-U.S. Citizen

Check here if you do not wish to provide any or all of the above information (excluding PI/PD name): ☐

REQUIRED: Check here if you are currently serving (or have previously served) as a PI, co-PI or PD on any federally funded project ☒

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White. A person having origins in any of the original peoples of Europe, the Middle East, or North Africa.

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List of Suggested Reviewers or Reviewers Not To Include (optional)

SUGGESTED REVIEWERS:
Not Listed

REVIEWERS NOT TO INCLUDE:
Not Listed

List of Suggested Reviewers or Reviewers Not To Include (optional)

SUGGESTED REVIEWERS:
Not Listed

REVIEWERS NOT TO INCLUDE:
Not Listed

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 09-29	FOR NSF USE ONLY
NSF 05-608 11/15/09	NSF PROPOSAL NUMBER
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)	
AST - EXTRAGALACTIC ASTRON & COSMOLO	

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
				125084723	

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)	SHOW PREVIOUS AWARD NO. IF THIS IS	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S)
941539563	☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE
University of California-Santa Cruz	1156 High Street SANTA CRUZ, CA 95064-4107
AWARDEE ORGANIZATION CODE (IF KNOWN) 0013219000	
NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE	ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE
PERFORMING ORGANIZATION CODE (IF KNOWN)	

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions) ☐ SMALL BUSINESS ☐ MINORITY BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS | ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 423,456	36 months	07/01/10	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR (GPG I.G.2)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
- ☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
- ☐ HISTORIC PLACES (GPG II.C.2.j)
- ☐ EAGER* (GPG II.D.2) ☐ RAPID** (GPG II.D.1)
- ☐ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date ________ PHS Animal Welfare Assurance Number ________
- ☐ HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number ________ Exemption Subsection ______ or IRB App. Date ________
- ☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j) ________
- ☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT	PI/PD POSTAL ADDRESS
Physics Department	1156 High Street Santa Cruz, CA 95064 United States
PI/PD FAX NUMBER 831-459-3043	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
PI/PD NAME Joel R Primack	PhD	1970	831-459-2580	joel@physics.ucsc.edu
CO-PI/PD Avishai Dekel	PhD	1980	722-658-4100	dekel@phys.huji.ac.il
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

CERTIFICATION PAGE

Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the Authorized Organizational Representative or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), nondiscrimination, and flood hazard insurance (when applicable) as set forth in the NSF Proposal & Award Policies & Procedures Guide, Part I: the Grant Proposal Guide (GPG) (NSF 09-29). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

Conflict of Interest Certification

In addition, if the applicant institution employs more than fifty persons, by electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of the NSF Proposal & Award Policies & Procedures Guide, Part II, Award & Administration Guide (AAG) Chapter IV.A; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

Drug Free Work Place Certification

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Drug Free Work Place Certification contained in Exhibit II-3 of the Grant Proposal Guide.

Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant is providing the Debarment and Suspension Certification contained in Exhibit II-4 of the Grant Proposal Guide.

Certification Regarding Lobbying

The following certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

Certification Regarding Nondiscrimination

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative is providing the Certification Regarding Nondiscrimination contained in Exhibit II-6 of the Grant Proposal Guide.

Certification Regarding Flood Hazard Insurance

Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:

(1) community in which that area is located participates in the national flood insurance program; and
(2) building (and any related equipment) is covered by adequate flood insurance.

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant located in FEMA-designated special flood hazard areas is certifying that adequate flood insurance has been or will be obtained in the following situations:

(1) for NSF grants for the construction of a building or facility, regardless of the dollar amount of the grant; and
(2) for other NSF Grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME		

TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS	FAX NUMBER

* EAGER - EArly-concept Grants for Exploratory Research
** RAPID - Grants for Rapid Response Research

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 09-29 NSF 05-608 11/15/09	FOR NSF USE ONLY NSF PROPOSAL NUMBER
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) AST - EXTRAGALACTIC ASTRON & COSMOLO	1009908

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
11/16/2009	3	03020000 AST	1217	173851965	11/16/2009 6:34pm

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)	SHOW PREVIOUS AWARD NO. IF THIS IS	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY?
856000401	☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	YES ☐ NO ☒ IF YES, LIST ACRONYM(S)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE **New Mexico State University**	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE New Mexico State University Corner of Espina St. & Stewart Las Cruces, NM. 880038002
AWARDEE ORGANIZATION CODE (IF KNOWN) 0026575000	
NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE	ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE
PERFORMING ORGANIZATION CODE (IF KNOWN)	

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions) ☐ SMALL BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 95,898	36 months	07/01/10	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

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- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
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- ☐ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date ________
  PHS Animal Welfare Assurance Number ________
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  Exemption Subsection ______ or IRB App. Date ________
- ☐ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
  ____
- ☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT Astronomy Department	PI/PD POSTAL ADDRESS Box 30001, Department 4500 Las Cruces, NM 880038001 United States
PI/PD FAX NUMBER 505-646-1602	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
PI/PD NAME Anatoly A Klypin	PhD	1980	505-646-1400	aklypin@nmsu.edu
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				
CO-PI/PD				

Electronic Signature

CERTIFICATION PAGE

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(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

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(2) building (and any related equipment) is covered by adequate flood insurance.

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant located in FEMA-designated special flood hazard areas is certifying that adequate flood insurance has been or will be obtained in the following situations:

(1) for NSF grants for the construction of a building or facility, regardless of the dollar amount of the grant; and
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Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population – PI: Joel Primack, Co-I: Avishai Dekel, in Collaboration with Anatoly Klypin

Intellectual Merits: The majority of the stellar mass in the universe lies in galactic spheroids, which also host supermassive black holes (SMBH). The origin of these key structures in the evolving population of galaxies can be clarified through the interplay of new observations including multiwavelength surveys such as AEGIS that are pushing to higher redshifts, and improving theory that will be essential for guiding and interpreting these new observations. Our proposed research focuses on the growth of cosmic structure and on the dominant mechanisms responsible for the two opposite major phenomena governing the formation of blue and red galaxies: early, efficient star formation, followed by a quenching of this process in massive dark-matter halos. We attempt to discriminate between galaxy spheroid buildup by cold gas inflows and disk instabilities vs. major and minor mergers. In our study of the processes that quench star formation and make galaxies red and keep them dead for cosmic times, we wish to identify the roles of AGN activity versus virial shock heating in halos above a threshold mass, distinguish satellite from central quenching, and understand the cross-talk between the shutdown of star formation and the development of spheroidal stellar components and SMBHs. We compare our detailed models of early-type galaxy formation with observations both of ongoing galaxy mergers and other galaxy formation processes out to high redshifts and also of nearby galaxies whose properties can be studied in detail.

This research is supported by a large program of computer simulations. These include our just-finished cosmological "Bolshoi" dissipationless simulation, which goes beyond Millennium both in using current (WMAP5) cosmological parameters and in having nearly an order of magnitude better mass and spatial resolution. Analysis of Bolshoi and follow-on simulations will establish the ΛCDM gravitational backbone of structure formation, clarify dark matter halo properties, and support improved semi-analytic models of galaxy formation and evolution. We are also doing high-resolution hydrodynamic simulations to clarify galaxy formation processes and to calculate kinematics, spectra, and images including dust scattering and absorption using our Sunrise code. It is crucial to observe our increasingly realistic simulations in ways that mimic accurately the observations of real galaxies, so that theory and observation can be properly compared. In particular, we are working to determine the rates of galaxy mergers from observations, using our simulations to estimate the timescales during which mergers would be observed by pair counts and various morphological measures.

Broader impacts of this research include teaching students including underrepresented groups and involving them in our research, improving astrophysical theory and the ability to understand the implications of the latest observations, pushing the computational envelope, making our codes and outputs available to the astrophysical community, and communicating this scientific progress to the larger public. Computer visualizations help us understand our simulations and also help make them accessible to our astronomical colleagues and to the public. Observational astronomy provides snapshots and spectra of galaxies as they were when the light we see left them; the role of theory is to make the conceptual movies that fit these pictures into a coherent scientific framework.

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1 Background and Scientific Motivation

The theoretical research proposed here is especially timely because of two recent observational developments: **(1) we finally are closing in on the true cosmological parameters; and (2) new observations at $z \sim 2$ are clarifying the processes by which most of the stars in the universe formed, and at $z \lesssim 1$ how present-day galaxies assembled.**

(1) The evolution of structure in the universe on all scales larger than the central regions of galaxies appears to be governed by the dark matter distribution predicted by ΛCDM (e.g., Conroy et al. 2006; Komatsu et al. 2009; Primack 2009c), although there are issues concerning possible disagreements with ΛCDM on smaller scales (Primack 2009a,b). The cosmological parameter σ_8, the normalization of the fluctuation power spectrum on the cluster scale 8 h^{-1} Mpc, controls the growth of structure as a function of redshift. For example, σ_8^{-2} appears in the exponential in Press-Schechter-type expressions (e.g., Sheth & Tormen 2002) for the abundance of dark matter halos as a function of redshift. This crucial parameter was found in the first-year WMAP1 analysis (Spergel et al. 2003) to be $\sigma_8 = 0.9 \pm 0.1$, in the third-year WMAP3 analysis (Spergel et al. 2007) ≈ 0.75, and in the fifth-year WMAP5 analysis (Komatsu et al. 2009) 0.817 ± 0.026, including data on baryon acoustic oscillations (BAO) and type Ia supernovae (SN). "Considering a range of extended models, we continue to find that the standard ΛCDM model is consistently preferred by the data," according to WMAP5 (Dunkley et al. 2009). Much recent data (e.g., Rozo et al. 2009; Vikhlinin et al. 2009) agrees with the WMAP5 cosmological parameters. In addition, recent N-body simulations (Macciò et al. 2008) show that halos with the WMAP5 cosmological parameters agree better with galaxy-scale observations than with WMAP1 and WMAP3 paramaters. The Millennium Run (Springel et al. 2006) and Millennium II (Boylan-Kolchin et al. 2009) were done with the WMAP1 cosmological parameters. Our recently-completed Bolshoi simulation[1] §3.1 was done with WMAP5 parameters, and also has much better mass and force resolution than the Millennium Run. **We propose to make the Bolshoi simulation the basis for better understanding of the dark matter backbone of structure formation and for a new generation of improved semi-analytic models (SAMs).**

(2) Recent observations of massive forming galaxies at $z \sim 2$ have shown that some of them are much more compact than present-day elliptical galaxies, but IFU observations show that many of these galaxies have large rotating gaseous disks with bright clumps of star formation (Genzel et al. 2008). Recent hydrodynamic simulations by our group (Ceverino et al. 2009) - which for the first time resolve the relevant physical size, temperature, and density scales - are finding similar behavior (Genzel 2009) and also predicting other phenomena such as Lyman-α blobs (Goerdt et al.) that appear to be in agreement with observations (§2.1 and §3.4). Meanwhile, large surveys such as DEEP2, AEGIS, and COSMOS are clarifying how galaxies assemble at $z \lesssim 1$ into the forms we see in the nearby universe, with proposed multiwavelength surveys using *Herschel* and the new WFC3 on *HST* pushing to $z \sim 3$ and beyond.

The origin and evolution of galactic spheroids, which comprise approximately three-fourths of the stellar mass in the Universe (Fukugita & Peebles 2004), **is a key problem that is therefore at last ripe for solution.** Although it is widely believed that many elliptical galaxies (Es) and most classical galactic bulges formed via galaxy mergers (Kormendy & Kennicutt 2004), co-I Dekel has proposed an alternative scenario for formation of massive Es at high redshift $z \gtrsim 2$ through instabilities in disks that formed via cold gas inflows (Dekel et al. 2008).

Perhaps the strongest evidence of the importance of major galaxy mergers is the rapid increase in the mass density of spheroids from $z \sim 1$ to the present (Bell et al. 2004; Faber et al. 2007). Our recent measurement of the merger rate (Lin et al. 2008; Lotz et al. 2008a, 2009a) suggests that

[1] `http://astronomy.nmsu.edu/aklypin/Bolshoi/`

these spheroids plausibly were created by the galaxy mergers, but the fraction of dissipationless vs. gas-rich mergers is uncertain. Only mergers involving disk galaxies can increase the total mass density of spheroids, although simulations show that disks can be regrown in gas-rich mergers (e.g., Springel & Hernquist 2005; Robertson et al. 2006). Mergers are also likely to be a key ingredient (Hopkins et al. 2008a) in the growing of supermassive black holes (SMBHs) and in producing the observed $M_{\rm BH}$-σ relation. We have developed tools to determine the rates of both gas-rich ("wet") and gas-poor ("dry") mergers reliably out at least to $z \sim 1$ (see §2.4), and we propose to extend them to higher redshifts.

