Cover Page for Proposal Submitted to the National Aeronautics and Space Administration

NASA Proposal Number

10-ATP10-0120

NASA PROCEDURE FOR HANDLING PROPOSALS

SECTION I - Proposal Information

Principal Investigator	E-mail Address	Phone Number
Joel Primack	joel@scipp.ucsc.edu	831-459-2580

Street Address (1)	Street Address (2)
1156 High St	Physics Department

City	State / Province	Postal Code	Country Code
Santa Cruz	CA	95064-1077	US

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

Proposed Start Date	Proposed End Date	Total Budget	Year 1 Budget	Year 2 Budget	Year 3 Budget	Year 4 Budget
01 / 01 / 2011	12 / 31 / 2013	510,487.00	167,153.00	178,184.00	165,150.00	0.00

SECTION II - Application Information

NASA Program Announcement Number	NASA Program Announcement Title
NNH10ZDA001N-ATP	Astrophysics Theory

For Consideration By NASA Organization *(the soliciting organization, or the organization to which an unsolicited proposal is submitted)*
NASA , Headquarters , Science Mission Directorate , Astrophysics

Date Submitted	Submission Method	Grants.gov Application Identifier	Applicant Proposal Identifier
06 / 04 / 2010	Electronic Submission Only		

Type of Application	Predecessor Award Number	Other Federal Agencies to Which Proposal Has Been Submitted
New		

International Participation	Type of International Participation
No	

SECTION III - Submitting Organization Information

DUNS Number	CAGE Code	Employer Identification Number (EIN or TIN)	Organization Type
125084723	1CV82	941539563	2A

Organization Name (Standard/Legal Name)	Company Division
University Of California, Santa Cruz	

Organization DBA Name	Division Number
CHANCELLOR'S OFFICE	

Street Address (1)	Street Address (2)
1156 HIGH ST	

City	State / Province	Postal Code	Country Code
SANTA CRUZ	CA	950641077	USA

SECTION IV - Proposal Point of Contact Information

Name	Email Address	Phone Number
Joel Primack	joel@scipp.ucsc.edu	831-459-2580

SECTION V - Certification and Authorization

Certification of Compliance with Applicable Executive Orders and U.S. Code

By submitting the proposal identified in the Cover Sheet/Proposal Summary in response to this Research Announcement, the Authorizing Official of the proposing organization (or the individual proposer if there is no proposing organization) as identified below:

- certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in the two Certifications and one Assurance contained in this NRA (namely, (i) the Assurance of Compliance with the NASA Regulations Pursuant to Nondiscrimination in Federally Assisted Programs, and (ii) Certifications, Disclosures, and Assurances Regarding Lobbying and Debarment and Suspension.

Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

Authorized Organizational Representative (AOR) Name	AOR E-mail Address	Phone Number
Riley Jordan	riajorda@ucsc.edu	831-459-2639

AOR Signature *(Must have AOR's original signature. Do not sign "for" AOR.)* **Date**

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION VI - Team Members

Team Member Role	Team Member Name	Contact Phone	E-mail Address
PI	**Joel Primack**	**831-459-2580**	**joel@scipp.ucsc.edu**
Organization/Business Relationship: **University Of California, Santa Cruz**		Cage Code: **1CV82**	DUNS#: **125084723**
International Participation: **No**	U.S. Government Agency:		Total Funds Requested: **0.00**
Co-I	**Avishai Dekel**	**972-2-6584100**	**dekel@phys.huji.ac.il**
Organization/Business Relationship: **University of California, Santa Cruz**		Cage Code: **N/A**	DUNS#: **N/A**
International Participation: **No**	U.S. Government Agency:		Total Funds Requested: **0.00**
Co-I	**Anatoly Klypin**	**505-646-1400**	**aklypin@nmsu.edu**
Organization/Business Relationship: **NEW MEXICO STATE UNIVERSITY**		Cage Code: **3X352**	DUNS#: **173851965**
International Participation: **No**	U.S. Government Agency:		Total Funds Requested: **0.00**
Collaborator	**James Bullock**	**949-824-7727**	**bullock@uci.edu**
Organization/Business Relationship: **University Of California, Irvine**		Cage Code: **0VWL0**	DUNS#: **046705849**
International Participation: **No**	U.S. Government Agency:		Total Funds Requested: **0.00**
Collaborator	**Thomas Cox**	**626-304-0284**	**tcox@obs.carnegiescience.edu**
Organization/Business Relationship: **Carnegie Institution Of Washington**		Cage Code: **4B564**	DUNS#: **072641707**
International Participation: **No**	U.S. Government Agency:		Total Funds Requested: **0.00**
Collaborator	**Sandra Faber**	**831-459-2944**	**faber@ucolick.org**
Organization/Business Relationship: **University Of California, Santa Cruz**		Cage Code: **1CV82**	DUNS#: **125084723**
International Participation: **No**	U.S. Government Agency:		Total Funds Requested: **0.00**
Collaborator	**Patrik Jonsson**	**775-572-8745**	**pjonsson@cfa.harvard.edu**
Organization/Business Relationship: **Smithsonian Institution/Smithsonian Astrophysical Observatory**		Cage Code: **1PPP1**	DUNS#: **003261823**
International Participation: **No**	U.S. Government Agency:		Total Funds Requested: **0.00**
Collaborator	**Mark Krumholz**	**510-761-2929**	**krumholz@ucolick.org**
Organization/Business Relationship: **University Of California, Santa Cruz**		Cage Code: **1CV82**	DUNS#: **125084723**
International Participation: **No**	U.S. Government Agency:		Total Funds Requested: **0.00**

Team Member Role **Collaborator**	Team Member Name **Jennifer Lotz**	Contact Phone **520-318-8223**	E-mail Address **lotz@noao.edu**
Organization/Business Relationship **Association Of Universities For Research In Astronomy, Inc.**		Cage Code **8X292**	DUNS# **057905887**
International Participation **No**	U.S. Government Agency		Total Funds Requested **0.00**
Team Member Role **Collaborator**	Team Member Name **rachel somerville**	Contact Phone **410-338-4893**	E-mail Address **somerville@stsci.edu**
Organization/Business Relationship **Space Telescope Science Institute**		Cage Code **4X357**	DUNS# **101460871**
International Participation **No**	U.S. Government Agency		Total Funds Requested **0.00**
Team Member Role **Collaborator**	Team Member Name **Alexander Szalay**	Contact Phone **410-516-7217**	E-mail Address **szalay@pha.jhu.edu**
Organization/Business Relationship **Johns Hopkins University**		Cage Code **5L406**	DUNS# **001910777**
International Participation **No**	U.S. Government Agency		Total Funds Requested **0.00**
Team Member Role **Collaborator**	Team Member Name **Risa Wechsler**	Contact Phone **650-704-6932**	E-mail Address **rwechsler@stanford.edu**
Organization/Business Relationship **Stanford University**		Cage Code **1KN27**	DUNS# **009214214**
International Participation **No**	U.S. Government Agency		Total Funds Requested **0.00**

PI Name : **Joel Primack**	**NASA Proposal Number**
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION VII - Project Summary

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 address 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 supermassive black holes. We compare our detailed models of early-type galaxy formation with observations both of ongoing galaxy mergers and other galaxy formation processes and of nearby galaxies whose properties can be studied in detail.

This research is supported by a large program of computer simulations. These include our new cosmological Bolshoi dissipationless simulation and follow-on simulations, starting from current cosmological parameters and with high mass and spatial resolution in order to establish the LCDM gravitational backbone of structure formation, clarify dark matter halo properties, and support improved semi-analytic models. 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. This allows us 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.

