October 31, 2013

Supercomputing the Universe

Joel R. Primack

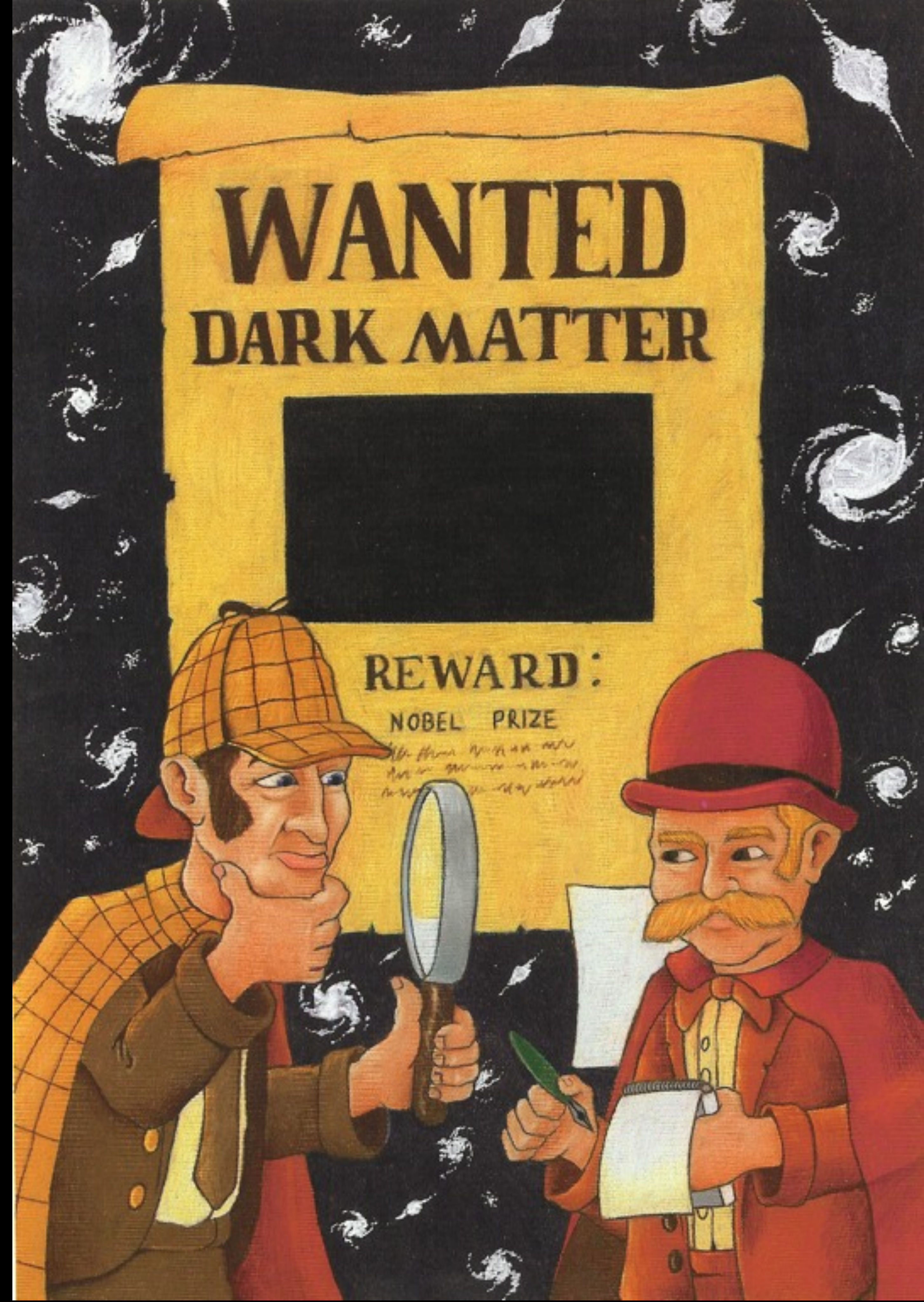
Distinguished Professor of Physics,
University of California, Santa Cruz

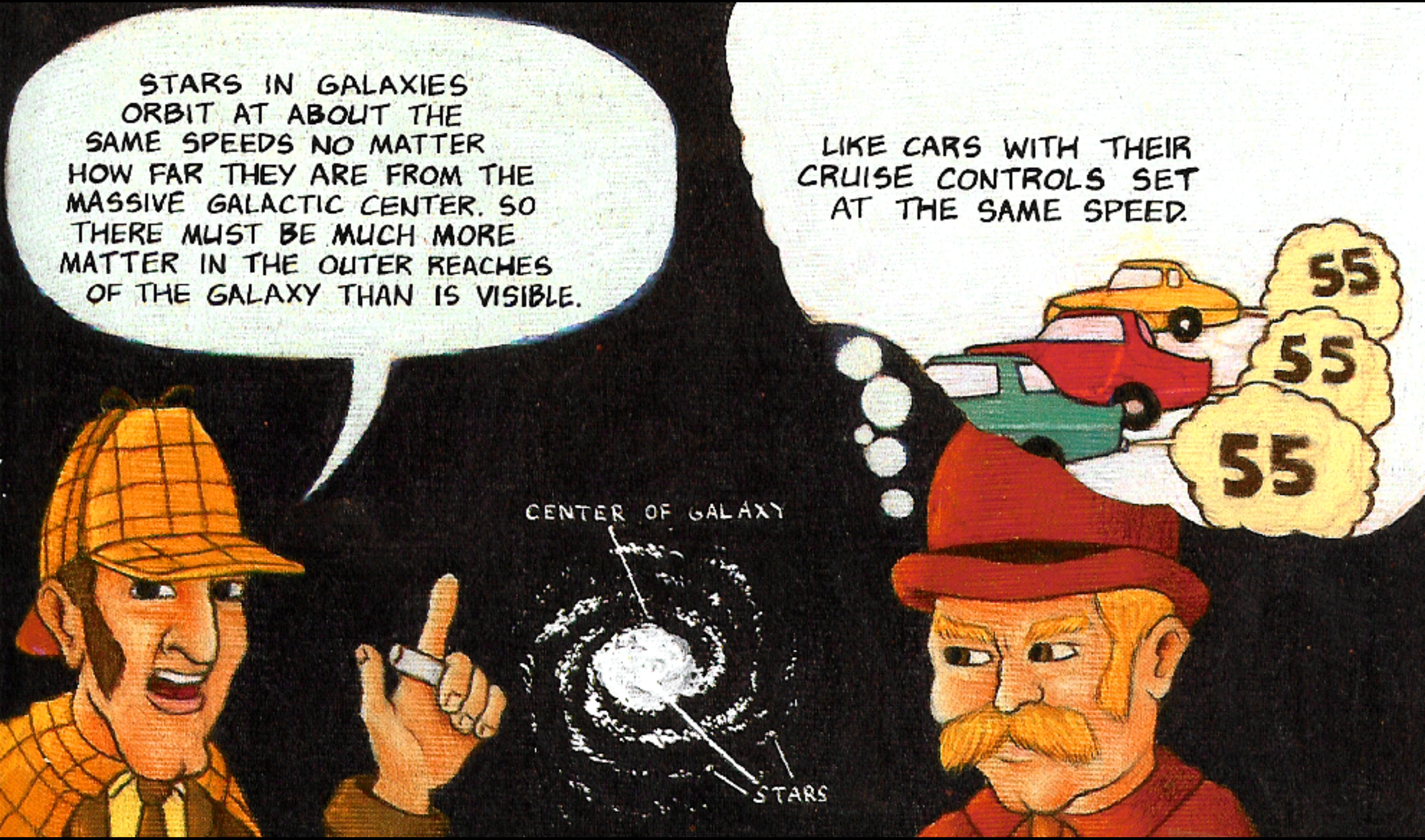
Director, University of California
High-Performance AstroComputing Center
(UC-HiPACC)

“The Case of the Dark Matter”

from *World Book Science Year 1990*

by Joel R. Primack




STARS IN GALAXIES ORBIT AT ABOUT THE SAME SPEEDS NO MATTER HOW FAR THEY ARE FROM THE MASSIVE GALACTIC CENTER. SO THERE MUST BE MUCH MORE MATTER IN THE OUTER REACHES OF THE GALAXY THAN IS VISIBLE.
LIKE CARS WITH THEIR CRUISE CONTROLS SET AT THE SAME SPEED.
55
55
55
CENTER OF GALAXY
STARS

Outline

- University of California AstroComputing Center
- Large Scale Simulations - Bolshoi
  - Halo Abundance Matching vs. Observations
  - Semi-Analytic Models vs. Galaxies Near and Far
  - Early/Fast Galaxy Evolution: Blue & Red Nuggets
- High Resolution Galaxy Simulations
  - Making Mock Observations with Sunrise
  - Comparing Mocks with CANDELS Galaxies
  - Galaxy Evolution Revisited
- The AGORA Galaxy Simulation Comparison Project
- Supercomputing the Universe: Challenges

The University of California
High-Performance AstroComputing Center

A consortium of nine UC campuses and three DOE laboratories

UC-HiPACC Support: ~$350,000/yr from the University of California

UC-HiPACC Executive Committee

Director: Joel Primack (UCSC) <joel@ucsc.edu>
Coordinator from Northern California: Peter Nugent (LBNL)
Coordinator from Southern California: Michael Norman (UCSD)

UC-HiPACC Council

UC Berkeley: Christopher McKee
UC Davis: Maruša Bradač
UC Irvine: James Bullock
UC Los Angeles: Steve Furlanetto
UC Merced: TBA
UC Riverside: Gillian Wilson
UC San Diego: Michael Norman
UC Santa Barbara: S. Peng Oh
UC Santa Cruz: Sandra Faber
Los Alamos National Lab: Thomas Vestrand
Lawrence Berkeley National Lab: Peter Nugent
Lawrence Livermore National Lab: Peter Anninos

UC-HiPACC Staff

UC-HIPACC Office Manager: Sue Grasso <hipacc@ucsc.edu>
Visualization Specialist: F. Alex Bogert <bogart.alex@gmail.com>
Senior Writer - Outreach and Proposals: Trudy Bell <t.e.bell@ieee.org>
Webmaster and Videographer: Eric Maciel <emaciel@ucsc.edu>

Annual Conferences in Northern and Southern California

HIPACC sponsors two large meetings each year especially (but not exclusively) for scientists working on computational astrophysics and related topics at the UC campuses and labs. Unlike the more specialized meetings of working groups, these larger meetings are broad,with the purpose of bringing theoretical astrophysicists together with computer science specialists, computer hardware experts, and observational astronomers. One meeting is in northern California and the other in southern California to promote maximum participation. In addition to sharing new information, these meetings highlight problems needing attention to advance the state-of-the-art and introduce participants to potential colleagues and begin collaborations.

Annual International AstroComputing Summer Schools (ISSAC)

HIPACC supports an annual school aimed at graduate students and postdocs who are currently working in, or actively interested in doing research in, AstroComputing. Topics and locations of the annual school rotate. Codes are put on a supercomputer where the students have accounts.

The 2010 school was at UCSC, on the topic of Hydrodynamic Galaxy Simulations. Lectures were presented by experts on the leading codes (AMR codes ART, Enzo, and RAMSES, and SPH codes Arepo, GADGET, and Gasoline) and the Sunrise code for making realistic visualizations including stellar SED evolution and dust reprocessing. There were 60 students, including 20 from outside the USA. Lecture slides and videos, codes, inputs and outputs are on the UC-HIPACC website http://hipacc.ucsc.edu. Funding from NSF helped to support non-UC participant expenses.

The 2011 school was July 11-23 at UC Berkeley/LBNL/NERSC, on the topic of Computational Explosive Astrophysics: novae, SNe, GRB, and binary mergers. The scientific organizers were Daniel Kasen (LBNL/UCB) and Peter Nugent (LBNL). There was additional funding from DOE.

The 2012 school was at UC San Diego/SDSC, on AstroInformatics and Astrophysical Data Mining. The scientific director was Alex Szalay (Johns Hopkins) and the host was Michael Norman, director, SDSC.

The 2013 school was at UCSC, on Star and Planet Formation; the director was Mark Krumholz.

The 2014 school will be at UC San Diego/SDSC, on Nuclear Astrophysics; the director is George Fuller.

UC-HiPACC Conferences & Workshops

- **August 16 - 18, 2010:** The 2010 Santa Cruz Galaxy Workshop, UC Santa Cruz
- **December 16 & 17, 2010:** The Future of AstroComputing Conference, San Diego Supercomputer Center
- **August 8 - 12, 2011:** The 2011 Santa Cruz Galaxy Workshop, UC Santa Cruz
- **June 14-16, 2012:** The Baryon Cycle, Beckman Center, UC Irvine

2010 Future of Astrocomputing, SDSC

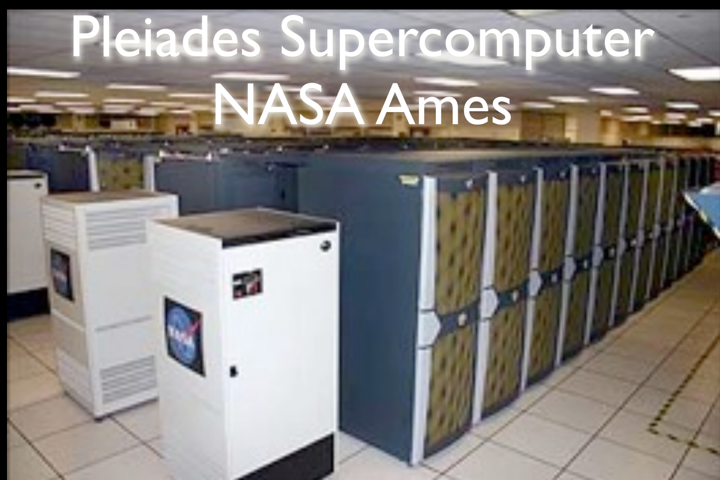
2011 Santa Cruz Galaxy Workshop

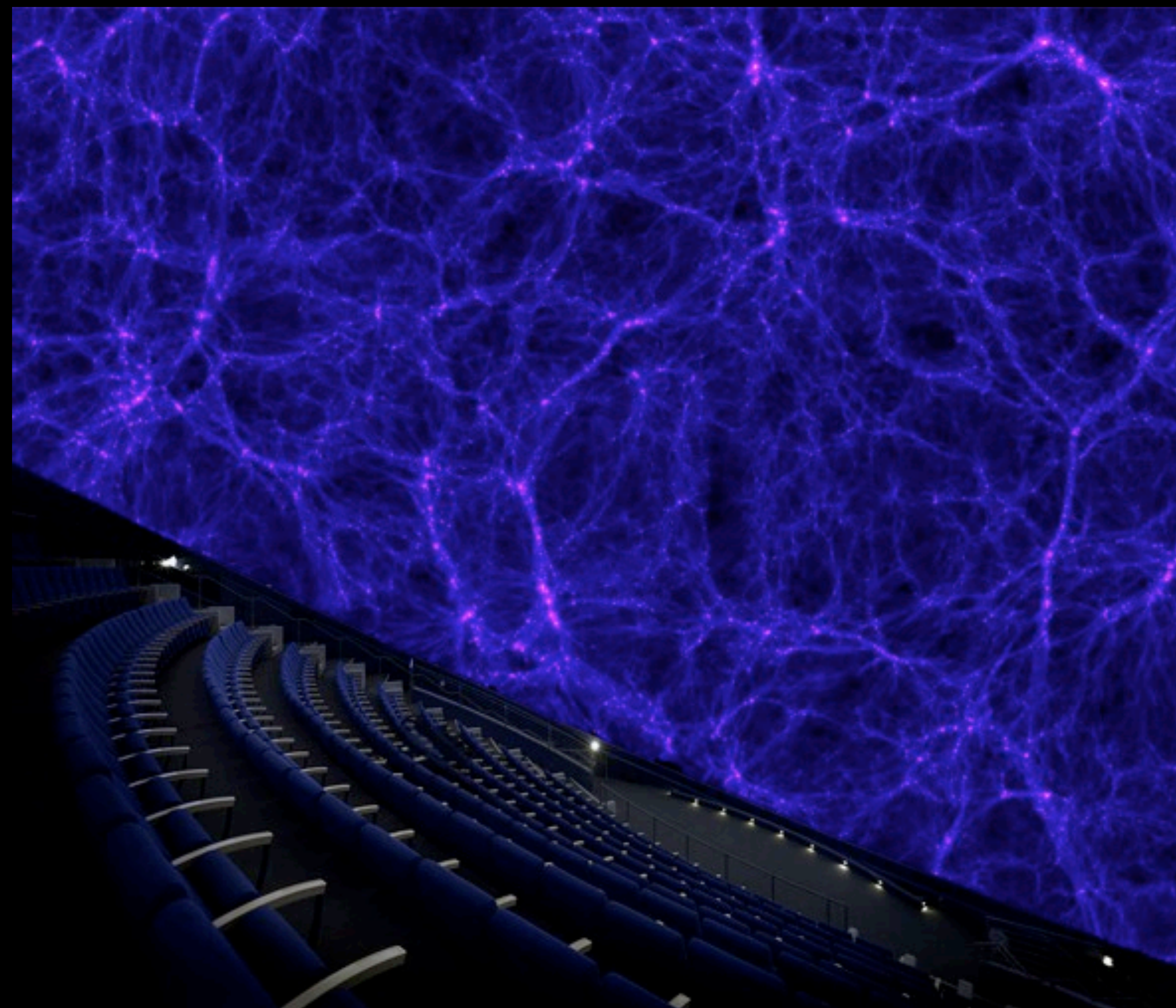
- **June 24-27, 2012:** The Computational Astronomy Journalism Boot Camp
- **August 13-17, 2012:** The 2012 Santa Cruz Galaxy Workshop, UC Santa Cruz
- **August 17-20, 2012:** High-Resolution Galaxy Simulations Workshop
- **August 12-15, 2013:** The 2013 Santa Cruz Galaxy Workshop, UC Santa Cruz
- **August 16-19, 2013:** AGORA Galaxy Simulation Workshop, UC Santa Cruz
- **February 12-14, 2014: Near-Field/Far-Field Cosmology, Beckman Center, UC Irvine**
- **August 11-15, 2014: 2014 Santa Cruz Galaxy Workshop, UCSC**

Astro-Computation Visualization and Outreach

Project lead: Prof. Joel Primack, Director, UC High-Performance AstroComputing Center
UC-HIPACC Visualization and Outreach Specialist: Nina McCurdy

http://hipacc.ucsc.edu



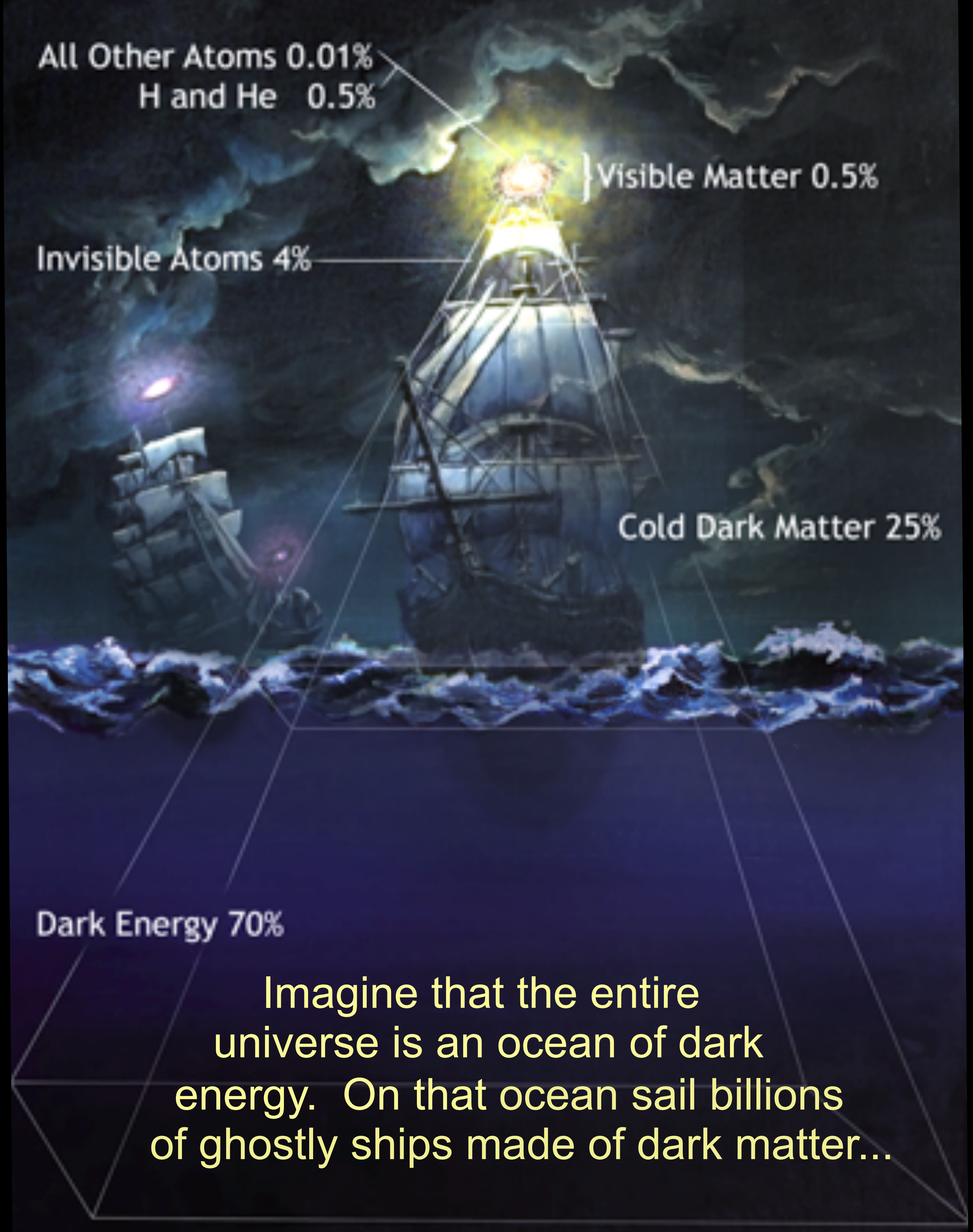


HIPACC is working with the Morrison Planetarium at the California Academy of Sciences (pictured here) to show how dark matter shapes the universe. We helped prepare their show *LIFE: a Cosmic Story* that opened in fall 2010, and also a major planetarium show that opened the new Adler Planetarium Grainger Sky Theater July 8, 2011.

This picture is beautiful but misleading, since it only shows about 0.5% of the cosmic density.

The other 99.5% of the universe is invisible.

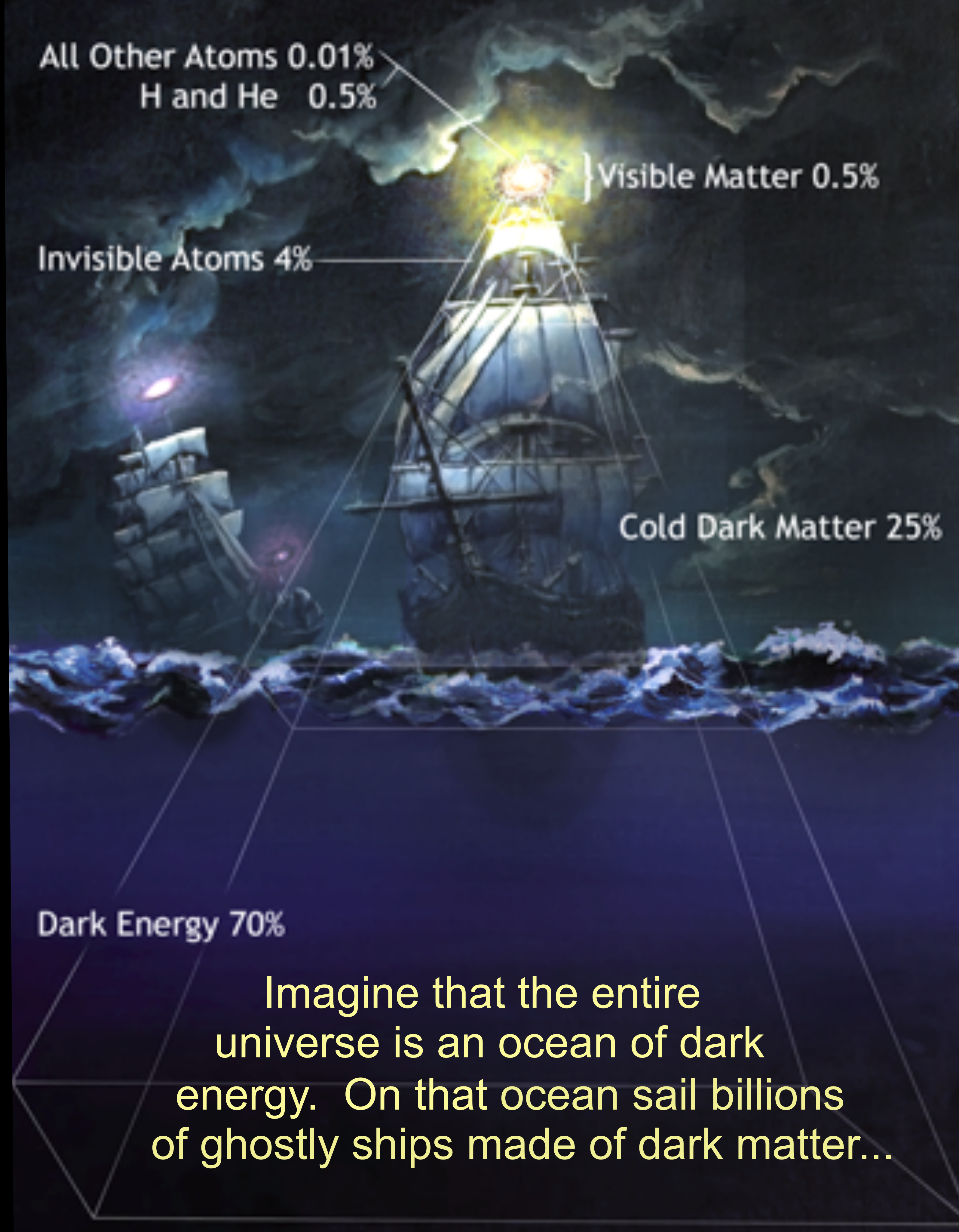
Matter and Energy Content of the Universe



Dark Matter Ships

on a

Dark Energy Ocean



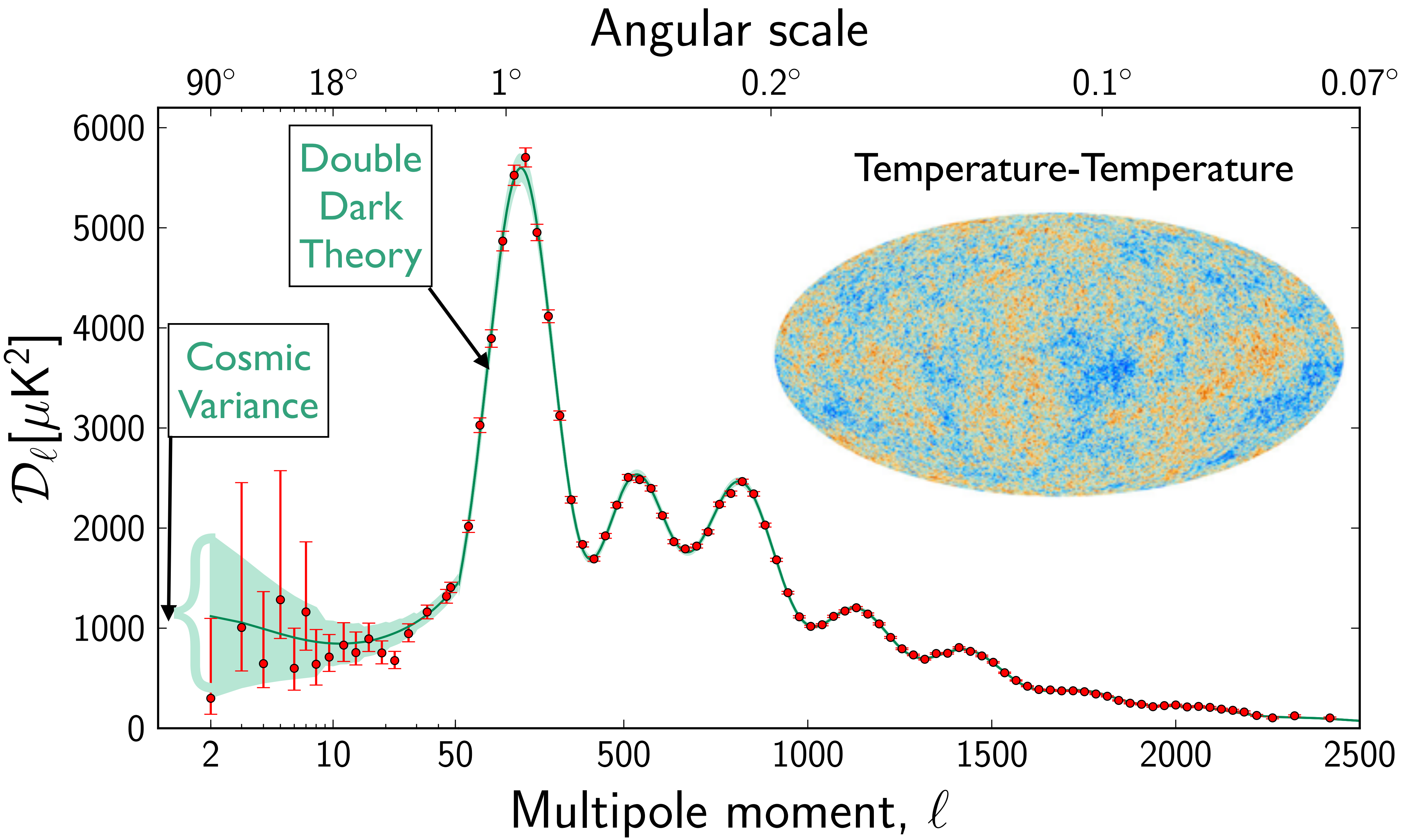
Matter and Energy Content of the Universe

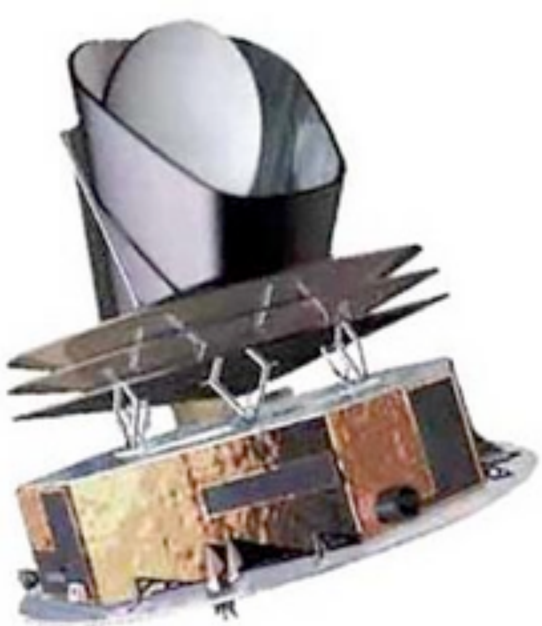
ΛCDM

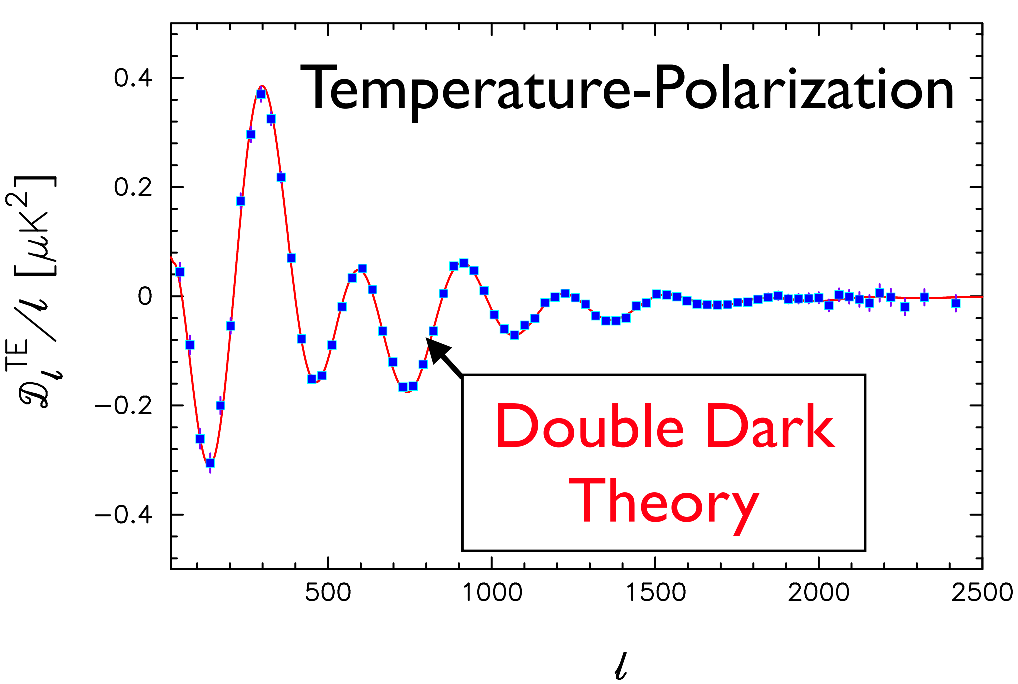
Double Dark Theory

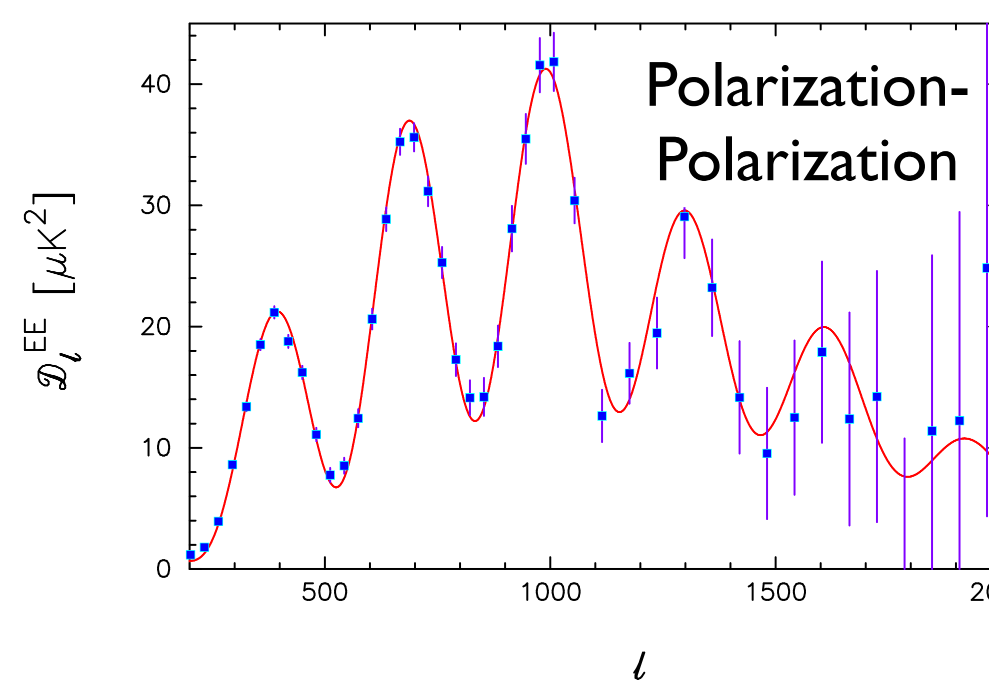
European Space Agency PLANCK Satellite Data