At long last, cosmological hydrodynamic simulations of galaxy formation, with higher resolution and better implementations of supernova feedback, are beginning to make realistic disk galaxies (Governato et al. 2007; Mayer et al. 2008; Ceverino & Klypin 2009). Hydrodynamic simulations of major mergers of gas-rich disk galaxies reproduce some key features of observed early-type galaxies (e.g., Barnes & Hernquist 1992; Cox et al. 2006a). Star formation in massive galaxies at high redshifts appears to convert gas into stars very efficiently (Genel et al. 2008). Major mergers may be responsible for the very luminous submillimeter galaxies, but infrared IFU observations suggest that much of the star formation at $z \gtrsim 2$ occurs in thick gaseous disks (Genzel et al. 2008; Shapiro et al. 2008). New hydrodynamic simulations of high-redshift galaxy formation by our group are showing that cold streams of gas can enter even rather massive galaxies at $z \gtrsim 2$, that these forming disks are unstable to clumping, and that such star-forming clumps merge to form stellar spheroids in such systems (Dekel et al. 2008, 2009; Ceverino et al. 2009). Our state-of-the-art AMR code (as opposed to the more common and easy to use SPH codes) permits zoom-in simulations of high-z galaxies in a cosmological setting with unprecedented resolution. This allows us to resolve the cold streams feeding the galaxies from the cosmic web, their penetration through the halo, their interaction with the inner disk, and, most importantly, the wild disk instability into giant clumps. The AMR code is also more appropriate for incorporating the subgrid physics of star formation and feedback from stars, supernovae and black holes. These simulations are therefore a unique tool for studying the new picture of high-z galaxy formation by cold streams. We address the relative importance of this mode of spheroid formation compared to binary mergers of gas-rich disks in §3.3-6 below.

A related question is the nature of the mechanism that shuts down star formation in galaxies and creates their bimodal color distribution out to $z \sim 2$ (Bell et al. 2004; Baldry et al. 2006; Faber et al. 2007; Brammer et al. 2009). Hydrodynamic simulations of binary galaxy mergers including a model for AGN accretion and feedback (Springel et al. 2005b), in which the black hole accretes rapidly during the final coalescence of the galaxies and expels all gas from the system, reproduce the observed $M_{\rm BH}$-σ relation (Di Matteo et al. 2005). They also naturally result in a shutdown of star formation after the merger and the formation of a red remnant (Springel et al. 2005a) and appear to be consistent with observations of the QSO luminosity function (Hopkins et al. 2005 and subsequent papers, reviewed in Hopkins et al. 2008b,a).

Despite its successes, it is not clear that the Springel-Hernquist-Hopkins AGN model is fully consistent with the observations. In this model, the intrinsic luminosity of the AGN is strongly peaked at the time the galactic nuclei merge. At that time, feedback from the accreting black hole blows out the gas from the merging galaxies and terminates most growth of both $M_{\rm SMBH}$ and $M_{\rm spheroid}$. This cannot be the complete story. The SAM based on this model (Somerville et al. 2008b) does not produce the correct redshift distribution of bright quasars. SDSS data on nearby galaxies (Schawinski et al. 2007) and AEGIS data on $z \sim 1$ galaxies (Nandra et al. 2007; Georgakakis et al. 2008) show that much of the AGN activity occurs *after* the spheroid is already turning red. Furthermore, we found that X-ray emission from AGN in galaxies at $z \sim 1$ seems to come mostly from early-type galaxies, not mergers (Pierce et al. 2007; Pierce 2009); and

LINER-type emission, presumably connected to low-level AGN activity, is observed to originate from post-starburst galaxies whose gas and dust appear not to have been cleared out during the starburst phase (Graves et al. 2007). The DEEP2 survey has turned up a two multiple AGN and 35 velocity-offset AGN (Comerford et al. 2009) in post-starburst galaxies, favoring a merger origin for these galaxies but suggesting that many of the SMBHs in the merging galaxies have not yet themselves merged.

A different mechanism must be responsible for quenching star formation over longer periods. Heating of the IGM by sustained low-level AGN activity ("radio-mode" AGN feedback (Croton et al. 2006)) is one possibility; the shutting down of cold gas inflow due to a virial shock when the halo mass grows larger than approximately $10^{12}\,M_\odot$ is another (Birnboim & Dekel 2003; Kereš et al. 2005; Birnboim et al. 2007; Dekel & Birnboim 2007).

The comparison between theory and observations is complicated by the difficulty of finding and identifying not only merging galaxies at high redshift, but also highly obscured AGN. The X-ray emission from these sources can be attenuated to the point that it becomes difficult to detect with current X-ray telescopes, but NuSTAR, scheduled for launch in 2011, should detect higher energy X-rays from even Compton-thick AGN. The infrared dust emission, on the other hand, is readily detected but can also originate in the highly obscured starbursts predicted by the merger picture.

In recent years, true multi-wavelength capabilities have become reality. The wavelength coverage of large galaxy surveys is increasing, and the AEGIS survey (Davis et al. 2007) has accumulated essentially panchromatic coverage including X-ray, far-ultraviolet, optical, near-infrared, mid-infrared, and radio wavelengths, with DEEP2 spectra of galaxies to $z \sim 1.4$. This will be extended to higher redshifts by the DEEP3 survey. The Herschel space telescope will extend wavelength coverage at far-infrared wavelengths out to redshifts around 2, and ALMA and SKA out to the epoch of reionization. Studies of galaxies that focus on single observables, like the luminosity function, are rapidly becoming outdated.

The challenge now is to measure the full multi-dimensional distribution of galaxies in *all* observables, and to develop a unified model of galaxy formation that can predict these quantities. To determine the role of galaxy mergers in fueling AGN and the buildup of spheroids compared to alternative mechanisms, more sophisticated methods for identifying merging galaxies in surveys are needed, utilizing all available observables. Creating such models and methods is a major goal of the research proposed here. We aim in particular to provide the main theoretical support for the DEEP3 and AEGIS surveys.

The research proposed here would accomplish the following:

- **Determine the ΛCDM gravitational backbone for structure formation** with current cosmological parameters by analyzing our Bolshoi simulation, running higher-resolution simulations of subregions, and determining halo properties and the halo merger tree (§3.1).
- Develop improved semi-analytic models (SAMs) based on the Bolshoi simulations and on our new analytic model of spheroid formation (§2.2) in order to **predict the properties of the evolving galaxy population** (§3.2).
- Develop improved hydrodynamic simulations of galaxy formation appropriate for higher redshifts, including **AGN, gas flow into galaxies, and environmental effects of large-scale structure** (§3.3-5).
- Use our improved Sunrise radiation transfer model (§2.3) and our new hydrodynamic simulations of galaxy formation (§2.1) to develop sophisticated **algorithms for identification and multiwavelength characterization of spheroid formation processes** in galaxy surveys (§3.5-6).
- All our models and outputs and all software developed will be **freely available**.

Our "Santa Cruz" style of running and analyzing simulations in close collaboration with observers builds on and extends our current research, detailed in §2. The proposed new research is described in more detail in §3, and the broader goals and impacts of our research in §4.

2 Our Recent and Current Work, and Proposed Continuations

This section describes our completed and ongoing research relevant to the present proposal, to provide a context for this proposal and to show that we are in a position to accomplish the proposed new work. We also describe proposed continuations of our current research.

2.1 Simulations of Early-type Galaxy Formation. We have done a large suite of high-resolution hydrodynamic simulations of binary galaxy mergers and compared them to observations in order to measure the rate of galaxy mergers out to redshifts $z \sim 1$. We have also initiated a program to simulate star formation in massive galaxies at higher redshifts, and as mentioned the results appear to be consistent with the latest observations.

Binary and multiple galaxy mergers. For the past several years, our group has been studying mergers of galaxies through high resolution hydrodynamic simulations of binary galaxy encounters, including star formation and supernova feedback. In our simulations, progenitorgalaxies are modeled as a stellar disk and bulge, a gas disk, and a dark-matter halo, with parameters chosen to match observed galaxies. Two of these galaxies are then placed on an approaching orbit, and the simulation is started. The simulations have typically used 170,000 particles per galaxy, with a smaller number of simulations using up to 1,700,000 particles per galaxy. They were run using the current version of the GADGET N-body/hydrodynamics code, including star formation and feedback. Using this method, a spatial resolution of $\sim 100\,\mathrm{pc}$ and a mass resolution of $\sim 10^6\,\mathrm{M}_\odot$ are attained.

Both as Primack's PhD student and during his subsequent postdoc at Harvard, our continuing Collaborator **T. J. Cox** ran a large suite of galaxy merger simulations that our group analyzed (Cox et al. 2004; Cox 2004)/We have done an extensive study of the effects of different supernova feedback parameterizations (Cox et al. 2006b), and for the first time conducted an extensive study of minor as well as major mergers (Cox et al. 2008), investigating how the properties of the merger-induced starbursts depend on the mass ratios of the merging galaxies.

We store many complete snapshots for each set of initial conditions, and we use our *Sunrise* code (§2.3) to turn this detailed tracking of gas, star formation, and metals into images in every waveband from far-UV to far-IR, including a realistic treatment of the effects of dust. We "observe" these outputs as observers do real galaxies, including redshifting and seeing effects, and analyze the resulting images morphologically using several analysis tools (§2.4). We find that close pairs (both in redshift and on the sky) are usually gas rich mergers, which also tend to produce morphologically Asymmetric galaxies. However, we find that own Gini-M_{20} tool (Lotz et al. 2004) can also detect minor mergers and gas-poor mergers. We measure the timespans over which merging galaxies will be observable as close pairs or as morphologically disturbed (Lotz et al. 2008c, 2009a,b,c). Combining this with AEGIS observations (Lotz et al. 2008a), we measure the actual rates of different types of mergers: gas rich vs. gas poor, and major vs. minor out to $z \sim 1$ (§2.4). Continuing this to higher redshifts (§3.3-6) is essential in order to determine the role of mergers in forming early-type galaxies.

We are comparing many properties of the merger remnants with observations of elliptical galaxies. One project concerned the radial dependence of the velocity dispersion in elliptical galaxies produced by mergers. Our study Dekel et al. (2005) refuted the argument that a low observed velocity dispersion in the outskirts of elliptical galaxies rules out the presence of a dark matter

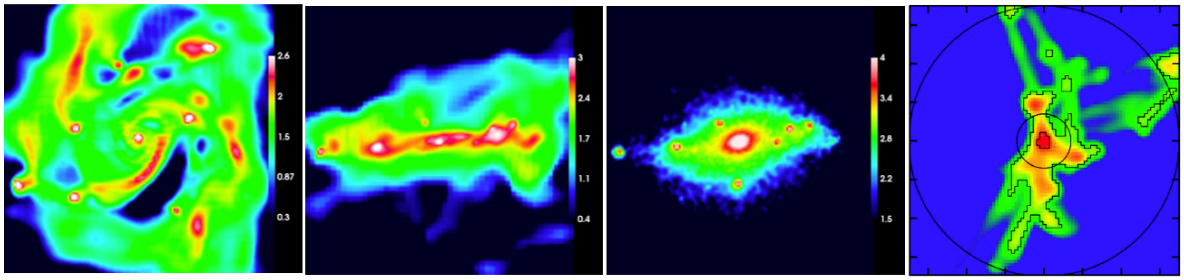

Figure 1: Gas surface density of a galaxy at $z \sim 2.3$ from a high-resolution cosmological simulation (Ceverino et al. 2009). The first three images are 10×10 kpc; the color code is log suface density in units of $M_\odot$ pc^{-2}. The face-on view (a) shows shows an extended disk broken into several giant clumps. The edge-on view (b) demonstrates that this is a well-defined gas disk, and the young stars in the giant clumps resemble observed "chain" galaxies (Elmegreen & Elmegreen 2006). The edge-on view of surface density of all stars (c) shows a large bulge formed by merging clumps that comprises about half of the stars. (d) Lyα "observed" surface brightness (contours mark 10^{-18} and 10^{-17} erg s^{-1} cm^{-2} arcsec^{-2}) from the simulation at $z = 2.3$ (Goerdt et al.), which resembles observed Lyα blobs (see §3.4). The outer circle shows the virial radius $R_{\rm vir} = 70$ kpc; the inner circle is $0.2 R_{\rm vir}$.

halo (Romanowsky et al. 2003). The low velocity dispersion is a natural outcome of the merging process, which naturally puts stars in the outer regions of the remnants on highly radial orbits via gravitational interactions with the merging galactic nuclei.

Greg Novak (who finished his PhD with Primack in September 2008 and is now a postdoc at Princeton) studied the shapes of the merger remnants and their dark halos and found that the stellar minor axis and the halo major axis are almost always close to perpendicular. The elongation is along the merger axis, and the stellar minor axis is oriented close to the angular momentum axis, with much of this angular momentum typically arising from the orbital angular momentum of the merging galaxies. These predictions (Novak et al. 2006) are being tested by observations of weak gravitational lensing (Parker et al. 2007). Novak (2008) [2] also compared with new strong lensing data on elliptical galaxies (Bolton et al. 2007), finding that our binary merger remnants agree with the data on Es with lower velocity dispersion σ_v but that Es with higher $\sigma_v \gtrsim 350$ km s^{-1} have higher central densities than are attained in binary mergers (Novak et al., in prep.). In agreement with the new SLACS lensing data (Bolton et al. 2008), we find that the total density in our simulations is very close to isothermal (r^{-2}).

Novak also did a detailed kinemetry comparison of the binary merger remnants with integral field unit observations of early-type galaxies in the SAURON survey (Emsellem et al. 2004, 2007). Prelminary results reported in Novak's PhD thesis (Novak 2008) indicate that our binary, gas-rich major mergers result in remnants that are very similar to the approximately 75% of SAURON ellipticals that are classified as "fast rotators" (Emsellem et al. 2007; Cappellari et al. 2007; Falcón-Barroso et al. 2008). However, the remaining ∼25% are slowly rotating, nearly spherical elliptical galaxies that are rarely produced in binary major merger simulations. A possible formation mechanism for these galaxies is **multiple** major or minor mergers (Weil & Hernquist 1996; Bournaud et al. 2007; Burkert et al. 2008; Naab et al. 2007; Novak 2008), that are expected to occur in dense regions at high redshifts. Novak (2008) ran an ambitious new series of simulations of multiple mergers to test this hypothesis, including both fully cosmological initial conditions and also simplified cases of interactions between many individual galaxies. Papers based on these and ongoing simulations will soon be submitted for publication.