This research supports NASA's goal of discovering the structure and evolution of the universe, and it is relevant to interpreting observations by NASA missions including Hubble, Spitzer, Chandra, and Fermi, and to preparing for future missions including JWST. Broader goals of this research include teaching students and involving them in our research, improving 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.

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION VIII - Other Project Information

Proprietary Information

Is proprietary/privileged information included in this application?
Yes

International Collaboration

Does this project involve activities outside the U.S. or partnership with International Collaborators?
No

Principal Investigator	Co-Investigator	Collaborator	Equipment	Facilities
No	**No**	**No**	**No**	**No**

Explanation :

NASA Civil Servant Project Personnel

Are NASA civil servant personnel participating as team members on this project (include funded and unfunded)?
No

Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year
Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs

PI Name : **Joel Primack**	**NASA Proposal Number**
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION VIII - Other Project Information

Environmental Impact

Does this project have an actual or potential impact on the environment? **No**	Has an exemption been authorized or an environmental assessment (EA) or an environmental impact statement (EIS) been performed? **No**

Environmental Impact Explanation:

Exemption/EA/EIS Explanation:

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION VIII - Other Project Information

Historical Site/Object Impact

Does this project have the potential to affect historic, archeological, or traditional cultural sites (such as Native American burial or ceremonial grounds) or historic objects (such as an historic aircraft or spacecraft)?

No

Explanation:

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION IX - Program Specific Data

Question 1 : Short Title:

Answer: Formation of Cosmic Structure and Galaxies

Question 2 : Type of institution:

Answer: Educational Organization

Question 3 : Will any funding be provided to a federal government organization including NASA Centers, JPL, other Federal agencies, government laboratories, or Federally Funded Research and Development Centers (FFRDCs)?

Answer: No

Question 4 : Is this Federal government organization a different organization from the proposing (PI) organization?

Answer: N/A

Question 5 : Does this proposal include the use of NASA-provided high end computing?

Answer: Yes

Question 6 : Research Category:

Answer: 1) Theory/computer modeling

Question 7 : Team Members Missing From Cover Page:

Answer:

Question 8 : This proposal contains information and/or data that are subject to U.S. export control laws and regulations including Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR).

Answer: No

Question 9 : I have identified the export-controlled material in this proposal.

Answer: N/A

Question 10 : I acknowledge that the inclusion of such material in this proposal may complicate the government's ability to evaluate the proposal.

Answer: N/A

Question 11 : Topic Category:

Answers :

Large Scale Cosmic Structures and Dark Matter

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Cumulative Budget

Budget Cost Category	Funds Requested ($)				
	Year 1 ($)	Year 2 ($)	Year 3 ($)	Year 4 ($)	Total Project ($)
A. Direct Labor - Key Personnel	36,662.00	37,763.00	38,896.00	0.00	113,321.00
B. Direct Labor - Other Personnel	56,138.00	57,822.00	46,996.00	0.00	160,956.00
Total Number Other Personnel	2	3	32	0	37
Total Direct Labor Costs (A+B)	92,800.00	95,585.00	85,892.00	0.00	274,277.00
C. Direct Costs - Equipment	0.00	0.00	0.00	0.00	0.00
D. Direct Costs - Travel	3,500.00	7,000.00	7,000.00	0.00	17,500.00
Domestic Travel	3,500.00	5,000.00	5,000.00	0.00	13,500.00
Foreign Travel	0.00	2,000.00	2,000.00	0.00	4,000.00
E. Direct Costs - Participant/Trainee Support Costs	0.00	0.00	0.00	0.00	0.00
Tuition/Fees/Health Insurance	0.00	0.00	0.00	0.00	0.00
Stipends	0.00	0.00	0.00	0.00	0.00
Travel	0.00	0.00	0.00	0.00	0.00
Subsistence	0.00	0.00	0.00	0.00	0.00
Other	0.00	0.00	0.00	0.00	0.00
Number of Participants/Trainees					0
F. Other Direct Costs	19,816.00	21,326.00	22,977.00	0.00	64,119.00
Materials and Supplies	0.00	0.00	0.00	0.00	0.00
Publication Costs	1,800.00	1,800.00	1,800.00	0.00	5,400.00
Consultant Services	0.00	0.00	0.00	0.00	0.00
ADP/Computer Services	0.00	0.00	0.00	0.00	0.00
Subawards/Consortium/Contractual Costs	0.00	0.00	0.00	0.00	0.00
Equipment or Facility Rental/User Fees	0.00	0.00	0.00	0.00	0.00
Alterations and Renovations	0.00	0.00	0.00	0.00	0.00
Other	18,016.00	19,526.00	21,177.00	0.00	58,719.00
G. Total Direct Costs (A+B+C+D+E+F)	116,116.00	123,911.00	115,869.00	0.00	355,896.00
H. Indirect Costs	51,037.00	54,273.00	49,281.00	0.00	154,591.00
I. Total Direct and Indirect Costs (G+H)	167,153.00	178,184.00	165,150.00	0.00	510,487.00
J. Fee	0.00	0.00	0.00	0.00	0.00
K. Total Cost (I+J)	167,153.00	178,184.00	165,150.00	0.00	510,487.00
Total Cumulative Budget					510,487.00

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
01 / 01 / 2011	**12 / 31 / 2011**	**Project**	**1**

A. Direct Labor - Key Personnel

Name	Project Role	Base Salary ($)	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
Primack, Joel	PI	0.00			.5	8,544.00	1,153.00	9,697.00
Dekel, Avishai	CO-I	0.00	1			13,390.00	1,875.00	15,265.00
Klypin, Anatoly	CO-I	0.00	1			10,000.00	1,700.00	11,700.00
							Total Key Personnel Costs	36,662.00

B. Direct Labor - Other Personnel

Number of Personnel	Project Role	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
2	Graduate Students		6	6	54,607.00	1,531.00	56,138.00
2	Total Number Other Personnel					Total Other Personnel Costs	56,138.00
						Total Direct Labor Costs (Salary, Wages, Fringe Benefits) (A+B)	92,800.00

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
01 / 01 / 2011	**12 / 31 / 2011**	**Project**	**1**

C. Direct Costs - Equipment

Item No.	Equipment Item Description	Funds Requested ($)
	Total Equipment Costs	**0.00**

D. Direct Costs - Travel

	Funds Requested ($)
1. Domestic Travel (Including Canada, Mexico, and U.S. Possessions)	**3,500.00**
2. Foreign Travel	**0.00**
Total Travel Costs	**3,500.00**

E. Direct Costs - Participant/Trainee Support Costs

		Funds Requested ($)
1. Tuition/Fees/Health Insurance		**0.00**
2. Stipends		**0.00**
3. Travel		**0.00**
4. Subsistence		**0.00**
Number of Participants/Trainees:	**Total Participant/Trainee Support Costs**	**0.00**

PI Name : **Joel Primack**	**NASA Proposal Number**
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
01 / 01 / 2011	**12 / 31 / 2011**	**Project**	**1**

F. Other Direct Costs

	Funds Requested ($)
1. Materials and Supplies	0.00
2. Publication Costs	1,800.00
3. Consultant Services	0.00
4. ADP/Computer Services	0.00
5. Subawards/Consortium/Contractual Costs	0.00
6. Equipment or Facility Rental/User Fees	0.00
7. Alterations and Renovations	0.00
8 . Other: **Gship and fees**	17,016.00
9 . Other: **Computer access and maintenance**	1,000.00
Total Other Direct Costs	19,816.00