Released March 21, 2013

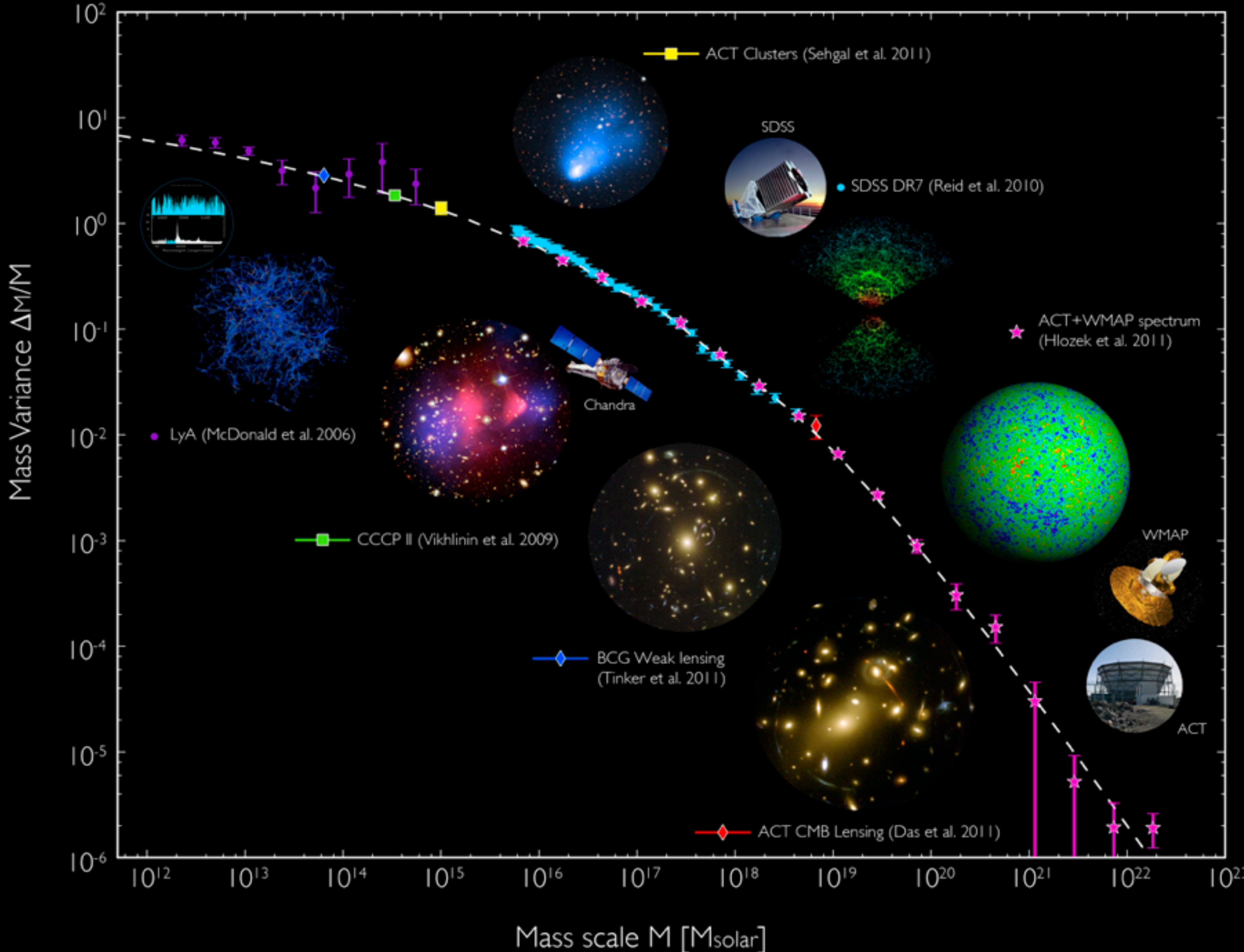








Matter Distribution Agrees with Double Dark Theory!

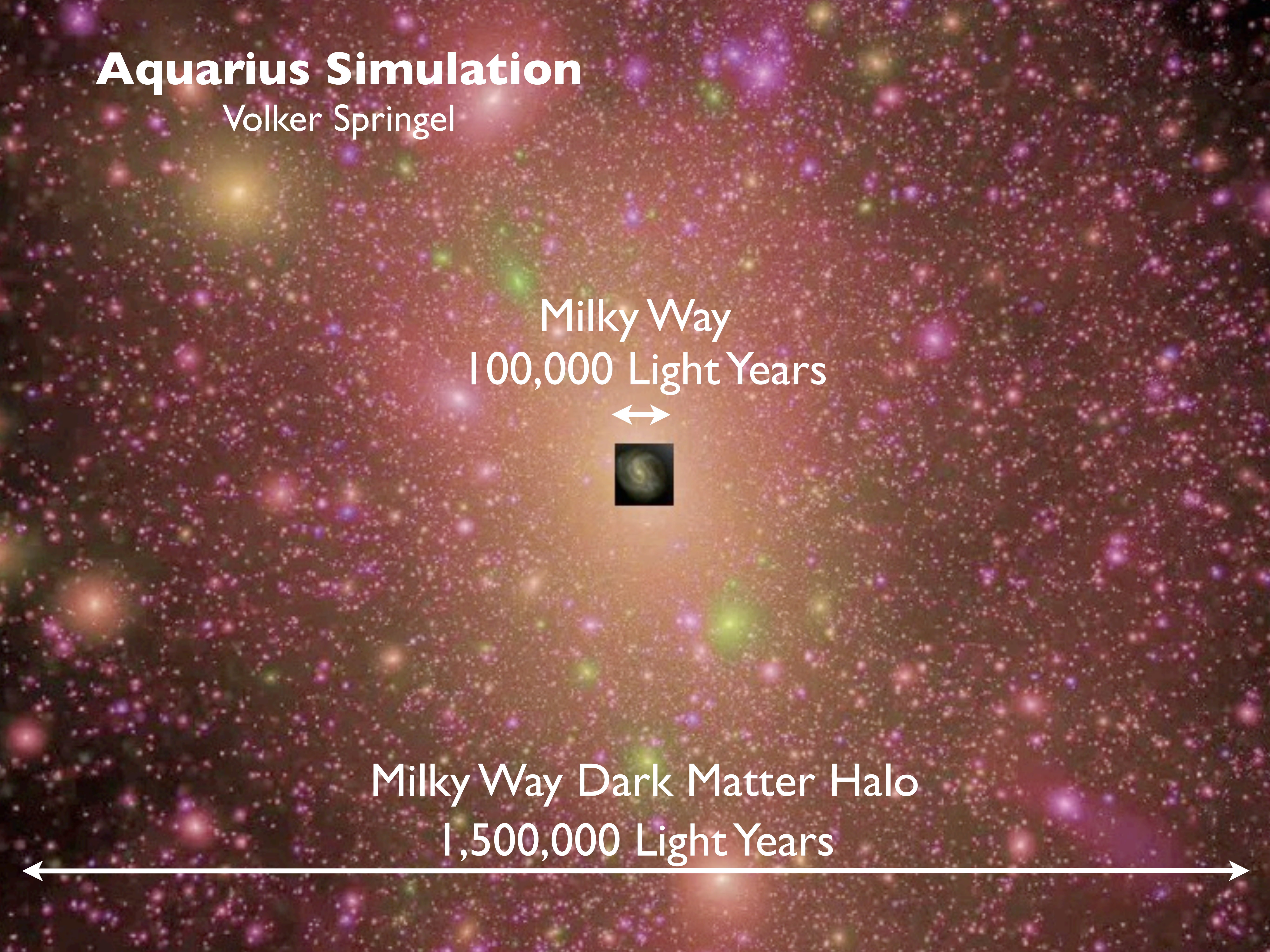


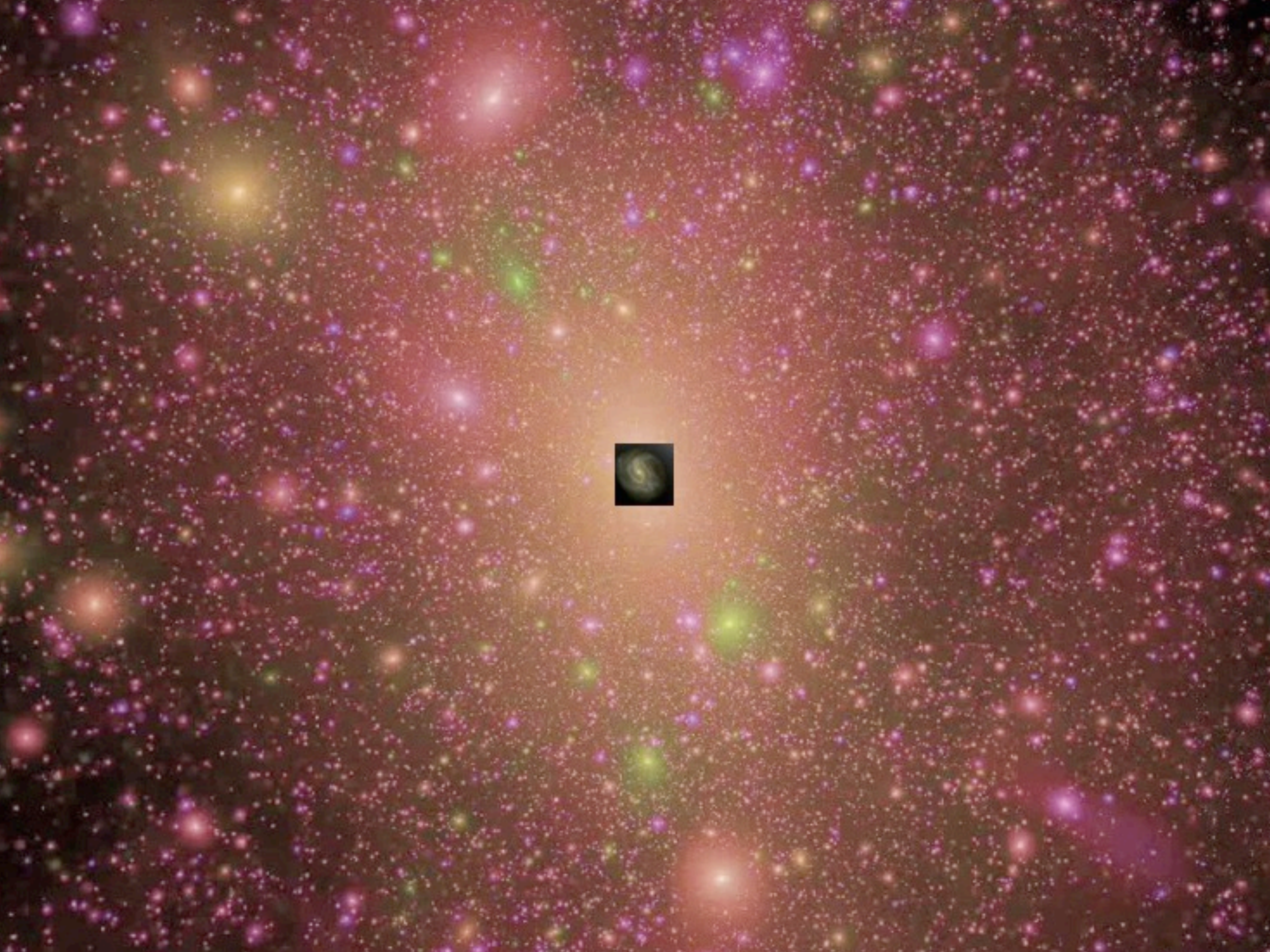
Cosmological Simulations

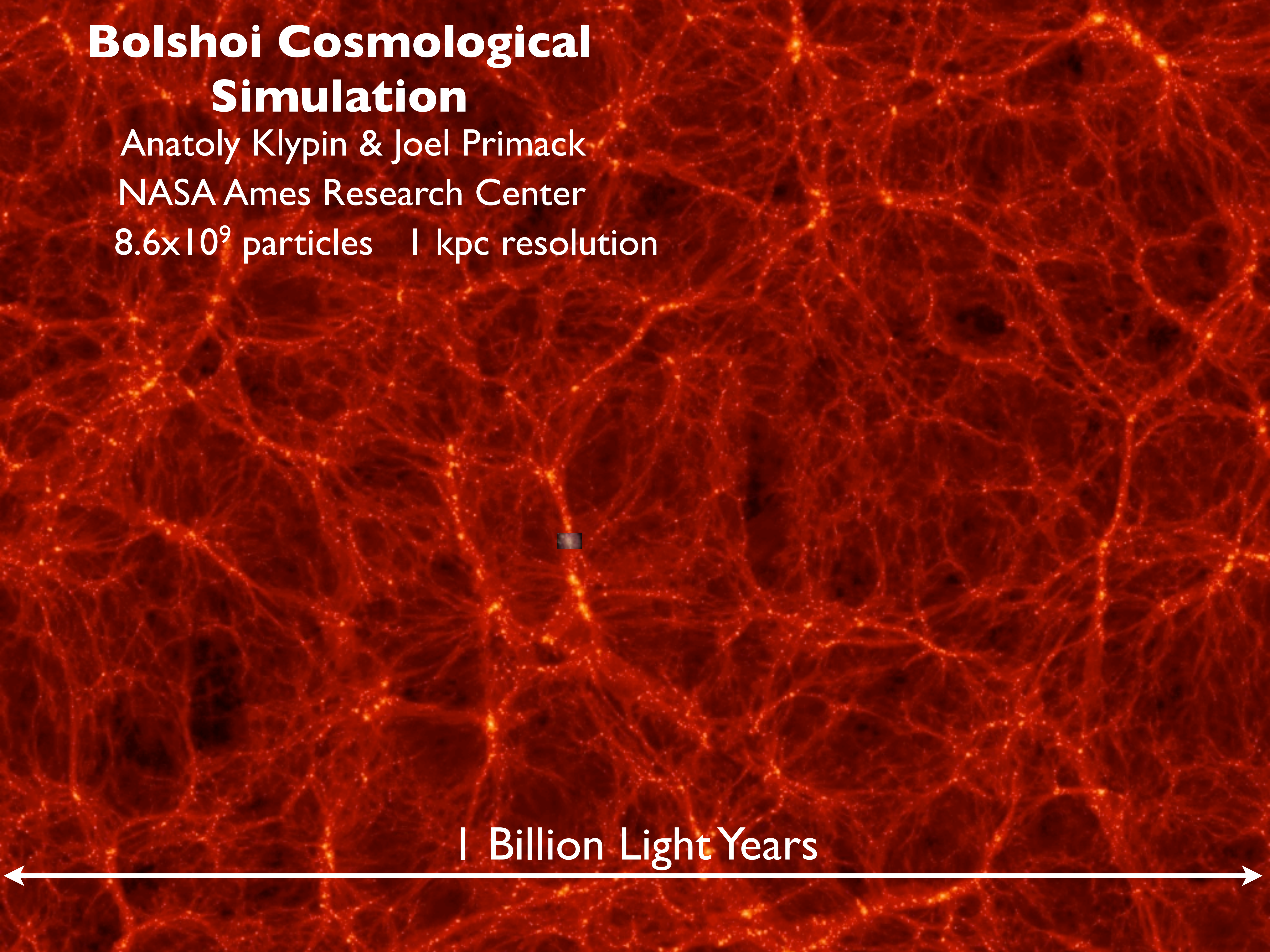
Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

Cosmological dark matter simulations show large scale structure, growth of structure, and dark matter halo properties

Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images in all wavebands including stellar evolution and dust

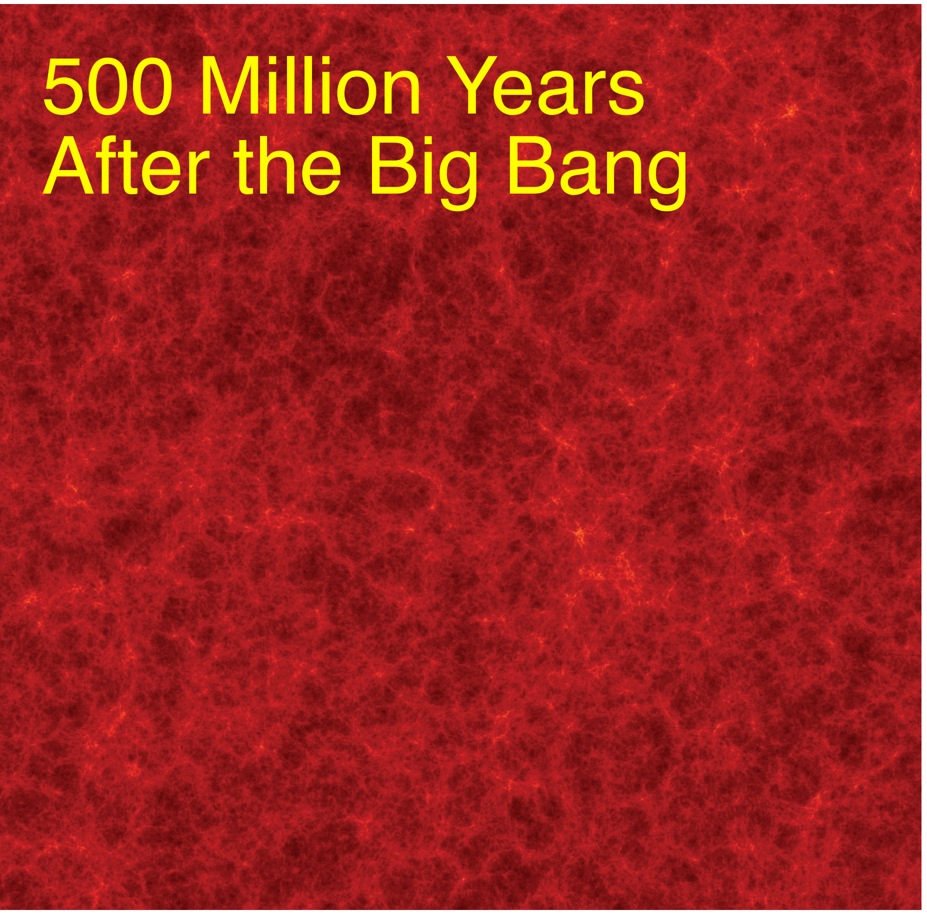

Aquarius Simulation
Volker Springel
Milky Way
100,000 Light Years
Milky Way Dark Matter Halo
1,500,000 Light Years

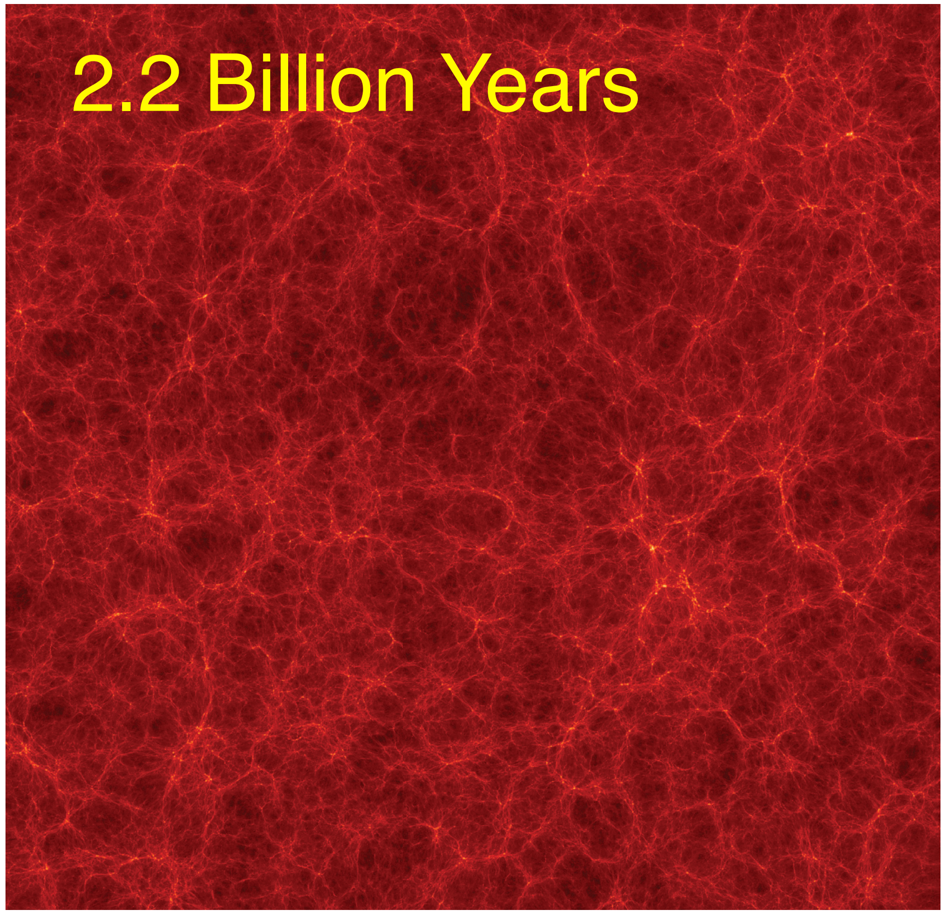




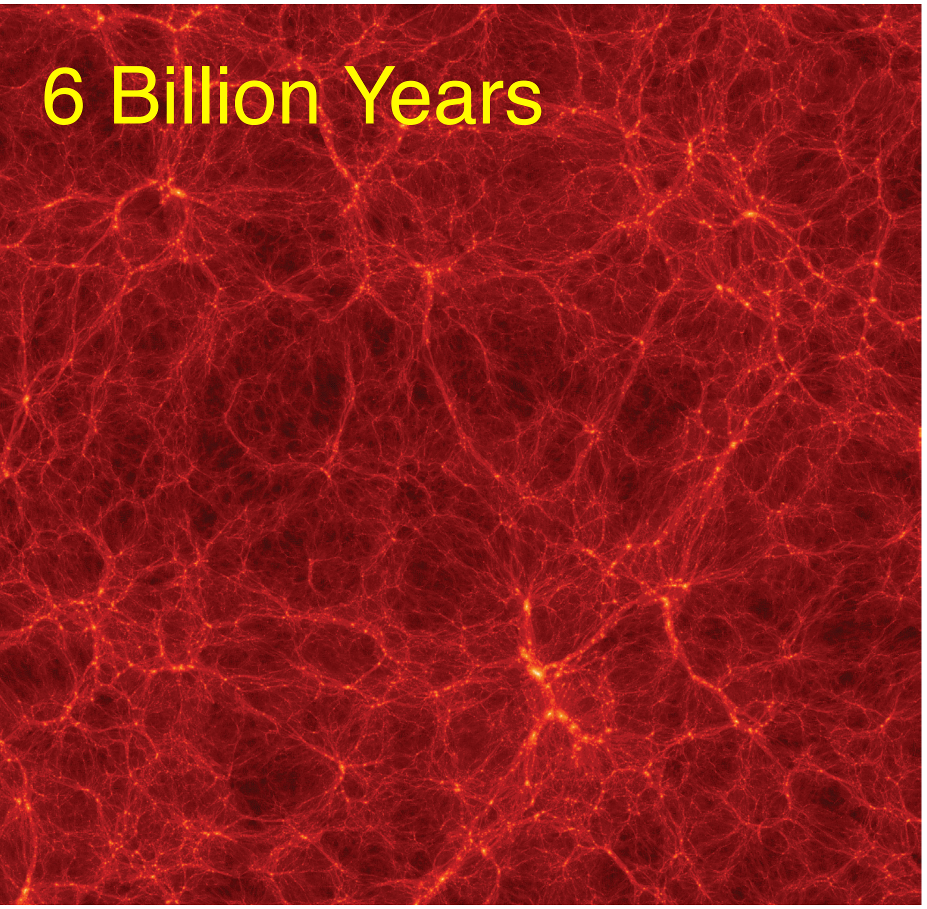
Bolshoi Cosmological Simulation
Anatoly Klypin & Joel Primack
NASA Ames Research Center
8.6x10^{9} particles 1 kpc resolution
1 Billion Light Years

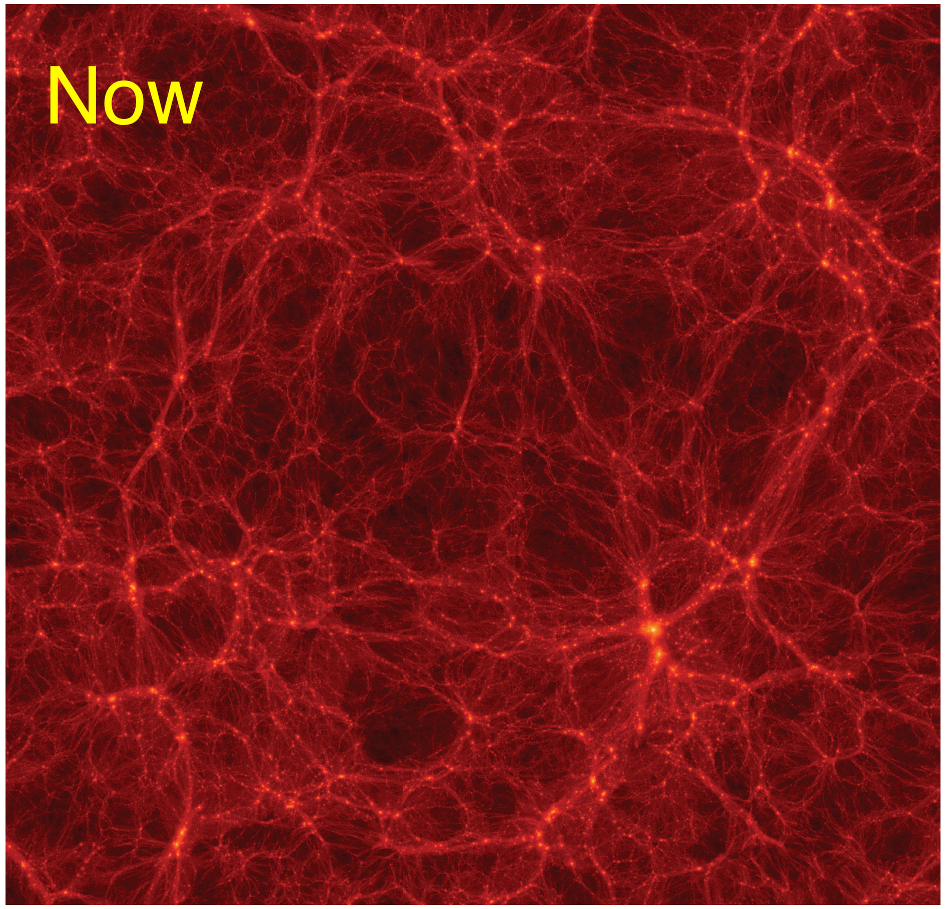
IEEE Spectrum - October 2012





THE UNIVERSE IN A SUPERCOMPUTER





COSMIC WEB: The Bolshoi simulation models the evolution of dark matter, which is responsible for the large-scale structure of the universe. Here, snapshots from the simulation show the dark matter distribution at 500 million and 2.2 billion years [top] and 6 billion and 13.7 billion years [bottom] after the big bang. These images are 50-million-light-year-thick slices of a cube of simulated universe that today would measure roughly 1 billion light-years on a side and encompass about 100 galaxy clusters.

SOURCES: SIMULATION, ANATOLY KLYPIN AND JOEL R. PRIMACK; VISUALIZATION, STEFAN GOTTLÖBER/LEIBNIZ INSTITUTE FOR ASTROPHYSICS POTSDAM

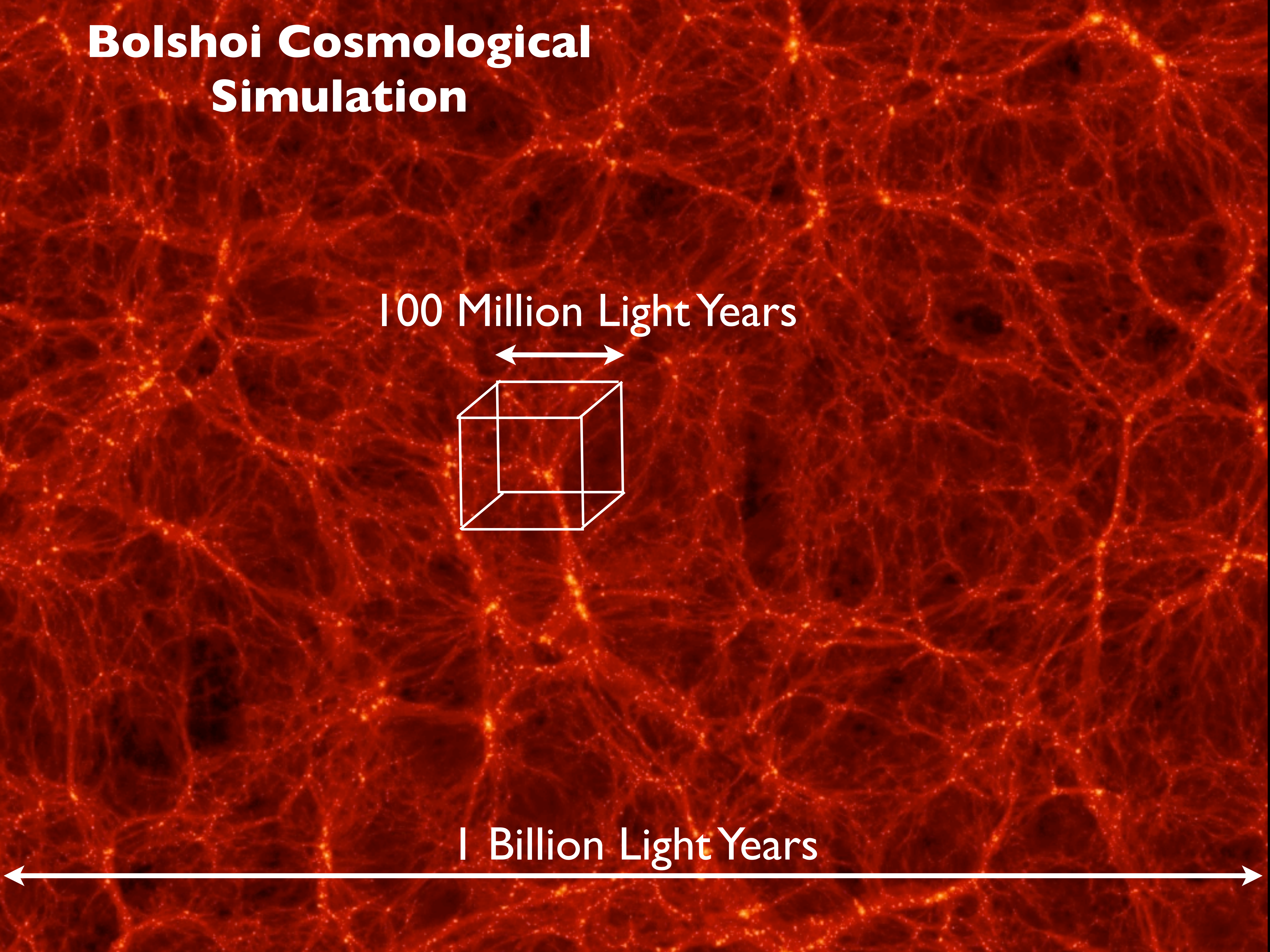
To understand the cosmos, we must evolve it all over again

By Joel R. Primack

WHEN IT COMES TO RECONSTRUCTING THE PAST, you might think that astrophysicists have it easy. After all, the sky is awash with evidence. For most of the universe's history, space has been largely transparent, so much so that light emitted by distant galaxies can travel for billions of years before finally reaching Earth. It might seem that all researchers have to do to find out what the universe looked like, say, 10 billion years ago is to build a telescope sensitive enough to pick up that ancient light.

Actually, it's more complicated than that. Most of the ordinary matter in the universe—the stuff that makes up all the atoms, stars, and galaxies astronomers can see—is invisible, either sprinkled throughout intergalactic space in tenuous forms that emit and absorb little light or else swaddled inside galaxies in murky clouds of dust and gas. When astronomers look out into the night sky with their most powerful telescopes, they can see no more than about 10 percent of the ordinary matter that's out there.