[2] `http://physics.ucsc.edu/~joel/Novak-thesis.pdf`

Daniel Ceverino (who finished his PhD with Collaborator Klypin in 2008 and is now a postdoc with Co-I Dekel) did pathbreaking hydrodynamical simulations of processes in the galactic interstellar medium (ISM) using the Eulerian hydrodynamics + N-body Adaptive Refinement Tree (ART) code developed by Klypin in collaboration with his former PhD student Andrey Kravtsov (Kravtsov et al. 1997; Kravtsov 1999, 2003). The ART-hydro code properly models the multicomponent ISM. Since it includes the heating and cooling rates from radiative processes and molecular as well as line cooling, it can simulate temperatures down to ~ 100 K, densities $n_{\rm H} > 10^{-3}$ cm^{-3}, and reach the thermodynamic conditions of molecular clouds. Instead of using a sub-resolution model of a multi-phase medium as in (Springel & Hernquist 2003; Cox et al. 2006c) their code resolves it, and naturally produces hot bubbles, chimneys, and galactic winds. Another important ingredient is runaway stars: massive stars ejected from the molecular clouds where they form. (Although most massive stars are found in stellar clusters and OB associations, 10-30% are found in the field with velocities consistent with such an ejection scenario.) Such runaway stars become supernovas 10-100 pc from molecular clouds, which greatly facilitates feedback. Having understood key physical processes in (4 kpc)^3 simulations of the ISM of a disk galaxy with resolution of a few pc, Ceverino and Klypin next checked that the same processes occurred in simulations with the ~ 35 pc resolution that their cosmological simulations could achieve. They found that the classic problems of disk galaxy formation – overcooling and loss of angular momentum resulting in unrealistically massive bulge formation – are avoided, with their simulated galaxies having nearly flat rotation curves (Ceverino & Klypin 2009). Finally they studied the effect of stellar feedback in galaxy formation at high redshift.

In ongoing cosmological simulations of the formation of the progenitors of massive elliptical galaxies at high redshift, run using Primack's allocations of supercomputer time, Ceverino has seen **cold flows of gas into galaxies feeding unstable dense gas-rich disks that form giant clumps, each a few percent of the disk mass, in which stars form rapidly**. The clumps migrate into a central bulge in ~ 0.5 Gyr, but cold gas inflow can maintain this phenomenon for up to several Gyr. Figure 1 shows such a clumpy disk galaxy. The resulting unstable gaseous disks resemble those found by Genzel and collaborators (Genzel et al. 2008), but the merging clumps can build a massive stellar spheroid. A sufficiently large stellar spheroid can then stabilize the disk and largely prevent further star formation. The model thus predicts a galaxy bimodality already by $z \sim 3$, with star-forming disks and reddening spheroids (Dekel et al. 2008, 2009). Continuing the Ceverino simulations and comparing them to observations is a major focus of this proposal (§3.4-5)

2.2 Improving Semi-Analytic Models of Galaxy Formation. Our simulations of galaxy formation have led to improved SAMs by enabling us to model the properties of the sphroids formed in mergers and also by improving treatment of absorption and reradiation by dust.

Matt Covington (who finished his PhD with Primack in September 2008 and is now a postdoc at the University of Minnesota) created an analytic model of the properties of remnants from our galaxy merger simulations. Covington's physical merger model accurately predicts the stellar half-mass radius and velocity dispersion of the stellar spheroids produced by gas-rich binary mergers based on energy transfer from orbital to internal kinetic energy in the first close pass of the merger (Covington et al. 2008). It is a major improvement over the simplified model used in Cole et al. (2000), which does not take radiative energy losses into account. The model works for a wide range of merger mass ratios, and it also accurately predicts the properties of spheroids formed in gas-poor ("dry") mergers. The only inputs required are the properties of the progenitor galaxies and their orbits, and work is in progress to create a simplified model that effectively integrates over cosmologically representative orbits (§3.2).

Such analytic models are useful for gaining an intuitive understanding of which physical processes are important, and also for use in conjunction with SAMs. In order to predict the properties of the evolving population of spheroidal galaxies, we combined this analytic model with two different SAMs, Somerville's new one (Somerville et al. 2008b) and one based on the Millennium simulation (Croton et al. 2006). We used the SAMs to predict the properties of the disk galaxies involved in all the mergers (mass, disk size, bulge to disk ratio, and gas content) and we summed with proper weighting over the orbits from cosmological simulations (Benson 2005). Somerville's SAM has disks with size-mass relation evolution in good agreement (Somerville et al. 2008a) with observations from low redshifts (Shen et al. 2003) out to high redshifts (Trujillo et al. 2006). The resulting stellar spheroids have a size-mass relation evolution with nearly the observed slope and zero point, both for SDSS spheroids and the systematically smaller ones out to $z \sim 3$. The dispersion in the spheroid sizes is smaller than that of the disks because the larger disk galaxies were also more gas rich, and in mergers with increasing gas fraction more gas is driven to the center and forms smaller stellar systems. The increasing gas content and smaller sizes of higher redshift disks accounts for the smaller spheroids resulting from their mergers. Similar results were obtained for the Millennium SAM; the slope of the spheroid size-mass relation was an even better match to the observations, although the Millenium SAM's unrealistically large disks resulted in a zero-point offset that was corrected when the observed sizes were instead used in the model. Covington (2008) [3] also found that the merger-produced stellar spheroids lie in a Fundamental Plane offset from the virial plane by the observed "tilt," because of an increased central star/dark matter ratio in more massive galaxies. These encouraging results, which will soon be submitted for publication, suggest that mergers of gas-rich disks form a significant fraction of elliptical galaxies, at least the lower-mass ones. They also suggest that the scaling relations of stellar spheroids are a consequence of those of the disk galaxies from which they form. The most massive elliptical galaxies cannot be produced by binary mergers of disks because of the absence of sufficiently massive and metal-rich disks (Naab & Ostriker 2009). As already mentioned (see also §3.4-5), they are possibly produced by multiple overlapping mergers and/or cold flows producing unstable clumpy disks.

In another project, Covington compared the kinematics of intermediate stages of our simulations with the Keck Observatory DEIMOS spectra of galaxies in the AEGIS survey. Although these AEGIS galaxies often had far lower rotation velocities for their stellar masses than the Tully-Fisher relation would predict, when their rotation velocities were added in quadrature to their velocity dispersions they were found to lie on a Tully-Fisher-like relation with remarkably little scatter (Kassin et al. 2007). When we mimic the AEGIS spectra by observing our simulations similarly, including seeing and using the same code to measure $V_{\rm rot}$ and σ as used to analyze the observed spectra, we find that intermediate stages of our galaxy mergers have kinematic properties very much like those observed (Covington et al. 2009). Our simulations are helping to interpret the observations. In particular, we have found that there is a close correlation between $S_{0.5} = (\sigma^2 + 0.5 V_{\rm rot}^2)^{1/2}$ and the total enclosed mass if they are both evaluated at (for example) the radius that encloses 80% of the stellar mass. Moreover, we found that the kinematics can help to determine the merger stage; for example, the rotation velocity often drops dramatically for about 100 Myr just after the coalescence of the galaxy nuclei. However, to truly mimic the observations we are now including the effects of dust in calculating these simulated spectra (§3.3-6), which is possible with the new version of *Sunrise*(§2.3).

Rudy Gilmore (who finished his PhD with Primack in June 2009 and will be a postdoc at SISSA) did an extensive study of the extragalactic background light (EBL) and gamma-ray attenuation using SAMs, in collaboration with Rachel Somerville (Primack et al. 2008; Gilmore 2009). This included a state-of-the-art calculation the evolving UV EBL using SAMs and models of the evolving AGN contribution, including processing of the ionizing radiation by the IGM in collaboration with Haardt and Madau (Gilmore et al. 2009a). In collaboration with Francisco

[3] `http://physics.ucsc.edu/~joel/Covington-PhD-thesis.pdf`

Prada, we used this new model of the UV background and GRB data to calculate the response to GRBs *Fermi* and of ground-based Atmospheric Cherenkov Telescopes like MAGIC (Gilmore et al. 2009b). We have major work in progress to improve the calculation of the EBL and to use gamma-ray data to constrain the cosmic history of star formation (§3.2).

2.3 The Radiation Transfer Model *Sunrise*. Hydrodynamic simulations alone cannot predict what the systems would look like when observed. Merger-driven starbursts, which are some of the most luminous galaxies in the local universe, are invariably highly extinguished by dust (e.g., Sanders & Mirabel 1996), so any attempt to compare the simulated galaxies with observations must take this into account. In order to calculate the effects of dust, Primack's PhD student and postdoc Patrik Jonsson developed the Monte-Carlo radiative-transfer code *Sunrise* (Jonsson 2004, 2006; Jonsson et al. 2006, 2009).

Using our *Sunrise* radiative-transfer code we have generated images of each simulated merger from many different viewpoints, in many wavelength bands, throughout the merger event. These images cover wavelengths from far-ultraviolet GALEX bands through optical ACS and ground-based filters and near-infrared NICMOS and the short-wavelength IRAC bands. Our simulations seem to replicate the properties of observed local starburst galaxies well (Jonsson et al. 2006). In particular, the simulations follow observed correlations between the IR/UV flux ratio and the ultraviolet spectral slope (Meurer et al. 1999; Goldader et al. 2002). Images and spectra of our simulations are available on a public web site,[4] and our intent is to provide access to the science data as well so that other researchers can use the simulations for their own analyses.

The current version of *Sunrise* uses a "polychromatic" algorithm, where every Monte Carlo ray samples every wavelength, which makes it possible to calculate spectra of unprecedented resolution. *Sunrise* has been adapted to use sub-resolution models of star-forming regions from the photoionization/dust code MAPPINGS III (Dopita et al. 2005). The emission from these star-forming regions includes emission lines, hot dust and PAH emission. Emission from diffuse dust is calculated self-consistently from the local radiation field, a calculation that we have sped up by two orders of magnitude using new Graphics Processing Units (GPUs) (Jonsson & Primack 2009). Taking all these features into account, *Sunrise* can generate realistic spectra of our galaxy simulations. Collaborator Jonsson, who recently joined Lars Hernquist's group at Harvard, will continue to improve *Sunrise*.

2.4 Galaxy Merger Identification, Timescales, and Rates. For the purpose of comparing simulations to observations, we have developed non-parametric measures quantifying galaxy morphology (Lotz et al. 2004). These measures separate local "normal" galaxies and ULIRGs remarkably well, and an analysis of ACS images of the EGS indicates that the local distribution of morphologies is present also at higher redshift (Lotz et al. 2008b). This method was used to estimate the merger fraction and merger rates in the AEGIS data (Lotz et al. 2008c) However, a key obstacle to understanding the galaxy merger rate and its role in galaxy evolution is the difficulty in constraining the timescales of mergers. Theoretical estimates for galaxy merger timescales are quite crude, and it is difficult to quantify the efficiency of various observational methods in selecting mergers. The combination of galaxy merger simulations and a realistic radiative transfer model is essential for calibrating these timescales. In work with Collaborator Jennifer Lotz (NOAO), we have applied morphological merger detection algorithms to simulated images of equal-mass mergers. This study shows that the timescales during which mergers may be identified are strongly dependent on the methods used (Lotz et al. 2008c). We are finding, for example, that Close Pairs and Asymmetry are primarily sensitive to gas-rich major mergers, while Gini-M_{20} can detect even gas-poor minor mergers that produce small morphological disturbances and little in-

[4] `http://governator.ucsc.edu/simulations`

duced star formation. As we explained in §2.1, the good news is that this reconciles apparently divergent estimates of the galaxy merger rate as a function of redshift, and it allows us to estimate the rates of various types of mergers.

2.5 Roles of Active Galactic Nuclei. Primack's student **Christy Pierce** finished her PhD in March 2009 and is now a postdoc at Georgia Tech. Her dissertation (Pierce 2009) was on the morphological and color characteristics of AGN host galaxies out to $z \sim 1$ in the AEGIS data. Preliminary results were presented in (Pierce et al. 2007), and detailed papers are now being submitted for publication. Identifying AGN using X-ray and radio emission and also optical spectra, Pierce showed that host galaxies of relatively bright AGN were usually early type galaxies rather than galaxy mergers. Pierce also found that only the brightest unobscured AGN change the central colors and morphologies significantly, so that our morphological classification tools are otherwise adequate to characterize AGN host galaxies (Pierce et al. 2009). We describe proposed research on AGN in galaxy formation in §3.5.