G. Total Direct Costs

	Funds Requested ($)
Total Direct Costs (A+B+C+D+E+F)	116,116.00

H. Indirect Costs

	Indirect Cost Rate (%)	Indirect Cost Base ($)	Funds Requested ($)
MTDC	51.50	99,100.00	51,037.00
Cognizant Federal Agency: **Wallace Chan on behalf of the Federal Government 415-437-7820**	**Total Indirect Costs**		51,037.00

I. Direct and Indirect Costs

	Funds Requested ($)
Total Direct and Indirect Costs (G+H)	167,153.00

J. Fee

	Funds Requested ($)
Fee	0.00

K. Total Cost

	Funds Requested ($)
Total Cost with Fee (I+J)	167,153.00

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
01 / 01 / 2012	**12 / 31 / 2012**	**Project**	**2**

A. Direct Labor - Key Personnel

Name	Project Role	Base Salary ($)	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
Primack, Joel	PI	0.00			.5	8,801.00	1,188.00	9,989.00
Dekel, Avishai	CO-I	0.00	1			13,792.00	1,931.00	15,723.00
Klypin, Anatoly	CO-I	0.00	1			10,300.00	1,751.00	12,051.00
							Total Key Personnel Costs	37,763.00

B. Direct Labor - Other Personnel

Number of Personnel	Project Role	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
3	Graduate Students		6	9	56,246.00	1,576.00	57,822.00
3	Total Number Other Personnel					Total Other Personnel Costs	57,822.00

Total Direct Labor Costs (Salary, Wages, Fringe Benefits) (A+B)	95,585.00

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
01 / 01 / 2012	**12 / 31 / 2012**	**Project**	**2**

C. Direct Costs - Equipment

Item No.	Equipment Item Description	Funds Requested ($)
	Total Equipment Costs	**0.00**

D. Direct Costs - Travel

	Funds Requested ($)
1. Domestic Travel (Including Canada, Mexico, and U.S. Possessions)	**5,000.00**
2. Foreign Travel	**2,000.00**
Total Travel Costs	**7,000.00**

E. Direct Costs - Participant/Trainee Support Costs

		Funds Requested ($)
1. Tuition/Fees/Health Insurance		**0.00**
2. Stipends		**0.00**
3. Travel		**0.00**
4. Subsistence		**0.00**
Number of Participants/Trainees:	**Total Participant/Trainee Support Costs**	**0.00**

PI Name : **Joel Primack**	**NASA Proposal Number**
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
01 / 01 / 2012	**12 / 31 / 2012**	**Project**	**2**

F. Other Direct Costs

	Funds Requested ($)
1. Materials and Supplies	0.00
2. Publication Costs	1,800.00
3. Consultant Services	0.00
4. ADP/Computer Services	0.00
5. Subawards/Consortium/Contractual Costs	0.00
6. Equipment or Facility Rental/User Fees	0.00
7. Alterations and Renovations	0.00
8 . Other: **Gship and fees**	18,526.00
9 . Other: **Computer access and maintenance**	1,000.00
Total Other Direct Costs	21,326.00

G. Total Direct Costs

	Funds Requested ($)
Total Direct Costs (A+B+C+D+E+F)	123,911.00

H. Indirect Costs

	Indirect Cost Rate (%)	Indirect Cost Base ($)	Funds Requested ($)
MTDC	51.50	105,385.00	54,273.00
Cognizant Federal Agency: **Wallace Chan on behalf of the Federal Government 415-437-7820**	**Total Indirect Costs**		54,273.00

I. Direct and Indirect Costs

	Funds Requested ($)
Total Direct and Indirect Costs (G+H)	178,184.00

J. Fee

	Funds Requested ($)
Fee	0.00

K. Total Cost

	Funds Requested ($)
Total Cost with Fee (I+J)	178,184.00

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
01 / 01 / 2013	**12 / 31 / 2013**	**Project**	**3**

A. Direct Labor - Key Personnel

Name	Project Role	Base Salary ($)	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
Primack, Joel	PI	0.00			.5	9,065.00	1,224.00	10,289.00
Dekel, Avishai	CO-I	0.00	1			14,205.00	1,989.00	16,194.00
Klypin, Anatoly	CO-I	0.00	1			10,609.00	1,804.00	12,413.00
							Total Key Personnel Costs	38,896.00

B. Direct Labor - Other Personnel

Number of Personnel	Project Role	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
32	Graduate Students		6	3	45,738.00	1,258.00	46,996.00
32	Total Number Other Personnel					Total Other Personnel Costs	46,996.00

Total Direct Labor Costs (Salary, Wages, Fringe Benefits) (A+B)	85,892.00

PI Name : **Joel Primack**	**NASA Proposal Number**
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
01 / 01 / 2013	**12 / 31 / 2013**	**Project**	**3**

C. Direct Costs - Equipment

Item No.	Equipment Item Description	Funds Requested ($)
	Total Equipment Costs	**0.00**

D. Direct Costs - Travel

	Funds Requested ($)
1. Domestic Travel (Including Canada, Mexico, and U.S. Possessions)	**5,000.00**
2. Foreign Travel	**2,000.00**
Total Travel Costs	**7,000.00**

E. Direct Costs - Participant/Trainee Support Costs

		Funds Requested ($)
1. Tuition/Fees/Health Insurance		**0.00**
2. Stipends		**0.00**
3. Travel		**0.00**
4. Subsistence		**0.00**
Number of Participants/Trainees:	**Total Participant/Trainee Support Costs**	**0.00**

PI Name : **Joel Primack**	**NASA Proposal Number**
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
01 / 01 / 2013	**12 / 31 / 2013**	**Project**	**3**

F. Other Direct Costs

	Funds Requested ($)
1. Materials and Supplies	0.00
2. Publication Costs	1,800.00
3. Consultant Services	0.00
4. ADP/Computer Services	0.00
5. Subawards/Consortium/Contractual Costs	0.00
6. Equipment or Facility Rental/User Fees	0.00
7. Alterations and Renovations	0.00
8 . Other: **Gship and fees**	20,177.00
9 . Other: **Computer access and maintenance**	1,000.00
Total Other Direct Costs	22,977.00

G. Total Direct Costs

	Funds Requested ($)
Total Direct Costs (A+B+C+D+E+F)	115,869.00

H. Indirect Costs

	Indirect Cost Rate (%)	Indirect Cost Base ($)	Funds Requested ($)
MTDC	51.50	95,692.00	49,281.00
Cognizant Federal Agency: **Wallace Chan on behalf of the Federal Government 415-437-7820**	**Total Indirect Costs**		49,281.00

I. Direct and Indirect Costs

	Funds Requested ($)
Total Direct and Indirect Costs (G+H)	165,150.00

J. Fee

	Funds Requested ($)
Fee	0.00

K. Total Cost

	Funds Requested ($)
Total Cost with Fee (I+J)	165,150.00

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
		Project	**4**

A. Direct Labor - Key Personnel

Name	Project Role	Base Salary ($)	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
Primack, Joel	**PI**	**0.00**				**0.00**	**0.00**	**0.00**
							Total Key Personnel Costs	**0.00**

B. Direct Labor - Other Personnel

Number of Personnel	Project Role	Cal. Months	Acad. Months	Summ. Months	Requested Salary ($)	Fringe Benefits ($)	Funds Requested ($)
0	Total Number Other Personnel					Total Other Personnel Costs	**0.00**
						Total Direct Labor Costs (Salary, Wages, Fringe Benefits) (A+B)	**0.00**

PI Name : **Joel Primack**	NASA Proposal Number
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type : **Project**	Budget Period : **4**

C. Direct Costs - Equipment

Item No.	Equipment Item Description	Funds Requested ($)
	Total Equipment Costs	**0.00**

D. Direct Costs - Travel

	Funds Requested ($)
1. Domestic Travel (Including Canada, Mexico, and U.S. Possessions)	**0.00**
2. Foreign Travel	**0.00**
Total Travel Costs	**0.00**