To make matters worse, cosmologists have discovered that if you add up all the mass and energy in the universe, only a small fraction is composed of ordinary matter. A good 95 percent of the cosmos is made up of two very different kinds of invisible and as-yet-unidentified stuff that is "dark," meaning that it emits and absorbs no light at all. One of these mysterious components, called dark matter, seems immune to all fundamental forces except gravity and perhaps the weak interaction, which is responsible for

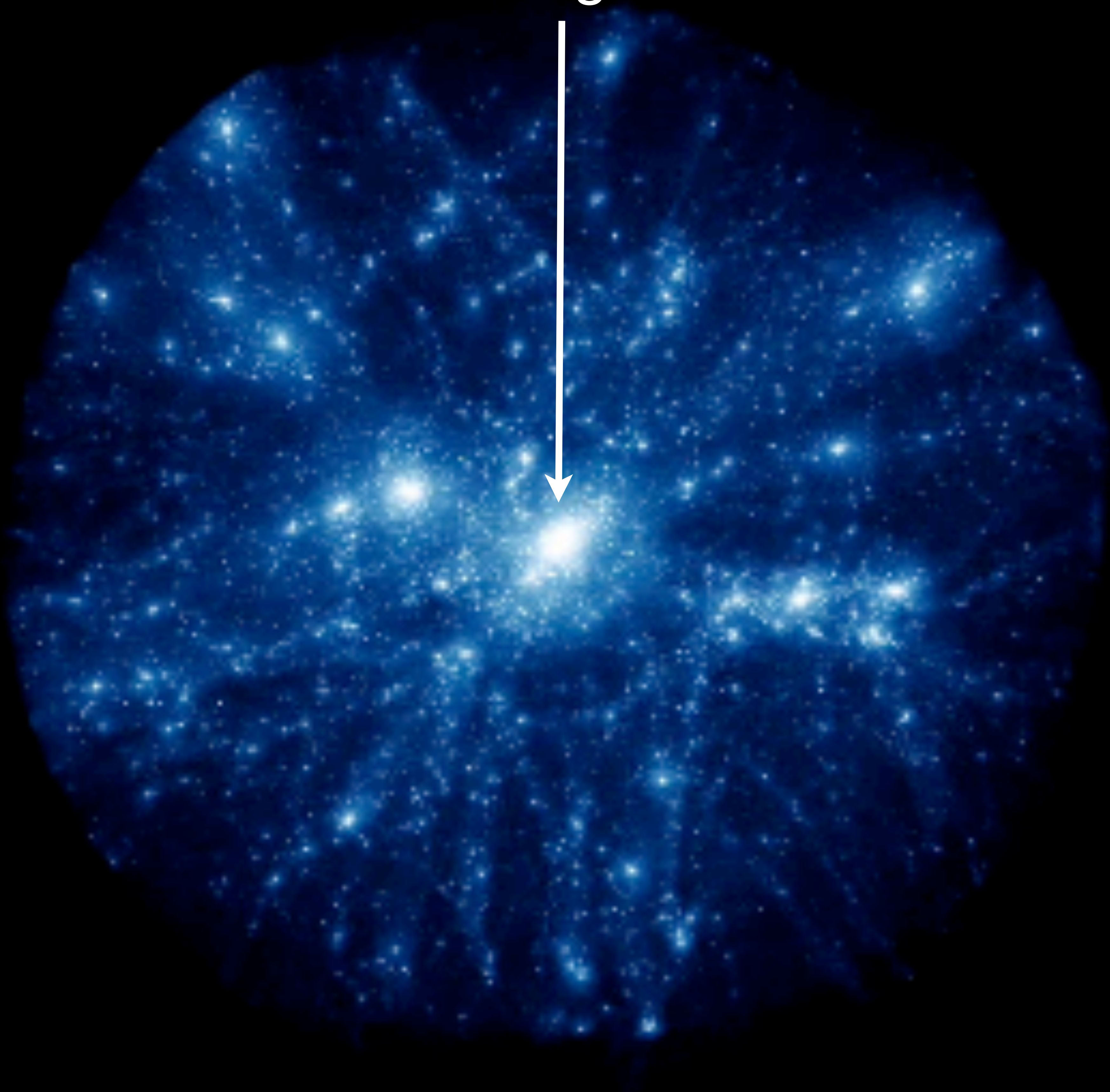

Bolshoi Cosmological Simulation
100 Million Light Years
1 Billion Light Years

Bolshoi Cosmological Simulation

100 Million Light Years

↔

How the Halo of the Big Cluster Formed



How the Halo of the Big Cluster Formed

Merger Tree (History) of All the Halos that Have Merged by Today

Peter Behroozi

Dark Matter Only simulations on Cosmic, Cluster, & Galactic scales

Name	Code	L_{box} [h^{-1} Mpc]	N_p [10^9]	m_p [h^{-1} $M_\odot$]	ε_{soft} [h^{-1} kpc]
Cosmic					
DEUS FUR	Ramses-Deus	21,000	550	1.2×10^{12}	40.0[a]
Horizon Run 3	GotPM	10,815	370	2.5×10^{11}	150.0
Millennium-XXL	Gadget-3	3000	300	6.2×10^9	10.0
Horizon-4Π	Ramses	2000	69	7.8×10^9	7.6[a]
Millennium	Gadget-2	500	10	8.6×10^8	5.0
Millennium-II	Gadget-3	100	10	6.9×10^6	1.0
MultiDark Run1	Art	1000	8.6	8.7×10^9	7.6[a]
Bolshoi	Art	250	8.6	1.4×10^8	1.0[a]

Name	Code	L_{hires} [h^{-1} Mpc]	$N_{p,hires}$ [10^9]	$m_{p,hires}$ [h^{-1} $M_\odot$]	ε_{soft} [h^{-1} kpc]
Cluster					
Phoenix A-1	Gadget-3	41.2	4.1	6.4×10^5	0.15

Name	Code	L_{hires} [Mpc]	$N_{p,hires}$ [10^9]	$m_{p,hires}$ [$M_\odot$]	ε_{soft} [pc]
Galactic					
Aquarius A-1	Gadget-3	5.9	4.3×10^9	1.7×10^3	20.5
GHalo	Pkdgrav2	3.89	2.1×10^9	1.0×10^3	61.0
Via Lactea II	Pkdgrav2	4.86	1.0×10^9	4.1×10^3	40.0

[a] For AMR simulations (Ramses, Art) ε_{soft} refers to the highest resolution cell width.

Table 2 in Kuhlen, Vogelsberger, Angulo 2012, Dark Universe 1, 50-93

Dark Matter Only simulations on Cosmic, Cluster, & Galactic scales

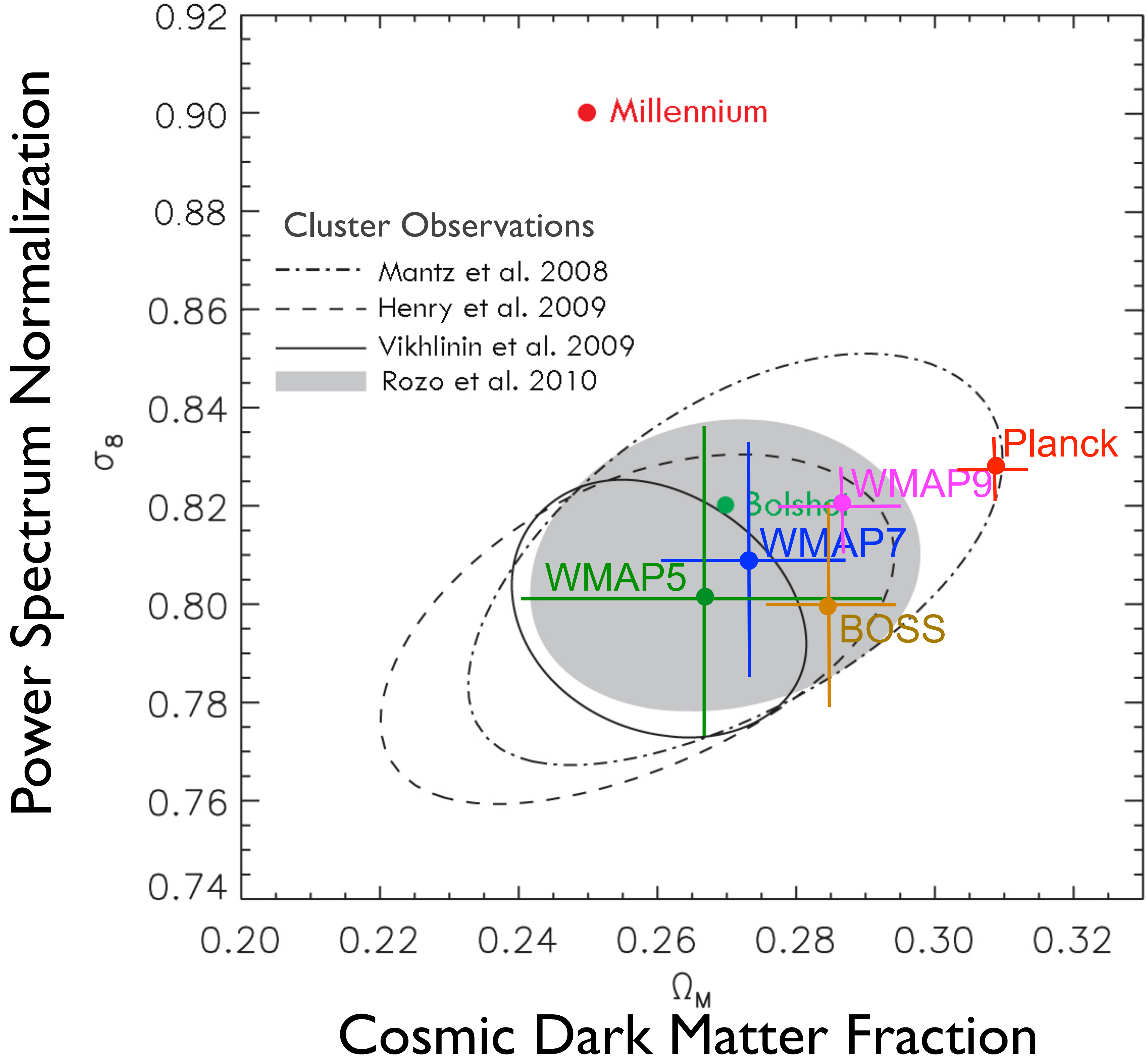
Supercomputers and computational resources utilized for each simulation.

Simulation	Supercomputer	Type	Center	Country	Core-hours [10^6]	N_{cores}	Memory [TB]	Disk space [TB]
DEUS FUR	*Curie Thin Nodes*	Bullx B510	Très Grand Centre de Calcul (TGCC)	France	10	38,016	230	3000
Horizon Run 3	*Tachyon II*	Sun Blades B6275	KISTI Supercomputing Center	Korea	4	8240	21	400
Millennium-XXL	*JuRoPa*	Bull/Sun Blades	Forschungzentrum Jülich	Germany	2.86	12,288	28.5	100
Horizon-4II	*Platine*	Bull Novascale 3045	Commissariat a l'Energie Atomique	France	8	6144	14.7	300
Millennium	*p690*	IBM Power 4	Rechenzentrum Garching	Germany	0.35	512	1	20
Millennium-II	*VIP*	IBM Power 6	Rechenzentrum Garching	Germany	1.4	2048	8	35
MultiDark Run1	*Pleiades*	SGI Altix ICE	NASA Ames Research Center	USA	0.4	4000	8	20
Bolshoi	*Pleiades*	SGI Altix ICE	NASA Ames Research Center	USA	6	13,900	12	100
Phoenix A-1	*DeepComp 7000*	HS21/ x3950 Cluster	Chinese Academy of Science	China	1.9	1024	3	15
Aquarius A-1	*HLRB-II*	SGI Altix 4700	Leibniz Rechenzentrum Garching	Germany	3.5	1024	3	45
GHalo	*Marenostrum*	IBM JS21 Blades	Barcelona Supercomputing Center	Spain	2	1000	1	60
Via Lactea II	*Jaguar*	Cray XT4	Oak Ridge National Lab	USA	1.5	3000	0.3	20

Table 3 in Kuhlen, Vogelsberger, Angulo 2012, Dark Universe 1, 50-93

Determination of σ_8 and Ω_M from CMB+

WMAP+SN+Clusters   Planck+WP+HighL+BAO



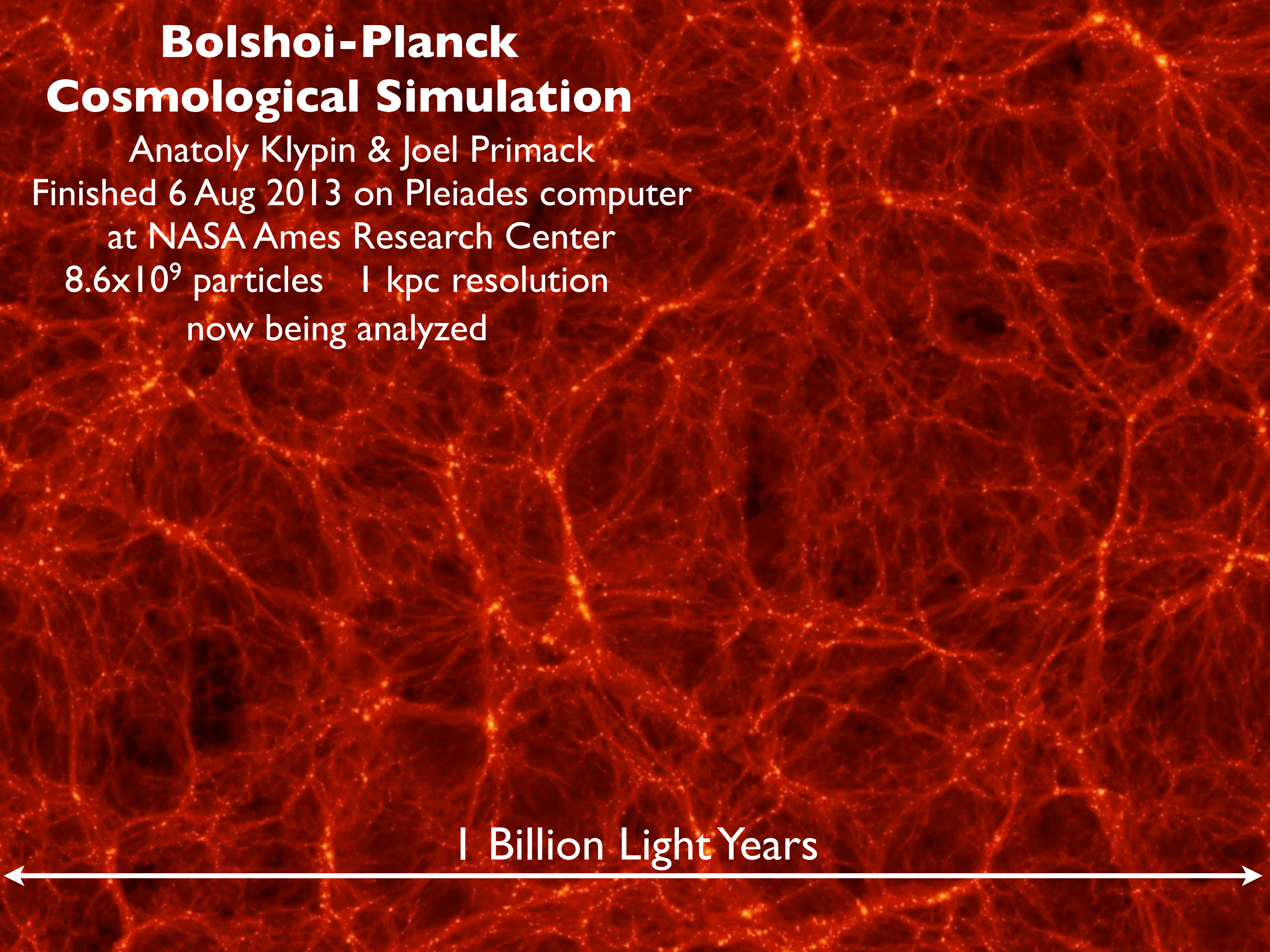
Bolshoi-Planck Cosmological Simulation

Anatoly Klypin & Joel Primack

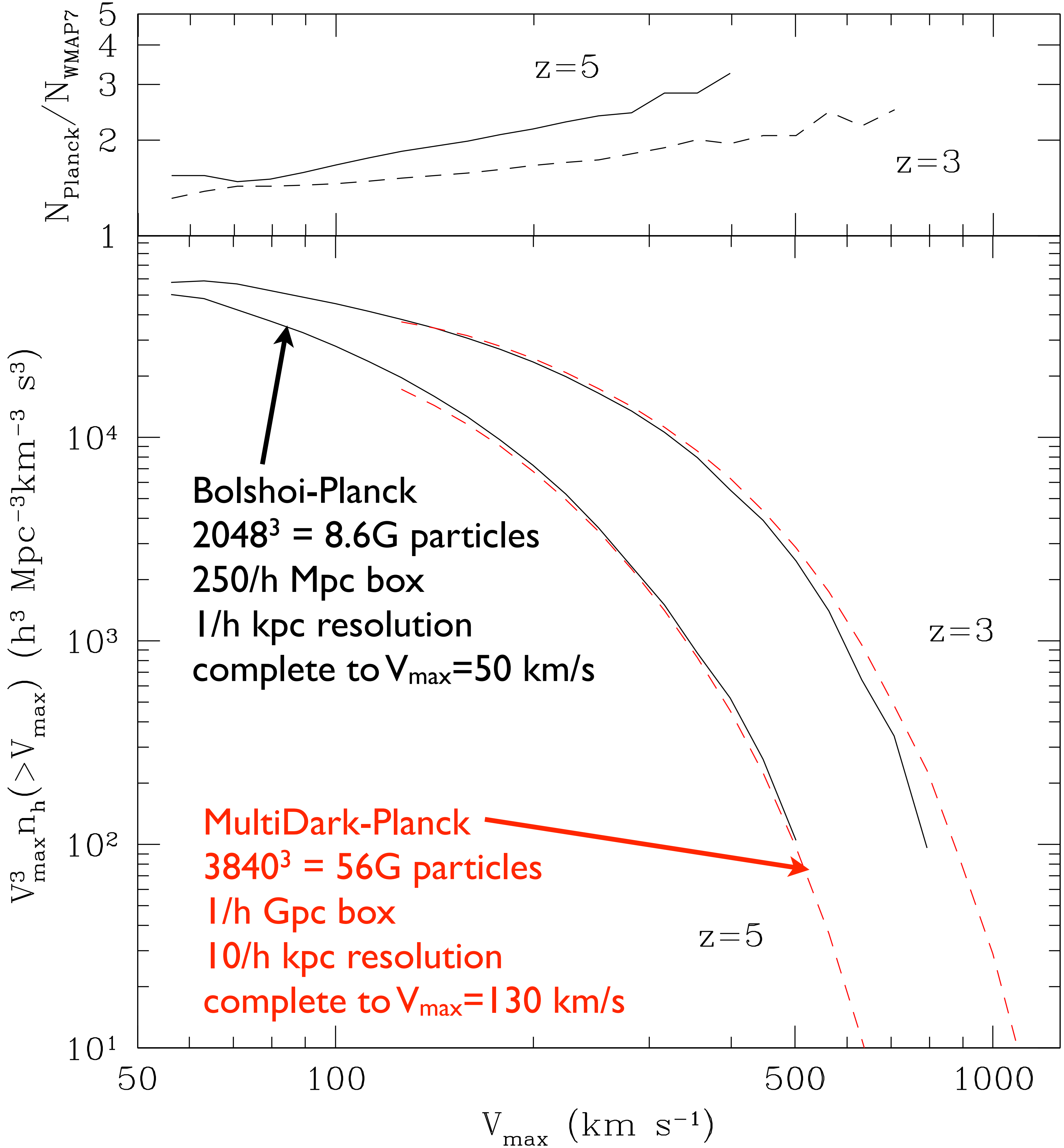
Finished 6 Aug 2013 on Pleiades computer at NASA Ames Research Center

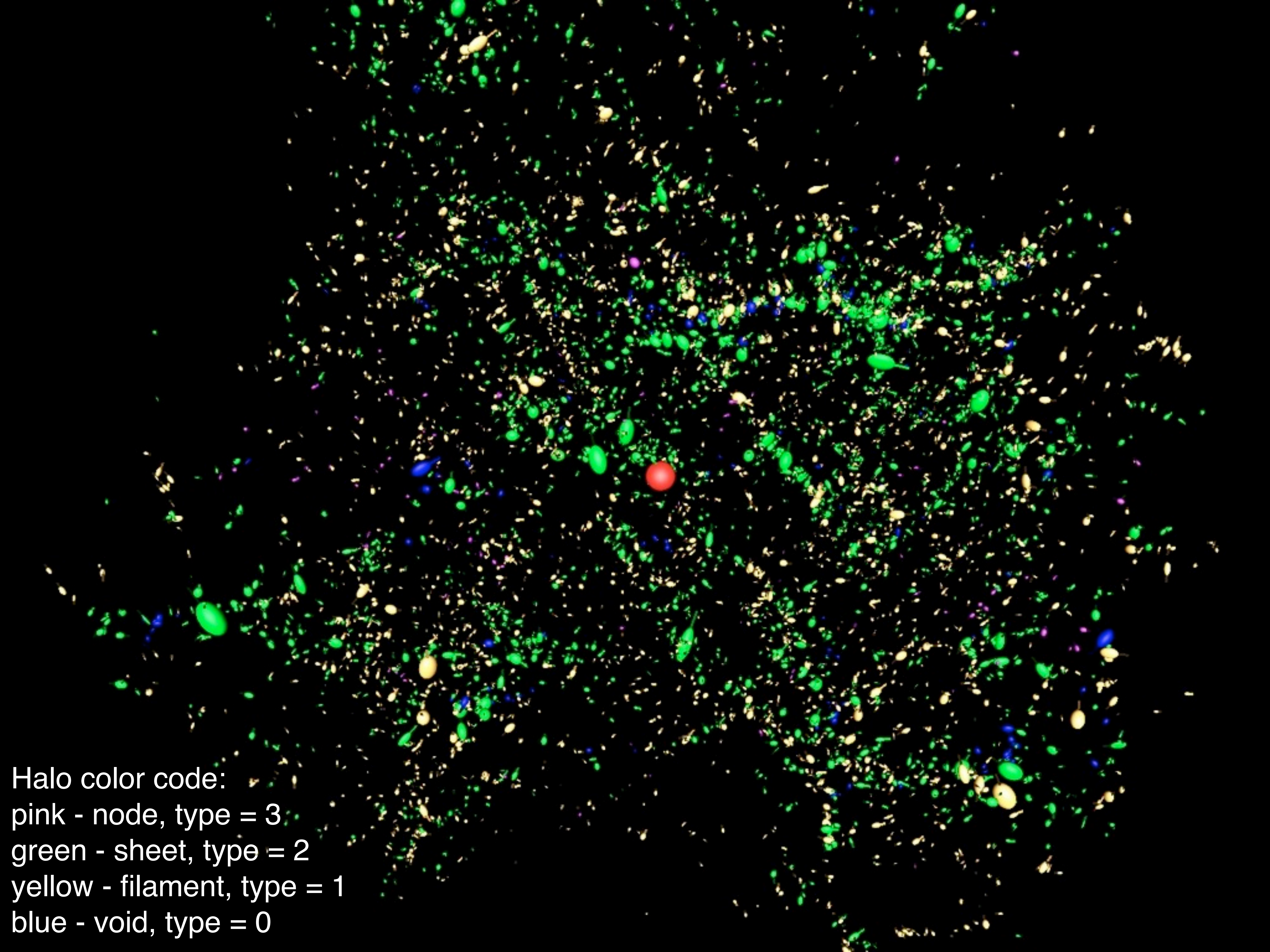
8.6×10^9 particles   1 kpc resolution

now being analyzed



Bolshoi-Planck has a lot more massive halos at high redshifts than Bolshoi!




Halo color code:
pink - node, type = 3
green - sheet, type = 2
yellow - filament, type = 1
blue - void, type = 0

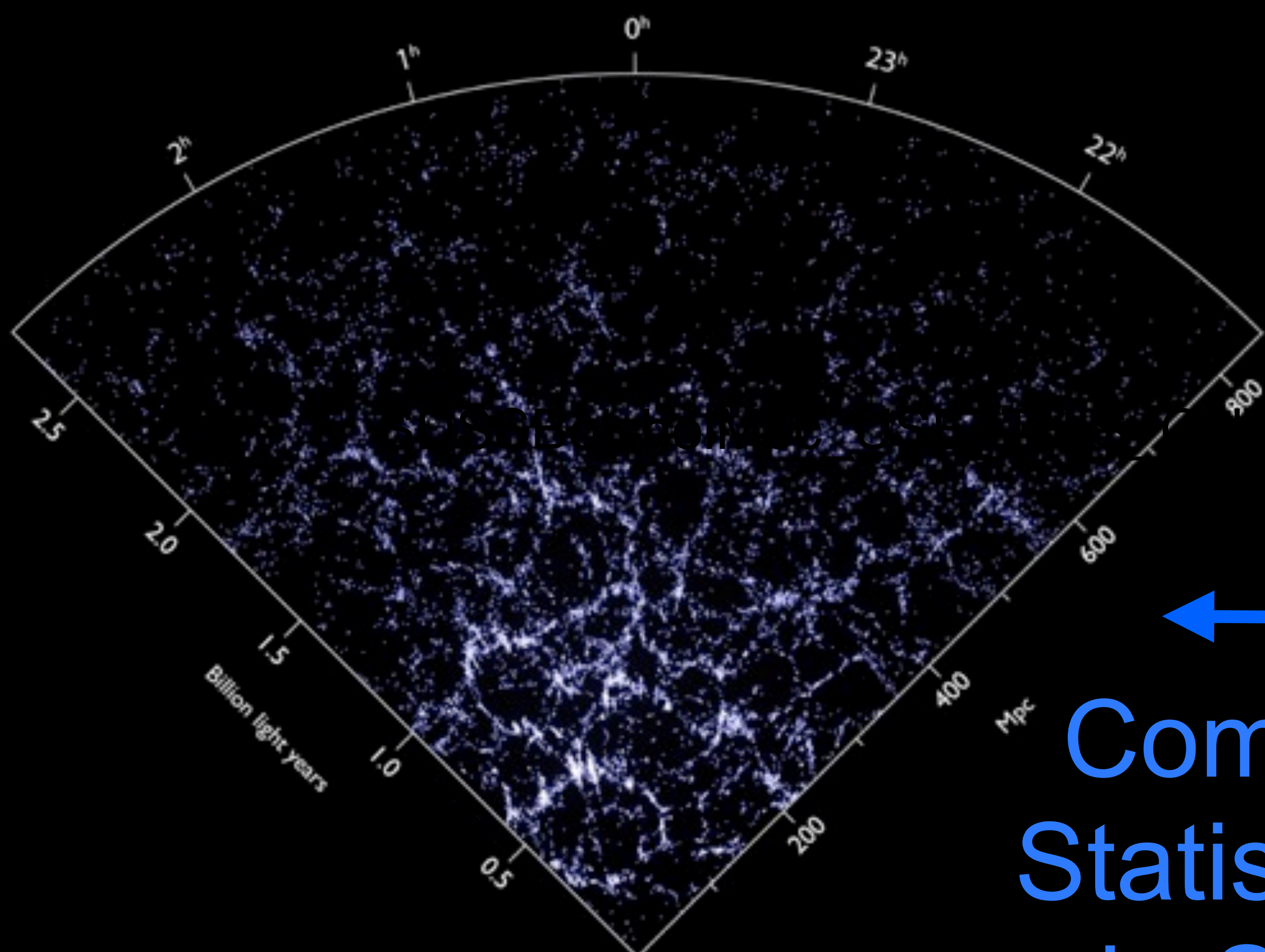
Observational Data

Sloan Digital Sky Survey

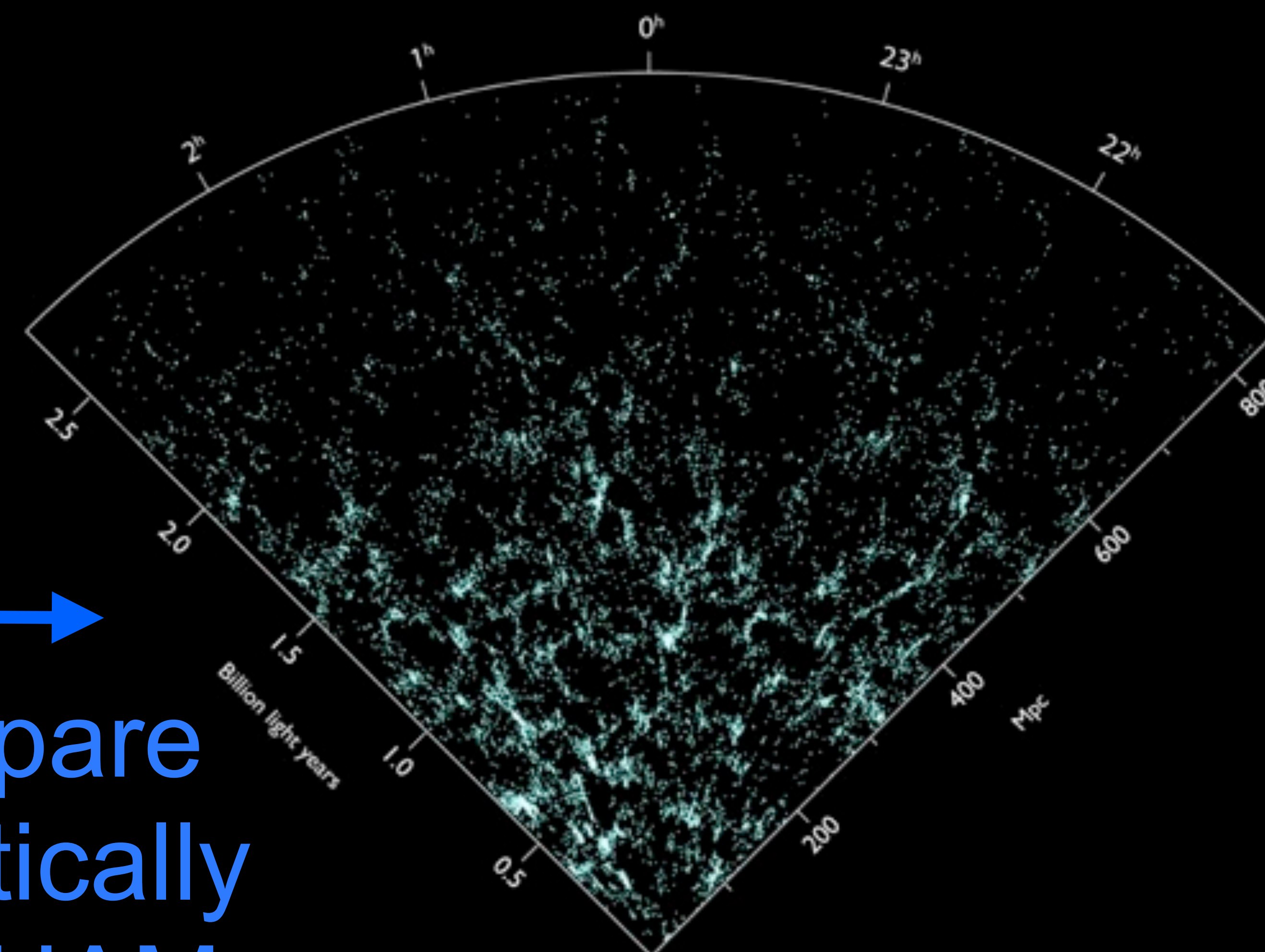
Bolshoi Simulation

Anatoly Klypin, Joel Primack, Peter Behroozi
Risa Wechsler, Ralf Kahler, Nina McCurdy