3 Proposed New Research

The goals of this project are ambitious, and our approach is correspondingly multipronged. **We are analyzing our just-completed high-resolution Bolshoi cosmological simulation, in order to understand better the details of ΛCDM structure formation and to provide the basis for better semi-analytic models of the evolving galaxy population.** Continuing the research just discussed, **we are running and analyzing high-resolution hydrodynamical simulations to clarify key phenomena in star formation and its quenching in galaxy formation. We are developing models, tools, and algorithms for predicting the detailed appearance, spectra, and panchromatic spectral energy distributions of galaxies from these simulations, including highly obscured AGN. And we are using these models to gain an understanding of galaxy mergers, cold gas inflows leading to unstable disks, the interplay between AGN feeding and feedback, and how these processes shape the evolution of the galaxy population, especially by comparing with observations like the DEEP2/3 and AEGIS galaxy surveys.** The specific questions we hope to answer were summarized in §1. Broadly, **we aim to clarify the processes governing star formation and its quenching in the formation of galactic spheroids, in order to understand the evolving population of early-type galaxies**. Here are details of the proposed research:

3.1 Bolshoi cosmological simulation. The Bolshoi simulation was run using the Adaptive Refinement Tree (ART) dissipationless code with 2048^3 particles in a comoving volume 250 h^{-1} Mpc on a side. The cosmological parameters were $h = 0.73$ and $\sigma_8 = 0.83$, consistent with WMAP5. The dynamic range was 262,000 and there were 400,000 major time steps. This simulation requred 6 million cpu-hours on 13824 cores and 12 Tb of RAM using early-user time on the new Pleiades machine at NASA Ames Research Center. The $10^8 h^{-1} M_\odot$ mass per particle and the force resolution of 1 h^{-1} kpc are almost an order of magntude better than the Millennium run, and the 170 timesteps saved (representing 75 Tb of data) are more than three times greater than for the Millennium run. A mini-Bolshoi simulation was also run with 1024^3 particles in 1/8 the volume.

We are now in the process of analyzing these simulations. Halos have been identified at all timesteps using Klypin's BDM halo-finder and are also being found using the Subfind halo-finder (Springel et al. 2001). Merger trees are now being constructed with our Collaborator Risa Wechsler and her postdoc Michael Busha. The Bolshoi simulation provides information about halo properties (such as mass and subhalo radial density profiles, concentrations, shapes, and angular momenta) and halo mass accretion and merger rates in different cosmological environments, which will be useful for many astrophysical purposes including halo occupation distribution (HOD) analyses. To give just one example: in dissertation research on the shapes of dark matter halos led by Primack's former grad student Brandon Allgood (Allgood et al. 2006), we found that to determine halo shapes accurately at several radii > 7000 particles are requred within the virial radius of the halo, which was achieved for halos with mass $> 9.3 \times 10^{11} h^{-1} M_{\odot}$ in a resimulated subregion of a larger simulation. The Bolshoi simulation has achieved better mass and force resolution in a volume 1000 times larger, and with the current best-fit cosmological parameters!

To study the distribution and evolution of satellite and dwarf galaxy halos in both typical and low-density environments, we plan to run **"sub-Bolshoi"** simulations of a number of subregions of the Bolshoi simulation with at least 64 times the mass resolution and force resolution of order 100 pc. These sub-Bolshoi runs will include hydrodynamic simulations of some of these subregions using the adaptive mesh ART-hydro code, including star and black hole formation and feedback.

Among the many applications of the Bolshoi simulation will be populating the backward light-cone and the creation of improved mock catalogs for redshift surveys, which Brian Gerke has agreed to do for the DEEP3 and AEGIS survey. Primack's grad students will all be involved in analyzing the Bolshoi simulation and applying these analyses to cosmological questions, as will the Co-I and Collaborators and their grad students. Collaborators Bullock and Wechsler are former PhD students of Primack whose dissertation research established fundamental properties of dark matter halo concentrations (Bullock et al. 2001b), angular momenta (Bullock et al. 2001a; Vitvitska et al. 2002; Maller et al. 2002), and mass accretion history (Wechsler et al. 2002), and who have often subsequently collaborated with him with and Dekel and Klypin.

3.2 Improving semi-analytic models and predicting the evolution of the galactic spheroid population. In addition to using our Bolshoi simulation as the basis for a new generation of SAMs, we are incorporating our analytic merger model (Covington et al. 2008) into the SAMs. As we discussed in §2.2 above, we can now use the analytic model together with SAM calculations of merging galaxy properties and orbits to predict the stellar mass, age, and metallicity, stellar half-light radius, stellar velocity dispersion, and other properties of the resulting spheroids at various redshifts. The great advantage of incorporating the analytic model into SAMs is that this will allow prediction of correlations of spheroid properties, for example with environment, and also allow us to determine the evolution of individual objects – thus seeing, for example, what compact ellipticals at high redshift evolve into at lower redshifts. This project is a high priority of our Collaboration with Rachel Somerville and Darren Croton, who are working with Primack and his grad students, especially Lauren Porter. Since her dissertation research with Primack (Somerville & Primack 1999; Somerville et al. 2001), Somerville has been an international leader in semi-analytic modeling of galaxy formation. Croton led the Millennium SAM (Croton et al. 2006).

In SAMs based on the Millennium run, most mergers involve "orphan galaxies," dark matter halos that have lost so many particles after they fall into a larger halo that they can no longer be identified by the halo finder. Such galaxies are assumed in these SAMs to merge onto the central galaxies in the larger halo after a residual merging time that is calculated by some variant of the classical dynamical friction formula, possibly including a model of stripping due to tidal interaction with the larger halo. **The uncertainties due to this approximate treatment will be largely avoided by the better mass and force resolution and the 170 saved timesteps of the Bolshoi simulation.**

We anticipate that the merger orbits will depend on the environment of the dark matter halo and on redshift. At any redshift, the rare halos that are much higher in mass than the typical mass of collapsing halos are fed from several (often three) filaments, while the more typical halos lie along filaments and infall into them occurs primarily along the filament axis (Dekel et al. 2008). We will test whether this is the main reason why lower-mass elliptical galaxies are typically elongated (along their host filament) and rotating (perpendicular to the long axis), properties that we showed are predicted by binary major merger simulations (Novak et al. 2006), while more massive ellipticals are typically more spherical and non-rotating.

Primack's student Lauren Porter has already used Covington's analytic merger model together with outputs from the Croton and Somerville SAMs to model the entire early-type galaxy population produced by major mergs of gas-rich disk galaxies. She has been comparing these results with the beautiful analysis of SDSS data on early-type galaxies in Genevieve Graves's just-finished PhD dissertation supervised by Collaborator Sandra Faber. By analyzing coadded SDSS spectra of elliptical galaxies binned by stellar half-light radius R_e and velocity dispersion σ_v, Graves has found that their light-weighted ages and metallicities are mainly functions of σ_v rather than R_e (Graves et al. 2009b,a). Porter is finding a similar behavior of light-weighted metallicity, but she finds that light-weighted stellar age is a function of R_e as well as σ_v since - as we mentioned in §2.2 discussing Covington's dissertation research - merging the smaller and more gas-rich disks typical at higher redshift produces smaller spheroids. Since our analytic merger model correctly predicts the results of dry as well as wet and minor as well as major mergers, Porter plans to extend this work by including all mergers predicted by the SAMs, including minor and dry mergers, to see whether doing this will reproduce the observed trends in elliptical galaxy stellar age and metallicity. Half of a typical elliptical galaxy's mass is accreted at $z \lesssim 0.8$, mostly in minor mergers (De Lucia et al. 2006; De Lucia & Blaizot 2007). Recent simulations suggest that several minor mergers can increase R_e by a factor of ~ 3 while only slightly decreasing σ_v (Naab et al. 2009).

By including the merger model in Bolshoi SAMs rather than postprocessing as Porter has done (§2.2), we can also predict environmental effects and compare to observations such as those indicating somewhat greater stellar ages of ellipticals in clusters compared to the field. We will also try to extend our analytic merger model to include the results of our new cosmologically based multi-merger and cold-flow hydrodynamnical simulations. Such analytic treatments are crucial to understand the simulations, as well as to interpolate and extrapolate beyond specific cases simulated. Preliminary attempts at such an analytic understanding (Dekel et al. 2009) are encouraging. That will allow these important galaxy-formation processes to be treated by SAMs, allowing prediction of the properties of the entire evolving galaxy population and comparisons to the growing observational data at higher redshifts to constrain such models.

Porter proposes to improve SAMs also by incorporating Type Ia as well as Type II supernovae, thus allowing us to predict the evolution of galaxy [Mg/H] and [Mg/Fe] as well as [Fe/H] and compare to observations. In addition, with Collaborator Somerville, Porter will further develop the ability to predict galaxy spectra in SAMs, continuing the program of Trager & Somerville (2009). Comparing these spectra directly to observations using the Lick indices will avoid biases inherent in mass-weighted ages and metallicities. Porter's undergraduate senior thesis at Caltech with Andrew Benson was on Galform SAM models of elliptical galaxies, and in addition to the SAM research with Croton and Somerville, Porter and Benson plan to work with Primack on a Galform SAM based on Bolshoi. It will be illuminating to compare the predictions of different SAMs in order to see the effects of the different assumptions they embody regarding gas cooling, star formation, feedback, and dust.

3.3 Comparing improved galaxy merger simulations to observations. We propose to extend our research described in §2.1 in three directions. One is to compare simulated with observed kinematics of stars and globular clusters (GCs) at larger radii; another is to model specific merging systems in order to constrain better the feedback and other uncertain parameters in the simulations. The third program, running cosmological adaptive-mesh hydrodynamic merger simulations, is discussed in §3.4.

Primack's grad student Chris Moody has been working with UCSC observational astronomer

Aaron Romanowsky to compare our simulated binary and multiple merger remnants with the stellar and GC kinematics data on nearby elliptical galaxies being obtained using powerful integral field unit spectrographs and multiobject spectrographs on large telescopes (e.g., Noordermeer et al. 2008). Recent Keck/DEIMOS observations, for example, have not only provided kinematics of many GCs in nearby elliptical galaxies, but the residual starlight has allowed measurement of stellar kinematics to radii $\gtrsim 3R_e$. One galaxy classified as a fast rotator at $r \leq R_e$ is slower rotating and rounder at larger radius; another classified as an elliptical fast rotator at $r \leq R_e$ is more elliptical and an even faster rotator at large radius. Moody is finding that such kinematic decoupling between inner and outer radii is relatively common in both binary and multiple merger remnants, and he is now working to understand the origin of these phenomena in the merging galaxy properties and orbits. Moody is also gearing up to run his own galaxy merger simulations, with Collaborator T. J. Cox, to model specific merger systems.

In addition to IFU studies of early-type galaxies, IFU data are increasingly being obtained for galaxies that appear to be interacting or merging. For example, our Collaborator Jennifer Lotz has obtained such data on nearby galaxies using Sparsepak on the WYN telescope, a French group has obtained such data at $z \sim 0.6$ (Neichel et al. 2008), the DEEP team is obtaining such data using the OSIRIS detector at Keck Observatory, and Genzel's group is obtaining 2D IR spectra using the SINFONI instrument at Paranal Observatory (Genzel et al. 2008). Our group is in a unique position to make theoretical predictions to compare with these observations, including the important effects of dust using the new version of *Sunrise*. This work could be very helpful in clarifying the astrophysics that is operating in these star-forming systems.

3.4 Comparing state-of-the-art galaxy formation simulations to observations. As we discussed in §2.1, Collaborator Klypin's former PhD student Daniel Ceverino, now a postdoc with Co-I Dekel, is using Primack's supercomputer time to perform very high resolution cosmological hydro simulations of galaxy evolution including the gaseous environment. These new simulations not only treat galactic gas inflows and outflows realistically, they also naturally include multiple mergers and cold flows that are likely to form many of the more massive elliptical galaxies at high redshift, as shown for example by the argeement of the simulations in Figure 1 with the observations of the Genzel group. These simulations naturally predict many quantities that can be compared to observations, including the evolution of the star formation rate, metallicity, stellar mass, half-light radius, morphology, and kinematics including velocity dispersion and rotation. For example, we are finding that the central stellar spheroids are rapidly rotating down to $z \sim 1.3$ (as far as these high-resolution hydro simulations have yet run) when formed by merging of star forming clumps from unstable gaseous disks. We have sped up the code significantly, and we are learning how to get it to scale on larger supercomputers. This will allow us to run many galaxy simulations down to $z = 0$, including mergers where the galaxies are continuously resupplied with gas from the filaments in which they reside.

These high-resolution hydro simulations make predictions that can be compared to many of the new observations now becoming possible. For example, the gas flowing along filaments into these forming galaxies converts gravitational potential energy into Lyα radiation (e.g., Dijkstra & Loeb 2009) as shown in Figure 1(d), with luminosity and morphology resembling Lyα blob observations (e.g., Matsuda et al. 2006, 2009). Comparing observed to simulated kinematics could help to discriminate between this galaxy formation scenario in which the gas is infalling vs. starburst models where the gas is outflowing.

We are working with our UCSC Collaborator Mark Krumholz to develop better treatments of feedback below the resolution scale, especially radiative feedback treated using ray-tracing, in order to improve our calculation of the star formation efficiency in mergers and in the star-forming clumps produced by disk instabilities (Figure 1). This may also enable us to explore the origin of globular clusters in forming elliptical galaxies. Primack will work with his student Moody to compare the kinematics and morphology of the simulated galaxies to observations, and with his student Porter to improve SAM treatment of galaxy formation at high redshift.