E. Direct Costs - Participant/Trainee Support Costs

		Funds Requested ($)
1. Tuition/Fees/Health Insurance		**0.00**
2. Stipends		**0.00**
3. Travel		**0.00**
4. Subsistence		**0.00**
Number of Participants/Trainees:	**Total Participant/Trainee Support Costs**	**0.00**

PI Name : **Joel Primack**	**NASA Proposal Number**
Organization Name : **University Of California, Santa Cruz**	**10-ATP10-0120**

Proposal Title : **Evolution of Cosmic Structure and Galaxies**

SECTION X - Budget

Start Date :	End Date :	Budget Type :	Budget Period :
		Project	**4**

F. Other Direct Costs

	Funds Requested ($)
1. Materials and Supplies	0.00
2. Publication Costs	0.00
3. Consultant Services	0.00
4. ADP/Computer Services	0.00
5. Subawards/Consortium/Contractual Costs	0.00
6. Equipment or Facility Rental/User Fees	0.00
7. Alterations and Renovations	0.00
Total Other Direct Costs	0.00

G. Total Direct Costs

	Funds Requested ($)
Total Direct Costs (A+B+C+D+E+F)	0.00

H. Indirect Costs

	Indirect Cost Rate (%)	Indirect Cost Base ($)	Funds Requested ($)
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
Cognizant Federal Agency:	**Total Indirect Costs**		0.00

I. Direct and Indirect Costs

	Funds Requested ($)
Total Direct and Indirect Costs (G+H)	0.00

J. Fee

	Funds Requested ($)
Fee	0.00

K. Total Cost

	Funds Requested ($)
Total Cost with Fee (I+J)	0.00

Evolution of Cosmic Structure and Galaxies

PI: Joel Primack, Co-Is: Avishai Dekel and Anatoly Klypin
Collaborators: James Bullock, T. J. Cox, Sandra Faber, Patrik Jonsson, Mark Krumholz, Jennifer Lotz, Rachel Somerville, Alex Szalay, and Risa Wechsler

Table of Contents

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; Primack 2009c; Komatsu et al. 2010), 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 WMAP3 analysis (Spergel et al. 2007) $\sigma_8 \approx 0.75$, in the WMAP5 analysis (Komatsu et al. 2009) $\sigma_8 = 0.817 \pm 0.026$, and in the WMAP7 analysis (Komatsu et al. 2010) the nearly identical $\sigma_8 = 0.809 \pm 0.024$, 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 (Klypin et al. 2010)[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 and new follow-on simulations with even higher resolution 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. 2009) 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 camera 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

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

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, 2010a,b) suggests that 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 §2.1), 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 (e.g., 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). Our hydro-ART AMR code (as opposed to the more common SPH) permits zoom-in simulations with unprecedented resolution, and allows us to resolve the cold streams feeding galactic disks. 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 (Dekel et al. 2008, 2009; Ceverino et al. 2009). 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 this 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 (e.g., 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 two multiple AGN and more than 30 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, although other interpretations of the data are possible (Rosario et al. 2010).

A different mechanism must be responsible for quenching star formation over longer periods. Heating of the IGM by sustained low-level AGN activity (called "radio-mode" AGN feedback by 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 $10^{12}\,\mathrm{M}_\odot$ 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 (Treister et al. 2010). 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 the wavelength coverage of large galaxy surveys has been 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 CANDELS and DEEP3 surveys. The Herschel space telescope will extend wavelength coverage at far-infrared wavelengths out to redshifts around 2, and ALMA out to the epoch of reionization.

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 theoretical support for the DEEP3, AEGIS, and CANDELS 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, cold 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 developing "toy models" that capture key elements of complex processes, and 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 our management plan and the broader goals and impacts of our research in §4.

2 Our Recent and Current Work, and Proposed Continuations

This section describes our recent research, 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 GADGET hydrodynamic simulations of binary galaxy encounters, including star formation and supernova feedback, with a spatial resolution of $\sim 100\,\mathrm{pc}$ and a mass resolution of $\sim 10^6\,\mathrm{M}_\odot$. In our simulations, progenitor galaxies 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.

Both as Primack's PhD student and during his subsequent postdocs at Harvard and now Carnegie Observatories, our continuing Collaborator **T. J. Cox** has run 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 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. These simulated galaxy merger images and associated data products are the first theoretical data to be included in the Multimission Archive at STScI (MAST).[2] We "observe" these outputs as observers do real galaxies, including redshifting and seeing effects, and analyze the resulting images morphologically using several analysis tools. In work led by Collaborator **Jennifer Lotz**, 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. 2008b, 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 $z \sim 1$. Continuing this to higher redshifts (§3.3-6) is essential in order to determine the role of mergers vs. other mechanisms in forming early-type galaxies.

We are comparing many properties of the merger remnants with observations of elliptical galaxies. 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 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 (Novak 2008)[3] and found that the stellar minor axis and the halo major axis are almost always close to perpendicular.

[2] http://archive.stsci.edu/prepds/diggss/index.html?print=1

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

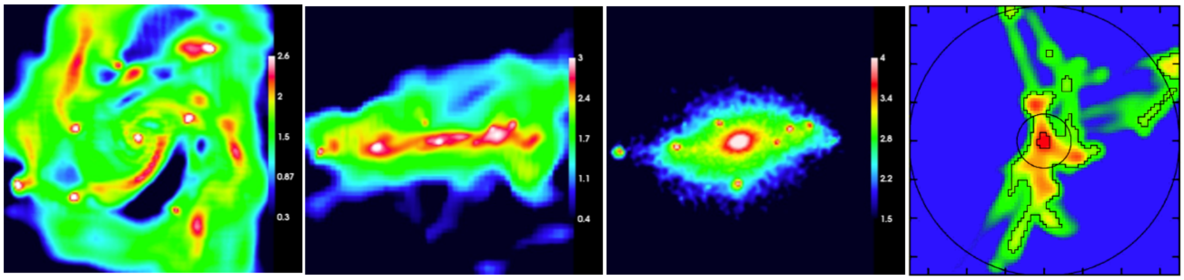

Figure 1: Gas surface density of a galaxy at $z \sim 2.3$ from a high-resolution cosmological simulation (Ceverino et al. 2009). The first three images are 10×10 kpc; the color code is log suface density in units of $M_\odot$ pc^{-2}. The face-on view (a) shows shows an extended disk broken into several 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. 2009), which resembles observed Lyα blobs (see §3.4). The outer circle shows the virial radius $R_{\rm vir} = 70$ kpc; the inner circle is $0.2 R_{\rm vir}$.

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). In agreement with the new SLACS strong lensing data (Bolton et al. 2008), we found 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 majority of SAURON ellipticals that are classified as "fast rotators" (Emsellem et al. 2007; Cappellari et al. 2007; Falcón-Barroso et al. 2008). However, the less common slowly rotating, nearly spherical, more massive elliptical galaxies 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) 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, which are being compared to observations by Primack's grad student Chris Moody (§3.3).

Daniel Ceverino (who finished his PhD with Collaborator Klypin in 2008 and is now a post-doc 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) our 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 outside their birth 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).

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 et al. (2009) saw **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 these simulations, adding supermassive black holes, 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 et al. 2008), which 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. 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 smaller ones observed 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 Croton's 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)[4] 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 the scaling relations of stellar spheroids are a consequence of those of the disk galaxies from which they form. However, 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. 2010). In particular, we have found that there is a close correlation between $S_{0.5} = (\sigma^2 + 0.5V_{\rm rot}^2)^{1/2}$ 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 is now 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 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; Jonsson & Primack 2010).