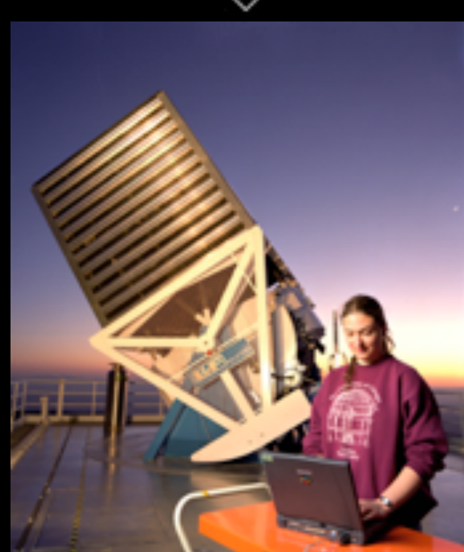
SDSS

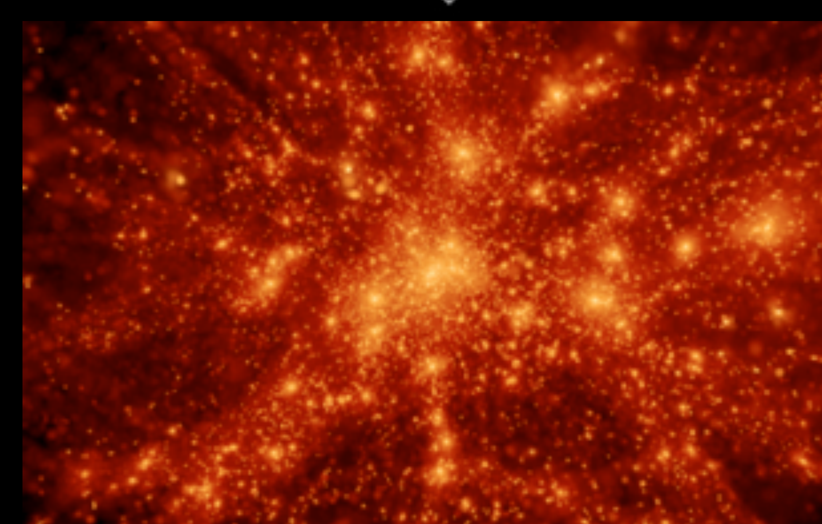


Bolshoi



Compare Statistically via SHAM

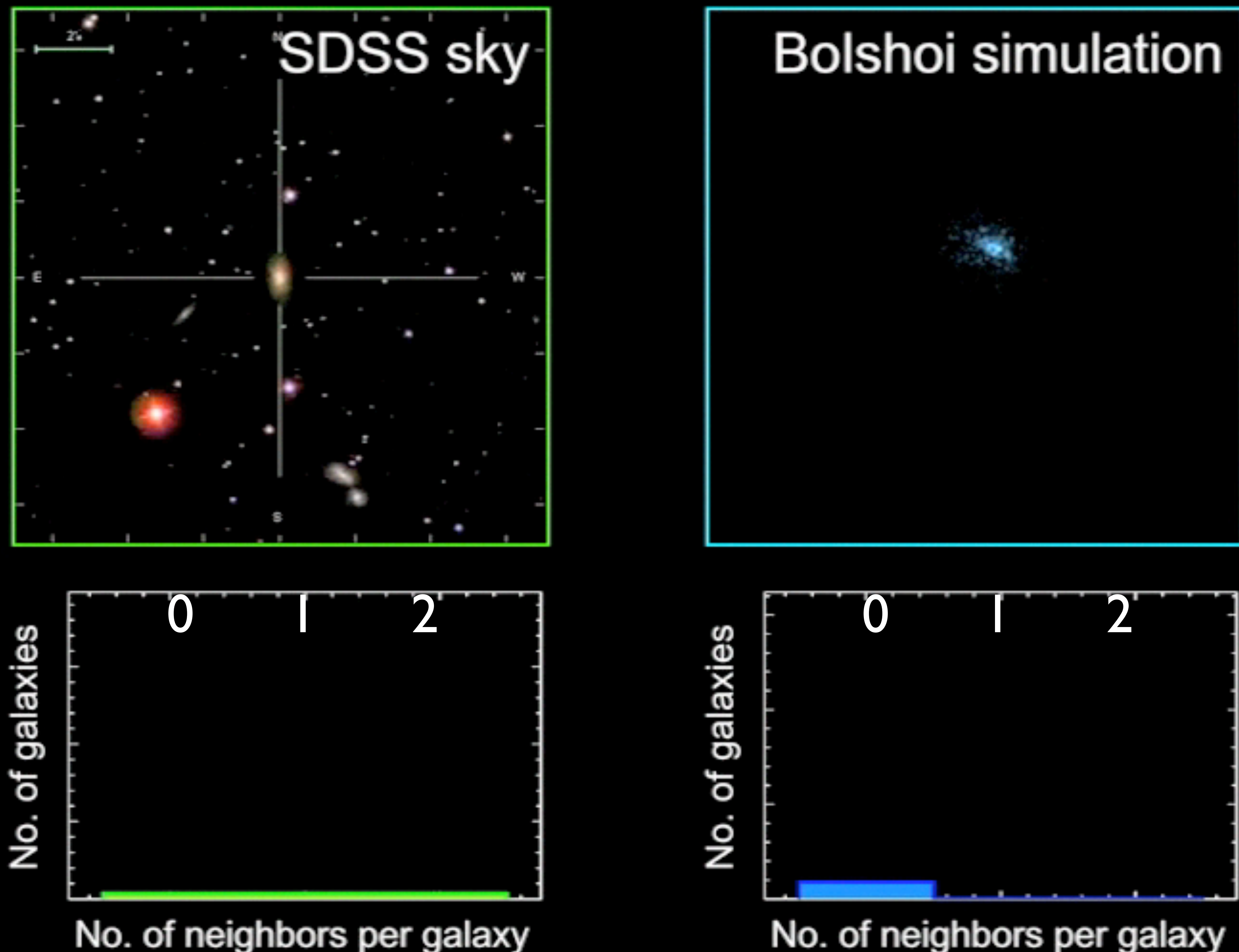




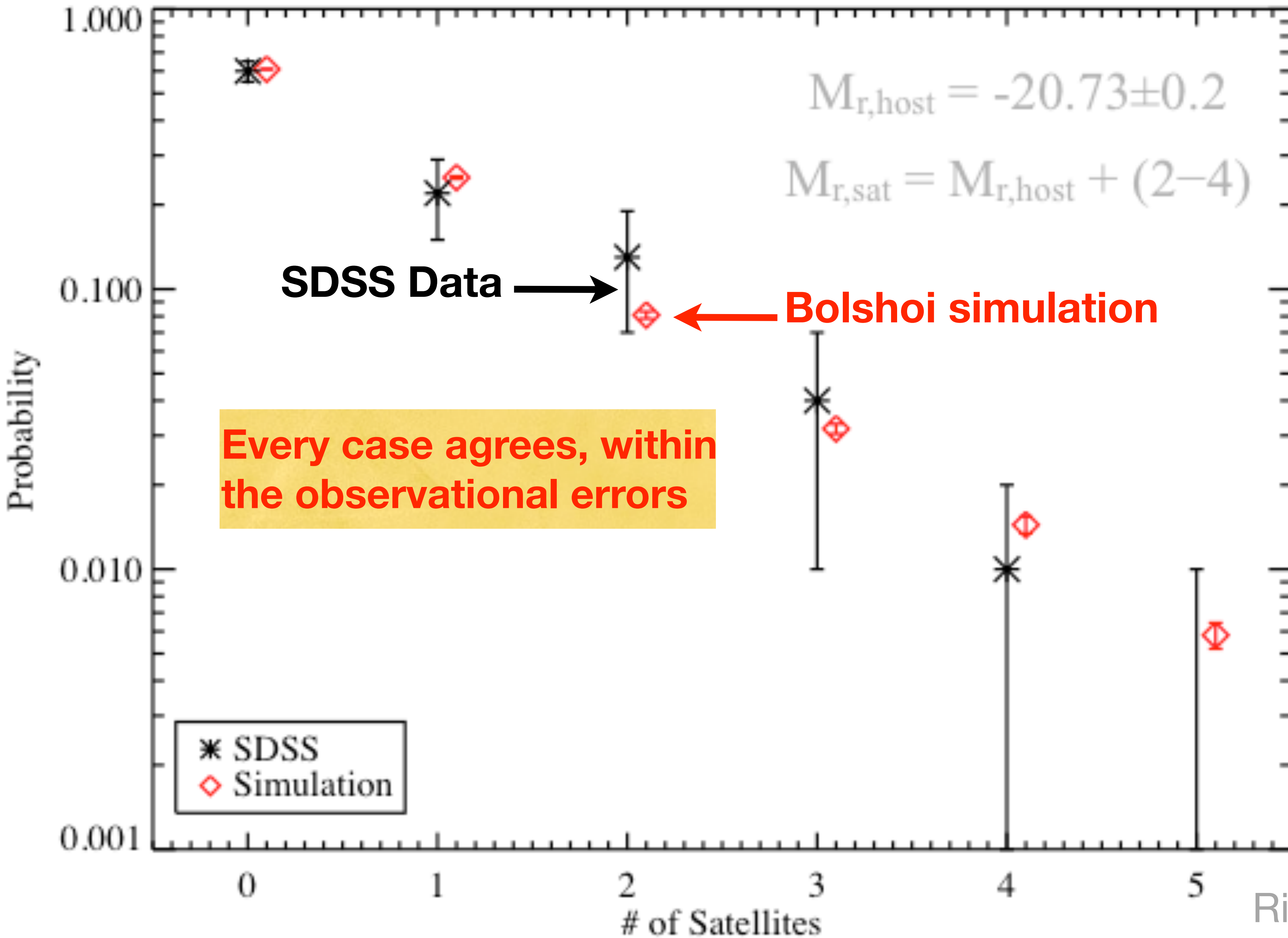
The Milky Way has two large satellite galaxies, the small and large Magellanic Clouds

How common is this?

The Bolshoi simulation + sub-halo abundance matching predict the likelihood of 0, 1, 2, 3, ... large satellites


SDSS sky
E
W
S
Bolshoi simulation
0
1
2
No. of galaxies
No. of neighbors per galaxy
0
1
2
No. of galaxies
No. of neighbors per galaxy

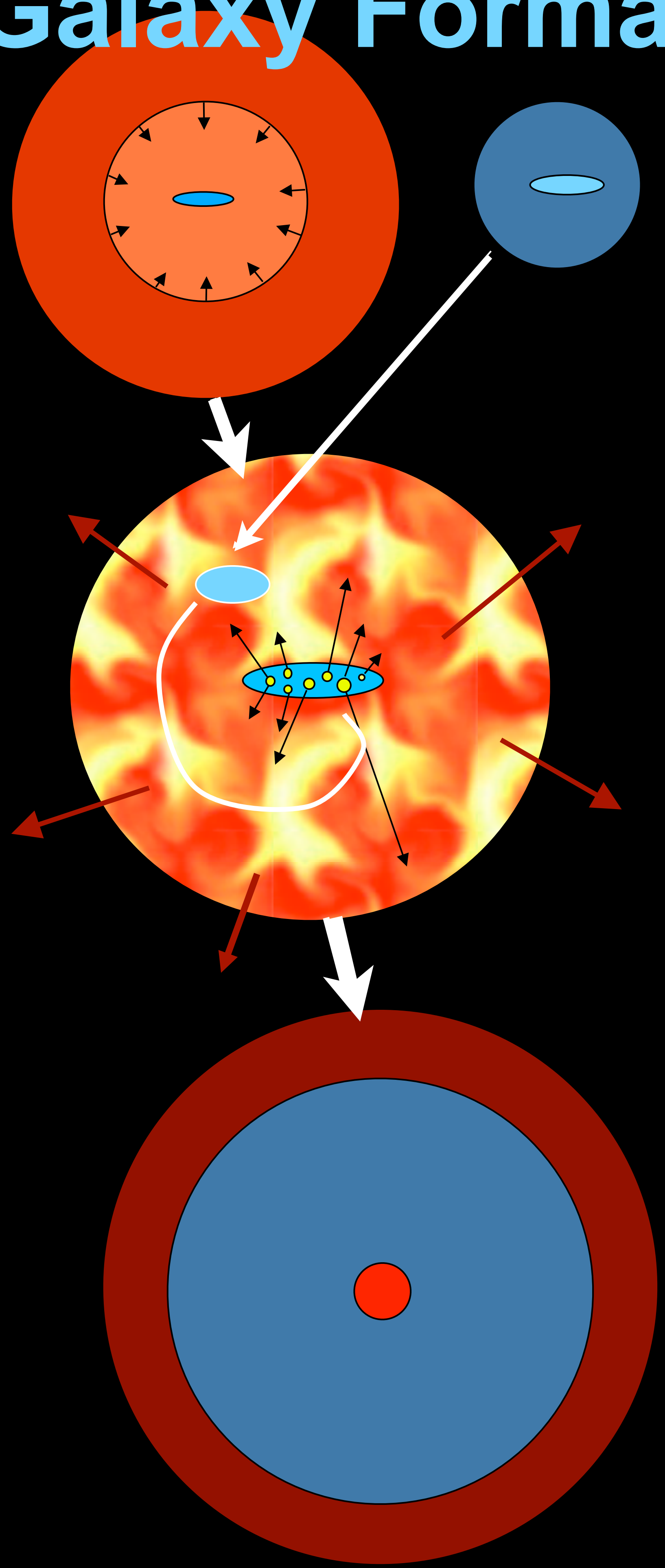
Statistics of MW bright satellites:
Sloan Digital Sky Survey data vs. Bolshoi simulation



Risa Wechsler

Busha et al. 2011 ApJ
Liu et al. 2011 ApJ

Galaxy Formation via SemiAnalytic Models



- gas is collisionally heated when perturbations ‘turn around’ and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law, metallicity effects?)
- massive stars and SNe reheat (and in small halos expel) cold gas and some metals
- galaxy mergers trigger bursts of star formation; ‘major’ mergers transform disks into spheroids and fuel AGN
- AGN feedback cuts off star formation
- **including effects of dissipation in gas-rich galaxy mergers leads to observed elliptical size-mass relation**
- **including spheroid formation by disk instability is essential to reproduce the observed elliptical luminosity function**

White & Frenk 91; Kauffmann+93; Cole+94; Somerville & Primack 99; Cole+00; Somerville, Primack, & Faber 01; Croton et al. 2006; Somerville +08; Fanidakis+09; Covington et al. 10, 11; Somerville, Gilmore, Primack, & Dominguez 11; Porter et al.

- Elliptical galaxies follow a size-mass relation. Our semi-analytic model correctly predicts this and the other scaling relations of elliptical galaxies.
- Disk galaxies follow a relation between their rotation velocity and their luminosity. The model also correctly predicts this.

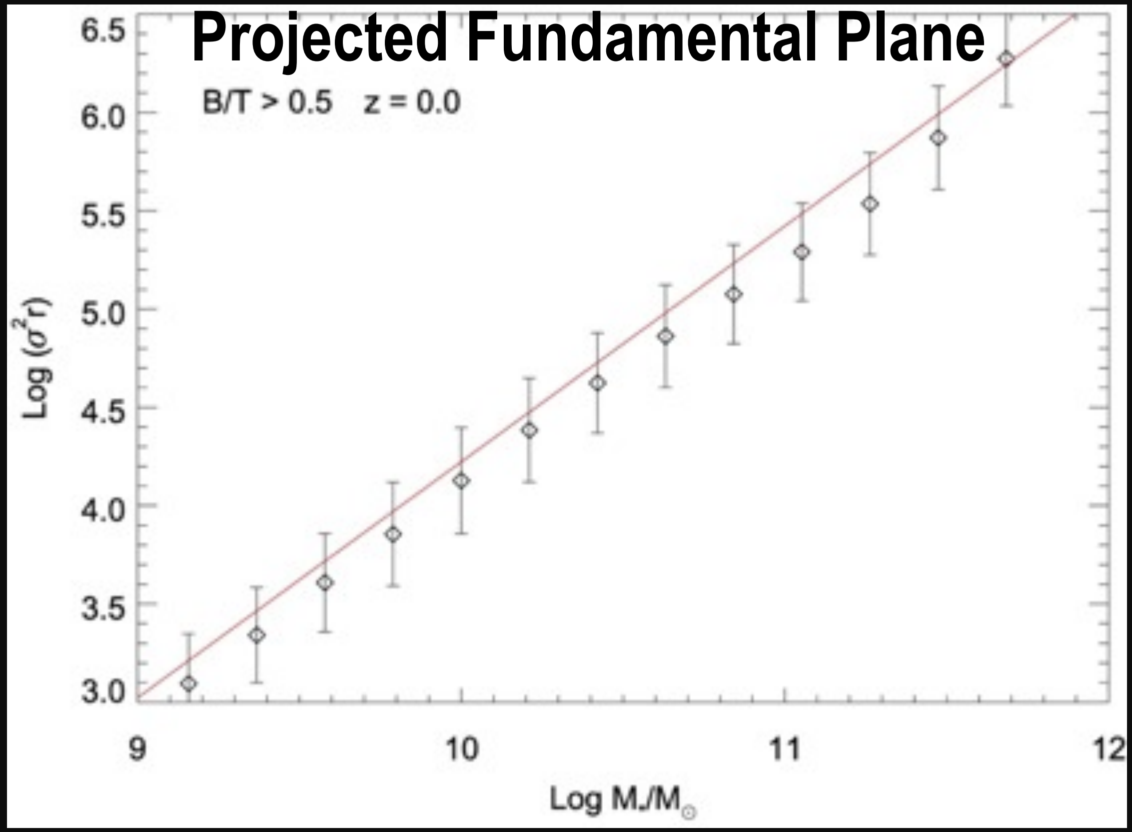




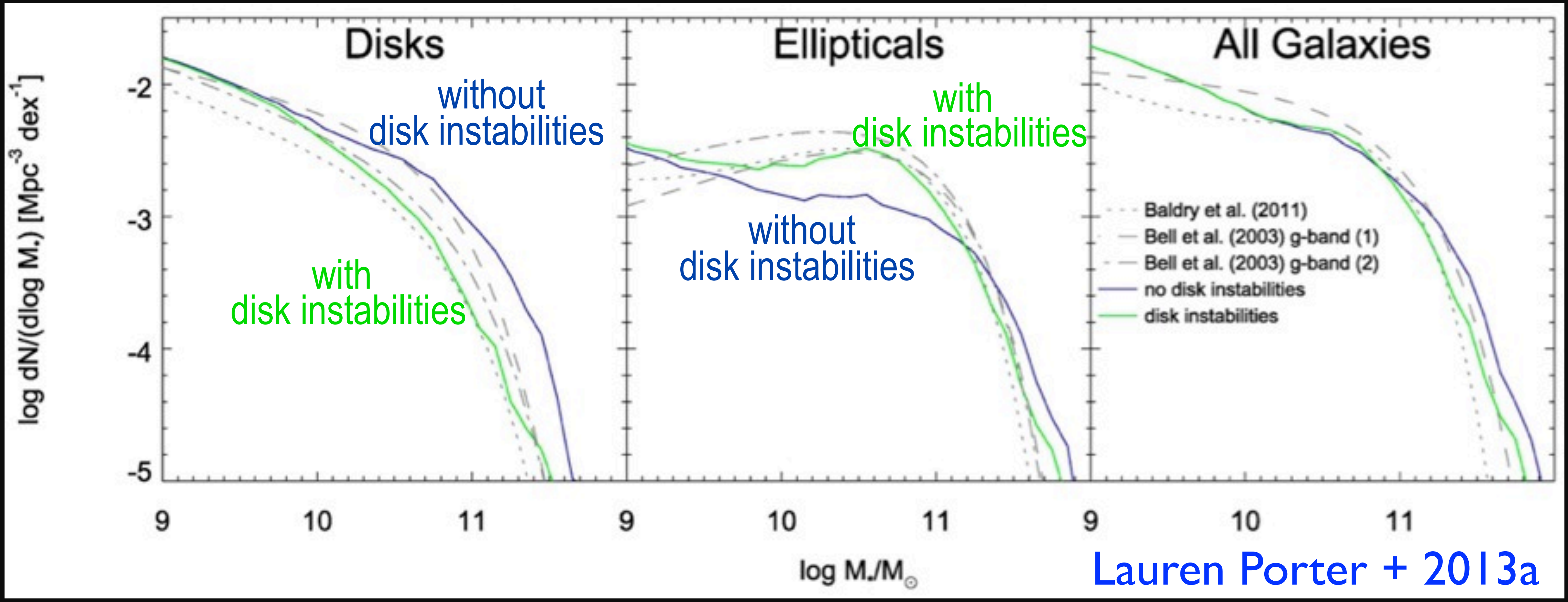



- Our semi-analytic model also correctly predicts the numbers of Disk galaxies and Elliptical galaxies of all masses.

SemiAnalytic Model Low-Redshift Galaxies



- Correctly reproduces the z=0 size-mass, Faber-Jackson, and Fundamental Plane relations
- Forming spheroids with major mergers + disk instabilities reproduces the morphology-selected z=0 mass function



Lauren Porter + 2013a

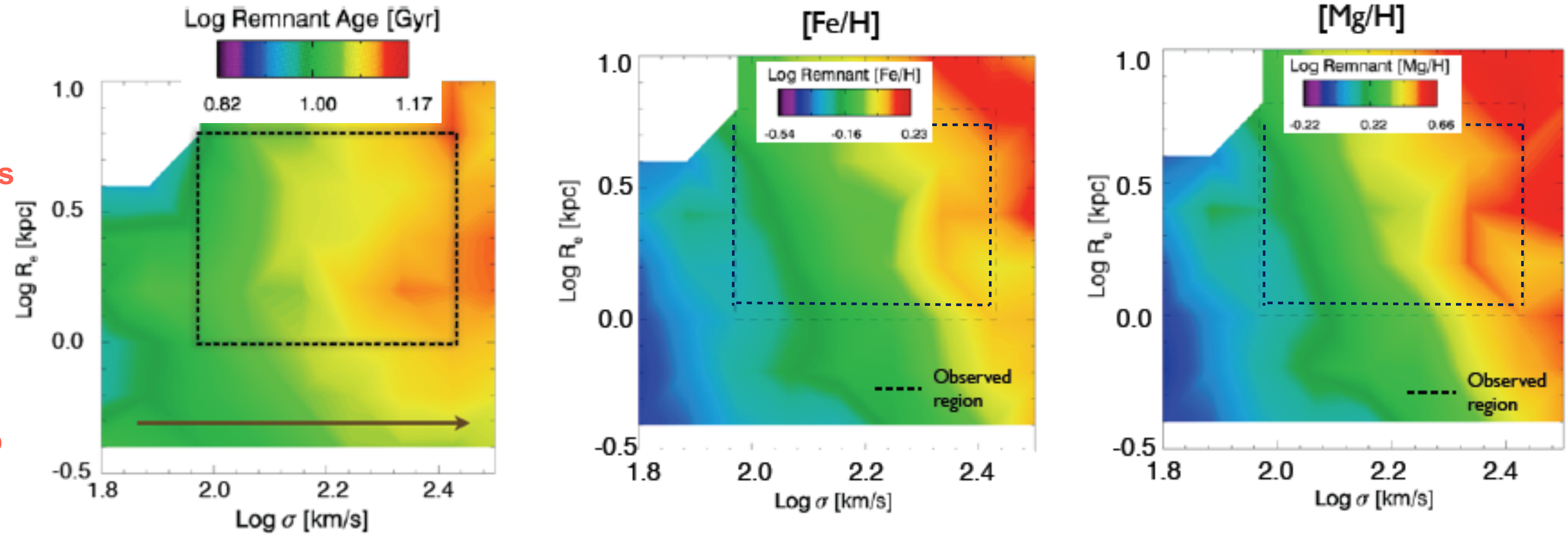
SAM Predictions vs. SDSS Observations

Galaxy Age

Galaxy Metallicity

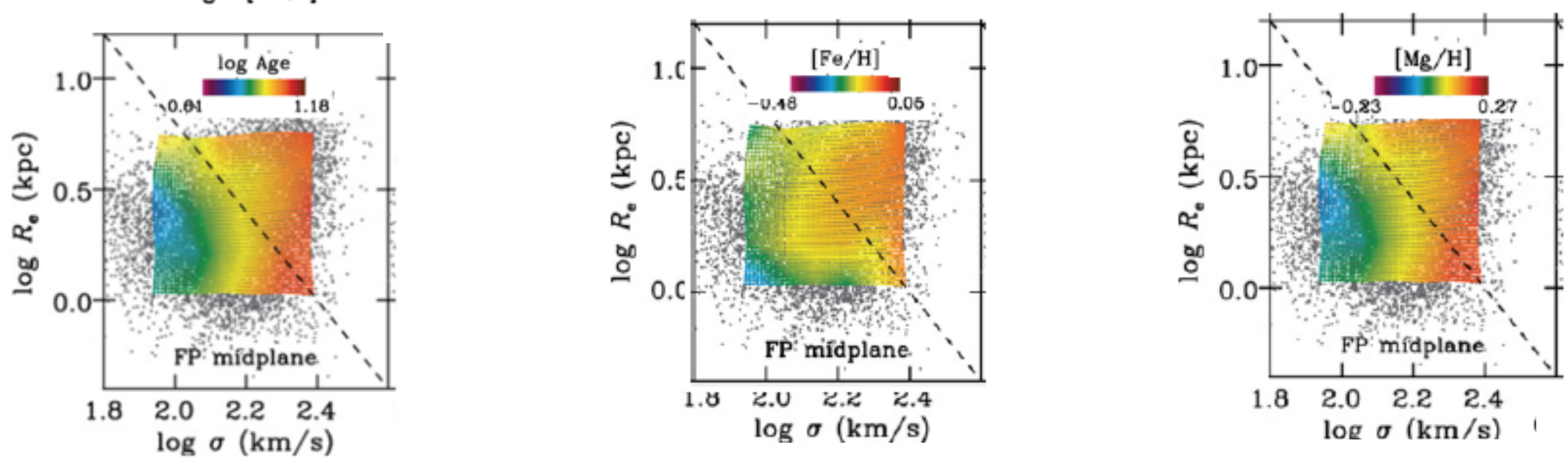
SAM
Predictions

Lauren Porter et al. 2013b



SDSS
Observations

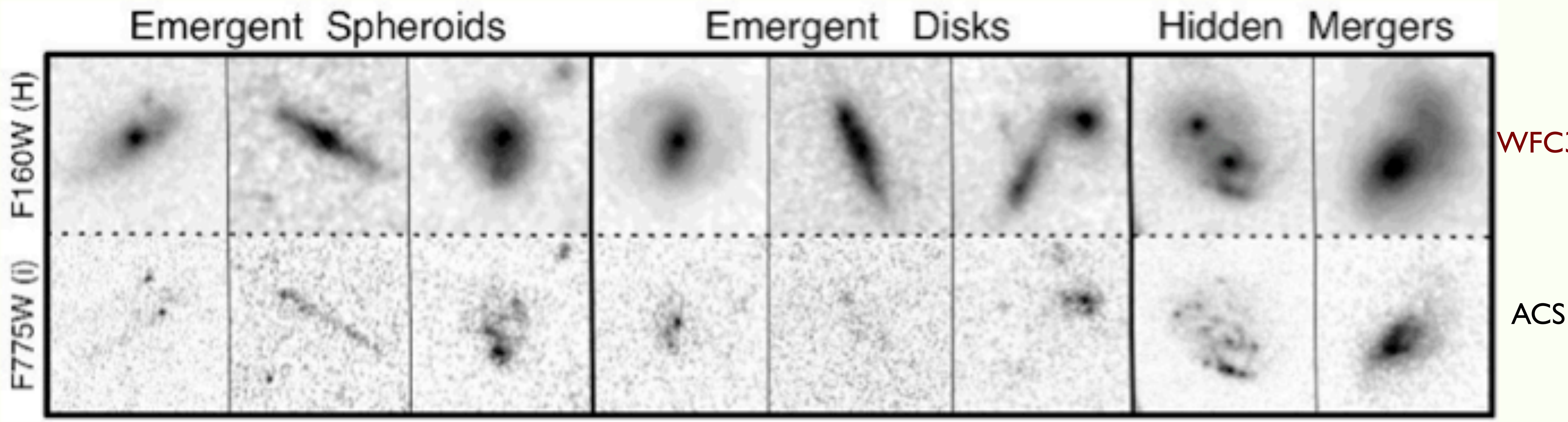
Jenny Graves et al. 2009



Lauren Porter + 2013b

The CANDELS Survey with new near-ir camera WFC3

GALAXIES ~10 BILLION YEARS AGO



CANDELS makes use of the near-infrared WFC3 camera (top row) and the visible-light ACS camera (bottom row). Using these two cameras, CANDELS will reveal new details of the distant Universe and test the reality of cosmic dark energy.

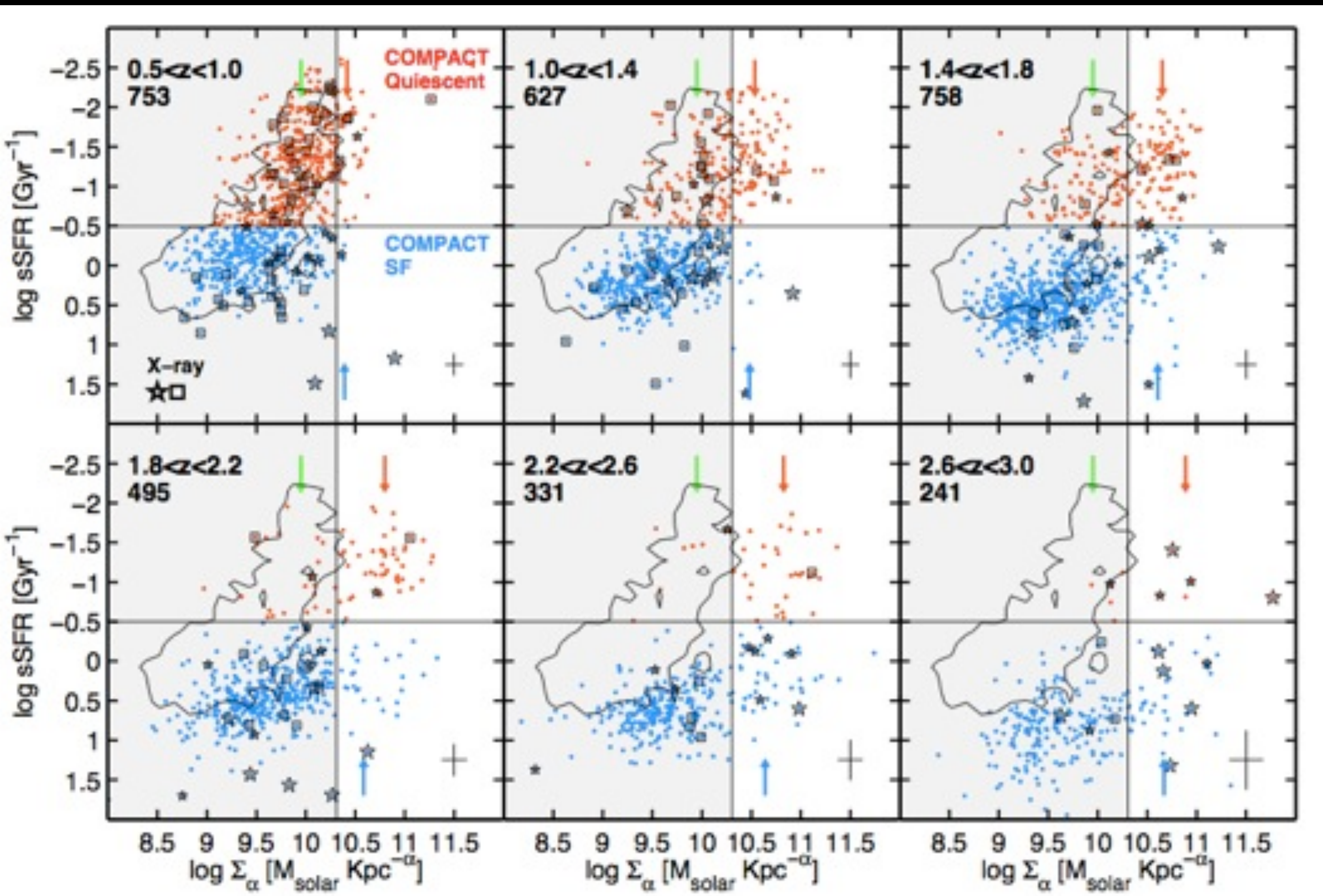
Hubble Space Telescope

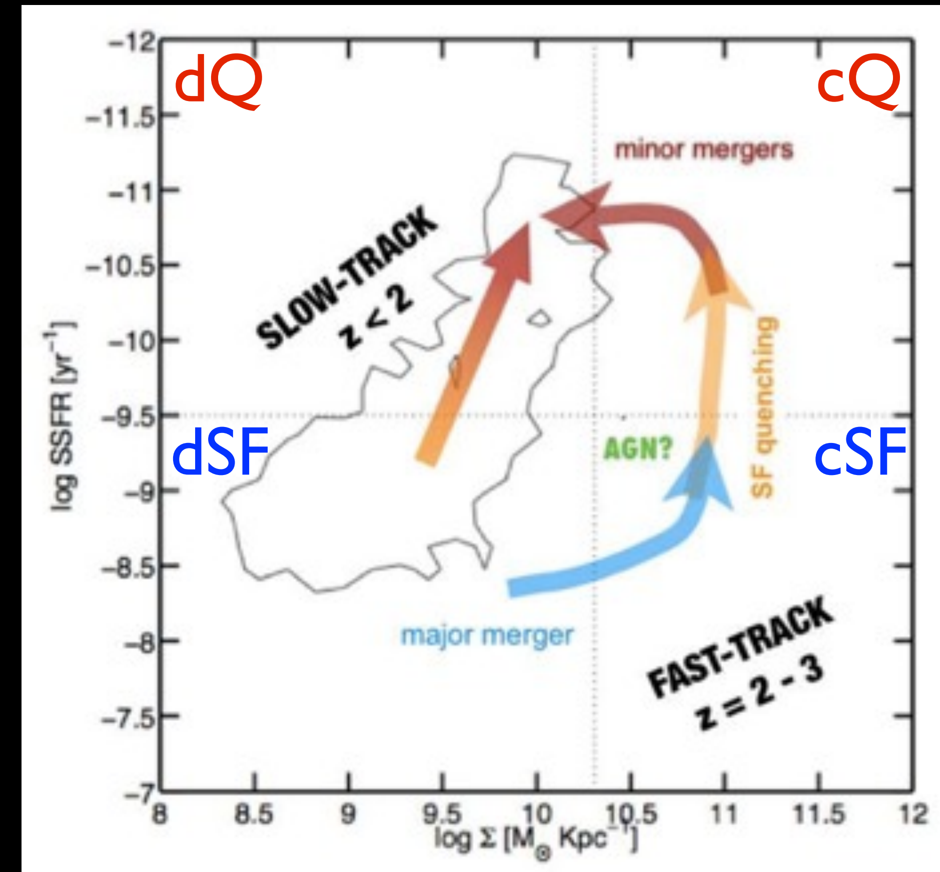
http://candels.ucolick.org

CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

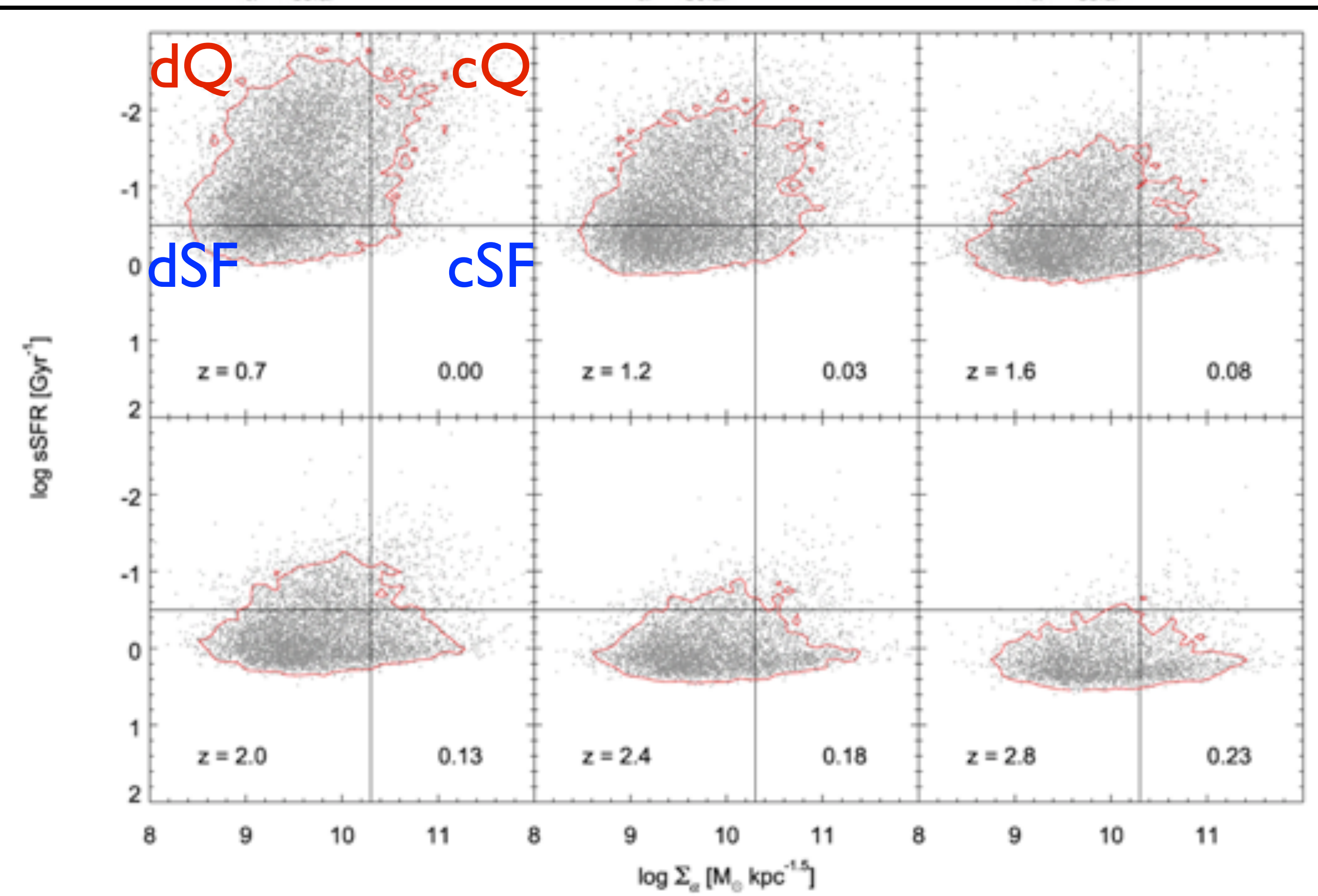
- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared WFC3 camera, installed on Hubble in May 2009. WFC3 is sensitive to longer, redder wavelengths, which permits it to follow the stretching of lightwaves caused by the expanding Universe. This enables CANDELS to detect and measure objects much farther out in space and nearer to the Big Bang than before. CANDELS also uses the visible-light ACS camera, and together the two cameras give unprecedented panchromatic coverage of galaxies from optical wavelengths to the near-IR.