3.5 Using improved models to interpret observations of AGN in forming galaxies. Current hydrodynamic simulations of AGN in merging galaxies (Hopkins et al. 2008b,a), mostly run by Collaborator T. J. Cox, have suggested that feedback from the rapidly accreting SMBH will clear the merging galaxies of cold gas, shut down star formation, and for a short while uncover the bright AGN before it runs out of gas. This scenario predicts that bright AGNs should be in major mergers of gas-rich galaxies, with the AGN luminosity peaking as the two galaxies' nuclei are merging. In contrast, analysis of the SDSS spectra of nearby galaxies shows that bright AGN typically appear hundreds of Myr after the starburst (Wild et al. 2007), and our analysis (§1,§2.5) of colors and morphology of X-ray emitting galaxies at $z \sim 1$ in the DEEP2 survey shows that they are mostly red-sequence (Nandra et al. 2007; Georgakakis et al. 2008) galaxies with early-type morphologies (Pierce et al. 2007; Pierce 2009), in apparent contradiction to the theoretical model. Data now becoming available at higher redshifts $z \gtrsim 2$ may agree better with the model. However, it remains unclear how SMBHs will be fueled in the multiple overlapping galaxy mergers that will be common at higher redshifts or where the main star formation occurs in clumps fed by cold flows. Primack's grad student Priya Kollipara is working with Daniel Ceverino to run new simulations like that shown in Figure 1, but **now including fueling and feedback from SMBHs** in order to explore these issues. We are assuming that seed black holes exist in the star-forming clumps in unstable disk galaxies, and following the resulting SMBH fueling. Although we do not know how AGN jets couple to the surrounding gas, we do compute energy and momentum transfer from radiative feedback using ray-tracing techniques, working with Collaborator Mark Krumholz. We also plan to include recycled gas from stars as a source of fuel for star formation and AGN fueling (Ciotti & Ostriker 2007).

These simulations can then be compared with multiwavelength data sets, especially those being assembled by the DEEP/AEGIS team, led by our Collaborator Sandra Faber, and those by Genzel's group. The challenge is to develop methods to measure both star formation and SMBH mass growth quantitatively in all stages of galaxy evolution. Primack's grad student Christy Pierce did part of this work in her just-finished dissertation (Pierce 2009), including estimating the effect of AGN on morphologies and colors of galaxies (Pierce et al. 2009). However, much remains to be done to calculate the appearance and spectra of star-forming galaxies including AGN from our new simulations, using our radiation transfer code *Sunrise*, and comparing them to multiwavelength observations. This project will be undertaken by UCSC grad student Priya Kollipara working with Primack and Collaborators Sandra Faber and Patrik Jonsson.

3.6 Understanding the role of cold flows in star formation and quenching. We will further study how efficiently cold flows penetrate through hot halos at high $z \gtrsim 2$ and thus can grow massive disks with high star formation rates even in massive halos. This is expected (Dekel & Birnboim 2006) because M_{shock} is much larger than the typical forming halo mass M_* at $z > 2$, while they are comparable at $z \lesssim 1$. The hypothesis is that rare halos (with $M >> M_*$) at $z > 2$ are fed by narrow, dense dark matter filaments. The gas riding these filaments cools rapidly and avoids the shock heating that occurs elsewhere in the halo. This has been demonstrated in a few simulations (Dekel et al. 2008), but it remains to be seen how common this phenomenon is in higher-resolution cosmological simulations and also whether the observed galaxies thought to exemplify this phenomenon actually have properties similar to those predicted by the simulations.

The properties of elliptical galaxies at $z \lesssim 2$ require a robust quenching of the cold gas supply for star formation above a threshold halo mass $M_{crit} \approx 10^{12} M_\odot$ (Dekel & Birnboim 2006; Croton et al. 2006; Cattaneo et al. 2006, 2008). Heating is also required in order to prevent cooling flows in galaxy clusters. AGN feedback is being considered, by us and others, as the source of quenching. However, as we mentioned above, how AGN feedback couples to the extended halo gas is a difficult open issue. Bright quasars have short duty cycles and cannot provide the required long-term maintanence, and the characteristic halo mass M_{crit} does not seem to emerge from the black hole physics. Gaseous major mergers, suggested as the trigger for quenching via starbursts or quasar activation (Hopkins et al. 2007), also have a hard time explaining the characteristic mass, and it is not clear that their frequency and starburst efficiencies are sufficient (Cox et al. 2008).

We propose to examine in detail using hydrodynamical simulations several alternative quenching mechanisms. One possibility is **gravitational quenching**, in which the gravitational energy associated with cosmological baryon accretion into dark matter halos is the major source maintaining quenching of star formation (Dekel & Birnboim 2008). Analytic calculations and hydrodynamical simulations reveal the existence of a threshold halo mass $M_{shock} \sim 10^{12} M_{\odot}$ for a stable shock at the virial radius (Birnboim & Dekel 2003; Dekel & Birnboim 2006). In smaller halos, rapid cooling prevents the post-shock pressure from suporting the shock against gravitational collapse. The accreted gas flows cold into the inner halo, where it may eventually shock, build a disk, and form stars. When the halo mass grows above M_{shock}, a stable shock rapidly propagates outward toward the virial radius, halting the infalling gas and creating a hot, quasi-static medium at the virial temperature. This is a most natural trigger for quenching star formation in massive galaxies, which may explain the threshold mass and provide the hot gas necessary for *any* quenching mechanism. We propose to pursue a detailed investigation of this process.

An alternative possibility is **morphological quenching**, whereby star formation in galactic disks becomes stabilized against fragmentation into star-forming clumps by the growth of a central stellar spheroid, as shown in Figure 1. In contrast with gravitational quenching and AGN feedback, which are limited to halos of total mass $\gtrsim 10^{12} M_{\odot}$, morphological quenching appears to be able to explain how field ellipticals can become red even in less massive halos. This process also needs to be explored via simulations compared to observations.

4 Broader Goals and Impacts

Our group has a long history of openness, giving access to codes and simulation outputs to researchers interested in performing their own analyses or comparisons. Our *Sunrise* radiation-transfer code is free software, enabling everyone interested to use and modify it for their needs. This will continue to be true for the software and algorithms that will be developed as part of this proposal, to the benefit of the general research community. The development of *Sunrise* has led to a Collaboration between our group and two of the foremost galaxy simulation groups in the U.S., those of Hernquist (CfA) and Governato (U Washington).

We also have a long tradition of collaborating closely with observers, especially our DEEP/AEGIS colleagues. We host a galaxy formation workshop at UCSC each summer attended not only by our group and the DEEP team but also our Collaborators and others. These summer workshops have proven to be extremely productive — they allow us to discuss new data and results, share ideas, and generate new projects. The program for our 2009 workshop includes slides from more than 50 talks.[5] The new University of California systemwide institute on AstroComputing, which Primack will lead starting in January 2010, will host an international school every summer and two research conferences per year, and support education and public outreach efforts.

There have been many opportunities for UCSC undergraduates to work on research projects as

[5] `http://physics.ucsc.edu/SCGW09/SCGF_program.html`

part of senior theses, typically one or two projects every year (Jhirad 2004; Cottrell 2005; Favoloro 2005; Rocha 2006; Davalos 2008; Planta 2009). Miguel Rocha is a Hispanic student who transfered to UCSC from a community college; his senior thesis and subsequent research, supervised by Jonsson and Primack, resulted in a published paper (Rocha et al. 2008). He is currently a graduate student in astrophysics at UC Irvine.

Our research has broadened the opportunities for underrepresented groups. Many of PI Primack's former grad students, including several women, are now leading researchers. Primack's talented grad students for whom support is sought in this proposal are a black woman (Lauren Porter), an Indian-American woman (Priya Kollipara), and a Hispanic man (Christopher Moody).

Primack has also been teaching with Nancy Abrams a popular UCSC undergraduate course on "Cosmology and Culture" for a decade and a half. This led to their popular book, *The View from the Center of the Universe: Discovering Our Extraordinary Place in the Cosmos*, published in the U.S. by Riverhead/Penguin and in the British Commonwealth by HarperCollins (2006), in French, Norwegian, and Portuguese translations (2008), with other translations in progress.[6] Primack developed "Einstein's Rocket" video games to teach key ideas of relativity; a java version is available on the UCSC Physics website.[7] Primack and his colleagues are also collaborating with Chris Henze at NASA Ames, Mark SubbaRao at Adler Planetarium, and Ryan Wyatt at Morrison Planetarium, to make our simulation outputs available to planetariums worldwide; Primack has applied for NASA funding to support these Education and Public Outreach efforts.

Our simulations provide striking illustrations of our research,[8] and have been featured in the NASA Spitzer Science Center video press releases,[9] and were attractions at supercomputing conferences SC04, SC06, and SC09, where they were presented by Primack's students. They were also featured in NERSC's 2004 and NASA Supercomputing Division's 2006 and 2008 Annual Reports. Visualizations of our simulations have been used to illustrate articles in magazines including *Astronomy* and *National Geographic.* A video submitted by Jonsson, Novak, and Primack of one of our galaxy merger simulations was a finalist in the 2008 NSF/Science Magazine Visualization Challenge.

[6] Many reviews and print and broadcast interviews can be found at `http://viewfromthecenter.com` including a list of over 100 popular lectures during 2006-09.

[7] `http://physics.ucsc.edu/~snof/er.html`

[8] `http://sunrise.familjenjonsson.org/coolstuff.html`

[9] "Showcase: Andromeda, Beauty and the Beast" and "Exposing the Exploding Cigar Galaxy" at `http://www.spitzer.caltech.edu/features/hiddenuniverse`.

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Somerville, R. S., Hopkins, P. F., Cox, T. J., Robertson, B. E. & Hernquist, L., 2008b. *A semi-analytic model for the co-evolution of galaxies, black holes and active galactic nuclei.* MNRAS, 391, 481.

Somerville, R. S. & Primack, J. R., 1999. *Semi-analytic modelling of galaxy formation: the local Universe.* MNRAS, 310, 1087.

Somerville, R. S., Primack, J. R. & Faber, S. M., 2001. *The nature of high-redshift galaxies.* MNRAS, 320, 504.

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Springel, V., Di Matteo, T. & Hernquist, L., 2005a. *Black Holes in Galaxy Mergers: The Formation of Red Elliptical Galaxies.* ApJ, 620, L79.

Springel, V., Di Matteo, T. & Hernquist, L., 2005b. *Modelling feedback from stars and black holes in galaxy mergers.* MNRAS, 361, 776.

Springel, V., Frenk, C. S. & White, S. D. M., 2006. *The large-scale structure of the Universe.* Nature, 440, 1137.

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Springel, V. & Hernquist, L., 2005. *Formation of a Spiral Galaxy in a Major Merger.* ApJ, 622, L9.

Springel, V., White, S. D. M., Tormen, G. & Kauffmann, G., 2001. *Populating a cluster of galaxies - I. Results at [formmu2]z=0.* MNRAS, 328, 726.

Trager, S. C. & Somerville, R. S., 2009. *Probing recent star formation with absorption-line strengths in hierarchical models and observations.* MNRAS, 395, 608.

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Vikhlinin, A., Kravtsov, A. V., Burenin, R. A., Ebeling, H., Forman, W. R., Hornstrup, A., Jones, C., Murray, S. S., Nagai, D., Quintana, H. & Voevodkin, A., 2009. *Chandra Cluster Cosmology Project III: Cosmological Parameter Constraints.* ApJ, 692, 1060.

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Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V. & Dekel, A., 2002. *Concentrations of Dark Halos from Their Assembly Histories.* ApJ, 568, 52.

Weil, M. L. & Hernquist, L., 1996. *Global Properties of Multiple Merger Remnants.* ApJ, 460, 101.

Wild, V., Kauffmann, G., Heckman, T., Charlot, S., Lemson, G., Brinchmann, J., Reichard, T. & Pasquali, A., 2007. *Bursty stellar populations and obscured active galactic nuclei in galaxy bulges.* MNRAS, 381, 543.

JOEL R. PRIMACK

Address: Physics Department, University of California, Santa Cruz, CA 95064
Phone: (831) 459-2580 Fax: (831) 459-3043 Email: joel@physics.ucsc.edu

EDUCATION

A.B. Physics, Princeton University, 1966 (Summa cum Laude)
Ph.D. Physics, Stanford University, 1970

PROFESSIONAL EXPERIENCE

1983–present Professor of Physics, UC Santa Cruz
1977–1983 Associate Professor of Physics, UC Santa Cruz
1973–1977 Assistant Professor of Physics, UC Santa Cruz
1970–1973 Junior Fellow, Society of Fellows of Harvard University

HONORS AND AWARDS (partial list)

A. P. Sloan Foundation Research Fellowship, 1974-1978
American Physical Society Forum on Physics and Society Award, 1977; Fellow, 1988
American Association for the Advancement of Science, Fellow, 1995
Humboldt Senior Award of the Alexander von Humboldt Foundation, 1999-2004

SELECTED PUBLICATIONS (* most relevant to this proposal)

GeV gamma-ray attenuation and the high-redshift UV background, by Rudy C. Gilmore, Piero Madau, Joel R. Primack, Rachel S. Somerville, and Francesco Haardt, MNRAS, 399, 1694 (2009).

* Galaxy Merger Morphologies and Time-Scales from Simulations of Equal-Mass Gas-Rich Disk Mergers, J. M. Lotz, P. Jonsson, T. J. Cox, J. R. Primack, MNRAS, 391, 1137 (2008).