Using our *Sunrise* radiative-transfer code we have generated images of many simulated merg-

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

ers, each from many different viewpoints, in many wavelength bands, at about 50 points in time 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,[5] and now at MAST,[2] 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 2010). 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*and help us use it to process new simulations (§3.3-6).

2.4 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 such as Gini-M_{20} are otherwise adequate to characterize AGN host galaxies (Pierce et al. 2010). 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 use our *Sunrise* code to predict 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. In particular, **we aim to clarify the processes governing star formation and its quenching in**

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

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 Simulations. The Bolshoi simulation (Klypin et al. 2010) 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 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 180 complete timesteps saved (representing 75 Tb of data, maximally compressed) are nearly three times greater than for the Millennium run.

Approximately 10^7 halos have been identified at all timesteps using the BDM halo-finder (Klypin & Holtzman 1997), and at some timesteps also using a friends-of-friends (FOF) halo finder. Complete merger trees have been constructed with our Collaborator Risa Wechsler. Information has been collected 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!

Among the many applications of the Bolshoi simulation will be populating the backward light-cone to create improved mock catalogs for redshift surveys. We have filled all the Bolshoi halos at $z = 0$ with galaxies according to a simple abundance-matching prescription, and found that the galaxy Luminosity-Velocity relation (generalizing the Tully-Fisher and Faber-Jackson relations) and Velocity Function agree remarkably well with an observational sample including both early-type and late-type galaxies across a wide luminosity range (Trujillo-Gomez et al. 2010).

We propose to run new **"sub-Bolshoi"** simulations of a number of subregions of the Bolshoi simulation with at least 64 times the mass resolution and ~ 100 pc force resolution. One sub-Bolshoi run will focus on early-forming halos that will host the first stars and begin reionizing the universe. This is important because we found that, while FOF halos agree well with BDM halos at low redshift and the abundance of FOF halos agrees with the Sheth & Tormen (2002) (ST) approximation out to high redshift, ST increasingly overpredicts the abundance of halos at high redshift – by an order of magnitude at $z = 10$. This happens because FOF halos at high redshift include unbound material along filaments that unrealistically increase their masses (Klypin et al. 2010). Another sub-Bolshoi simulation will better resolve many average ~ 10 Mpc regions, and thus give statistics on the accretion history and satellites of at least 100 Milky-Way-size halos. We will work especially with Collaborators Bullock and Wechsler to analyze this simulation and compare predictions to observations.

Primack's grad students will all be involved in analyzing the Bolshoi simulations and applying these analyses to cosmological questions, as will the Co-Is 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 and with Co-Is Dekel and Klypin.

3.2 Improving Semi-Analytic Models and Predicting the Evolution of the Galactic Spheroid Population. We are incorporating our analytic merger model (Covington et al. 2008) into our new SAMs based on the Bolshoi merger trees. As we discussed in §2.2, we can now use the analytic model together with SAM calculations of merging galaxy properties 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 180 saved timesteps of the Bolshoi simulation.**

We anticipate that the galaxy properties will depend on the location of the dark matter halo in the cosmic web (Forero-Romero et al. 2009) 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 2009 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 somewhat 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). 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 our analytic merger model in Bolshoi SAMs rather than postprocessing as Porter has done thus far, 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 hydrodynamical 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 all 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.

In addition, with Collaborator Somerville, Porter will further develop the ability to predict galaxy spectra in SAMs, continuing the program of Trager & Somerville (2009); Arrigoni et al. (2010). Comparing these spectra directly to observations using the Lick indices will avoid biases inherent in mass-weighted ages and metallicities. These models also relax the instantaneous recycling approximation and include Type Ia as well as core collapse supernovae, thus allowing us to predict the evolution of galaxy [Mg/H] and [Mg/Fe] as well as [Fe/H] and compare to observations. Porter's undergraduate research 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, the residual starlight has also 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 seen 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.

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 of these star-forming systems.

3.4 Comparing State-of-the-ART Galaxy Formation Simulations to Observations. As 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-ART 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 $z \sim 1$ when formed by merging of star forming clumps from unstable gaseous disks. We are especially interested in seeing how much baryonic angular momentum gets transported out of the galaxy centers, and the correlation of the rotation of the stellar disks with the spin parameter of the host dark matter halos – a cornerstone assumption for SAMs. We have sped up the ART code significantly. This will allow us to run many AMR 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) from our paper Goerdt et al. (2009), 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 (Steidel et al. 2010). We are working to include radiative transport in these calculations, and 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 is working with his students Moody to compare the kinematics and morphology of the simulated galaxies to observations, Porter to improve SAM treatment of galaxy formation at high redshift, and Kollipara to include supermassive black holes (SMBH) in the simulations.

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 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 our simulations follow the resulting SMBH accretion and feedback. 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/CANDELS 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.

3.6 Understanding the Roles 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 Technical Plan

The PI, Joel Primack, will be responsible for overall management of the effort, and Co-Is Dekel and Klypin and the Collaborators will constitute a management committee to consider all important issues. We will meet frequently, by phone and email, and at our annual summer workshop at UCSC.

The division of labor between the PI, Co-Is, and Collaborators will be that the UCSC team will be mainly responsible for analyzing the new hydrodynamic simulations and running some of them along with Cox, Ceverino, and Klypin; developing improved analytic models based on the simulations; and using the radiative transfer code *Sunrise* to make multiwavelength comparisons between simulations and the AEGIS data in collaboration with Jonsson and Lotz and with Faber and the AEGIS team. Dekel will be involved in all this work, especially during his frequent visits to UCSC, and his HU team will run and analyze hydrodynamic simulations to explore star formation and quenching. Krimholz will help improve the treatment of star formation and feedback in our hydrodynamic simulations. Bullock and Wechsler and their groups will help analyze the new cosmological simulations, and Croton and Somerville will use the resulting merger trees for improved SAMs including our analytic models for predicting spheroid properties.

We have plenty of computer power to carry out the proposed research. Primack has for several years had large allocations on the powerful NASA Ames supercomputers; his 2010-11 Pleiades allocation is 6.6 million cpu-hours. We have also worked closely with Chris Henze, director of the Columbia visualization team. At UCSC we have the Pleiades astrophysics computer, with more than 800 fast processors; as a Co-I, Primack is entitled to 0.7 million node-hours per year. As (an unfunded) PI on the UCSC SCIPP DOE grant, Primack also has access to the powerful NERSC supercomputers at LBNL. We have adequate workstations at UCSC to analyze the outputs from these supercomputer simulations, although we request modest funds for maintenance and connection fees.

4.1 Milestones: During the first year, 2011, we plan to use our analysis of the Bolshoi simulation, including halo catalogs, merger trees, and semi-analytic models, to begin detailed comparisons with observations. We will run and analyze higher-resolution Bolshoi follow-on simulations. We will also run ~ 10 new high resolution cosmological galaxy formation simulations, and analyze several of them using *Sunrise* to allow detailed multiwavelength comparisons with observations. We also plan to add supermassive black holes to our galaxy formation simulations, including models of AGN accretion beyond the Bondi approximation, using *Sunrise* to predict their multiwavelength spectra and morphology including the dust attenuation. During 2012 we plan to run new high-resolution dissipationless and hydrodynamical simulations of both small volumes, to study galaxy formation, and of cosmological volumes, to understand environmental effects in detail. By 2013 DEEP3 and other surveys with ACS, WF3, and COS on HST and with new satellites such as NuSTAR will have greatly added to the available data on galaxy formation out to high redshift, and we will critically compare our theoretical models with this data treasure trove in order to answer the questions posed at the beginning of this proposal. This research supports NASA's goal of discovering the structure and evolution of the universe, and it is relevant to interpreting observations by NASA missions including Hubble, Spitzer, Chandra, and Fermi, and to preparing for future missions including JWST.