Evolution of Galaxies: CANDELS Observations vs. Theory

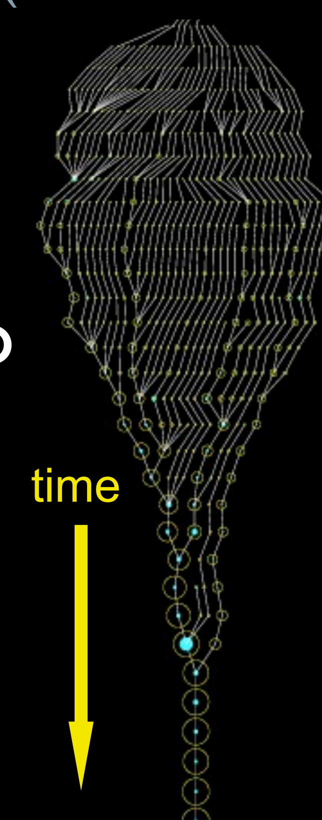




Barro et al. (2013 - Hubble Observations)



Bolshoi DM Halo Merger Tree



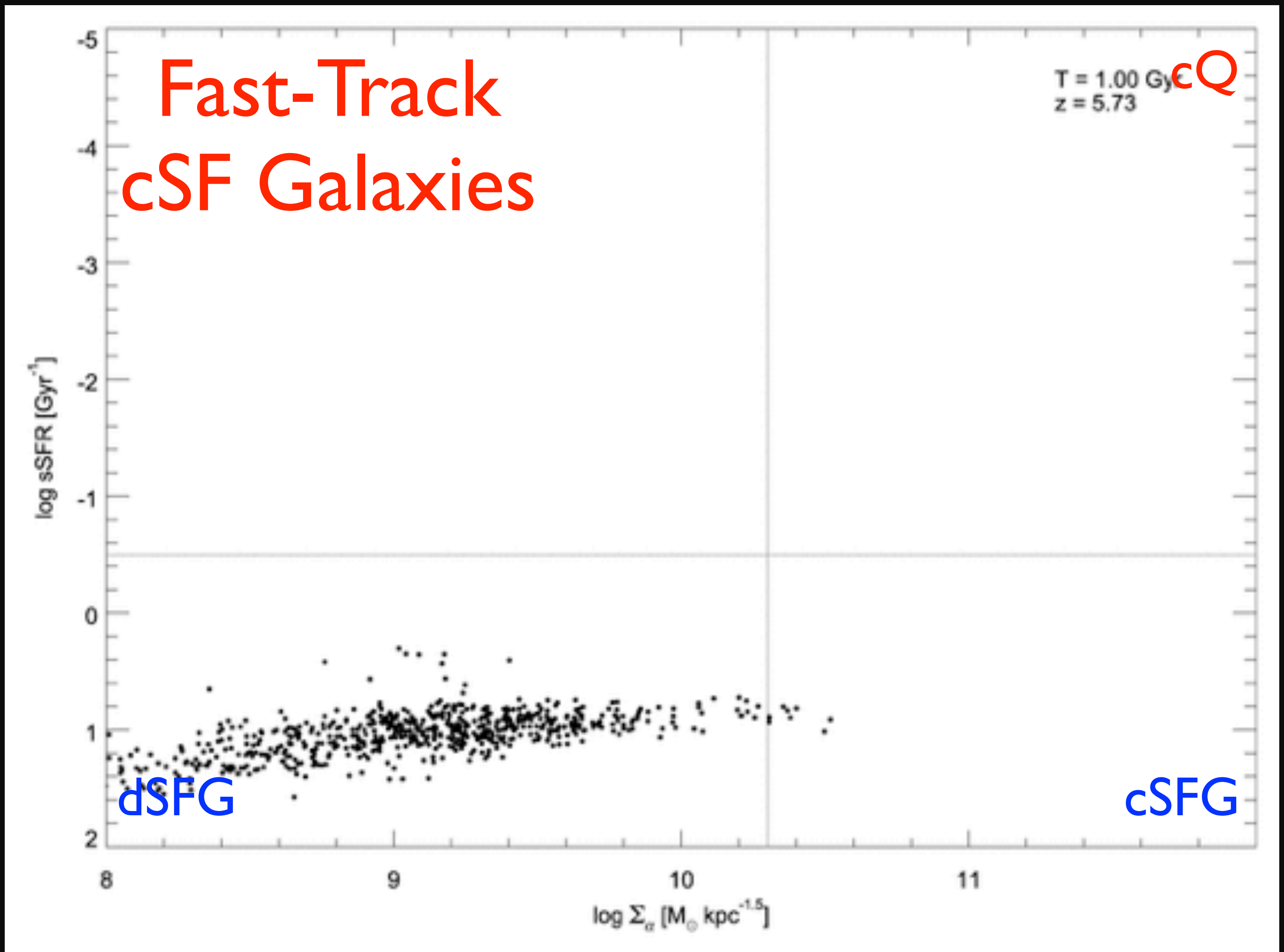
Astrophysical processes modeled:

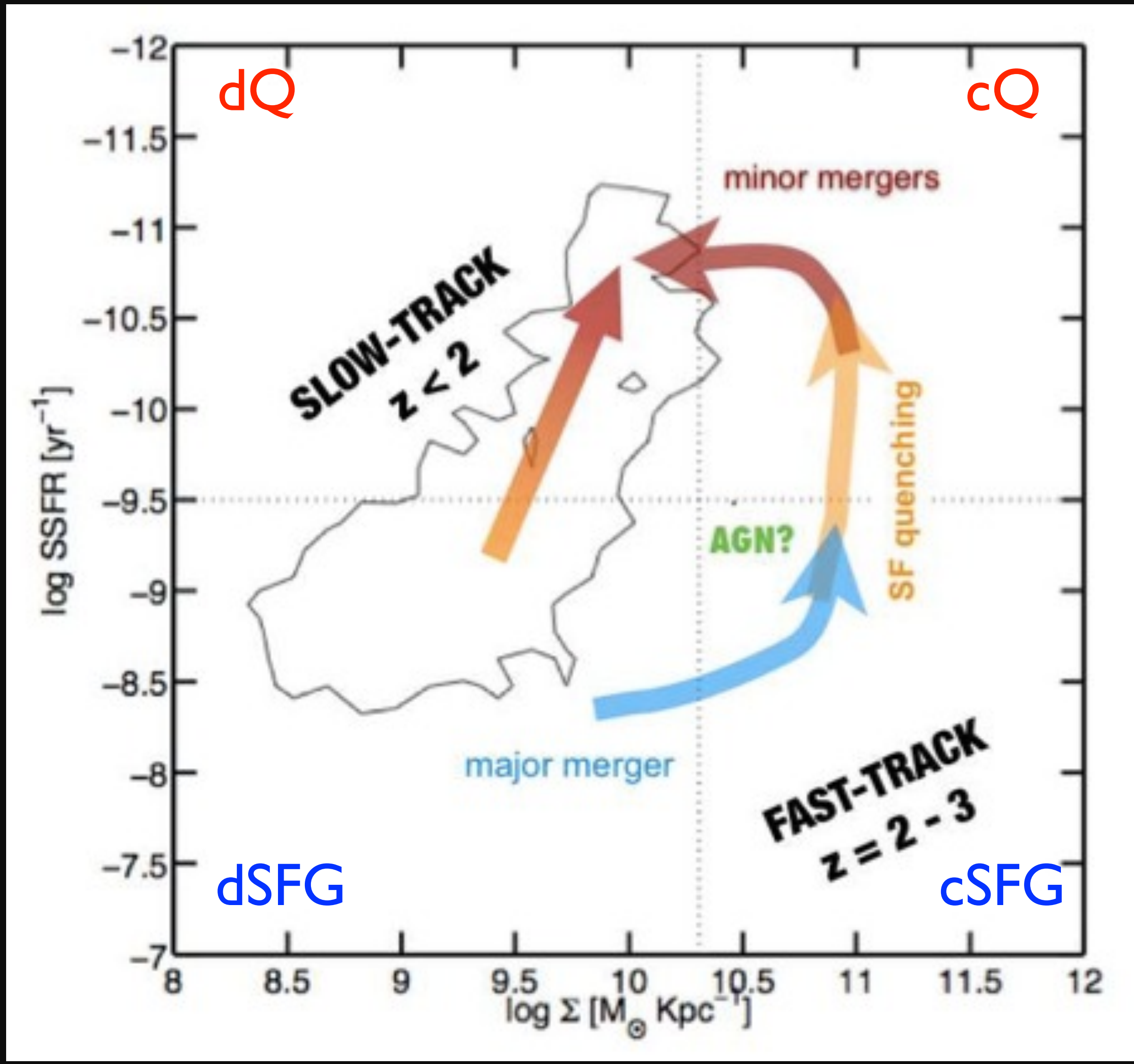
- shock heating & radiative cooling
- photoionization squelching
- merging
- star formation (quiescent & burst)
- SN heating & SN-driven winds
- AGN accretion and feedback
- chemical evolution
- stellar populations & dust

Porter et al. 2013c - Bolshoi SAM

Fast-Track Evolution of Compact Star-Forming Galaxies According to Bolshoi-based Semi-Analytic Model

Observed Evolution of Galaxies from Latest Hubble Telescope Data





Gas-rich merger in past Gyr
Gas-poor merger in past Gyr

cSFG at z = 2.4

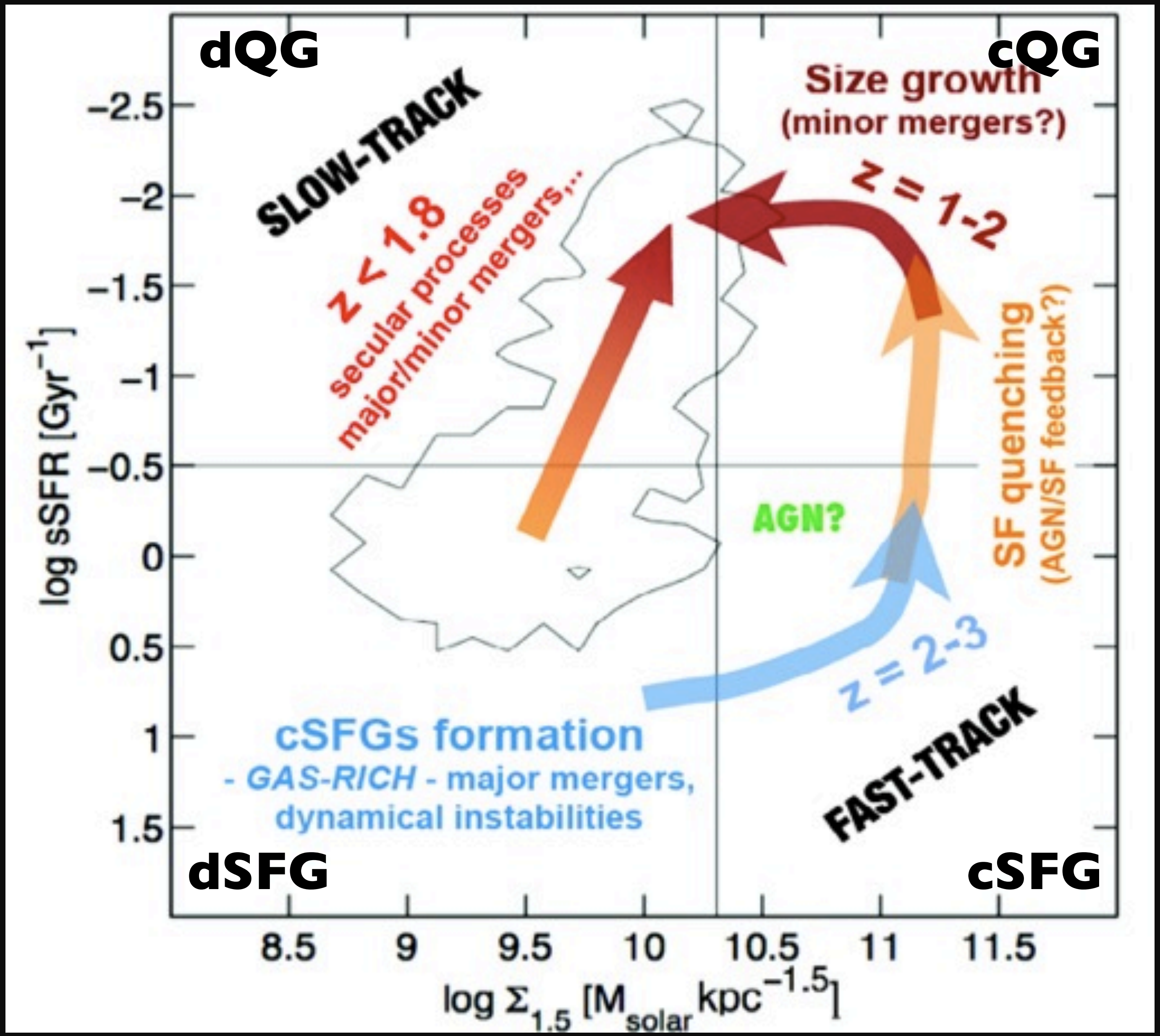
Barro et al. (2012 - Hubble Observations)

Porter et al. 2013c - Bolshoi SAM

Summary

SAM Predictions

- **Galaxies move from dSFG to cSFG through disk instabilities, as well as gas-rich major and minor mergers. Major mergers may *not* be the dominant mechanism for creating compact galaxies.**
- **Minor mergers decrease the surface density of cSFG, but most remain compact down to redshift 0.**
- **High-resolution galaxy simulations appear consistent with this.**



Barro et al. (2012)

Porter et al. 2013c - Bolshoi SAM

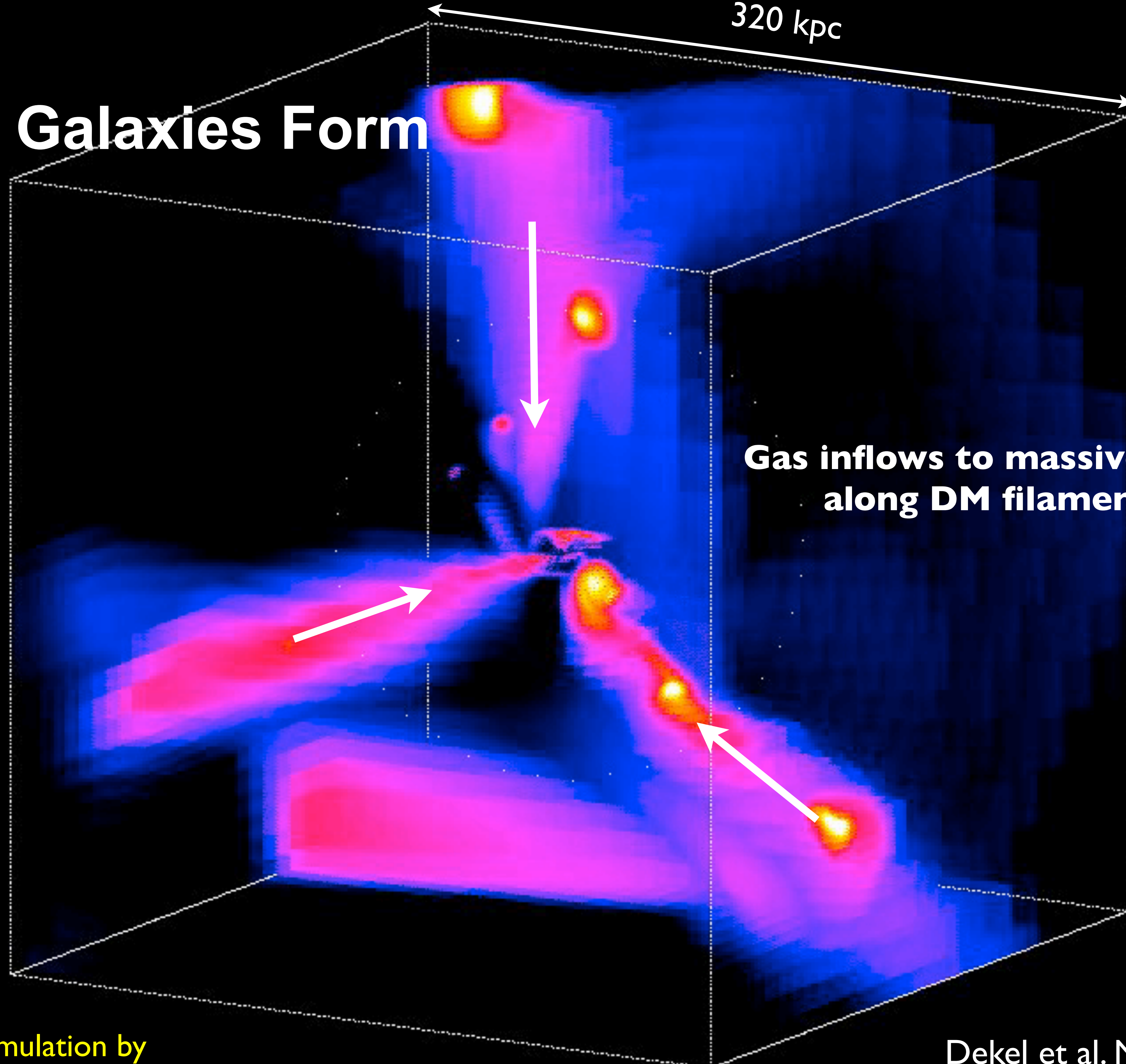
Cosmological Simulations

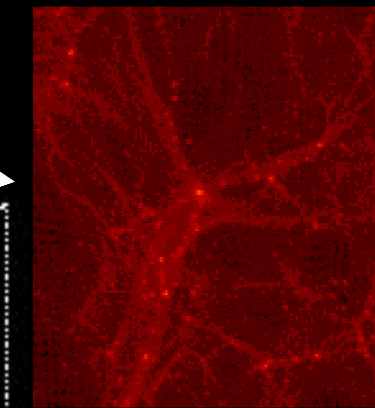
Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

Cosmological dark matter simulations show large scale structure, growth of structure, and dark matter halo properties

Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images in all wavebands including stellar evolution and dust

How Galaxies Form

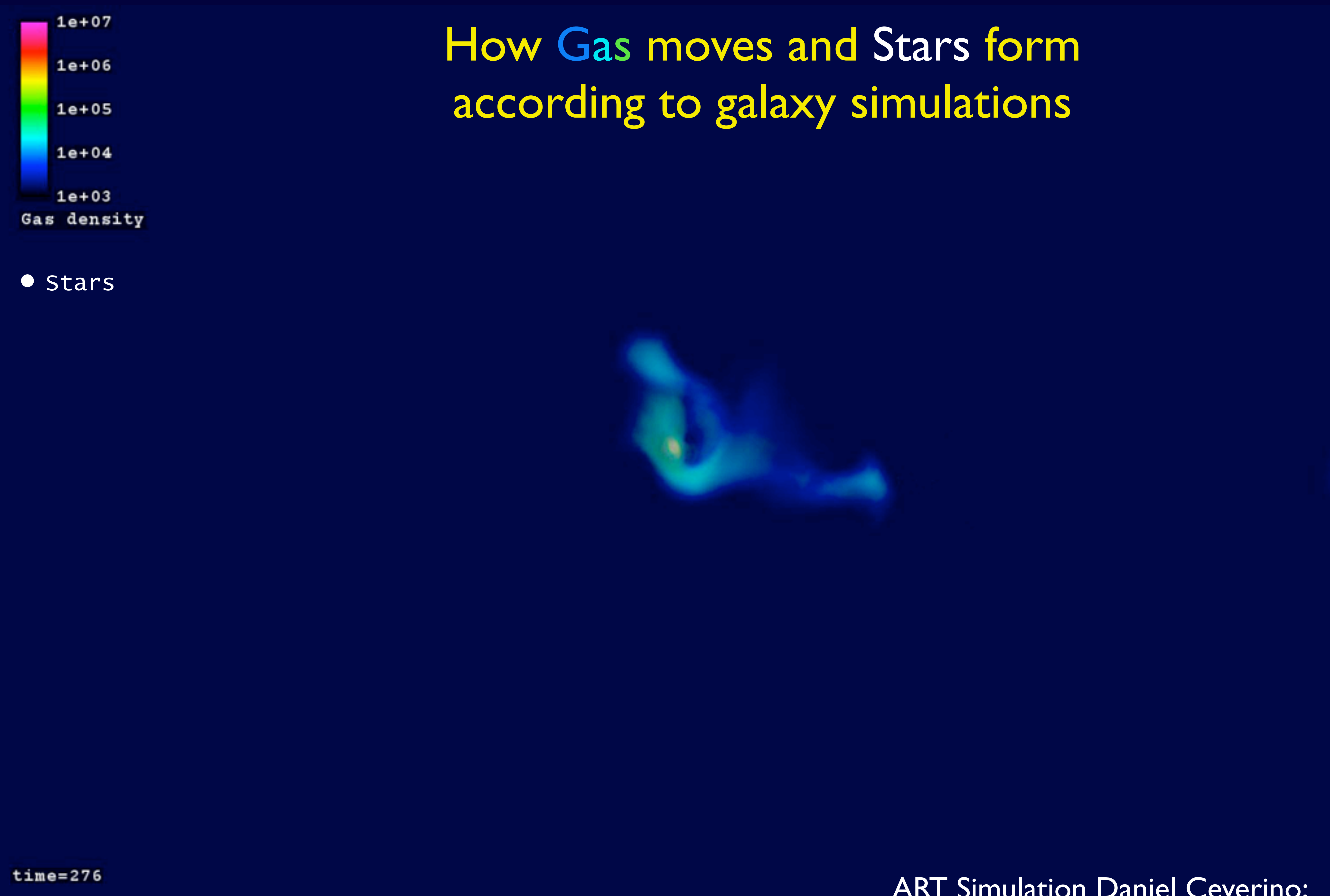




RAMSES simulation by
Romain Teyssier on Mare Nostrum supercomputer, Barcelona

Dekel et al. Nature 2009

How Gas moves and Stars form according to galaxy simulations

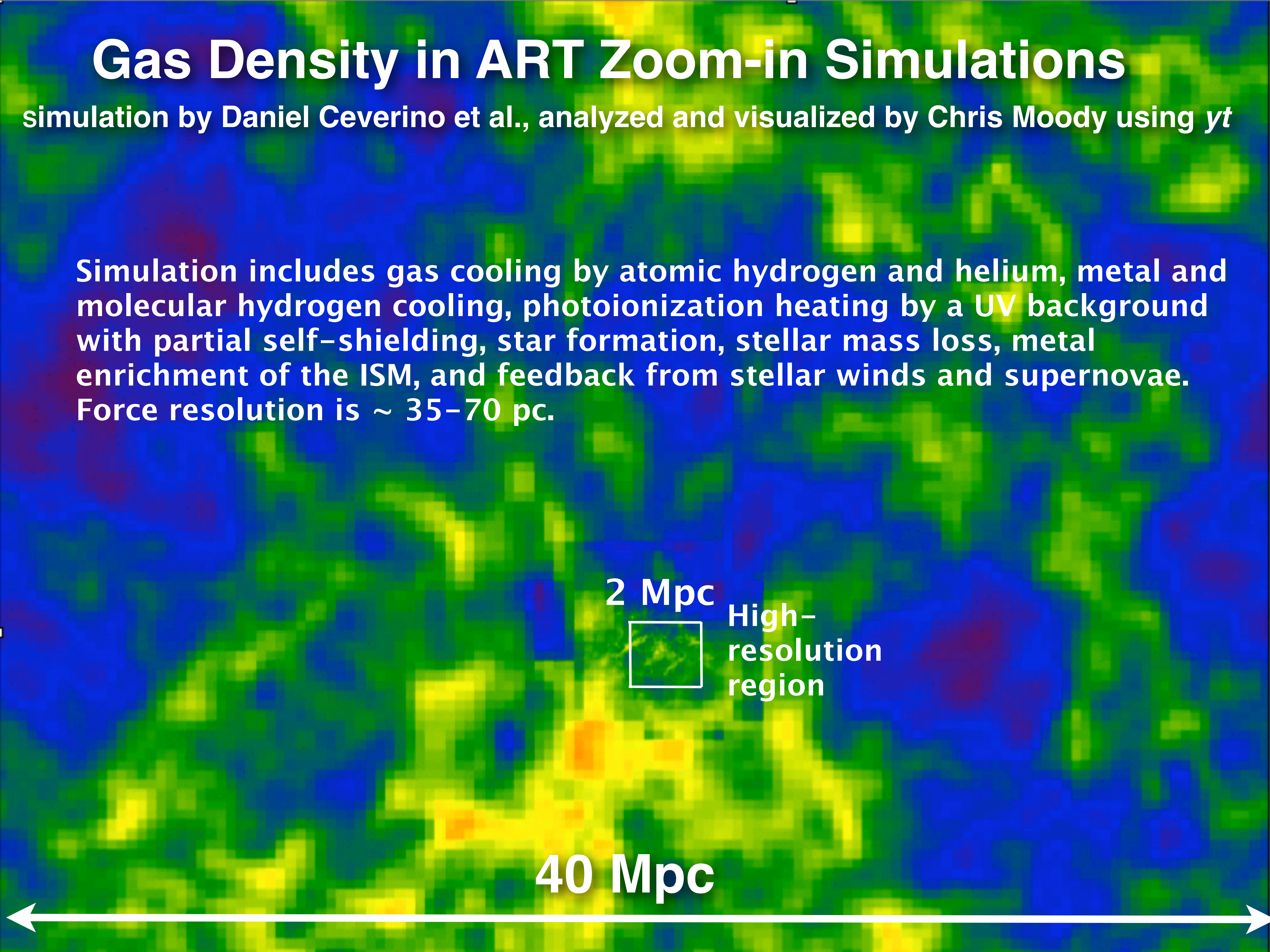


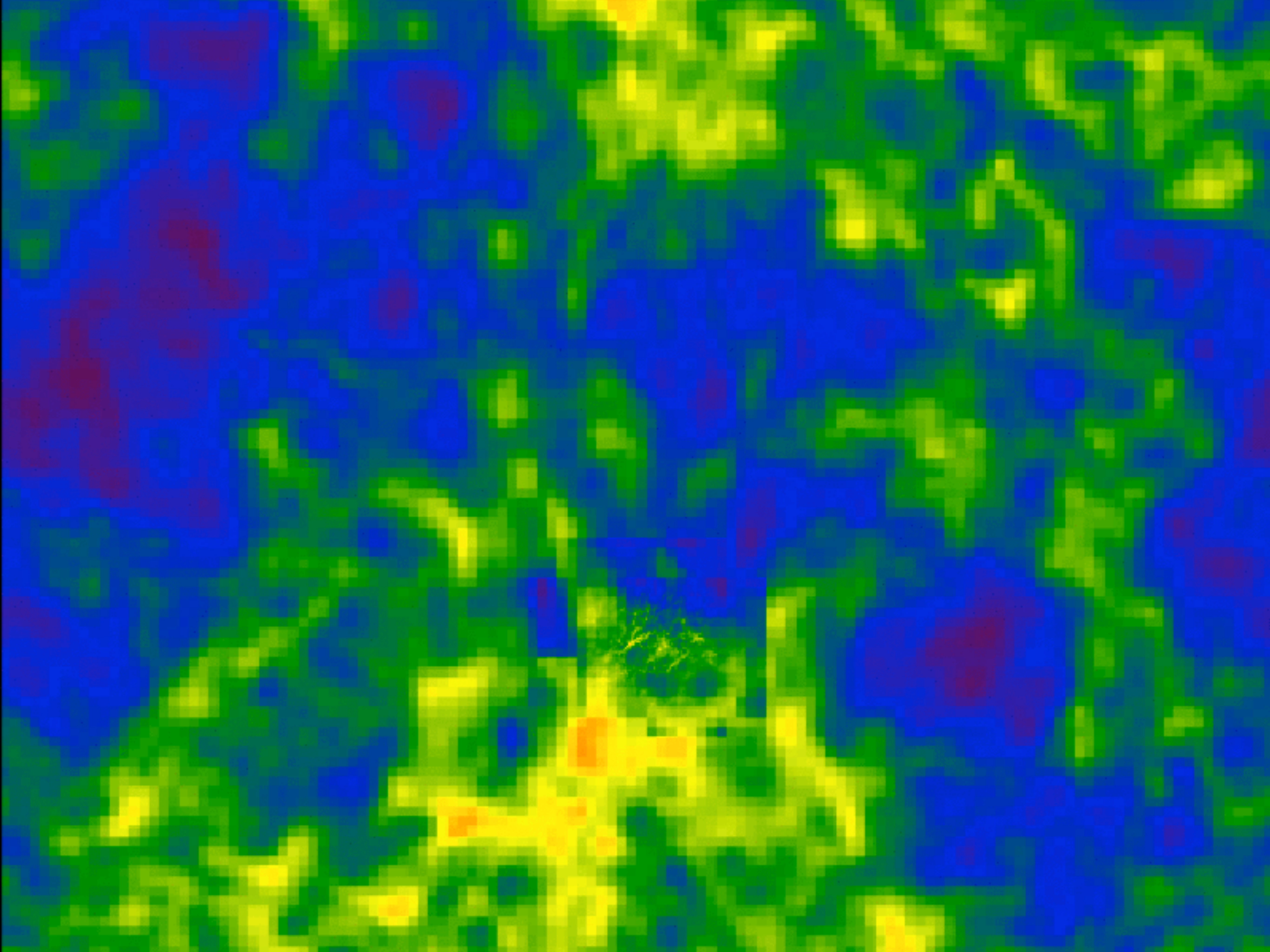
ART Simulation Daniel Ceverino;
Visualization: David Ellsworth

Gas Density in ART Zoom-in Simulations

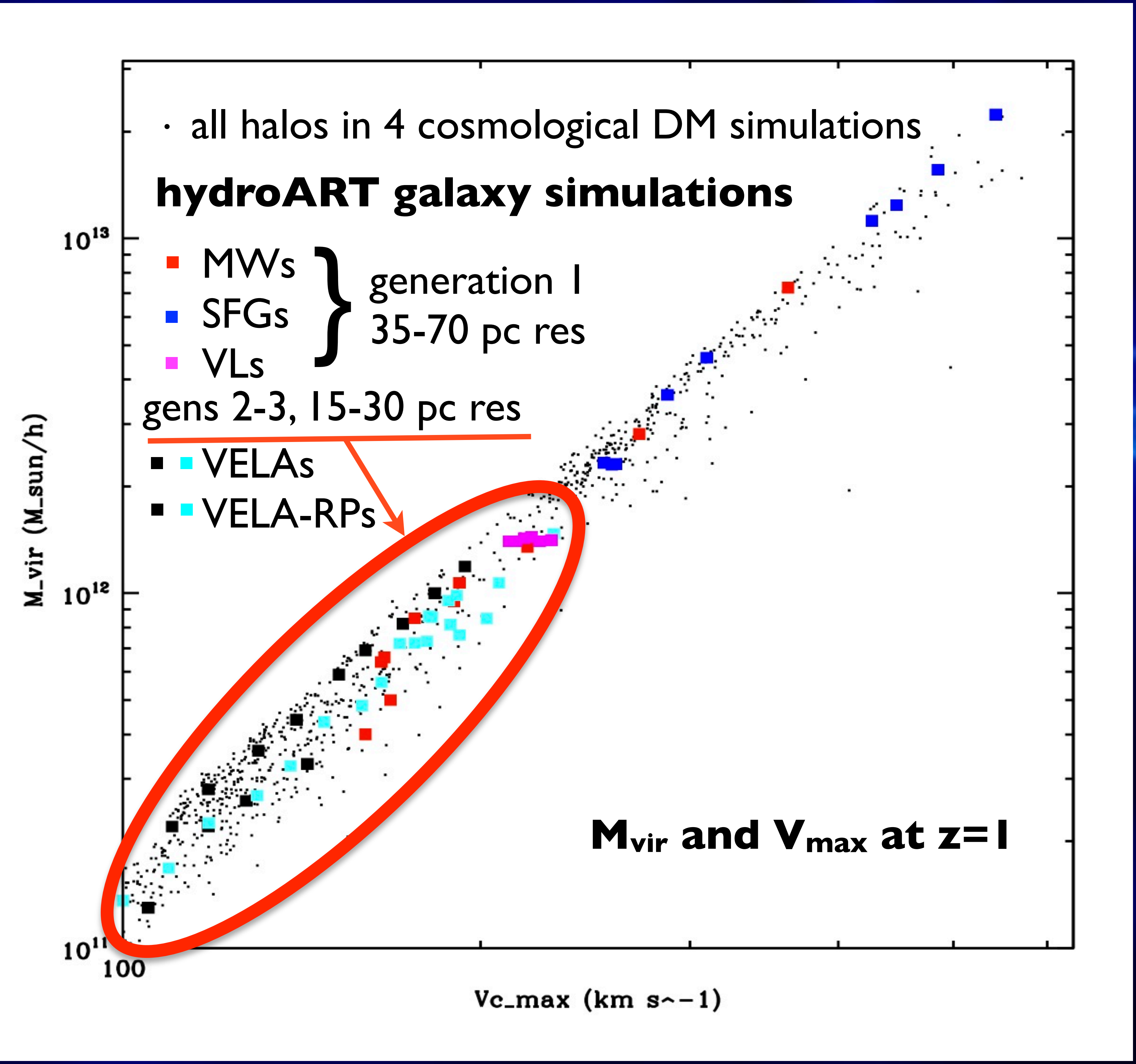
simulation by Daniel Ceverino et al., analyzed and visualized by Chris Moody using *yt*

Simulation includes gas cooling by atomic hydrogen and helium, metal and molecular hydrogen cooling, photoionization heating by a UV background with partial self-shielding, star formation, stellar mass loss, metal enrichment of the ISM, and feedback from stellar winds and supernovae. Force resolution is ~ 35-70 pc.