* Predicting the Properties of the Remnants of Dissipative Galaxy Mergers, by M. Covington, A. Dekel, T. J. Cox, P. Jonsson, and J. R. Primack, MNRAS, 384, 94 (2008).

* The Effect of Galaxy Mass Ratio on Merger–Driven Starbursts, by T. J. Cox, P. Jonsson, R. S. Somerville, J. R. Primack, and A. Dekel, MNRAS, 384, 386 (2008).

AEGIS: Host Galaxy Morphologies of X-ray and Infrared-selected AGN at $0.2 < z < 1.2$, by C. Pierce, J. M. Lotz, J. R. Primack, et al., ApJ Letters, 660, L19 (2007).

* Simulations of Dust in Interacting Galaxies I: Dust Attenuation, by Patrik Jonsson, T. J. Cox, Joel R. Primack, Rachel S. Somerville, ApJ, 637, 255 (2006).

* Feedback in Simulations of Disk Galaxy Major Mergers, T. J. Cox, Patrik Jonsson, Joel R. Primack, and Rachel S. Somerville, MNRAS, 373, 1013 (2006).

Dark-Matter Haloes in Elliptical Galaxies: Lost and Found, by A. Dekel, F. Stoehr, G.A. Mamon, T.J. Cox, G.S. Novak, & J.R. Primack, Nature, 437, 707 (2005).

* A New Non-Parametric Approach to Galaxy Morphological Classification, Jennifer M. Lotz, Joel Primack, and Piero Madau, AJ, 128, 163-182 (2004).

SYNERGISTIC AND SERVICE ACTIVITIES (partial list)

Advice: SAGENAP advisory panel to DOE/NSF 2000-2001; NSF Astronomy Theory Review Panel 2000; DOE Lehman Review of SNAP Proposal 2001; Chair, NASA Cosmology panel on LTSA and ADP 2001; Cosmology Panel, Hubble Space Telescope Time Allocation Committee 2003; Editorial Board, Journal of Cosmology and Astroparticle Physics 2003-06; National Academy Beyond Einstein panel, 2006-07.

American Physical Society activities: Executive Committee, APS Division of Astrophysics 2000-2002; APS Panel on Public Affairs (POPA) 2002-2004; Chair, POPA Task Force on NASA Moon-Mars Program and Funding for Astrophysics 2004; Chair, APS Forum on Physics and Society 2005

Outreach: Smithsonian National Air and Space Museum, Advisory Committee on "Cosmic Voyage" IMAX film, 1994–1996. Co-organizer, "Cosmic Questions" Conference, Smithsonian National Museum of Natural History, Washington, DC, April 14-16, 1999. Author of several recent articles on cosmology in magazines and encyclopedias. Often give popular lectures at universities, planetariums, museums, and conferences.

Service: Director, University of California Systemwide Institute on AstroComputing, starting January 2010.

Popular teaching: UCSC Freshman Seminar on Cosmology 2002-2004. Cotaught UCSC course Cosmology and Culture offered regularly since 1996, which is the basis for a popular book, *The View from the Center of the Universe* (2006) with several foreign editions in preparation including French, Korean, Norwegian, and Portuguese.

RECENT COLLABORATORS

Bill Atwood, Pauline Barmby, A. A. Berlind, Jean Brodie, Kevin Bundy, Alison Coil, Chris Conselice, Mike Cooper, Marc Davis, Avishai Dekel, Julien Devriendt, Aaron Dutton, David Elbaz, Richard Ellis, Sandra Faber, Andreas Faltenbacher, Henry Ferguson, Ricardo Flores (supervised PhD 1984), Antonis Georgakakis, Mauro Giavalisco, Oleg Gnedin, Stefan Gottloeber, Raja Guhathakurta, S. Gwyn, Francesco Haardt, Jon Holtzman (PhD 1989), J. Huang, Susan Kassin, Anatoly Klypin, David Koo, Andrey Kravtsov, Ofer Lahav, Elise Laird, E. Le Floc'h, Piero Madau, Gary Mamon, Paul Nandra, Jeff Newman, Kai Noeske, Richard Nolthenius, Casey Papovich, S. Q. Park, Manolis Plionis, Cristiano Porciani, Jason Prochaska, George Rieke, Aaron Romanowsky, D. Schiminovich, Felix Stoehr, Volker Springel, Louis Strigari, Wil van Breugel, Maya Vitvitska, Ben Weiner, David Williams, S. P. Willner, and Andrew Zentner, plus the students and postdocs listed below.

Recent postdocs: Tsafrir Kolatt (1996-9), Kelvin Wu (2000), Jennifer Lotz (2002-3), Patrik Jonsson (2004-9).

Recent students: Brandon Allgood (supervised PhD 2005), James Bullock (PhD 1999), Matt Covington (PhD 2008), T. J. Cox (PhD 2004), Rudy Gilmore (PhD 2009), Anthony Gonzalez, Michael Gross (PhD 1997), Priya Kollipara, Michael Kuhlen, Patrik Jonsson (PhD 2004), Ari Maller (PhD 1999), Christopher Moody, Greg Novak (PhD 2008), Christina Pierce (PhD 2009), Lauren Porter, Rachel Somerville (PhD 1997), and Risa Wechsler (PhD 2001). Supervised a total of 10 postdocs, and all or part of the research of 39 graduate students. PhD Advisor: Sidney D. Drell.

CURRICULUM VITA: Avishai Dekel

Address: Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel.

Specialization:

Theoretical physics, astrophysics, cosmology, formation and dynamics of galaxies and large-scale structure in the universe, dark matter, cosmic flows. Teaching physics and astrophysics. Popularization of physics and astrophysics.

Education:

1980: Ph.D., Physics, The Hebrew University of Jerusalem (supervisor: J. Shaham).
1975: B.Sc., Physics and Mathematics, The Hebrew University of Jerusalem.

Positions:

2007-....: Andre Aisenstadt Chair of Theoretical Physics, HU.
1997-2001: Head, Racah Institute of Physics, HU.
1991-....: Professor, The Hebrew University of Jerusalem.
1986-1991: Associate Professor, The Hebrew University of Jerusalem.
1985-1986: Senior Researcher, Weizmann Institute of Science.
1982-1985: Assistant Professor, Yale University.
1980-1982: Research Fellow, California Institute of Technology (supervisor: P. Goldreich).

Five Recent Publications Related to the Proposal:

• Profiles of Dark Haloes: Evolution, Scatter, and Environment; Bullock, J.S., Kolatt, T.S., Sigad, Y., Somerville, R.S., Kravtsov, A.V., Klypin, A.A., Primack, J.R., & Dekel, A. 2001, MNRAS, 321, 559 [980 citations]

• Lost & Found Dark Matter in Elliptical Galaxies; Dekel, A., Stoehr, F., Mamon, G.A., Cox, T.J., Novak, G.S. & Primack, J.R. 2005, Nature, 437, 70 [90 citations]

• Galaxy Bimodality due to Cold Flows and Shock Heating; Dekel, A. & Birnboim, Y. 2006, MNRAS, 368, 2 [240 citations]

• The Effect of Galaxy Mass Ratio on Merger-Driven Starbursts; Cox, T.J., Jonsson, P., Somerville, R.S., Primack, J.R., Dekel, A. 2008, MNRAS, 384, 386 [55 citations]

• Cold streams in early massive hot haloes as the main mode of galaxy formation; Dekel, A., Birnboim, Y., Engel, G., Freundlich, J., Goerdt, T., Mumcuoglu, M., Neistein, E., Pichon, C., Teyssier, R., Zinger, E. 2008, Nature, 457, 451 [75 citations]

Other Significant Relevant Publications:

• The Origin of Dwarf Galaxies, Cold Dark Matter, and Biased Galaxy Formation; Dekel, A. & Silk, J. 1986, ApJ, 303, 39 [1060 citations]

• Physical Mechanisms for Biased Galaxy Formation; Dekel, A. & Rees, M.J. 1987, Nature, 326, 455 [192 citations]

• Dynamics of Cosmic Flows; Dekel, A. 1994, Ann Rev. A&A, 32, 371 [250 citations]

• A Universal Angular-Momentum Profile: Bullock, J.S., Dekel, A., Kolatt, T.S., Kravtsov, A.V., Klypin, A.A., Porciani, C., & Primack, J.R. 2001, ApJ, 555, 240 [280 citations]

• Concentrations of Dark Halos from their Assembly Histories; Wechsler, R.H., Bullock, J.S., Primack, J.R., Kravtsov, A.V., & Dekel, A. 2002, ApJ, 568, 52 [380 citations]

• Star Formation in AEGIS Field Galaxies Since $z = 1.1$; Noeske, K.G., Faber, S.M., Weiner, B.J., Koo, D.C., Primack, J.R., Dekel, A., et al., 2007, ApJL, 660, L47 [80 citations]

• Predicting the Properties of the Remnants of Dissipative Galaxy Mergers; Covington, M., Dekel, A., Cox, T.J., Jonsson, P., Primack, J.R. 2008, MNRAS, 384, 94

• Formation of Massive Galaxies at High Redshift: Cold Streams, Clumpy Disks and Compact Spheroids; Dekel, A., Sari, R., Ceverino, D. 2009, ApJ, 703, 785

Publications: More than 130 articles in refereed journals, 60 invited lectures in scientific conferences, 20 popular articles. A text book. About 10,000 scientific citations. H-factor 53.

Selected Recent Awards and Visiting Positions:

2004-2006:	Blaise Pascal International Chair, Ecole Normale & IAP, Paris
May-Sept. 2004:	Visiting Research Physicist, UC Santa Cruz.
Jan.-April 2004:	Miller Visiting Professor, UC Berkeley.
Every summer 1985-08:	Visiting Research Physicist, UC Santa Cruz.

Synergistic Activities:

• 2008-... Service as the President of the Israel Physics Society

• 2005-... Service as the Dean of the Authority for the Community and Youth at HU, providing advanced science education to 30,000 high-school students every year

• Service as the organizor of a weekly public lecture series "Madua" at HU.

• Organizor of 3 graduate winter schools in cosmology and 4 workshops

Collaborators (last 4 years): Arad, Binney, Birnboim, Blaizot, Bullock, Bournaud, Carollo, Cattaneo, Courteau, Covington, Cox, Dale, Devriendt, Dutton, Engel, Faber, Freinlich, Goerdt, Guiderdoni, Hahn, Hoffman, Jonsson, Klypin, Kravtsov, Lokas, MacArthur, Maller, Mamon, Martig, McIntosh, Mumcouglu, Neistein, Noeske, Novak, Pichon, Porciani, Primack, Sari, Shaviv, Somerville, Stoer, Teyssier, van den Bosch, Wechsler, White, Woo, Zinger.

Junior associates under supervision (last 5 years):

• Postdoctoral Fellows at HU: Arad (01-05), Cattaneo (04-05), Desjaques (05-07), Libeskind (06-08), Birnboim (07-08), Goerdt (07-10), Ceverino (08-11), Cacciato (09-12).

• Completed Ph.D. and M.Sc. (total 11+19): Birnboim (PhD 07), Neistein (PhD 08), Zinger (MSc 05), Woo (MSc 06), Seleson (MSc 06).

Anatoly Klypin

Address: Astronomy Department, New Mexico State University, Las Cruces, NM 88001.
E-mail: aklypin@nmsu.edu Ph: 505-646-1400 Fax: 505-646-1602

Employment: Full Professor, New Mexico State University (2005 - present)
Associate Professor, New Mexico State University (1999 - 2005)
Assistant Professor, New Mexico State University (1994 - 1999)
College Assistant Professor and Tombaugh Fellow at NMSU, (1993-1994)
Research Associate at the University of Kansas: (1992)
Visiting Fellow at the Canadian Institute for Theoretical Astrophysics and
Visiting Associate at the Canadian Institute for Advanced Research: (1991)
Senior Scientist, Lebedev Physical Institute, Moscow: (1989-1990)
Senior Scientist, Space Research Institute, Moscow: (1987-1989)
Junior Scientist, Institute of Applied Mathematics, Moscow: (1980-1987)

Education:

Ph.D in Physics. Institute for Applied Mathematics, Moscow. (1980)
M.S. in Physics, Moscow State University, (1976)

Related Publications

The emptiness of voids: yet another overabundance problem for the cold dark matter model, A.Tikhonov, A. Klypin, MNRAS, 2009, 395, 1915.

The role of stellar feedback in the formation of galaxies, D.Ceverino, A.Klypin, 2009, ApJ, 2009, 695, 292.

Is there Evidence for Flat Cores in the Halos of Dwarf Galaxies?: The Case of NGC 3109 and NGC 6822, Valenzuela, O., Rhee, G., Klypin, A., Governato, F., Stinson, G., Quinn, T., & Wadsley, J., 2007, ApJ, 657, 773

The rotation curves of dwarf galaxies: a problem for Cold Dark Matter?, Rhee, G., Klypin, A., & Valenzuela, O., ApJ, 2004, 617,93.