4.2 Broader 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. 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. In particular, we are working with Collaborator Alex Szalay to make multiple outputs from our Bolshoi simulations and SAMs available through the Virtual Astronomical Observatory.

We also have a long tradition of collaborating closely with observers, especially our DEEP, AEGIS, and CANDELS 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 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.[6]

The new University of California systemwide High-Performance AstroComputing center (UC-HIPACC), which Primack directs, will host an international Astro-Computing school every summer and two research conferences per year, and support education and public outreach efforts. The 2010 school is on galaxy simulations, directed by Co-I Klypin.

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 (2006) with many foreign editions.[7] Primack developed "Einstein's Rocket" video games to teach key ideas of relativity; a java version is available on the UCSC Physics website.[8]

Our simulations provide striking illustrations of our research,[9] and have been featured in the NASA Spitzer Science Center video press releases,[10] and were attractions at supercomputing conferences SC04, SC06, and SC09, where they were presented by Primack's students. They were also featured on the NERSC website,[11] and 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[12] submitted by Jonsson, Novak, and Primack of one of our galaxy merger simulations was a semifinalist in the 2008 NSF/Science Magazine Visualization Challenge. 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 create dome and 3D shows that explain how dark and luminous matter interact to produce galaxies and the large scale structure of the Universe, and to make our simulation outputs available to planetariums and other educational venues worldwide. Primack has applied for a NASA EPOESS grant to support these Education and Public Outreach efforts.

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

[7] Many reviews and print and broadcast interviews can be found at `http://viewfromthecenter.com` including a list of over 100 popular lectures during 2006-2010.

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

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

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

[11] `http://www.lbl.gov/cs/Archive/news032210.html`

[12] `http://www.youtube.com/watch?v=agqLEbOFT2A`

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Joel R. Primack

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Education: Princeton University A.B. 1966 Physics (Summa cum Laude)
Stanford University PhD 1970 Physics

Academic Positions: Junior Fellow, Society of Fellows, Harvard University 1970-73
Assistant Professor of Physics, UCSC 1973-1977; Associate Professor of Physics, UCSC, 1977-1983; Professor of Physics, UCSC 1983-present; Distinguished Professor 2007-
Director, University of California systemwide High-Performance Astro-Computing Center, 2010-; Chair, UCSC Committee on Computing and Telecommunications, 2008-2011; Chair, University Committee on Computing and Communications, 2010-11

Advice (partial list): 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 (partial list): Executive Committee, APS Division of Astrophysics, 2000-2002; APS Panel on Public Affairs (POPA) 2002-2004; Chair, POPA Task Force on Moon-Mars Program and Funding for Astrophysics 2004; Chair, APS Forum on Physics and Society 2005; Chair, APS Sakharov Prize committee 2009

Outreach (partial list): 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. Co-author of popular book *The View from the Center of the Universe* (2006). Over 100 public lectures on cosmology, including Sackler Lecture (UC Berkeley, 2006); J. Robert Oppenheimer Memorial Lecture (Los Alamos, 2007); APS Public Lecture (St. Louis, 2008); Terry Lectures (with Nancy Abrams, Yale, 2009)

Honors (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

Books
• Joel R. Primack and Frank von Hippel, *Advice and Dissent: Scientists in the Political Arena* (New York: Basic Books, 1974; New American Library, 1976)
• Joel R. Primack and Nancy Ellen Abrams, *The View from the Center of the Universe: Discovering Our Extraordinary Place in the Cosmos* (New York: Riverhead/Penguin, 2006; London: HarperCollins, 2006; Paris: Laffont, 2008; and other foreign editions)

Selected peer-reviewed publications (in chronological order)

Supersymmetry, cosmology, and new physics at teraelectronvolt energies 1982, *Phys. Rev. Letters* **48**, 223. Pagels, Heinz, and **Primack, Joel R.** (*334 citations in NASA Astrophysics Data System*)

Formation of galaxies and large-scale structure with cold dark matter 1984, *Nature* **311**, 517. Blumenthal, G. R.; Faber, S. M.; **Primack, J. R**.; Rees, M. J. (*849 ADS cites*)

Contraction of dark matter galactic halos due to baryonic infall 1986, *ApJ* **301**, 27. Blumenthal, G. R.; Faber, S. M.; Flores, R.; **Primack, J. R. (***517 ADS***)**

Dynamical effects of the cosmological constant 1991, *MNRAS* **251**, 128. Lahav, Ofer; Lilje, Per B.; **Primack, Joel R.**; Rees, Martin J. (*379 ADS*)

Semi-analytic modeling of galaxy formation: the local Universe 1999, *MNRAS* **310**, 1087. Somerville, Rachel S.; **Primack, Joel R.** (*613 ADS*) *

The nature of high-redshift galaxies 2001, *MNRAS* **320**, 504. Somerville, Rachel S.; **Primack, Joel R.**; Faber, S. M. (*449 ADS*) *

Profiles of dark haloes: evolution, scatter and environment 2001, *MNRAS* **321**, 559. Bullock, J. S.; Kolatt, T. S.; Sigad, Y.; Somerville, R. S.; Kravtsov, A. V.; Klypin, A. A.; **Primack, J. R.**; Dekel, A. (*1052 ADS*) *

Concentrations of dark halos from their assembly histories 2002, *ApJ* **568**, 52. Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V., Dekel, A. (*403 ADS*) *

A New Non-Parametric Approach to Galaxy Morphological Classification 2004, AJ, 128, 163-182. Jennifer M. Lotz, **Joel Primack**, and Piero Madau (*124 ADS*)

Feedback in Simulations of Disk Galaxy Major Mergers 2006, MNRAS, 373, 1013. T. J. Cox, Patrik Jonsson, **Joel R. Primack**, and Rachel S. Somerville (*114 ADS*) *

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

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

The effect of galaxy mass ratio on merger–driven starbursts 2008, MNRAS, 384, 386. T. J. Cox, P. Jonsson, R. S. Somerville, **J. R. Primack**, A. Dekel

GeV Gamma-Ray Attenuation and the High-Redshift UV Background 2009, MNRAS, in press, R.C. Gilmore, P. Madau, **J. R. Primack**, R. S. Somerville, F. Haardt *

* These papers are based on PhD dissertation research supervised by **Joel Primack**

CURRICULUM VITA: Avishai Dekel

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Specialization:

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

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.
1982-1985:	Assistant Professor, Yale University.
1980-1982:	Research Fellow, California Institute of Technology (supervisor: P. Goldreich).