3 Generations of hydroART simulations



Generations 2 & 3

- ~35 zoom-in simulations
- 15-30 pc reso
- M_{DM}=8 10^4 Ms
- M_*=10^3 Ms
- z=1-3

10^{11} Ms/h < M_H < 10^{12} Ms/h
Vc_max =100-200 km/s @ z=1

Daniel Ceverino

Toy Models for Galaxy Formation versus Simulations

A. Dekel, A. Zolotov, D. Tweed, M. Cacciato, D. Ceverino, J.R. Primack (2013)

We find that

(a) the inflow rate is proportional to mass and to $(1+z)^{5/2}$, (b) the penetration to the inner halo is ~ 50% at z = 4–2,
(c) the $R_{disc} \sim 0.05\ R_{vir}$, (d) the galaxies reach a steady state with the SFR following the galaxy accretion rate,
(e) there is an intense inflow through the disc, comparable to the SFR, following the predictions of violent disk instability (VDI), and
(f) the galaxies approach a steady state with the bulge mass comparable to the disc mass, where the draining of gas by SFR, outflows, and disc inflows is replenished by fresh accretion.

Given the agreement with simulations, these toy models are useful for understanding the complex phenomena in simple terms and for back-of-the-envelope predictions.

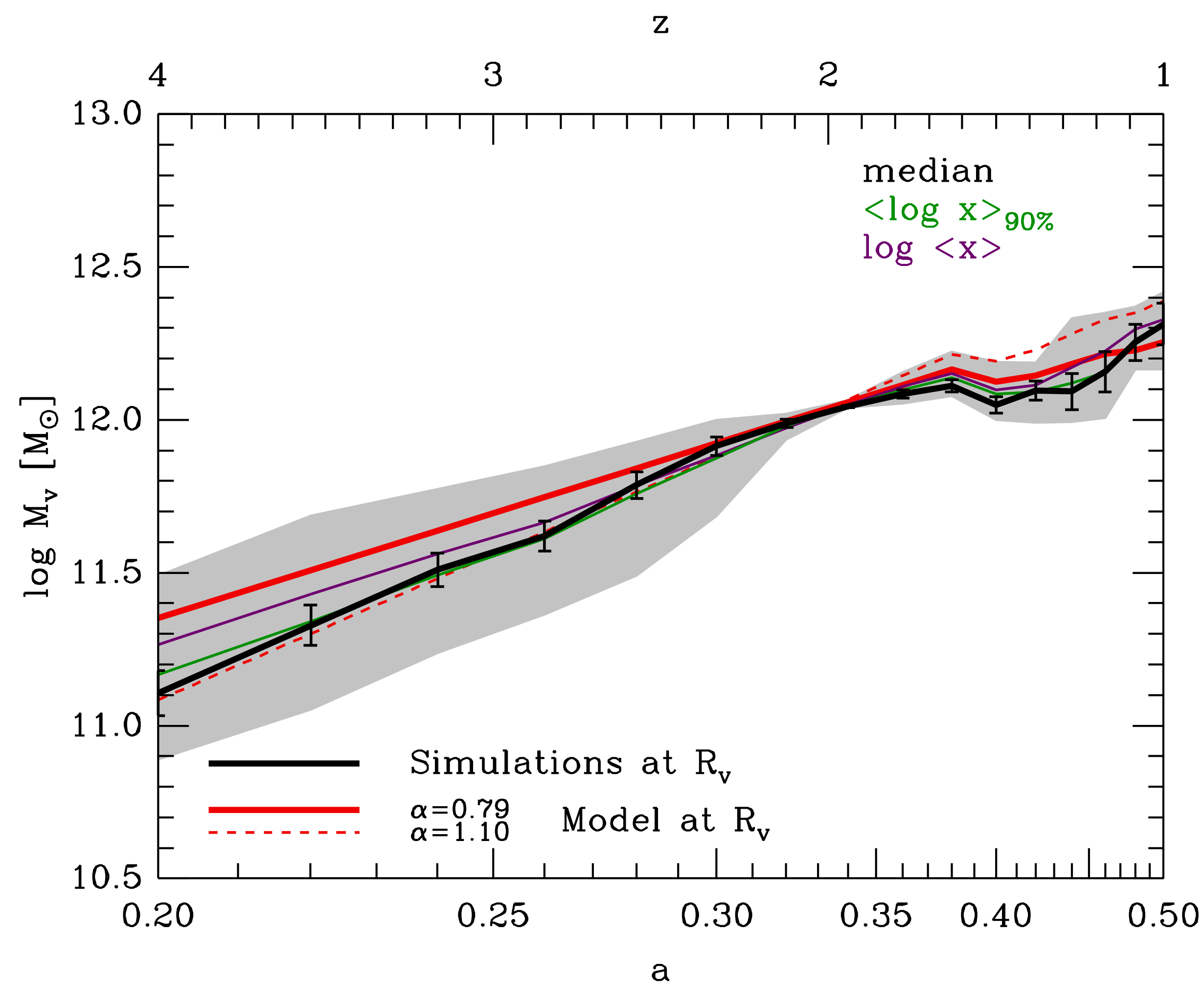
For example, in a simple toy model, valid for massive galaxies at z > 1,

$$\dot{M}/M = s\,(1+z)^{5/2}, \quad s \simeq 0.030\ \mathrm{Gyr}^{-1}$$

This can be simply integrated to a growth of halo mass as a function of redshift z, where the mass at some fiducial redshift z_0 is M_0,

$$M_v = M_0\, e^{-\alpha(z-z_0)}\,, \quad \alpha \simeq 0.79,$$

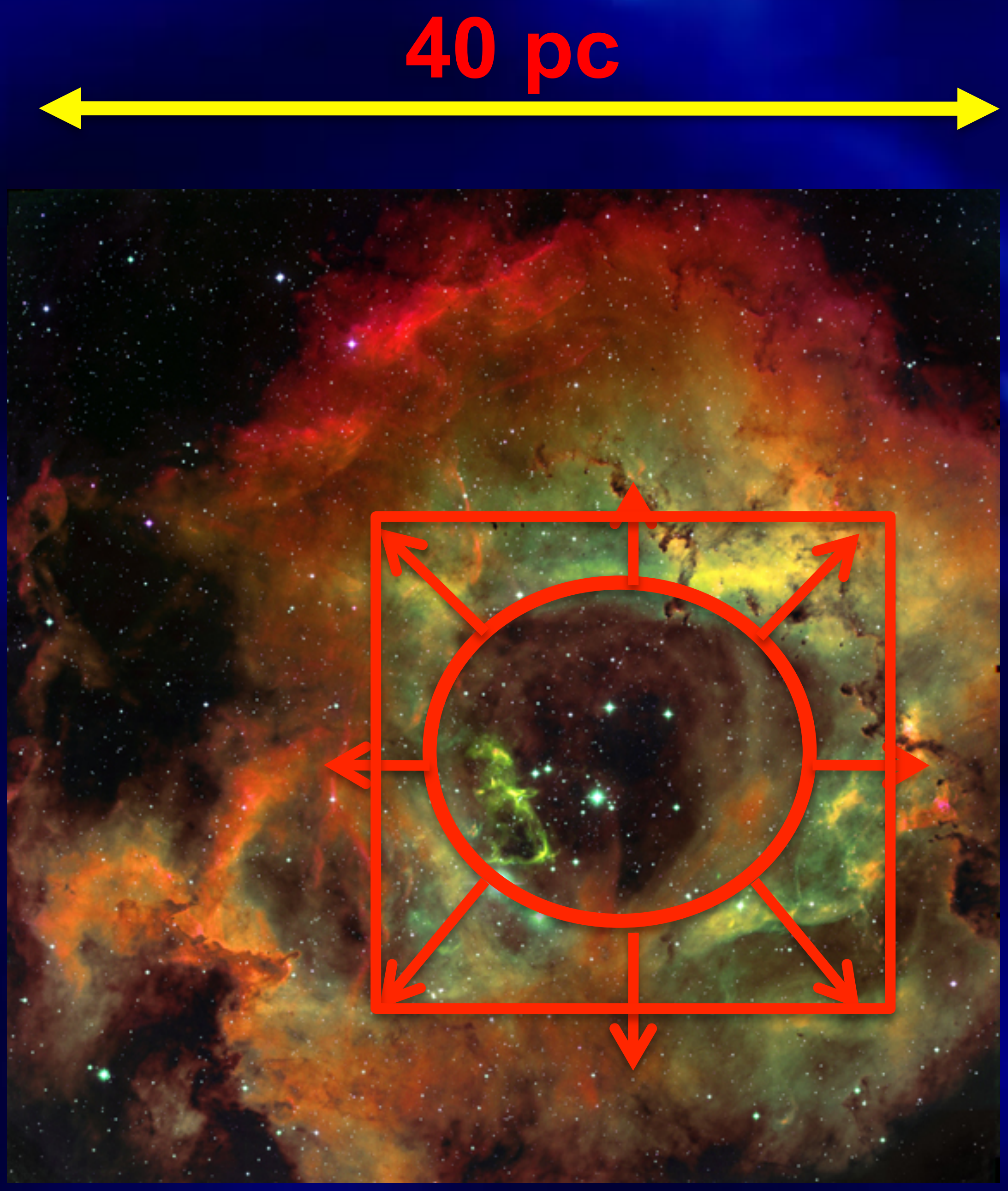
in agreement with Wechsler et al. 2002. The figure at the right compares this with our high-resolution hydro simulations.



Cosmological accretion of total mass: growth of virial mass. The virial mass of each galaxy has been scaled before stacking by the median at z = 2. Shown in comparison is the toy model prediction with α = 0.79, normalized like the simulations at z = 2 (thick smooth red).

Radiative feedback

Rosette Nebula



No Supernova explosion yet

Stellar winds

Thermal pressure

Radiation pressure

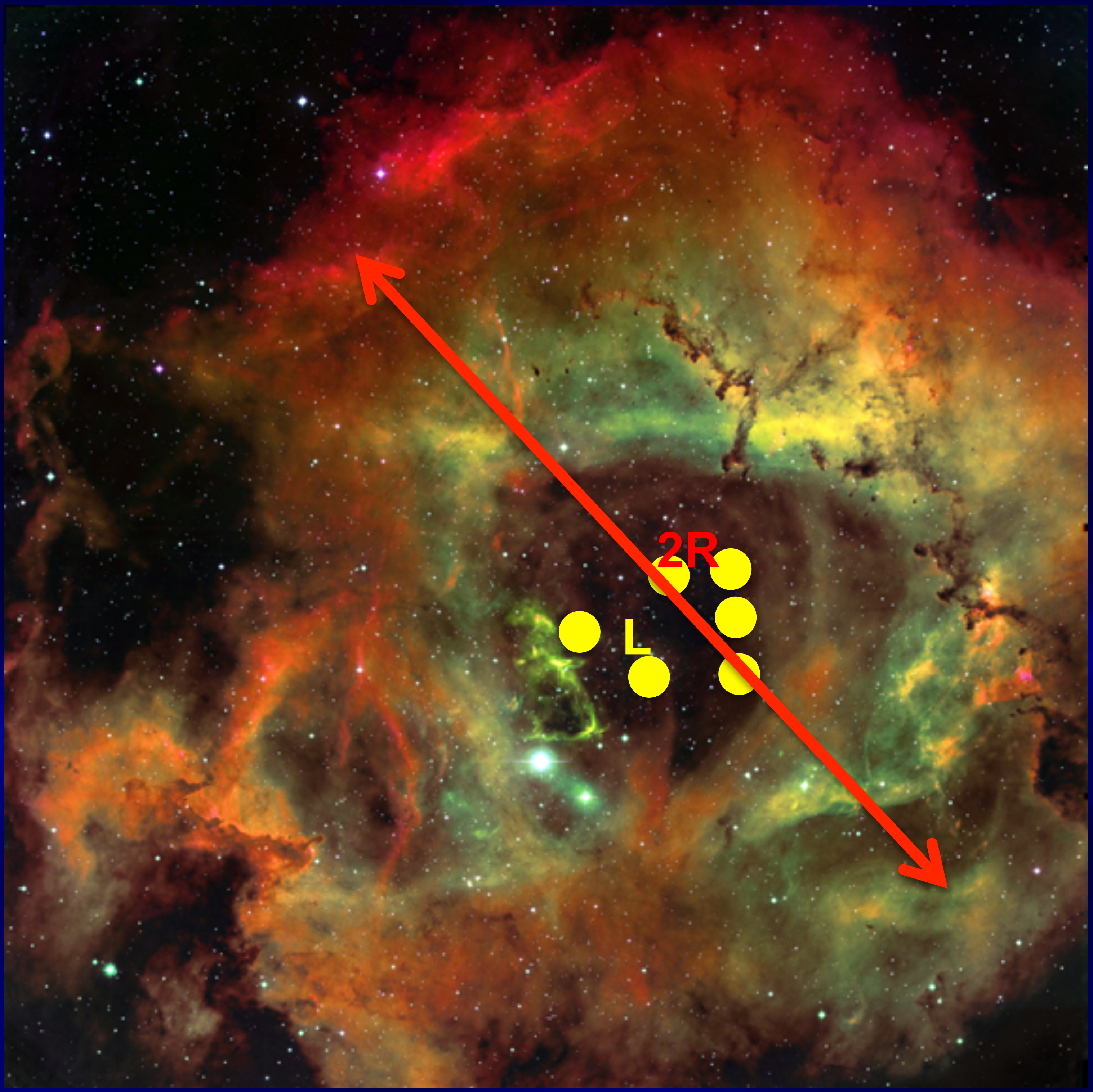
from ionizing photons

Typical resolution of our zoom-in, cosmological simulation: ~ 20 pc

Daniel Ceverino

- At high column densities

- Add pressure



$$P_{rad} = L / (R^2 c)$$

$$L = M_* \Gamma$$

Γ = cte for 5 Myr

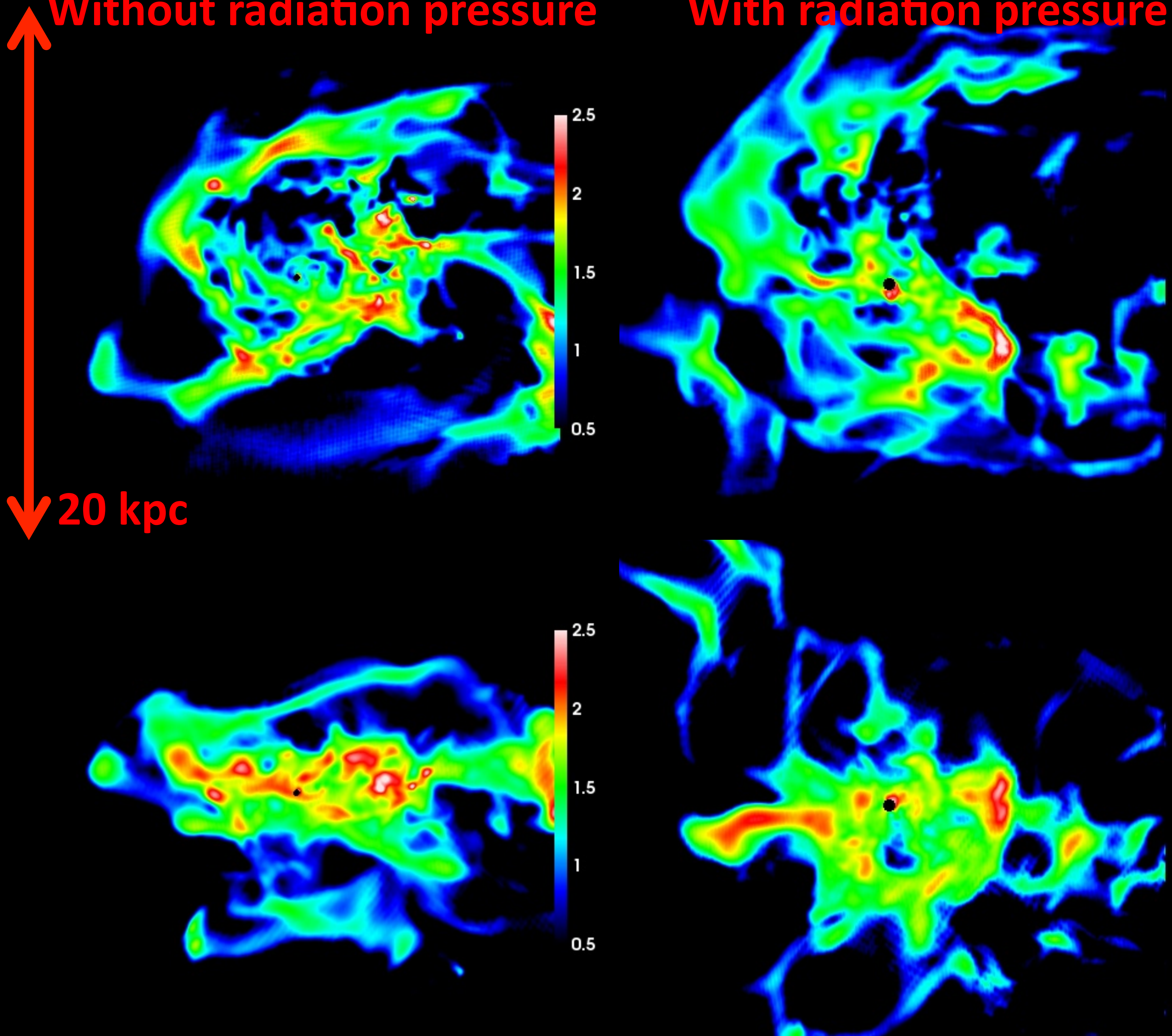
For column densities $>10^{21}$ cm^{-2}

No free parameters

Daniel Ceverino

Gas distributions

Without radiation pressure **With radiation pressure**



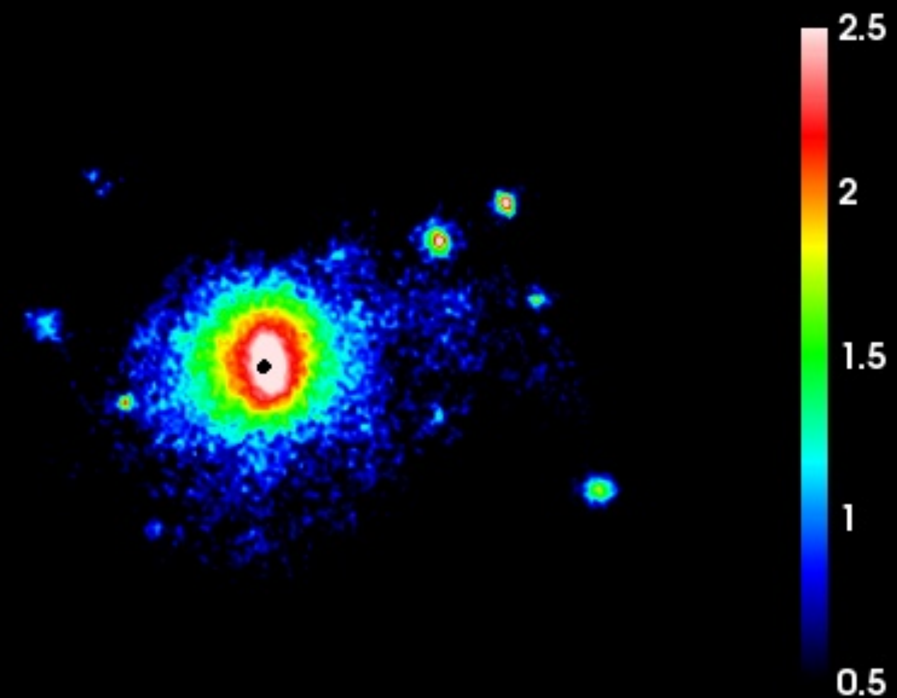
Gas face-on

Gas edge-on

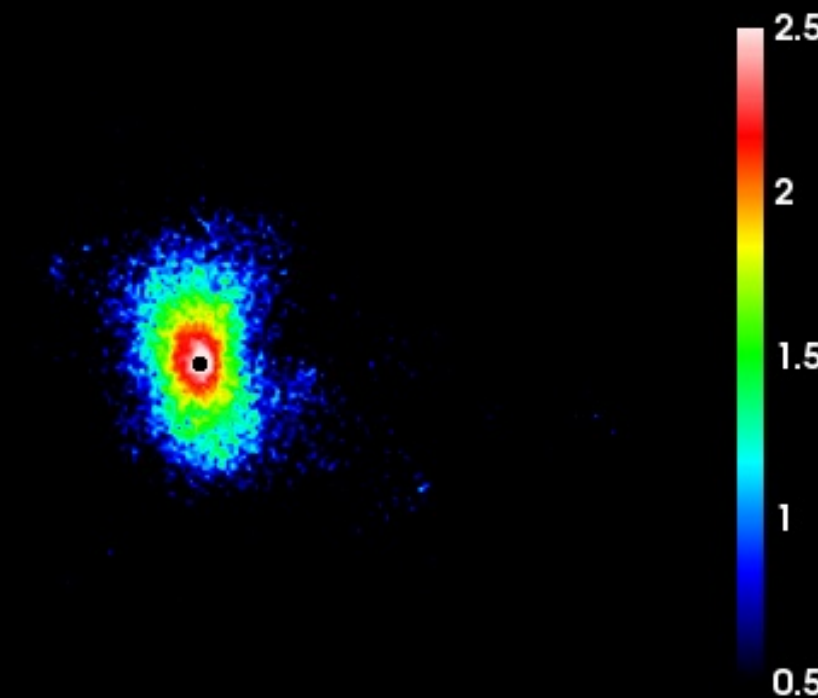
Daniel Ceverino

Stars face-on

Without radiation pressure

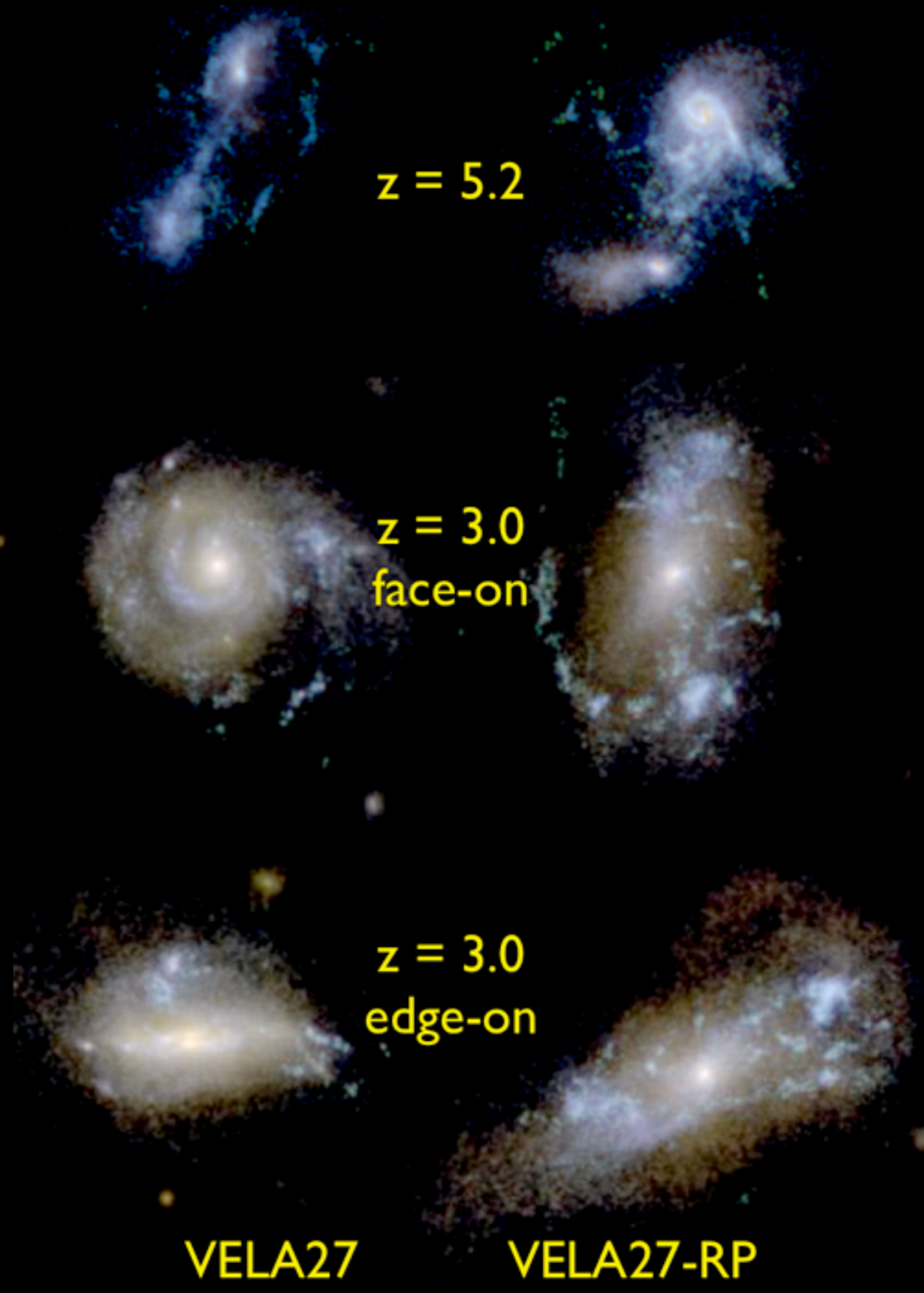


With radiation pressure



20 kpc

Daniel Ceverino

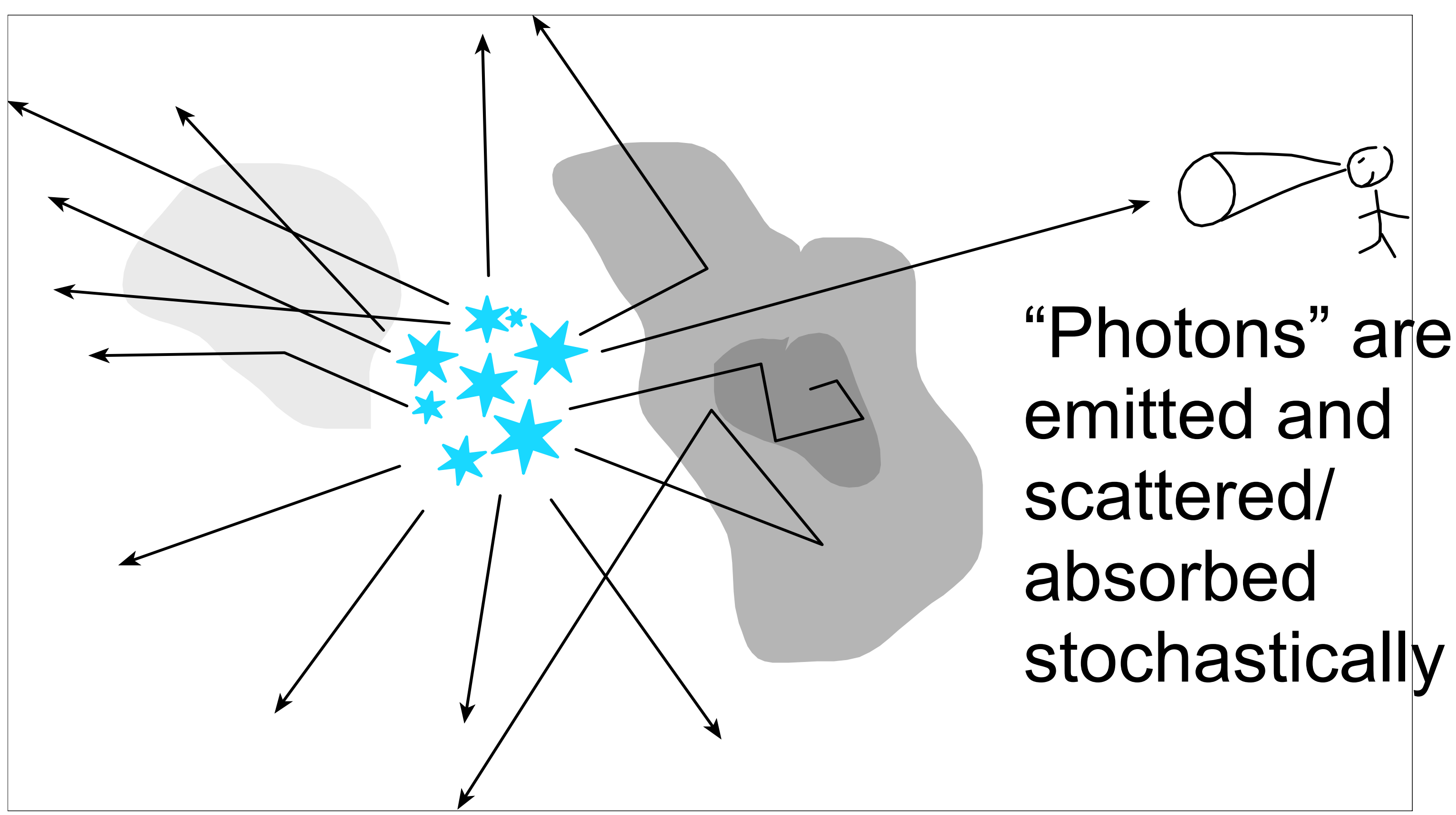

z = 5.2
z = 3.0
face-on
z = 3.0
edge-on
VELA27
VELA27-RP

Sunrise Radiative Transfer Code

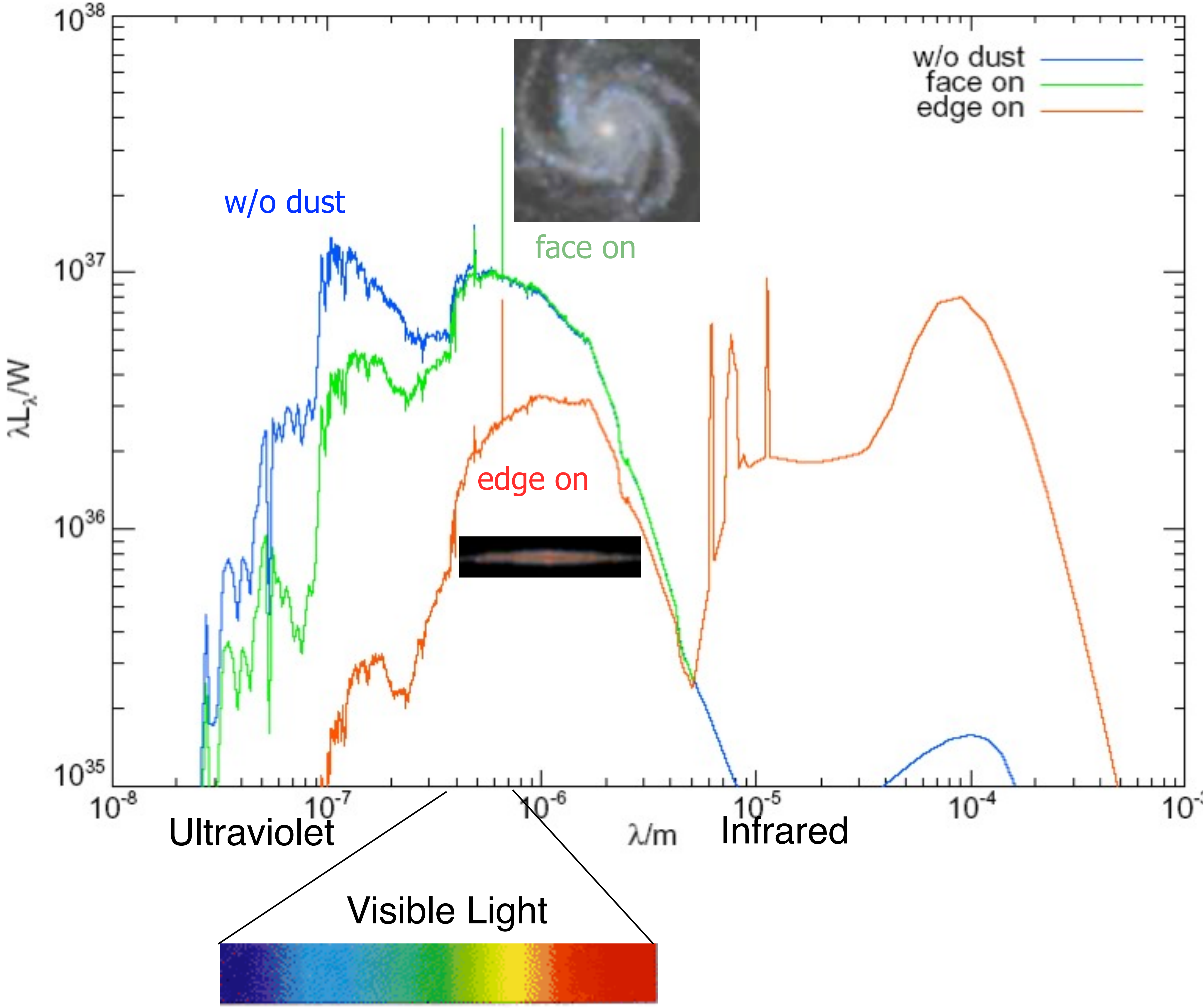
Patrik Jonsson
& Joel Primack

For every simulation snapshot:

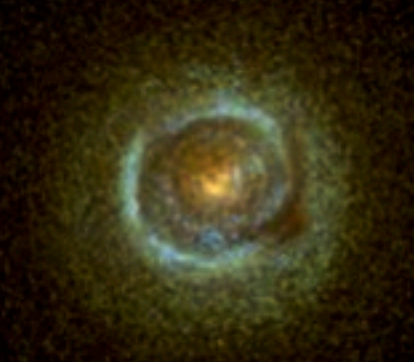
- Evolving stellar spectra calculation
- Adaptive grid construction
- Monte Carlo radiative transfer
- “Polychromatic” rays save 100x CPU time
- Graphic Processor Units give 10x speedup



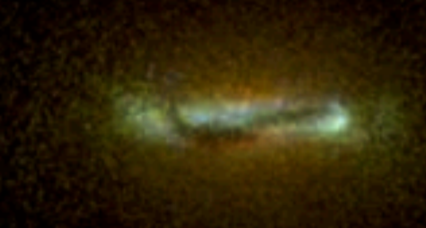
Spectral Energy Distribution



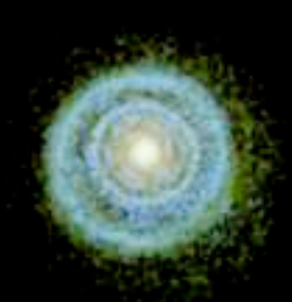
What's the effect of including dust?



with
dust



Dramatic effects on
-Appearance
-Half-mass radii (bigger with dust)
-Sersic index (lower with dust)



stars
only

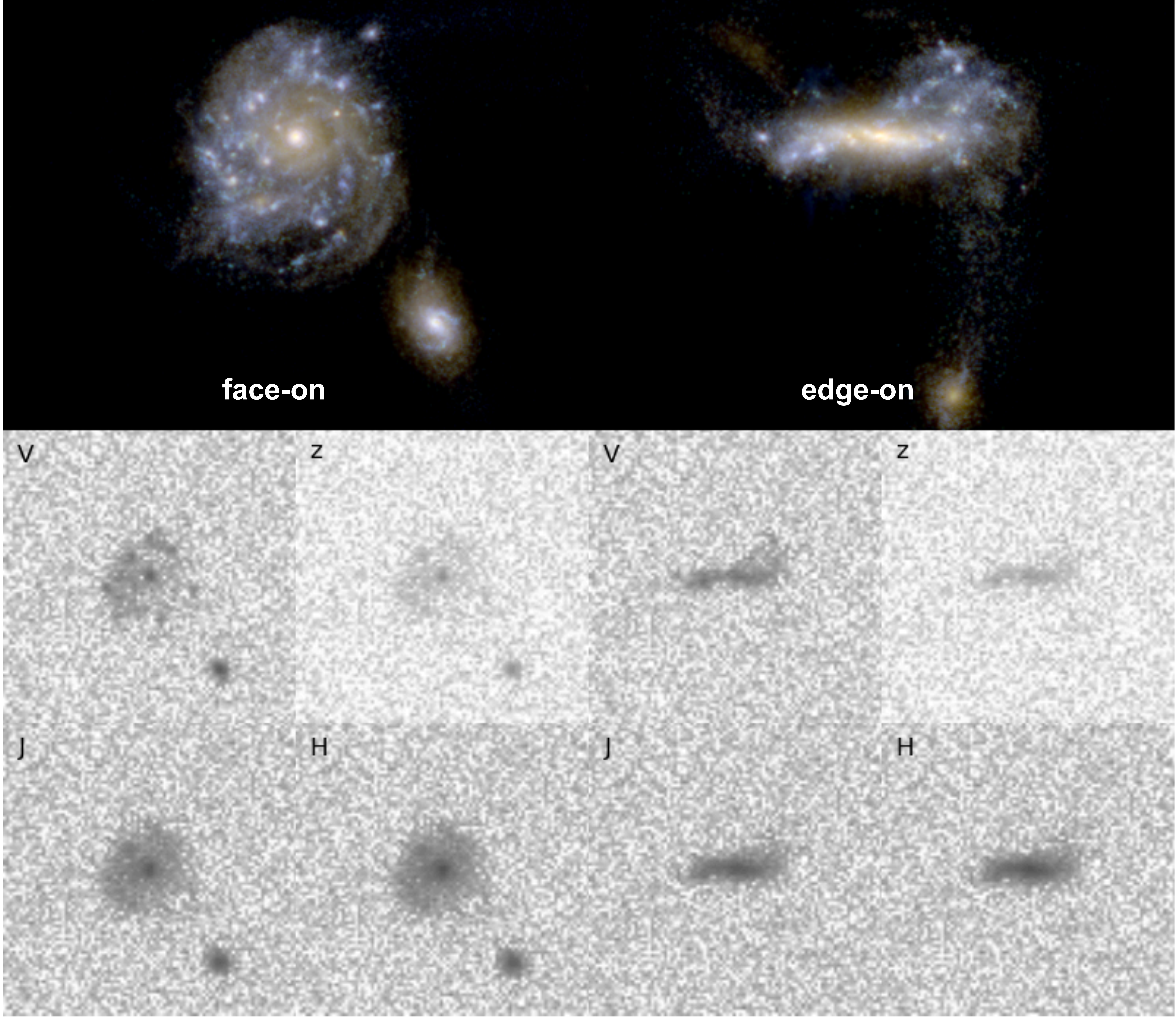
cemoody.imgur.com

Simulated Galaxy 10 billion years ago

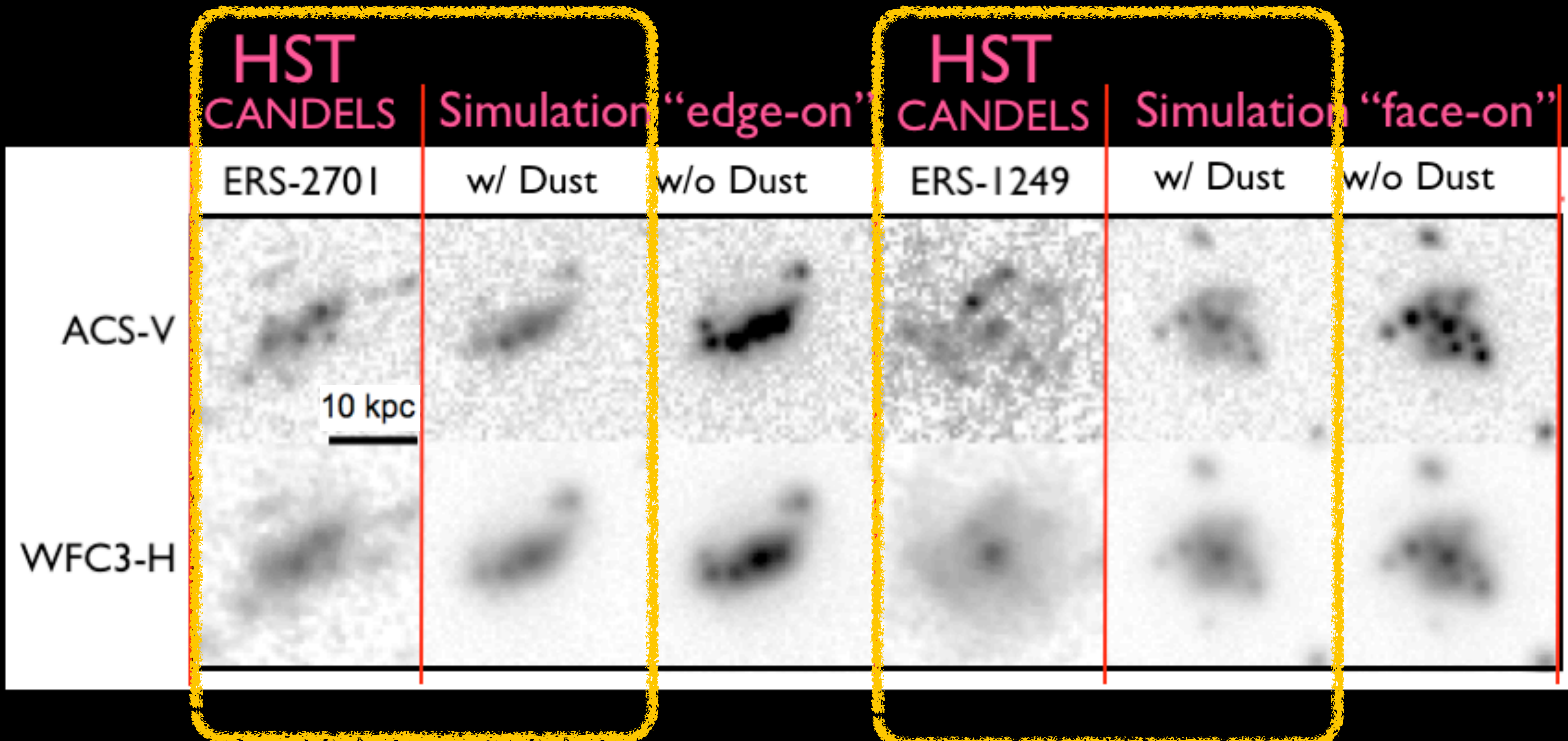
as it would appear nearby to our eyes

as it would appear to Hubble's ACS visual camera

as it would appear to Hubble's WFC3 infrared camera



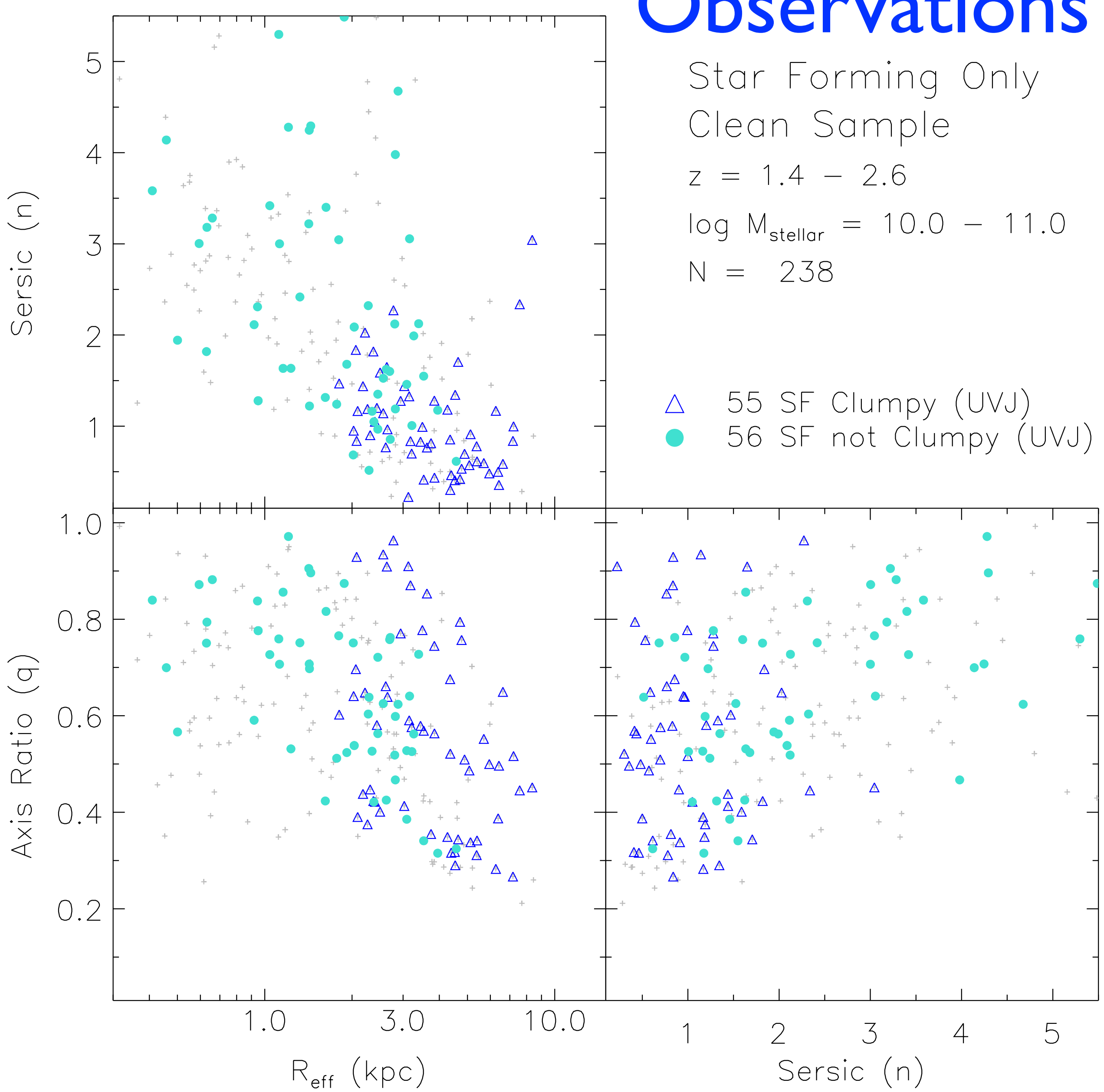
Our Simulations w/ Dust look a lot like galaxies from 10 billion years ago that we see with Hubble Space Telescope



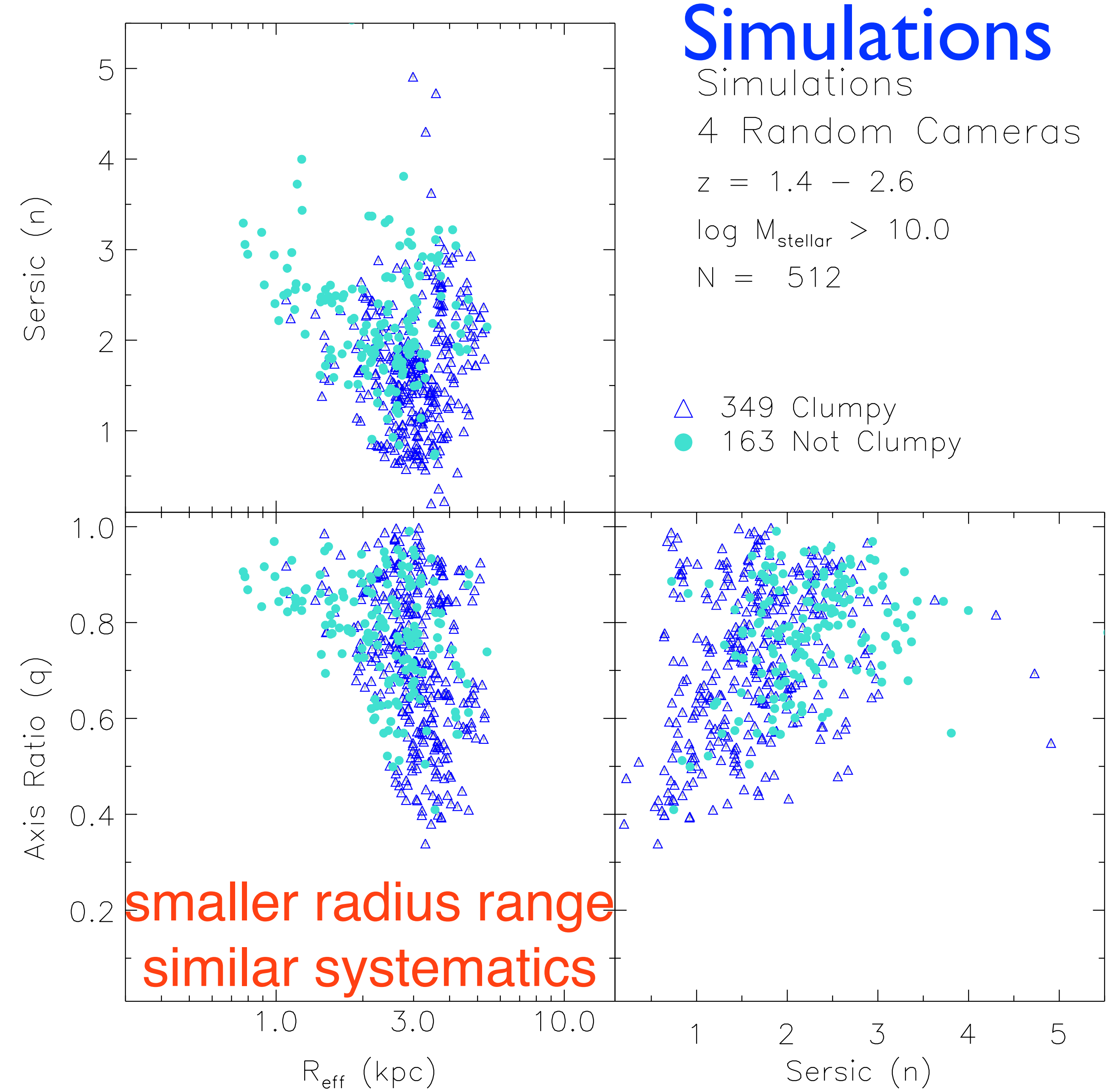
We are now systematically comparing simulated and observed galaxy images

CANDELS Galaxies Compared with Generations 1 & 2 hydroART simulations using R_{eff}, Axis Ratio q, Sersic n, with clumpy vs. not clumpy from by-eye classification

Observations

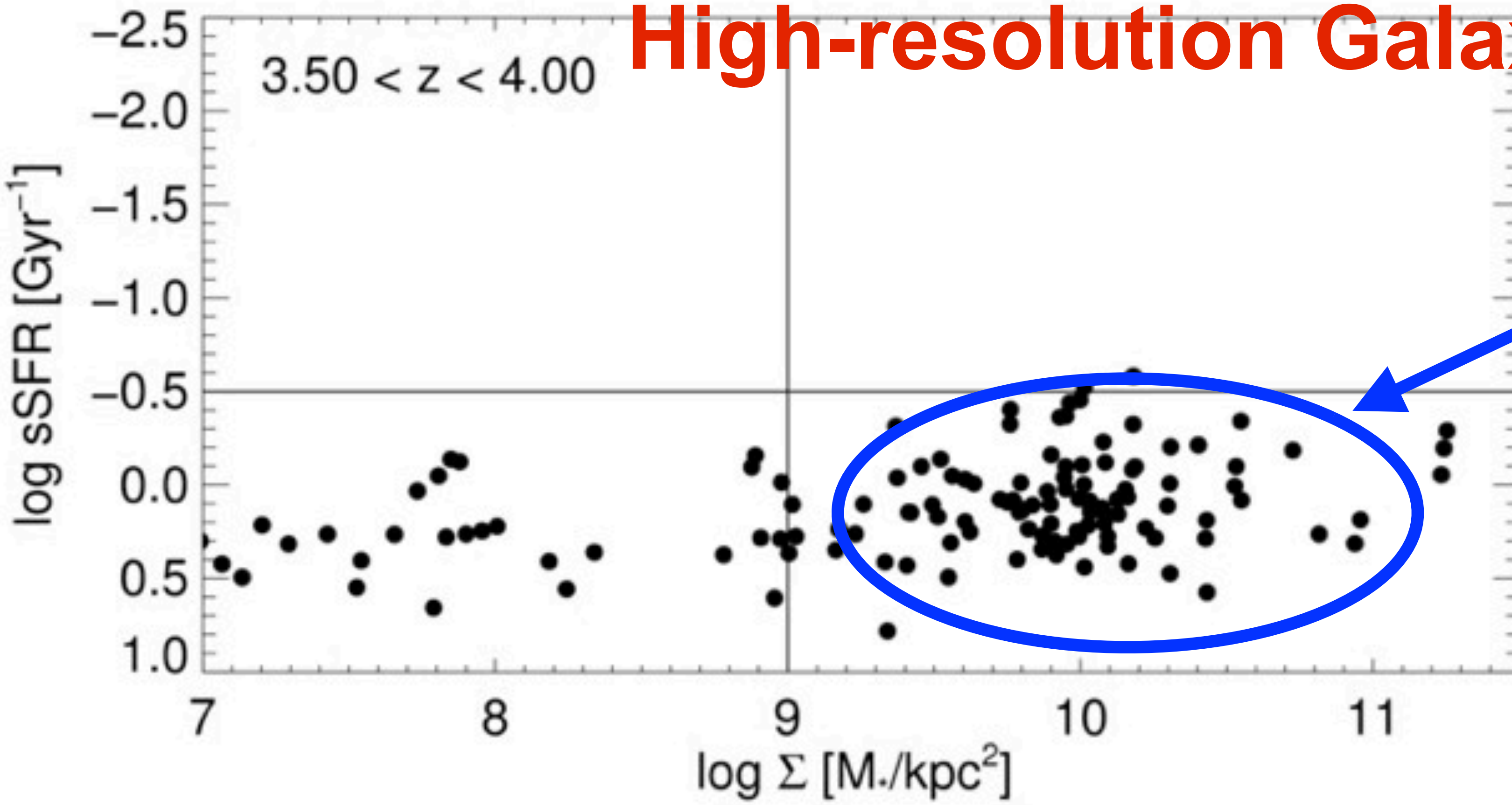


Simulations



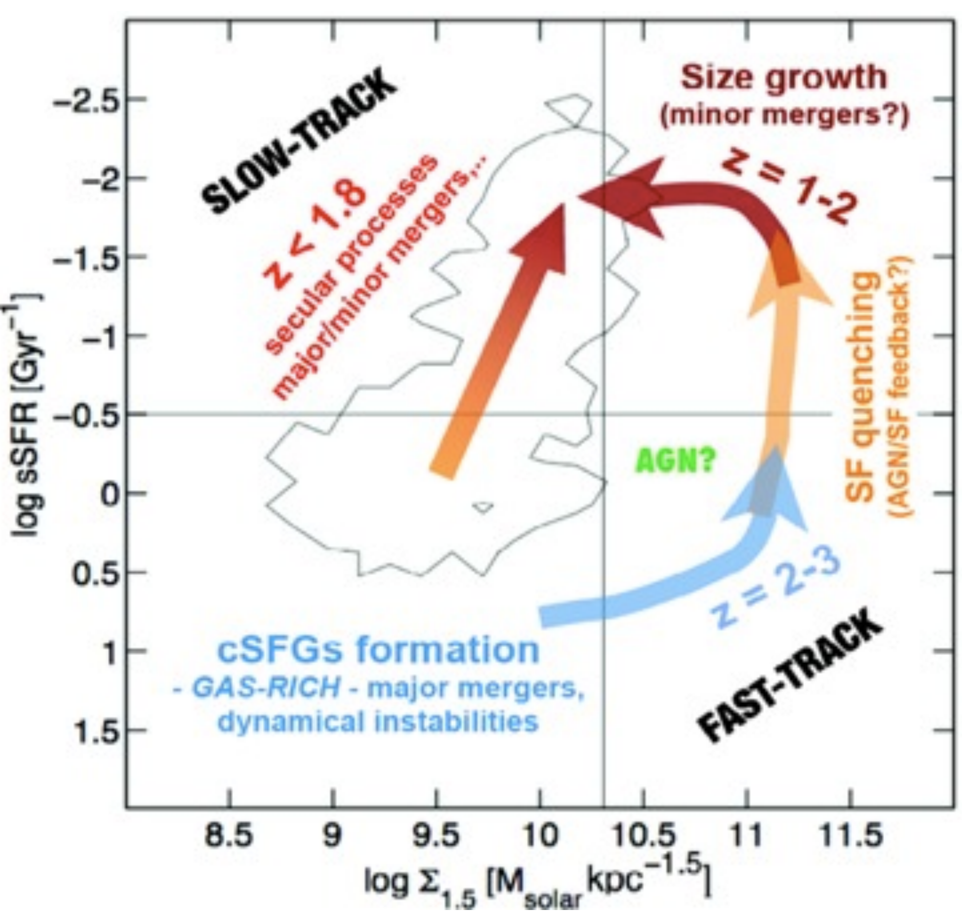
Mark Mozena (in prep)

High-resolution Galaxy Simulations

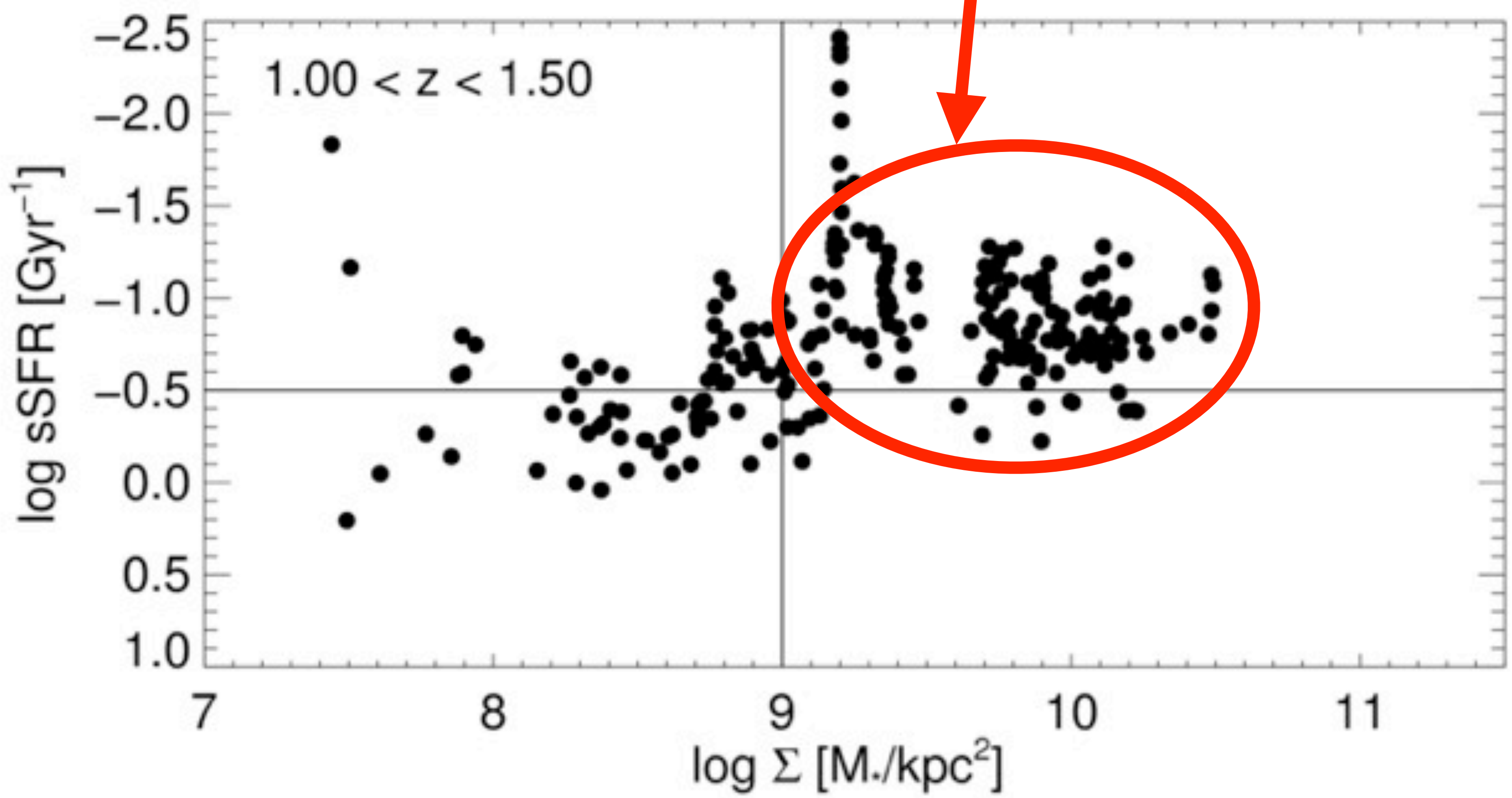


compact, SF galaxies at hi-z

compact, quiescent galaxies at low-z

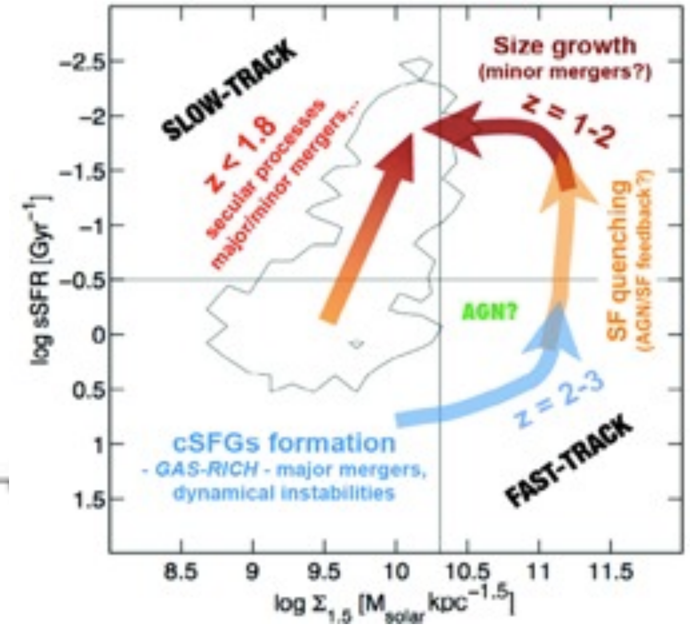


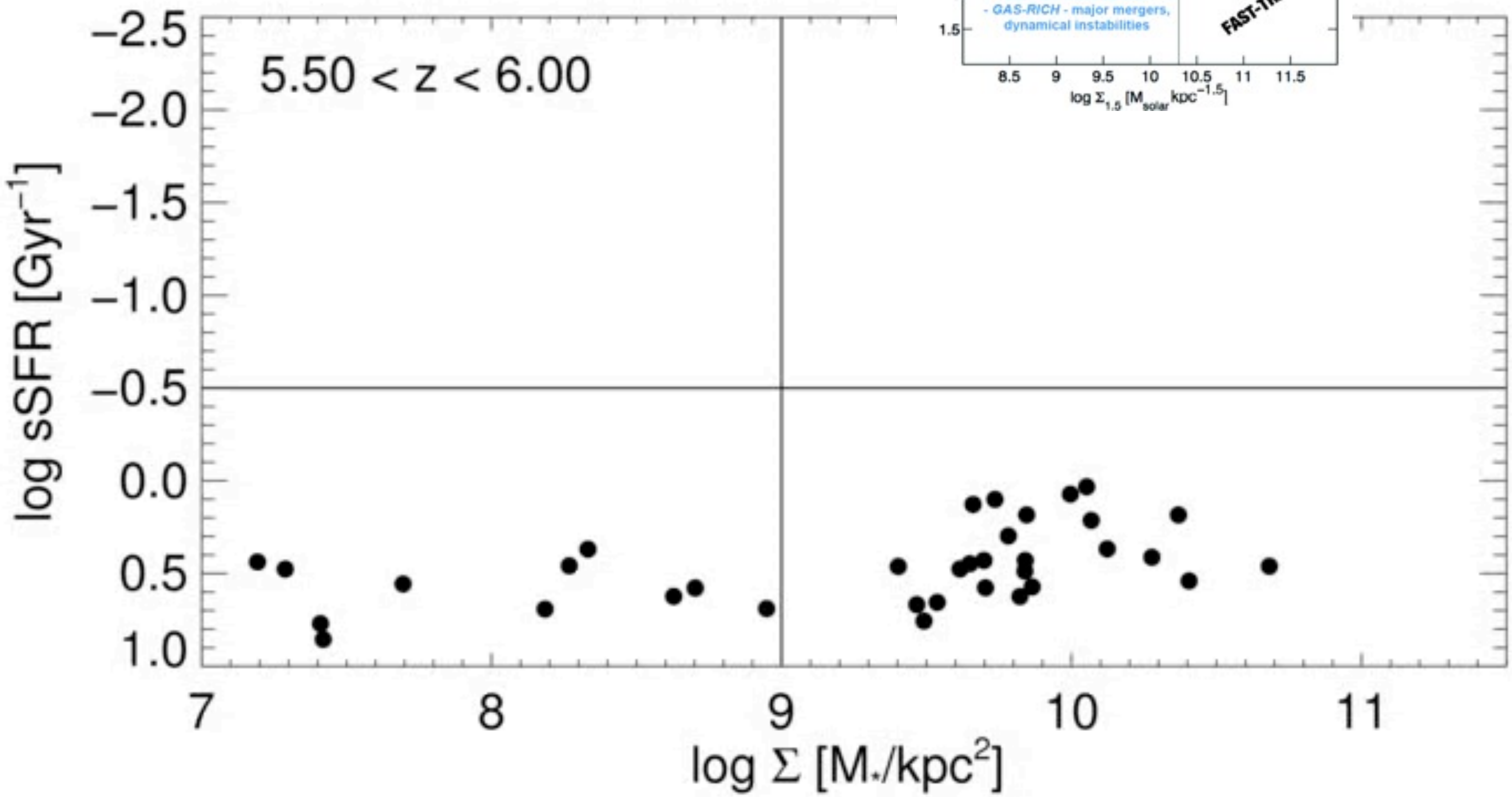
Barro+ (CANDELS) 2013



Ceverino+ simulations analyzed by Zolotov+ (in prep.)