LCDM-based models for the Milky Way and M31 I: Dynamical Models, Klypin, A., Zhao, H. & Somerville, R.S., ApJ., 2002, 573, 597

Most Cited Publications

Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. "Where Are the Missing Galactic Satellites?", 1999, Astrophys.J., 522, 82 (876 citations)

Bullock, J. S., Kolatt, T. S., Sigad, Y., Somerville, R. S., Kravtsov, A. V., Klypin, A. A., Primack,

J. R., & Dekel, A. 2001, MNRAS, 321, 559 "Profiles of dark haloes: evolution, scatter and environment" (975 citations)

Kravtsov, A., Gnedin. O., Klypin,A. ApJ, 2004, 609, 482 "The Tumultuous Lives of Galactic Dwarfs and the Missing Satellites Problem" (245 citations)

Klypin, A., Holtzman, J., Primack, J., Regos, E., Astrophys.J., 1993, 416, 1 "Structure formation with Cold + Hot dark matter" (218 citations)

List of Recent (4years) collaborators:

J. Bullock (UC Irvine), D. Ceverino (HU, Jerusalem), P. Colin (UNAM, Mexico), A. Dekel (HU, Jerusalem), S. Gottloeber (AIP, Germany), G. Rhee (UNLV), O. Gnedin (Michigan), F. Governato (U.Wash), T. Quinn (U.Wash), Y. Hoffman (HU, Jerusalem), J. Holtzman (NMSU), A. Kravtsov (Chicago), E. Lokas (Warsaw, Poland), V. Mueller (AIP, Germany), F. Prada (Granada, Spain), J. Primack (UCSC), H.-W. Rix (MPIA, Germany), R. Somerville (STSci), O. Valenzuela (UNAM, Mexico), J. Wadsley (McMaster, Canada), R. Wechsler (Stanford), A. Zentner (Pittsburgh), HS. Zhao (St.Andrews, UK)

Synergetic activities

Our group provides images and animations for numerous requests from mass media. Those were used by BBC, Sky and Telescope, National Geographic. Recently we created and now maintain our group website with general public access to many high-quality images and animations; http://astronomy.nmsu.ed/aklypin/CosSim. We made some of our numerical codes available for astronomical community. A.Klypin served 4 times on NSF and NASA review panels.

Organization of conferences and workshops:

Leiden, Netherlands, July 2009 "Distribution of Mass in the Milky Way Galaxy"
Socorro, NM, May 2008 "Galaxies in the cosmic web"
Potsdam, Germany, July 2006, director of Helmholtz-Institute summer school "Supercomputational Cosmology"
Las Vegas, March 2005 "Dynamics of Galaxies: Baryons and Dark Matter"
Madrid, Spain, May 2005 "Cosmology: group workshop"
Granada, Spain, May 2004 "Galaxy Formation: group workshop"
La Palma, Spain, June 2003 "Satellites and tidal streams"
Ruidoso, New Mexico, May 1997 "Clusters of Galaxies at different redshifts"

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION: University of California-Santa Cruz			FOR NSF USE ONLY		
			PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: Joel R Primack			AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Joel R Primack - none	0.00	0.00	0.00	$ 0	$
2. Avishai Dekel - none	1.00	0.00	0.00	13,390	
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (2) TOTAL SENIOR PERSONNEL (1 - 6)	1.00	0.00	0.00	13,390	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (3) GRADUATE STUDENTS				43,547	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				56,937	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				3,074	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				60,011	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				3,500	
2. FOREIGN				0	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 0					
2. TRAVEL 0					
3. SUBSISTENCE 0					
4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				1,800	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				17,788	
TOTAL OTHER DIRECT COSTS				19,588	
H. TOTAL DIRECT COSTS (A THROUGH G)				83,099	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 51.5000, Base: 66311)					
TOTAL INDIRECT COSTS (F&A)				34,150	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				117,249	
K. RESIDUAL FUNDS				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 117,249	$
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME: Joel R Primack	FOR NSF USE ONLY		
	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

1 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI 6969411

SUMMARY PROPOSAL BUDGET

YEAR 2

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
University of California-Santa Cruz

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Joel R Primack

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Joel R Primack - none**	0.00	0.00	0.50	$ **8,801**	$
2. **Avishai Dekel - none**	1.00	0.00	0.00	**13,792**	
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**2**) TOTAL SENIOR PERSONNEL (1 - 6)	1.00	0.00	0.50	**22,593**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**0**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**	
3. (**3**) GRADUATE STUDENTS				**56,201**	
4. (**0**) UNDERGRADUATE STUDENTS				**0**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**78,794**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**4,694**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**83,488**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**5,000**	
2. FOREIGN				**2,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**1,800**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**19,467**	
TOTAL OTHER DIRECT COSTS				**21,267**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**111,755**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **MTDC (Rate: 51.5000, Base: 93288)**					
TOTAL INDIRECT COSTS (F&A)				**48,043**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**159,798**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **159,798**	$

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME	FOR NSF USE ONLY		
Joel R Primack	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI 6969411

SUMMARY PROPOSAL BUDGET

YEAR 3

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
University of California-Santa Cruz

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Joel R Primack

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Joel R Primack - none	0.00	0.00	0.50	$ 9,065	$
2. Avishai Dekel - none	1.00	0.00	0.00	14,205	
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (2) TOTAL SENIOR PERSONNEL (1 - 6)	1.00	0.00	0.50	23,270	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (2) GRADUATE STUDENTS				45,692	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				68,962	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				4,470	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				73,432	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				5,000	
2. FOREIGN				2,000	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				1,800	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				21,313	
TOTAL OTHER DIRECT COSTS				23,113	
H. TOTAL DIRECT COSTS (A THROUGH G)				103,545	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) MTDC (Rate: 51.5000, Base: 83232)					
TOTAL INDIRECT COSTS (F&A)				42,864	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				146,409	
K. RESIDUAL FUNDS				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 146,409	$

M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Joel R Primack

ORG. REP. NAME*

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI 6969411

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION University of California-Santa Cruz				FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR Joel R Primack				AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Joel R Primack - none	0.00	0.00	1.00	$ 17,866	$
2. Avishai Dekel - none	3.00	0.00	0.00	41,387	
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (2) TOTAL SENIOR PERSONNEL (1 - 6)	3.00	0.00	1.00	59,253	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (8) GRADUATE STUDENTS				145,440	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				204,693	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				12,238	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				216,931	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				13,500	
2. FOREIGN				4,000	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				5,400	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				58,568	
TOTAL OTHER DIRECT COSTS				63,968	
H. TOTAL DIRECT COSTS (A THROUGH G)				298,399	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				125,057	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				423,456	
K. RESIDUAL FUNDS				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 423,456	$

M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $		
PI/PD NAME Joel R Primack	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

BUDGET JUSTIFICATION

Salaries and Benefits. Our personnel expenses are mainly support for graduate students whose research is described in the Project Description. This includes summer support plus partial support during the academic year including required fees. (Some of the students will receive partial support from other sources including teaching assistantships.) PI Primack is not requesting summer salary for 2010 and requesting only 1/2 month of summer salary for 2011 and 2012, in order to make this proposal as lean as possible. We request a month per year of summer salary for Co-PI Avishai Dekel.

Dekel, a professor at The Hebrew University of Jerusalem and a Visiting Professor at UCSC, has been engaged in long-term collaborations with Primack, Faber, and all of the other Collaborators. He has visited UCSC for at least a month every year since 1985 – several months per year in recent years. Primack has visited Hebrew University many times, most recently in June 2008. Primack has helped to supervise two of Dekel's graduate students, and Dekel has helped to supervise five of Primack's graduate students. The UCSC Astronomy/Physics graduate courses on cosmology have been co-taught by Primack and Dekel many times, most recently in 2009.

Travel. We are requesting modest travel funds for presentation of our results at domestic and foreign scientific meetings, which is especially important for graduate students, and also partial support for our Collaborators to visit us at UCSC. Every August we have a collaboration meeting at UCSC led by Dekel, Faber, and Primack. All of the Collaborators participate for at least a week, and several of them plan longer visits. We plan to use the funds requested to share travel and lodging expenses with our Collaborators' own grants.

Other Direct Costs. The support we request for page charges is for roughly 15 pages per year (we have actually published more than this in ApJ in recent years). We request only modest computing support for connection charges and maintanence. We run simulations on the 800-processor Pleiades cluster at UCSC and at remote supercomputers, but we analyze many of the outputs at UCSC. We also plan to make these outputs available to the community. These tasks require large storage on our local machines. We presently have 10 Tb of local RAID on our local storage server, and occasionally have to replace the disks.

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION **New Mexico State University**				FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Anatoly A Klypin**				AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)	
1. **Anatoly A Klypin - Professor**	0.00	0.00	1.00	$ **9,274**	$	
2.						
3.						
4.						
5.						
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**		
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	1.00	**9,274**		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (**0**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**0**		
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**		
3. (**1**) GRADUATE STUDENTS				**4,870**		
4. (**0**) UNDERGRADUATE STUDENTS				**0**		
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**		
6. (**0**) OTHER				**0**		
TOTAL SALARIES AND WAGES (A + B)				**14,144**		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**1,811**		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**15,955**		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)						
TOTAL EQUIPMENT				**0**		
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**1,500**		
2. FOREIGN				**2,500**		
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**						
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				**1,000**		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**1,000**		
3. CONSULTANT SERVICES				**0**		
4. COMPUTER SERVICES				**0**		
5. SUBAWARDS				**0**		
6. OTHER				**0**		
TOTAL OTHER DIRECT COSTS				**2,000**		
H. TOTAL DIRECT COSTS (A THROUGH G)				**21,955**		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Total indirect costs (Rate: 45.6000, Base: 21955)**						
TOTAL INDIRECT COSTS (F&A)				**10,011**		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**31,966**		
K. RESIDUAL FUNDS				**0**		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **31,966**	$	
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $					
PI/PD NAME **Anatoly A Klypin**				FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Susan Coker**				Date Checked	Date Of Rate Sheet	Initials - ORG

1 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET

YEAR 2

FOR NSF USE ONLY					
PROPOSAL NO.	DURATION (months) Proposed	Granted			
AWARD NO.					

ORGANIZATION
New Mexico State University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Anatoly A Klypin

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Anatoly A Klypin - Professor	0.00	0.00	1.00	$ 9,274	$
2.					
3.					
4.					
5.					
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	1.00	9,274	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (1) GRADUATE STUDENTS				4,870	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				14,144	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				1,811	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				15,955	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				1,500	
2. FOREIGN				2,500	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 0					
2. TRAVEL 0					
3. SUBSISTENCE 0					
4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				1,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				1,000	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				2,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				21,955	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) Total indirect costs (Rate: 45.6000, Base: 21955)					
TOTAL INDIRECT COSTS (F&A)				10,011	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				31,966	
K. RESIDUAL FUNDS				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 31,966	$

M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $

PI/PD NAME	FOR NSF USE ONLY		
Anatoly A Klypin	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG
Susan Coker			

2 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 3

ORGANIZATION **New Mexico State University**				FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Anatoly A Klypin**				AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Anatoly A Klypin - Professor**	0.00	0.00	1.00	$ **9,274**	$
2.					
3.					
4.					
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**1**) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	1.00	**9,274**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**0**) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	**0**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**	
3. (**1**) GRADUATE STUDENTS				**4,870**	
4. (**0**) UNDERGRADUATE STUDENTS				**0**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**14,144**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**1,811**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**15,955**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**1,500**	
2. FOREIGN				**2,500**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **0**					
TOTAL NUMBER OF PARTICIPANTS (**0**) TOTAL PARTICIPANT COSTS				**0**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**1,000**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**1,000**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**0**	
TOTAL OTHER DIRECT COSTS				**2,000**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**21,955**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Total indirect costs (Rate: 45.6000, Base: 21955)**					
TOTAL INDIRECT COSTS (F&A)				**10,011**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**31,966**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **31,966**	$
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME **Anatoly A Klypin**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME* **Susan Coker**	Date Checked	Date Of Rate Sheet	Initials - ORG

3 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION: **New Mexico State University**			FOR NSF USE ONLY		
			PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Anatoly A Klypin**			AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Anatoly A Klypin - Professor**	0.00	0.00	3.00	$ 27,822	$
2.					
3.					
4.					
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (1) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	3.00	27,822	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (3) GRADUATE STUDENTS				14,610	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				42,432	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				5,433	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				47,865	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				0	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				4,500	
2. FOREIGN				7,500	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 0					
2. TRAVEL 0					
3. SUBSISTENCE 0					
4. OTHER 0					
TOTAL NUMBER OF PARTICIPANTS (0) TOTAL PARTICIPANT COSTS				0	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				3,000	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				3,000	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				0	
TOTAL OTHER DIRECT COSTS				6,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				65,865	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				30,033	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				95,898	
K. RESIDUAL FUNDS				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 95,898	$
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $				

PI/PD NAME: **Anatoly A Klypin**	FOR NSF USE ONLY		
	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*: **Susan Coker**	Date Checked	Date Of Rate Sheet	Initials - ORG

C ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

Budget Justification

Salaries
The budget is for one month summer salary for Anatoly Klypin.

We request summer support for one graduate student.

Fringes
18% is applied to the PI's summer salary and 2.9% to the student's salary

Travel, Domestic
We request funds to attend one US conference for PI per year and for one trip of the graduate student either to a conference or to our collaborators. Exact dates and locations of the conferences cannot be provided because those are announced typically within 1/2 yr before conferences start.

Travel, Foreign
We request funds to attend one international conference for PI per year and for one trip to our collaborators in Germany, Israel, or Spain.

Other Direct Costs
Materials and Supplies - Funds are requested for replacements of failing hardware (hard drives, monitors, power supplies) used for this project and for small miscellaneous item.
Publication Costs/Pages - funds to cover publication costs are also requested.