Five Recent Publications Related to the Proposal:

- 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 [96 citations]
- Galaxy Bimodality due to Cold Flows and Shock Heating; Dekel, A. & Birnboim, Y. 2006, MNRAS, 368, 2 [297 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 [80 citations]
- Cold streams in early massive hot haloes as the main mode of galaxy formation; Dekel, A., et al. 2009, Nature, 457, 451 [137 citations]
- Gravity-Driven Lyman-Alpha Blobs from Cold Streams into Galaxies; Goerdt, T., Dekel, A., Ceverino, D., Teyssier, R., Primack, J.R. 2010, MNRAS, in press (arXiv:0911.5566)

Other Significant Relevant Publications:

- The Origin of Dwarf Galaxies, Cold Dark Matter, and Biased Galaxy Formation; Dekel, A. & Silk, J. 1986, ApJ, 303, 39 [1,093 citations]
- Profiles of Dark Haloes: Evolution, Scatter, and Environment; Bullock, J.S., ..., Somerville, R.S., Kravtsov, A.V., Klypin, A.A., Primack, J.R., & Dekel, A. 2001, MNRAS, 321, 559 [1,051 citations]
- Star Formation in AEGIS Field Galaxies Since $z = 1.1$; Noeske, K.G., Faber, S.M., ..., Koo, D.C., Primack, J.R., Dekel, A., et al., 2007, ApJL, 660, L47 [92 citations]
- Formation of Massive Galaxies at High Redshift: Cold Streams, Clumpy Disks and Compact Spheroids; Dekel, A., Sari, R., Ceverino, D. 2009, ApJ, 703, 785 [52 citations]

Anatoly Klypin

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Born: May 06, 1953. Sevastopol, Russia **citizenship:** USA

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)

Main research interests:

- Testing cosmological scenarios with different dark matter and dark energy models. Comparison of the models with observational data.
- Physics of galaxy formation. Interplay of dark matter, gas, stars, and radiation in the processes leading to formation of galaxies.
- Development of large scalable numerical N-body and gasdynamical codes for cosmological simulations and for dynamics of individual galaxies.

Publications: Total: 240 publications, 8600 citations. Selected publications:

- *Halos and galaxies: results from the Bolshoi simulation*, Klypin, A., Trujillo-Gomez, S., Primack, J., 2010, astro-ph, ApJ, submitted.
- *The role of stellar feedback in the formation of galaxies*, Ceverino, D., Klypin, A., 2009, ApJ, 695, 292
- *Response of Dark Matter Halos to Condensation of Baryons: Cosmological Simulations and Improved Adiabatic Contraction Model*, Gnedin, O. Y., Kravtsov, A. V., Klypin, A. A., & Nagai, D. 2004, ApJ, 616, 16
- *LCDM-based models for the Milky Way and M31 I: Dynamical Models*, Klypin, A., Zhao, H. & Somerville, R.S., ApJ., 2002, 573, 597
- *Where Are the Missing Galactic Satellites?*, Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. "Where Are the Missing Galactic Satellites?", 1999, Astrophys.J., 522, 82

JOEL R. PRIMACK: CURRENT AND PENDING SUPPORT

JOEL R. PRIMACK: CURRENT AWARDS 2010

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	2/06/07-2/05/11	$353,601	1 summer month 2007, 08, 09 Commitment: 35% all year
NASA ATP NNX10AHH11G	Evolution of Structure and of the Cosmic Population of Galactic Spheroids PI: Primack	6/01/10-9/30/10	$25,000	0 funding for PI, only grad students
NASA Fermi NNX09AT98G	Cosmology Gamma-Ray Attenuation PI: Primack; Co-Is: Madau, Prada	8/14/09-8/13/10	$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 month during 2010-2014 Commitment: 10% of Academic Yr

JOEL R. PRIMACK: CURRENT AND PENDING SUPPORT

JOEL R. PRIMACK: PENDING AWARDS 2010

NSF AST	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 2011-12 Commitment: 35% Academic Yr + 1½ summer months each year
DOE	UC-HIPACC Astro-Computing Summer School on Galaxy Simulations PI: Primack, Co-I: Klypin	7/01/10- 12/31/10	$20,000	Commitment: PI: ½ month Co-I: ½ month
NSF	UC-HIPACC Astro-Computing Summer School on Galaxy Simulations PI: Primack, Co-I: Klypin	7/01/10- 12/31/10	$20,000	Commitment: PI: ½ month Co-I: 1 month
NASA EPOESS	Public Education and Outreach via Cosmological Simulation Visualizations PI: Primack, Co-Is: Ash, SubbaRao, Wyatt Collaborators: Cox, Henze, Jonsson, Klypin, Prada, Somerville, von Ahnen, Wechsler	1/1/11- 12/31/13	$774,113	½ month/year Commitment: 2 months/yr
NASA Fermi	Improved Cosmological Models of Gamma-Ray Attenuation PI: Primack, Co-Is: Gilmore, Madau, Prada	11/1/10- 10/31/11	$77,000	½ summer mo. Commitment: 1 month/yr

AVISHAI DEKEL: CURRENT AND PENDING SUPPORT May 2010

Agency: Israel Science Foundation
Title: ``Star Formation and its Shutdown in Galaxies"
PI: Dekel
Duration: October 2008 -- September 2012
Budget: $ 40 k per year
Mostly students and a postdoc in Israel, some computing cost.
No summer salary, no travel.

Agency: German-Israel Project Cooperation
Title: ``Dynamics and Cosmological Evolution of Galaxies and Massive Black Holes"
PI: Sternberg (TAU). Co-I: Dekel (HU), Alexander (WIS), Netzer (TAU), Maoz (TAU), Zucker (TAU)
Duration: January 2009 -- December 2013
Budget for Dekel: 50,000 ERO per year
Mostly travel to Germany, computing equipment in Israel, students and postdocs in Israel.
No summer salary, no travel to the US.

Agency: NASA
Title: "Evolution of Cosmic Structure and Galaxies" (this proposal)
PI: Primack (UCSC), Co-Is: Dekel (HU), Klypin (NMSU)
Budget for Dekel: 1 summer month each year
Will devote 25% of my time to the NASA research proposed here during the academic year, and full time during two months in the summer.

ANATOLY KLYPIN: CURRENT AND PENDING SUPPORT 2010

Current:

Collaborative research: Baryons and dark matter in galaxies
NSF AST-0708185 $201,460 09/01/07- 08/31/10 summer:1month

Probing the Galaxy-halo/Cosmic Web interface and galaxy evolution
NSF AST-0708210 $285,679 07/01/07- 06/30/10 Summer:1 month

Pending:

Collaborative Research: Evolution of Cosmic Structure and of
the Galactic Spheroid Population
NSF $95,898 07/01/10- 06/30/13 Summer: 1month

Collaborative Research: Dwarf galaxies: confrontation of
theory with data
NSF $217,944 07/01/10-07/30/13 Summer: 1month

Absorption Line Analysis to Interpret Cosmological Simulations of
Galaxy Formation and Feedback,
NASA ATP, $290,195, (PI Ch.Churchill, NMSU), Summer: 1month

Evolution of Cosmic Structure and Galaxies (this proposal),
NASA ATP, $490,000 (PI J.Primack, UCSC), Summer: 1month

UNIVERSITY OF CALIFORNIA, SANTA CRUZ

BERKELEY • DAVIS • IRVINE • LOS ANGELES • MERCED • RIVERSIDE • SAN DIEGO • SAN FRANCISCO

SANTA BARBARA • SANTA CRUZ

June1, 2010

To Whom It May Concern:

I would like to introduce myself as a collaborator on the Astrophysics Theory proposal by Joel Primack of UC Santa Cruz entitled "Evolution of Cosmic Structure and Galaxies." This proposal assembles a team of world-leading theorists to construct models of galaxy formation using a variety of pathbreaking techniques. All of approaches, however, rest on a powerful new dark matter simulation called "Bolshoi" (for "big"). This simulation has the best combination of size and dynamical resolution yet produced and locates accurately the centers of dark matter haloes, which are then filled with luminous galaxies using a variety of approaches.

My direct role is as an observational astronomer who is leading the massive CANDELS imaging survey with the Hubble Space Telescope. CANDELS stands for Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey and is being conducted with both the ACS and the new WFC3 camera on Hubble. With 902 orbits, it is the largest Hubble proposal ever assigned, and the goal is to use the new long-wavelength capability of the WFC3 camera to follow galactic evolution out to redshifts as high as z~8.