The Formation of Compact Galaxies 1 < z <6



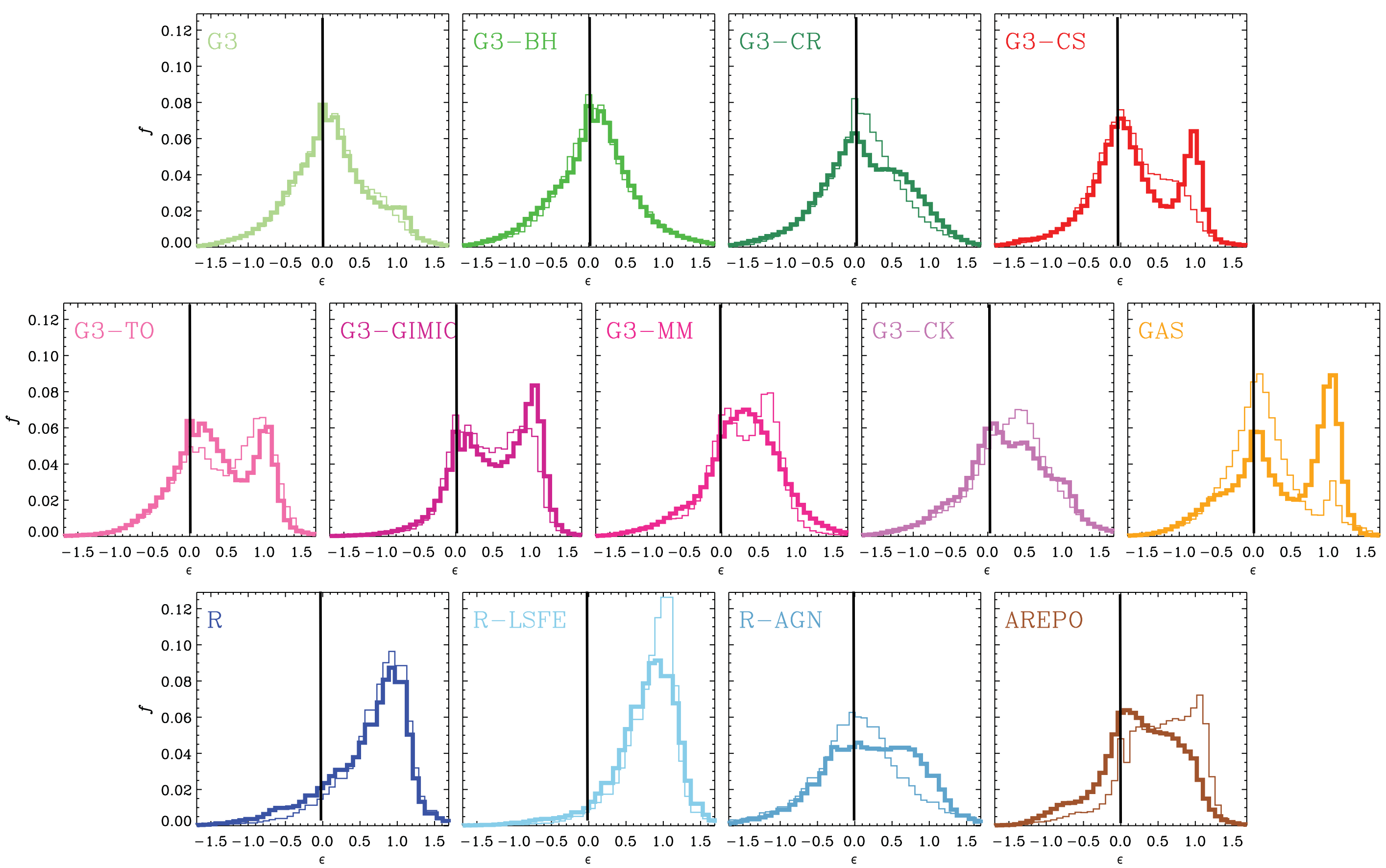


Analysis of Ceverino et al. simulations by Zolotov, Tweed, Dekel+ (in prep.)

The Angular Momentum Catastrophe

In practice it is not trivial to form galaxies with massive, extended disks and small spheroids. The angular momentum content of the disk determines its final structure. None of the 2012 Aquila low-resolution galaxy simulations had realistic disks.

fraction of stars with given angular momentum



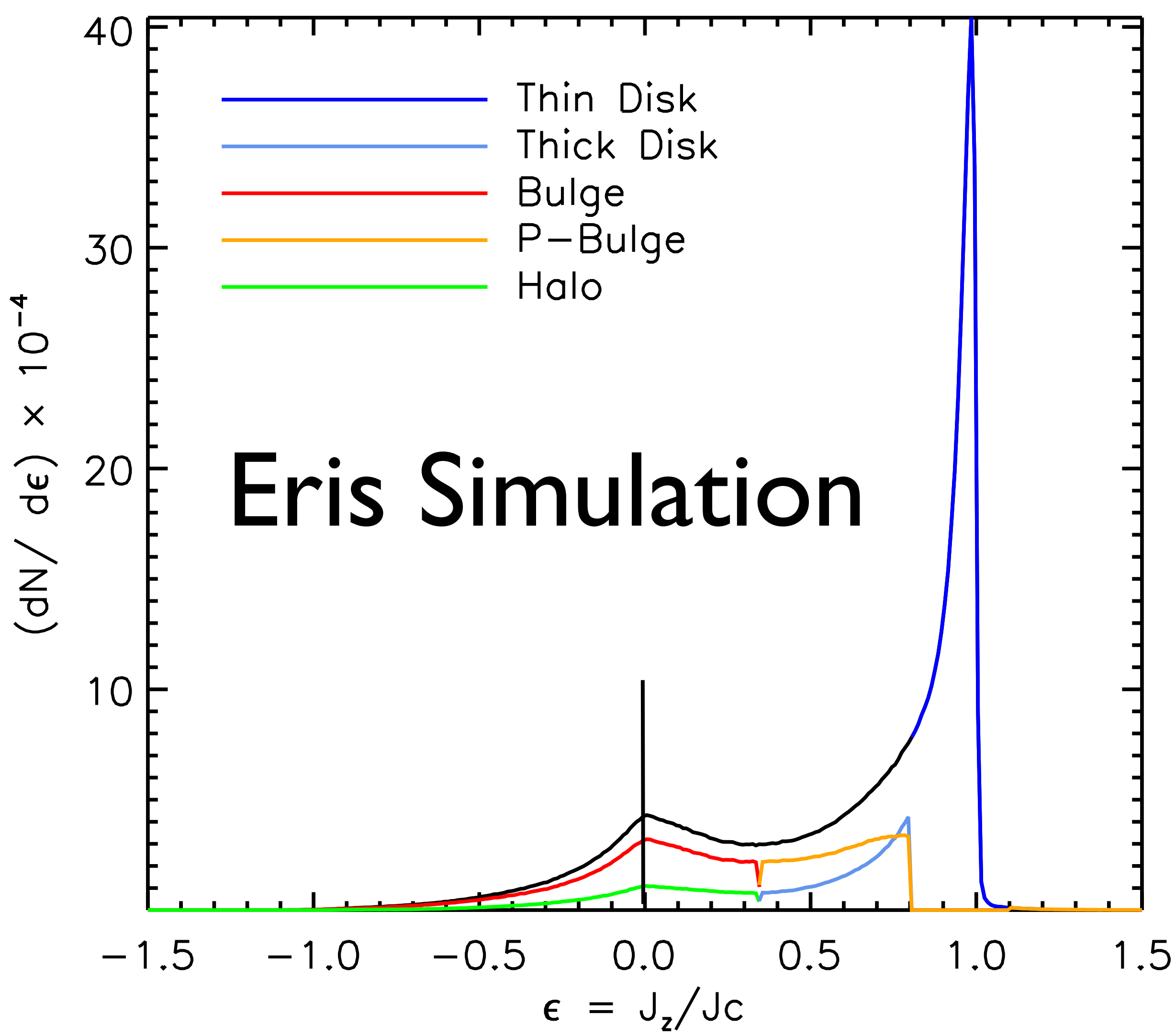
j_z/j_c

$\neq$

Scannapieco et al., Aquila Galaxy Simulation Comparison, 2012

The Angular Momentum ~~Catastrophe~~

Eris, the first high-resolution simulation of formation of a ~10^{12} $M_\odot$ galaxy, produced a realistic spiral galaxy. Adequate resolution and physically realistic feedback appear to be sufficient.



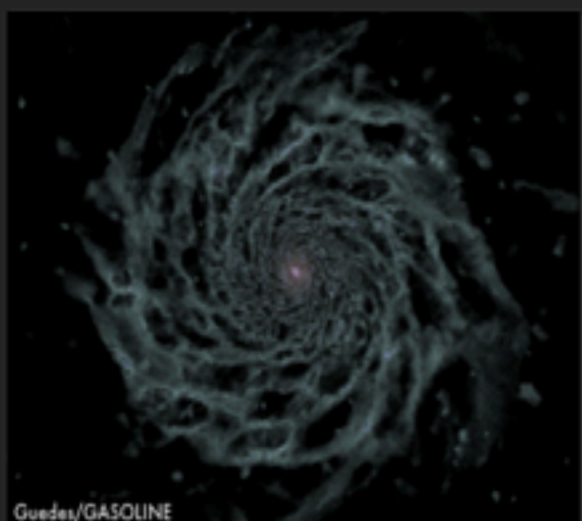
=

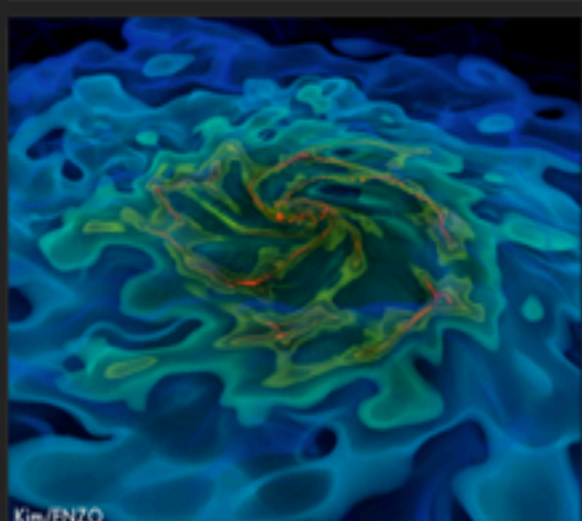
Guedes, Callegari, Madau, Mayer 2011 ApJ

AGORA Assembling Galaxies of Resolved Anatomy

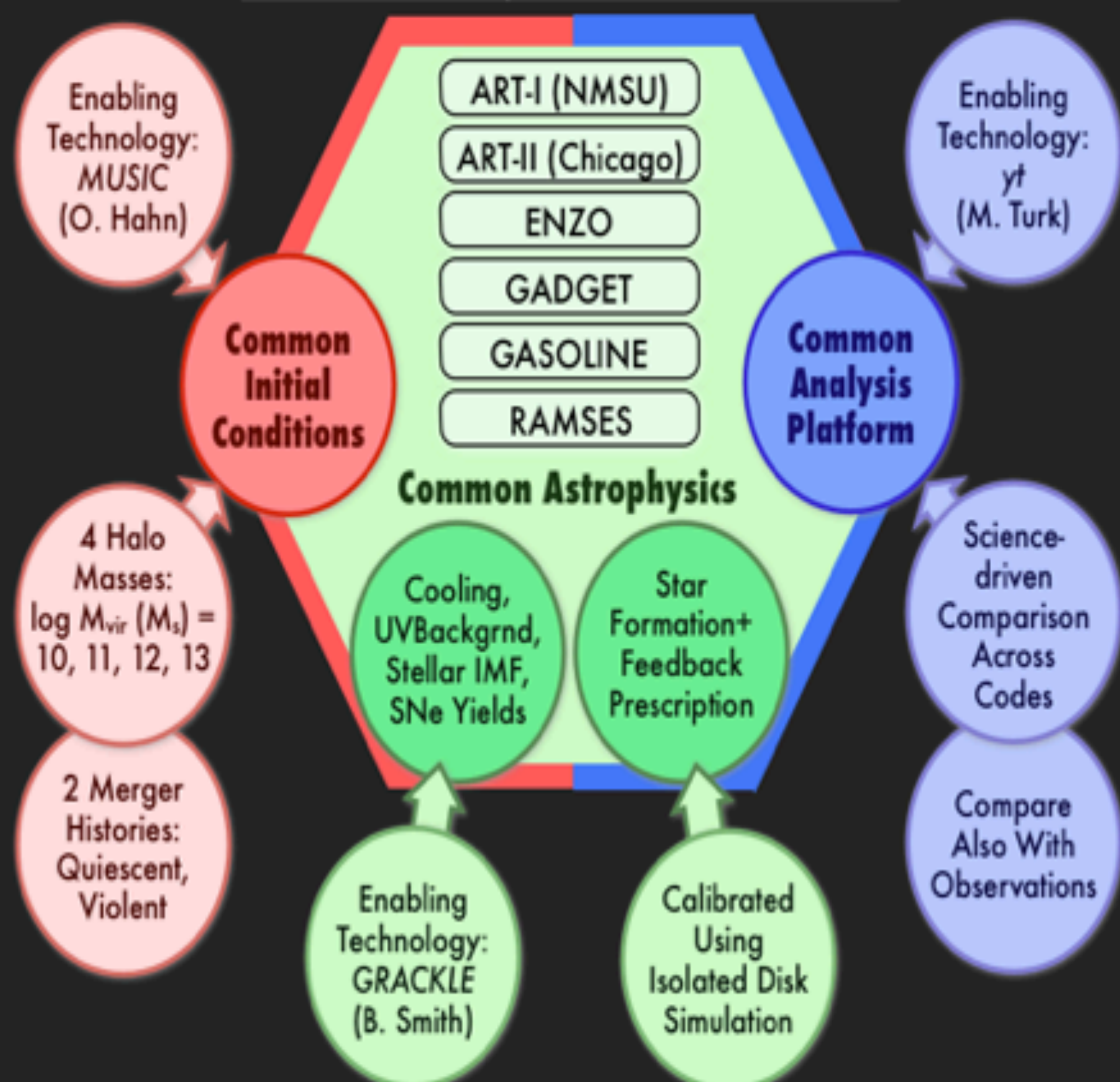
A High-resolution Galaxy Simulations Comparison Initiative To Tackle Longstanding Challenges in Galaxy Formation

High-res Galaxy Simulations





AGORA Comparison Infrastructure



AGORA Goal & Team

- GOAL: A multi-platform study to raise the realism and predictive power of high-resolution (<100 pc) galaxy simulations collectively
- TEAM: 4 task working groups and 9+ science working groups, 94 participants from 47 institutions as of 2nd Workshop, Aug. 2013
- DATA SHARE: Simulation data will be radpily available to public

- AGORA First light: Flagship paper by Ji-hoon Kim et al. (arXiv:1308.2669; www.AGORAsimulations.org)
- Project funded in part by:

University of California
High-Performance
AstroComputing Center
(UC-HiPACC)
Joel Primack, Director

University of California
Santa Cruz
Next Telescope Science
Institute (NEXSI)
Piero Madau, Director

Assembling Galaxies of Resolved Anatomy
AGORA High-Resolution Galaxy Simulation Comparison Project Steering Committee

Piero Madau & Joel R. Primack, UCSC, Co-Chairs
Tom Abel, Stanford
Nick Gnedin, Chicago/Fermilab
Lucio Mayer, University of Zurich
Romain Teyssier, Saclay & Zurich
James Wadsley, McMaster

Ji-hoon Kim, UCSC (Coordinator)

94 astrophysicists using 10 codes have joined AGORA

www.AGORAsimulations.org

AGORA High-Resolution Simulation Comparison

Initial Conditions for Simulations

MUSIC galaxy masses at $z\sim0$: $\sim10^{10}$, 10^{11}, 10^{12}, 10^{13} $M_\odot$

with both quiet and busy merging trees

isolation criteria agreed for Lagrangian regions

Isolated Spiral Galaxy at $z\sim1$: $\sim10^{12}$ $M_\odot$

Astrophysics that all groups will include

UV background (Haardt-Madau 2012)

cooling function (based on ENZO and Eris cooling)

Tools to compare simulations based on *yt*, to be available for all codes used in AGORA

Images and SEDs for all timesteps from *yt* ➠ *Sunrise*

www.AGORAsimulations.org

www.AGORAsimulations.org

AGORA Task-Oriented Working Groups

	Working Group	Objectives and Tasks
T1	Common Astrophysics	UV background, metal-dependent cooling, IMF, metal yields
T2	ICs: Isolated	common initial conditions for isolated low-z disk galaxies
T3	ICs: Cosmological	common initial conditions for cosmological zoom-in simulations
T4	Common Analysis	support `yt` and other analysis tools, define quantitative and physically meaningful comparisons across simulations

AGORA Science Working Groups

	Working Group	Science Questions (includes, but not limited to)
S1	Isolated Galaxies and Subgrid Physics	tune the subgrid physics across platforms to produce similar results for similar astrophysical assumptions
S2	Dwarf Galaxies	simulate $\sim 10^{10} M_\odot$ halos, compare results across all platforms
S3	Dark Matter	radial profile, shape, substructure, core-cusp problem
S4	Satellite Galaxies	effects of environment, UV background, tidal disruption
S5	Galactic Characteristics	surface brightness, stellar properties, metallicity, images, SEDs
S6	Outflows	outflows, circumgalactic medium, metal absorption systems
S7	High-redshift Galaxies	cold flows, clumpiness, kinematics, Lyman-limit systems
S8	Interstellar Medium	galactic interstellar medium, thermodynamics
S9	Massive Black Holes	black hole growth and feedback in galactic context
S10	Lyα Absorption and Emission	prediction of Lyα maps for simulated galaxies and their environments including effects of radiative transfer

THE *AGORA* HIGH-RESOLUTION GALAXY SIMULATIONS COMPARISON PROJECT

JI-HOON KIM[1], TOM ABEL[2], OSCAR AGERTZ[3,4], GREG L. BRYAN[5], DANIEL CEVERINO[6], CHARLOTTE CHRISTENSEN[7], CHARLIE CONROY[1], AVISHAI DEKEL[8], NICKOLAY Y. GNEDIN[3,9,10], NATHAN J. GOLDBAUM[1], JAVIERA GUEDES[11], OLIVER HAHN[11], ALEXANDER HOBBS[11], PHILIP F. HOPKINS[12,13], CAMERON B. HUMMELS[7], FRANCESCA IANNUZZI[14], DUŠAN KEREŠ[15], ANATOLY KLYPIN[16], ANDREY V. KRAVTSOV[3,10], MARK R. KRUMHOLZ[1], MICHAEL KUHLEN[1,13], SAMUEL N. LEITNER[17], PIERO MADAU[1], LUCIO MAYER[18], CHRISTOPHER E. MOODY[1], KENTARO NAGAMINE[19,20], MICHAEL L. NORMAN[15], JOSE OÑORBE[21], BRIAN W. O'SHEA[22], ANNALISA PILLEPICH[1], JOEL R. PRIMACK[23], THOMAS QUINN[24], JUSTIN I. READ[4], BRANT E. ROBERTSON[7], MIGUEL ROCHA[21], DOUGLAS H. RUDD[10, 25], SIJING SHEN[1], BRITTON D. SMITH[22], ALEXANDER S. SZALAY[26], ROMAIN TEYSSIER[18], ROBERT THOMPSON[7, 19], KEITA TODOROKI[19], MATTHEW J. TURK[5], JAMES W. WADSLEY[27], JOHN H. WISE[28], AND ADI ZOLOTOV[8] FOR THE *AGORA* COLLABORATION[29]

Draft version August 14, 2013

ABSTRACT

We introduce the *AGORA* project, a comprehensive numerical study of well-resolved galaxies within the ΛCDM cosmology. Cosmological hydrodynamic simulations with force resolutions of ~ 100 proper pc or better will be run with a variety of code platforms to follow the hierarchical growth, star formation history, morphological transformation, and the cycle of baryons in and out of 8 galaxies with halo masses $M_{\rm vir} \simeq 10^{10}$, 10^{11}, 10^{12}, and 10^{13} $M_\odot$ at $z = 0$ and two different ("violent" and "quiescent") assembly histories. The numerical techniques and implementations used in this project include the smoothed particle hydrodynamics codes GADGET and GASOLINE, and the adaptive mesh refinement codes ART, ENZO, and RAMSES. The codes will share common initial conditions and common astrophysics packages including UV background, metal-dependent radiative cooling, metal and energy yields of supernovae, and stellar initial mass function. These are described in detail in the present paper. Subgrid star formation and feedback prescriptions will be tuned to provide a realistic interstellar and circumgalactic medium using a non-cosmological disk galaxy simulation. Cosmological runs will be systematically compared with each other using a common analysis toolkit, and validated against observations to verify that the solutions are robust – i.e., that the astrophysical assumptions are responsible for any success, rather than artifacts of particular implementations. The goals of the *AGORA* project are, broadly speaking, to raise the realism and predictive power of galaxy simulations and the understanding of the feedback processes that regulate galaxy "metabolism." The initial conditions for the *AGORA* galaxies as well as simulation outputs at various epochs will be made publicly available to the community. The proof-of-concept dark matter-only test of the formation of a galactic halo with a $z = 0$ mass of $M_{\rm vir} \simeq 1.7 \times 10^{11}$ $M_\odot$ by 9 different versions of the participating codes is also presented to validate the infrastructure of the project.

AstroComputing is Prototypical Scientific Computing

Astronomy has several advantages:

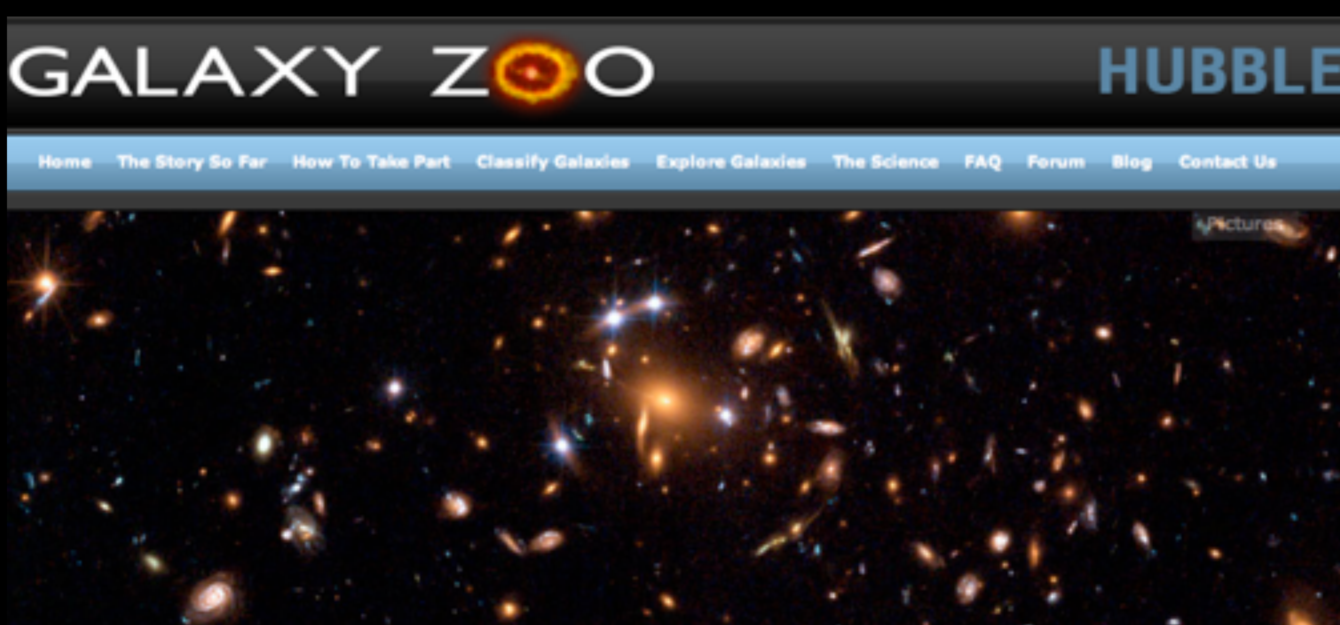
The data tends to be pretty clean

The data is (mostly) non-proprietary

The research is (mostly) funded

The data is pretty sexy

There's a lot of public involvement:



Big Challenges of AstroComputing

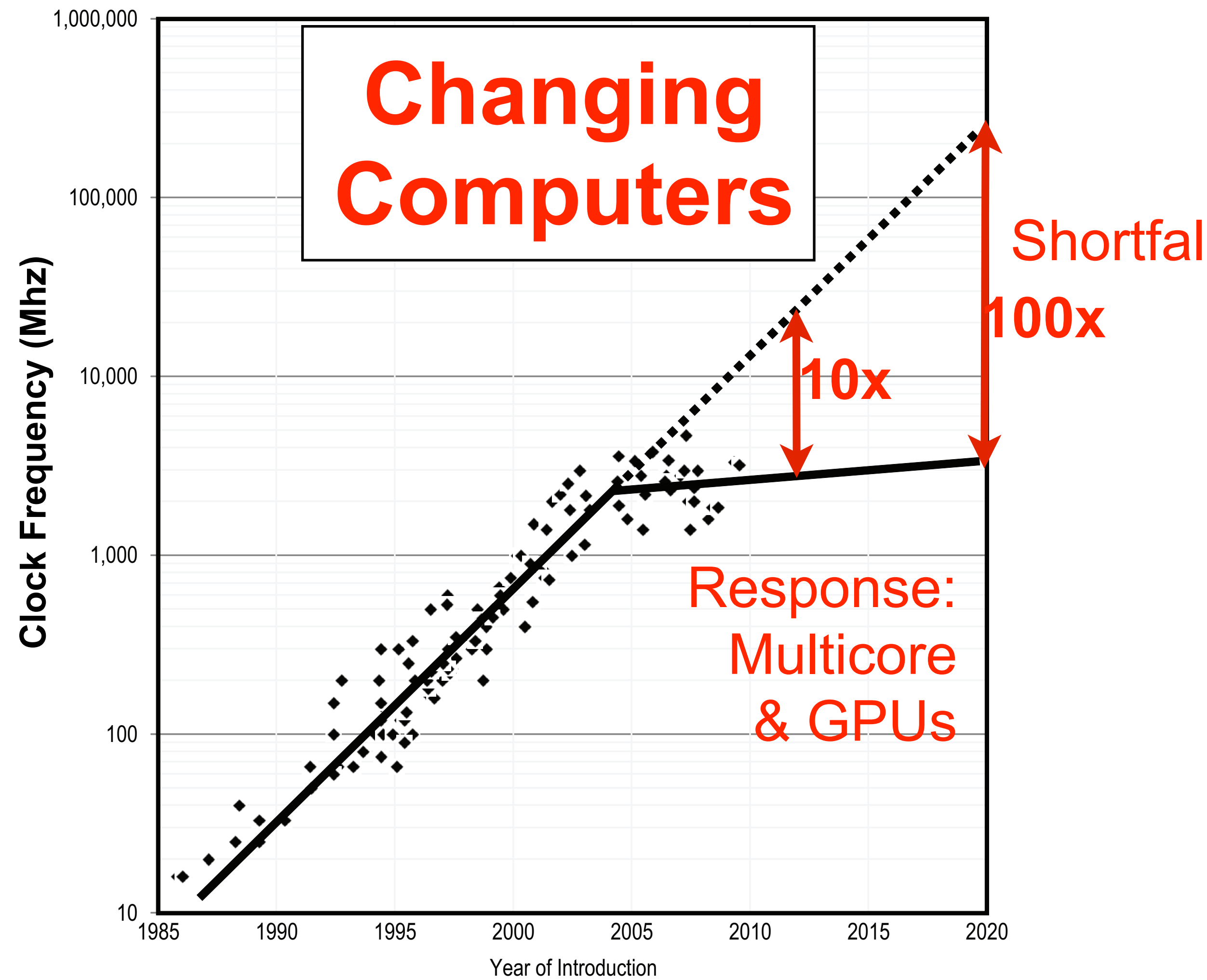
Big Data

Sloan Digital Sky Survey (SDSS) 2008
- 2.5 Terapixels of images
- 40 TB raw data ➠120 TB processed
- 35 TB catalogs

Mikulski Archive for Space Telescopes (MAST) 2013
- 185 TB of images
- 25 TB/year ingest rate
- >100 TB/year retrieval rate

Large Synoptic Survey Telescope (LSST) 2019
- 15 TB per night for 10 years
- 100 PB image archive
- 20 PB final database catalog

Square Kilometer Array (SKA) ~2024
- 1 EB per day (~ internet traffic today)
- 100 PFlop/s processing power
- ~1 EB processed data/year



Increasingly inhomogeneous computers are harder to program! We need computational scientists and engineers and new compilers that generate code for nodes with cores+accelerators with automatic load balancing and fault tolerance.

High Performance Scientific Computing Needs

The challenges facing us are

- "Big data" -- too large to move -- from more powerful observations, larger computer outputs, and falling storage costs
- Changing high-performance computer architecture -- from networked single processors to multicore and GPUs

These challenges demand new collaborations between natural scientists and computer scientists to develop

- Tools and scientific programmers to convert legacy code and write new codes efficient on multicore/GPU/MIC architectures, including fault tolerance and automatic load balancing
- New ways to visualize and analyze big data remotely
- Train new generations of scientific & engineering computer users
- Improve education and outreach

UC-HiPACC is proposing a California Scientific Computing Institute in Silicon Valley to work on these issues -- we welcome collaboration!

Thanks!

Supercomputing the Universe

Joel R. Primack, UCSC

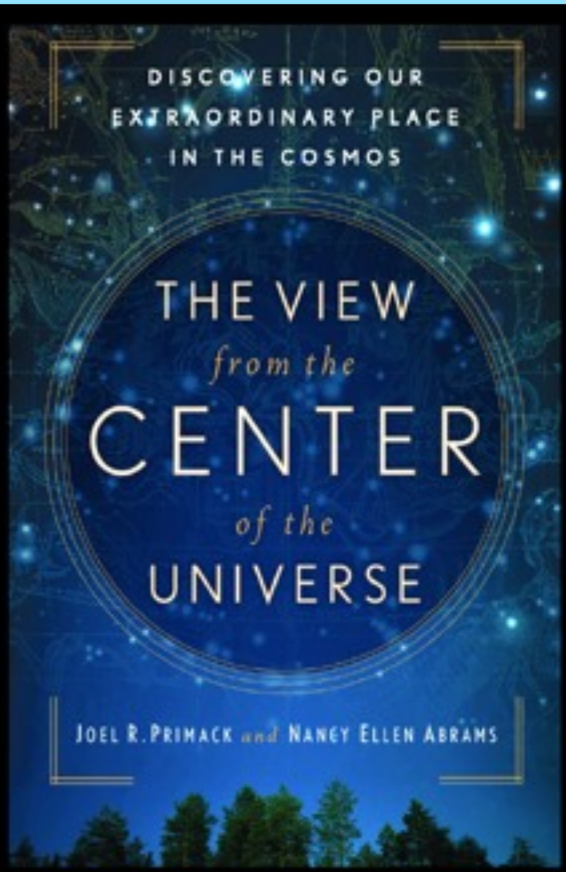
http://scipp.ucsc.edu/personnel/profiles/primack.html

Websites related to this talk:

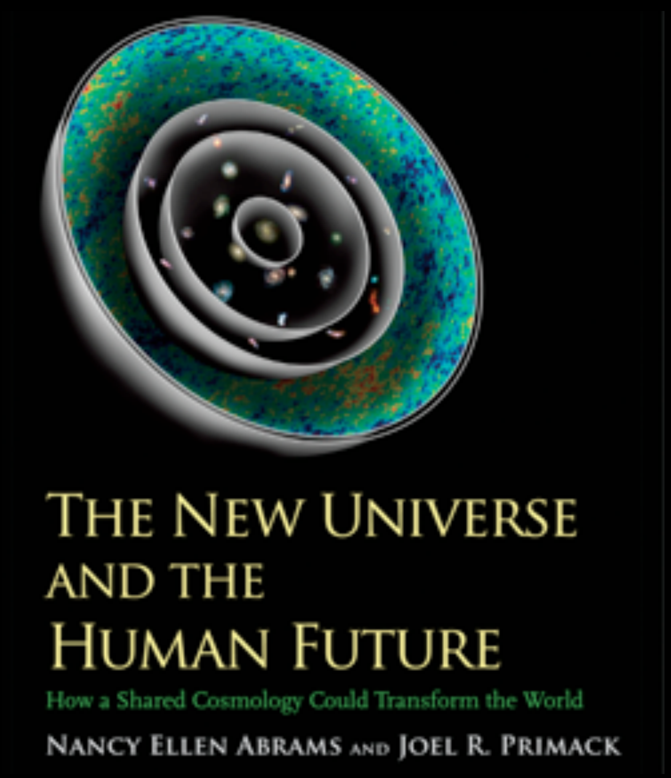
http://hipacc.ucsc.edu University of California High-Performance AstroComputing Center (UC-HiPACC)
http://hipacc.ucsc.edu/v4/ International Astronomy Visualization Gallery
http://hipacc.ucsc.edu/Bolshoi Bolshoi simulations
http://candels.ucolick.org CANDELS survey
http://code.google.com/p/sunrise/ Sunrise dust code

Abrams & Primack Book Websites with images and videos:

ViewfromtheCenter.com



New-Universe.org



El-Nuevo-Universo.org