Facilities and Administration
45.6% is applied to the total direct costs.

JOEL R. PRIMACK: CURRENT AND PENDING SUPPORT

JOEL R. PRIMACK: CURRENT AWARDS 2009

AGENCY	TITLE	DATES	AMOUNT	MONTHS FUNDED & COMMITMENT
NASA ATP NNX07AG94G	Galaxy Interactions and the Formation and Structure of Elliptical Galaxies PI: Primack; Co-I: Dekel; Collaborators: Faber, Jonsson, Lotz, Somerville	2/06/07-2/05/10	$353,601	1 summer month 2007, 08, 09 Commitment: 35% all year
NASA GLAST NNX09AT98G	Modeling Gamma-Ray Attenuation PI: Primack; Co-Is: Madau, Prada	10/1/08-9/30/09	$65,000	½ summer month 2010
UCSC-NASA UARC-ARP NAS2-03144	Simulation and Visualization for Astronomy and Public Education PI: Primack	3/3/09-9/30/10	$50,000	0 funding for PI (just for students)
UC MRPI Multi-Campus Research Unit	University of California High Performance AstroComputing Center PI: Primack; Collaborators: Anninos, Bullock, Faber, Furlanetto, Habib, McKee, Norman, Nugent, Oh, Sprague, Wilson	1/1/10-12/31/14	$350,000 per yr for 4 staff, conferences, summer school, etc.	½ summer month 2010-2014 Commitment: 10% of Academic Yr + ½ summer mo each year

JOEL R. PRIMACK: PENDING AWARDS 2009

AGENCY	TITLE	DATES	AMOUNT	MONTHS FUNDED & COMMITMENT
NSF AST (this proposal)	Collaborative Research: Evolution of Cosmic Structure and of the Population of Galactic Spheroids PI: Primack; Co-I: Dekel; Collaborators: Bullock, Cox, Croton Faber, Jonsson, Klypin, Lotz, Somerville, Wechsler	7/1/10-6/30/13	$423,456	0 month 2010 ½ month 2011, 2012 Commitment: 35% Academic Yr + 1½ summer months each year

AVISHAI DEKEL: CURRENT AND PENDING SUPPORT

AVISHAI DEKEL: CURRENT AWARDS 2009

AGENCY	TITLE	DATES	AMOUNT	MONTHS FUNDED & COMMITMENT
NASA ATP NNX07AG94G	Galaxy Interactions and the Formation and Structure of Elliptical Galaxies PI: Primack; Co-I: Dekel; Collaborators: Faber, Jonsson, Lotz, Somerville	2/06/07-2/05/10	$353,601	1 summer month 2007, 08, 09 Commitment: 25% Acad Yr + 2 mo each summer
Israel Science Foundation	Star Formation and Its Shutdown in Galaxies PI: Dekel	10/1/08-9/30/12	$40,000 per year	no funding for PI (students, postdoc)
German-Israel Science Foundation	Galaxy Formation: Interfacing Theoretical Models with the Observed Universe PIs: Dekel, Nusser, Somerville, White	1/1/07-12/31/09	75,000 Euros per year	no funding for PI (students, postdoc, travel to Europe)
German-Israel Project Cooperation	Dynamics and Cosmological Evolution of Galaxies and Massive Black Holes PI: Sternberg, Co-Is: Alexander, Dekel, Netzer, Maoz, Zucker	1/1/09-12/31/13	200,000 Euros per year	no funding for PI (students, postdoc, travel to Germany, computers)

AVISHAI DEKEL: PENDING AWARDS 2009

AGENCY	TITLE	DATES	AMOUNT	MONTHS FUNDED & COMMITMENT
NSF AST (this proposal)	Collaborative Research: Evolution of Cosmic Structure and of the Population of Galactic Spheroids PI: Primack; Co-I: Dekel; Collaborators: Bullock, Cox, Croton Faber, Jonsson, Klypin, Lotz, Somerville, Wechsler	7/1/10-6/30/13	$423,456	1 summer month 2010, 2011, 2012 Commitment: 25% Academic Yr + 2 summer months each year

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Anatoly Klypin

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Baryons and dark matter in galaxies

Source of Support: NSF AST-0708185

Total Award Amount: $ 201,460 Total Award Period Covered: 09/01/07 - 08/31/10

Location of Project: NMSU

Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Probing the Galaxy-halo/Cosmic Web interface and galaxy evolution

Source of Support: NSF AST-0708210

Total Award Amount: $ 285,679 Total Award Period Covered: 07/01/07 - 06/30/10

Location of Project: NMSU

Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population

Source of Support: NSF AST-0708210

Total Award Amount: $ 95,898 Total Award Period Covered: 07/01/10 - 06/30/13

Location of Project: NMSU

Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Dwarf galaxies: confrontation of theory with data

Source of Support: NSF

Total Award Amount: $ 217,944 Total Award Period Covered: 01/01/00 - 06/30/13

Location of Project: NMSU

Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

FACILITIES, EQUIPMENT & OTHER RESOURCES

FACILITIES: Identify the facilities to be used at each performance site listed and, as appropriate, indicate their capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Use "Other" to describe the facilities at any other performance sites listed and at sites for field studies. USE additional pages as necessary.

Laboratory:

Clinical:

Animal:

Computer: We have plenty of computer power to carry out the proposed research. At UCSC we have Pleiades, a Beowulf-type machine with more than 800 fast processors with 2 Gb ram per processor, which was made possible by a NSF MRI grant for astrophysical computation. As a Co-Investigator on this

Office: PI Primack’s grad students have offices near his on the same floor of the building housing the UCSC Astronomy and Physics Departments.

Other:

MAJOR EQUIPMENT: List the most important items available for this project and, as appropriate identifying the location and pertinent capabilities of each.

OTHER RESOURCES: Provide any information describing the other resources available for the project. Identify support services such as consultant, secretarial, machine shop, and electronics shop, and the extent to which they will be available for the project. Include an explanation of any consortium/contractual arrangements with other organizations.

COMPUTER FACILITIES (continued):

grant, Primack is entitled to at least 700,000 node-hours per year. Primack has for several years also had large allocations on the powerful NASA Ames supercomputers Columbia and Pleiades. We have also worked closely with Chris Henze, director of the Columbia visualization team.
As (an unfunded) PI on the UCSC SCIPP Department of Energy grant, Primack also has access to the powerful NERSC supercomputers at Lawrence Berkeley National Laboratory. We have adequate workstations at UCSC to analyze the outputs from these supercomputer simulations, although we request very modest funds for maintenance and connection fees. Co-I Dekel and Collaborator Klypin have allocations on major supercomputers in Europe.

FACILITIES, EQUIPMENT & OTHER RESOURCES

FACILITIES: Identify the facilities to be used at each performance site listed and, as appropriate, indicate their capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Use "Other" to describe the facilities at any other performance sites listed and at sites for field studies. USE additional pages as necessary.

Laboratory:

Clinical:

Animal:

Computer: Our group at NMSU will use two computer servers for this proposal:
(1) 16-cores, 16Gb Opteron 2.4GHz system with 6TB disk space
(2) 8-cores, 16GB Opteron 2.4GHz system with 2TB disk space

Office: A. Klypin has an office in the Astronomy department at NMSU

Other:

MAJOR EQUIPMENT: List the most important items available for this project and, as appropriate identifying the location and pertinent capabilities of each.

OTHER RESOURCES: Provide any information describing the other resources available for the project. Identify support services such as consultant, secretarial, machine shop, and electronics shop, and the extent to which they will be available for the project. Include an explanation of any consortium/contractual arrangements with other organizations.

UNIVERSITY OF CALIFORNIA

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SCHOOL OF PHYSICAL SCIENCES
DEPARTMENT OF PHYSICS AND ASTRONOMY

IRVINE, CALIFORNIA 92697-4575
4129 FREDERICK REINES HALL
Phone (949) 824-6911

November 9, 2009

Dear Program Officer,

I acknowledge that I am identified by name as Collaborator to the investigation entitled ``Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population" that is being submitted by PI Joel Primack to the National Science Foundation, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Sincerely yours,

James Bullock
Associate Professor
Physics and Astronomy Department
University of California, Irvine

THE OBSERVATORIES

OF THE CARNEGIE INSTITUTION OF WASHINGTON

November 9, 2009

Dear Joel,

I acknowledge that I am identified by name as Collaborator to the investigation entitled ``Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population'' that you are submitting to the National Science Foundation. I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

I am looking forward to a continuation of our productive collaboration over the next years.

Sincerely,

Thomas J. Cox

813 SANTA BARBARA STREET • PASADENA • CALIFORNIA 91101-1232

TELEPHONE 626 577 1122 – FAX 626 795 8136 – www.ociw.edu

Subject: Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population
From: Darren Croton <dcroton@astro.swin.edu.au>
Date: Tue, 10 Nov 2009 17:20:15 -0800
To: Joel Primack <joel@scipp.ucsc.edu>

Dear Joel (and to whom it may concern).

I acknowledge that I am identified by name as Collaborator to the investigation entitled ``Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population" that is being submitted by PI Joel Primack to the National Science Foundation, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Thanks.
Darren

--
Darren Croton
Senior Lecturer
Centre for Astrophysics & Supercomputing
Swinburne University of Technology
PO Box 218, Hawthorn, VIC 3122, Australia
Phone: 61-3-9214-5537; Fax: 61-3-9214-8797
http://astronomy.swin.edu.au/~dcroton

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SANTA BARBARA • SANTA CRUZ

November 6, 2009

To: Astronomy Program Officers, National Science Foundation
Re: Letter of collaboration with Joel Primack

Dear colleagues:

I acknowledge that I am identified by name as Collaborator to the investigation entitled "Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population" that is being submitted by PI Joel Primack to the National Science Foundation, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

My specific role will center on the comparison of theory to observations at many wavelengths from X-ray to infra-red.

Regards,

SM Faber

Sandra M. Faber
University Professor
Astronomer, University of California Observatories
Professor and Chair, Department of Astronomy and Astrophysics, UC Santa Cruz

Subject: Re: please send collaboration letter for NSF proposal
From: Patrik Jonsson <patrik@familjenjonsson.org>
Date: Tue, 10 Nov 2009 15:42:19 -0500
To: Joel Primack <joel@scipp.ucsc.edu>

Dear Joel,

I acknowledge that I am identified by name as Collaborator to the investigation entitled ``Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population" that is being submitted by PI Joel Primack to the National Science Foundation, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Regards,

Patrik Jonsson

UNIVERSITY OF CALIFORNIA, SANTA CRUZ

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DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS
201 INTERDISCIPLINARY SCIENCES BUILDING
SANTA CRUZ, CALIFORNIA 95064

+1 (831) 459-2844
FAX +1 (831) 459-5265

Prof. Mark Krumholz
PHONE: +1 (831) 459-1312
EMAIL: krumholz@ucolick.org

November 9, 2009

Prof. Joel Primack
Physics Department
UC Santa Cruz

Dear Professor Primack,

I acknowledge that I am identified by name as Collaborator to the investigation entitled "Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population" that is being submitted by PI Joel Primack to the National Science Foundation, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. My role in the proposal will be to aid in improving the models for star formation, star formation feedback, and black hole feedback that are used in the galaxy formation simulations. The single largest focus will be on adding radiative feedback.

Sincerely,

Mark Krumholz

NOAO
National Optical Astronomy Observatory
Kitt Peak National Observatory • Cerro Tololo Inter-American Observatory • NOAO Gemini Science Center

National Science Foundation
4201 Wilson Boulevard
Arlington, VA 22230

November 15, 2009

To Whom It May Concern:

I acknowledge that I am identified by name as a Collaborator to the investigation entitled "Evolution of Cosmic Structure and of the Galactic Spheroid Population" that is being submitted by PI Joel Primack to the National Science Foundation, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

I plan to use the high resolution numerical simulations discussed in this proposal to better understand the structural signatures and timescales of galaxy mergers. Working with Joel and the other collaborators on this proposal, I will then use these results combined with the statistical distributions of galaxy mergers from the superior merger trees of the Bolshoi cosmological simulation to make theoretical predictions about the distribution of galaxy merger structures, spectral properties, and kinematics that can be directly compared to observations. This work is timely, given that surveys by HST WFC3 and Herschel will soon observe the epoch of spheroid assembly at z~2 in great detail. Interpreting these observations and disentangling the role of mergers and gas accretion in spheroid assembly will require the theoretical work that we propose.

Sincerely,

Dr. Jennifer M. Lotz

Jennifer M. Lotz

Leo Goldberg Fellow
NOAO
950 N. Cherry Ave.
Tucson, AZ 8571

Subject: letter of collaboration
From: rachel somerville <somer@stsci.edu>
Date: Mon, 09 Nov 2009 11:57:17 -0500
To: Joel Primack <joel@scipp.ucsc.edu>

Dear Joel,

I acknowledge that I am identified by name as Collaborator to the investigation entitled ``Collaborative Research: Evolution of Cosmic Structure and of the Galactic Spheroid Population" that is being submitted by PI Joel Primack to the National Science Foundation, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Best Regards,

rachel somerville

Associate Astronomer, STScI
Associate Research Professor, Johns Hopkins University

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-+
dr. rachel somerville somerville@stsci.edu
Archive Sciences Branch tel: 410-338-4893
Space Telescope Science Institute fax: 410-338-5088
-+