The work proposed by Dr. Primack and his collaborators is crucial for interpreting the CANDELS data. The simulations and mock catalogs produced from the Primack program will be the standard data against which the real CANDELS data will be compared. The flexible halo-based and/or semi-analytic modeling approaches used in the Primack program permit computations of many different scenarios for galaxy formation, many more than are possible with exact but time-consuming hydrodynamic models. We are developing advanced data-mining techniques to determine which of the Bolshoi catalogs best matches the Universe. The work carried out by this program is thus an indispensable component for reaping the scientific rewards of the Hubble CANDELS data set.

Sincerely,

SM Faber

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

JOHNS HOPKINS
U N I V E R S I T Y

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Prof. Joel Primack
Dept. of Physics
University of California, Santa Cruz
Santa Cruz, CA 95064

Baltimore, May 31, 2010

Dear Joel,

I acknowledge that I am identified by name as a collaborator to the investigation, entitled "*Evolution of Cosmic Structure and Galaxies*", that is submitted by Dr. Joel R. Primack to the NASA ATP Program, 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 these proposals will be considered during peer review in determining in part the merits of these proposals. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation.

In particular, I will be willing to create a publicly available service to host the output of the Bolshoi cosmological simulations (halo catalogs, merger trees, and complete data for z=0, and possibly semi-analytic models) at the 1.2 petabyte GrayWulf facility that has been built by my group at the Johns Hopkins University. These services will be part of the Virtual Astronomical Observatory (VAO), recently funded by NASA and NSF.

Szalay Szalay

Dr. Alexander Szalay
Alumni Centennial Professor
The Johns Hopkins University

Evolution of Cosmic Structure and Galaxies

PI: Joel Primack, Co-Is: Avishai Dekel and Anatoly Klypin
Collaborators: James Bullock, T. J. Cox, Sandra Faber, Patrik Jonsson, Mark Krumholz, Jennifer Lotz, Rachel Somerville, Alex Szalay, and Risa Wechsler

Budget Justification: Narrative

The PI requests ½ month of summer salary/year and the two Co-Is each request 1 month summer salary/year. Dekel and Klypin have long collaborated with Primack, and they each plan to visit UCSC for at least one month per year for the research proposed here. PI Primack commits one summer month per year to this project plus at least 25% time during the academic year. Co-I Dekel commits two summer months per year to this project plus 25% time during the academic year. Co-I Klypin commits at least one summer month to this project per year.

Partial support is requested for three UCSC graduate students, who are supervised by PI Primack but will also work with Co-Is Dekel and Klypin and with the Collaborators. This continues our longstanding arrangements, as Dekel and Klypin have co-supervised or collaborated with many of Primack's students for many years. The three students (at least initially) are Priya Kollipara, Chris Moody, and Lauren Porter, all of whom are now working with Primack on computer-intensive astrophysics research. Kollipara has a graduate fellowship that pays her tuition and stipend during the academic year, so only summer support is requested for her. Two academic quarters (6 months) of support plus summer support are requested for Moody and Porter.

Funds are requested to permit each graduate student researcher and occasionally also the PI and Co-Is to attend national and international conferences and meetings. In addition, Primack has hosted summer research workshops at UCSC each summer for many years, and all of the Co-Is and Collaborators attend, along with many of their graduate students and postdocs. Most of their expenses are covered by their own grants, but modest additional support is requested to cover local expenses for visiting researchers essential to the proposed research, including Dr. Daniel Ceverino (Klypin's former student and Dekel's current postdoc).

Primack has adequate computer support at UCSC, so the only additional direct support requested per year is $1800 for pages charges and $1000 for computer maintenance and software.

Primack has submitted a separate proposal to support Public Outreach efforts connected with this research.

Printed on 5/27/2010

University of California Santa Cruz
Office of Sponsored Projects
Detailed Agency Budget

Title Evolution of Cosmic Structure and Galaxies

Budget Prepared Date

Preparer Riley Jordan

SC# 20101226

PI Name Primack, Joel **Agency** NASA/Shared Services Center

Start Date 1/1/2011 **End Date** 12/31/2013

Salaries:

Title/Name	SalaryType/Level		Year 1	Year 2	Year 3	Total
PI Summer	PROFFULL	NA	8,544	8,801	9,065	26,410
Joel Primack	Months/Time%		0.5 100%	0.5 100%	0.5 100%	
Co-I	VSTGACAD	NA	13,390	13,792	14,205	41,387
Avishai Dekel	Months/Time%		1.0 100%	1.0 100%	1.0 100%	
Co-I	VSTGACAD	NA	10,000	10,300	10,609	30,909
Anatoly Klypin	Months/Time%		1.0 100%	1.0 100%	1.0 100%	
GSR x 2 Summer	GSR-Res	IV	21,556	22,203	22,869	66,628
Moody & Porter	Months/Time%		3.0 100%	3.0 100%	3.0 100%	
GSR x 2 Academic	GSR-Res	IV	21,556	22,203	22,869	66,628
Moody & Porter	Months/Time%		6.0 50%	6.0 50%	6.0 50%	
GSR Summer	GSR-Res	V	11,495	11,840	0	23,335
Kollipara	Months/Time%		3.0 100%	3.0 100%		
	Salaries:		86,541	89,139	79,617	255,297

Fringe:

Title/Name	SalaryType/Fringe Rate		Year 1	Year 2	Year 3	Total
PI Summer	PROFFULL	NA	1,153	1,188	1,224	3,565
Joel Primack	13.5%					
Co-I	VSTGACAD	NA	1,875	1,931	1,989	5,795
Avishai Dekel	14.0%					
Co-I	VSTGACAD	NA	1,700	1,751	1,804	5,255
Anatoly Klypin	17.0%					
GSR x 2 Summer	GSR-Res	IV	647	666	686	1,999
Moody & Porter	3.0%					
GSR x 2 Academic	GSR-Res	IV	539	555	572	1,666
Moody & Porter	2.5%					
GSR Summer	GSR-Res	V	345	355	0	700
Kollipara	3.0%					
	Fringe:		6,259	6,446	6,275	18,980
	Salaries & Fringe:		92,800	95,585	85,892	274,277

Domestic:

Name	Destination	Year 1	Year 2	Year 3	Total
GSRs	Professional Meeting	1,500	3,000	3,000	7,500
Collaborators	collaborator visits	2,000	2,000	2,000	6,000

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University of California Santa Cruz
Office of Sponsored Projects
Detailed Agency Budget

	Domestic:	3,500	5,000	5,000			13,500
Foreign:							
Name	**Destination**						
PI or GSRs	research meeting	0	2,000	2,000			4,000
	Foreign:	0	2,000	2,000			4,000
	Total Travel:	3,500	7,000	7,000			17,500

Other Direct Costs:

Type	**Description**						
Publication Costs/Page Charges	$120/pg x 15/pgs/year	1,800	1,800	1,800			5,400
Other	computer access &maintenance	1,000	1,000	1,000			3,000
	Other Direct Costs:	2,800	2,800	2,800			8,400
Fees:	Non-resident Tuition:						
	Graduate Student Health Insurance Program:	3,840	4,032	4,234			12,106
	Graduate Student Registration Fees:	13,176	14,494	15,943			43,613
	Graduate Fee Override:						
	Total Graduate Fees:	17,016	18,526	20,177			55,719
	Total Other Direct Costs:	19,816	21,326	22,977			64,119

Totals:	**Total Direct Costs:**	116,116	123,911	115,869			355,896
	Indirect Cost Base:	99,100	105,385	95,692			300,177
	Indirect Cost Base Override:						
	IC Rate:	51.5%	51.5%	51.5%	51.5%	51.5%	
	Total Indirect Costs:	51,037	54,273	49,281			154,591
TOTAL BUDGET:		167,153	178,184	165,150			510,487