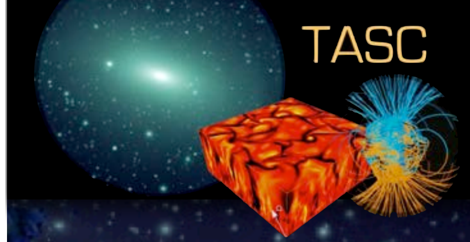
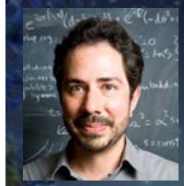
TASC



Theoretical Astrophysics Santa Cruz



Anthony Aguirre
Physics

Cosmology; inflation; gravity; galaxy formation;

Erik Asphaug
Earth & Planetary Sciences

Origin and evolution of the solar system; comets and asteroids

Nic Brummell
Applied Math

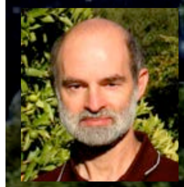
Planetary and stellar interiors; computational magnetohydrodynamics;

Jonathan Fortney
Astronomy & Astrophysics

Planetary atmosphere and interior physics

Pascale Garaud
Applied Math

Solar and stellar interiors; disk dynamics

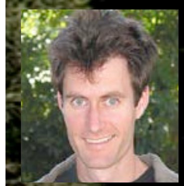


Gary Glatzmaier
Earth & Planetary Sciences

Computer simulations of stellar and planetary dynamos

Mark Krumholz
Astronomy & Astrophysics

Star formation; interstellar medium; numerical methods



Greg Laughlin
Astronomy & Astrophysics

Extrasolar planets; stellar evolution; disk dynamics

DON'T BE DISTRACTED...

...by the redwood trees, pristine beaches, and brilliant sunshine...

SANTA CRUZ HOSTS HARDCORE ASTROPHYSICS.

UCSC's astrophysics group is one of the world's best, boasting top faculty across a broad range of subjects, great access to instrumental and computational resources, and a top-notch graduate training program. And yes, exceptional quality of life. Interested?

TASC is a research unit spanning four affiliated departments. We work closely with each other and with experimentalists, instrumentalists, and observers at the University of California Observatories, the Santa Cruz Institute for Particle Physics, the Center for Adaptive Optics, the Center for the Origin, Dynamics, and Evolution of Planets, and the Institute for Geophysics and Planetary Physics. As part of TASC, you will also have opportunities to access our new world-class Pleiades Supercomputer and to become deeply involved in science using GLAST, Hubble, Keck, Spitzer, VERITAS, NuSTAR, planetary spacecraft, and other world-class instruments.

TASC science tackles a wide range of problems, such as: How do stars and planets form, evolve, move, and die? Is Earth unique? How were the elements created? How do black holes impact the Universe? What is the nature of dark matter and dark energy? How do galaxies form and evolve? How did the Universe begin (and are there other universes)?

DID YOU KNOW?...

- Cold-dark-matter galaxy formation theory began at UCSC.
- The hypernova model for GRBs was invented at UCSC.
- UCSC's physics faculty is the nation's most highly cited.
- Most known extrasolar planets were discovered with UCSC-built equipment.
- UCSC physicists are major builders and users of GLAST.
- UCSC pioneered giant optical telescopes like Keck, and is making the key technology breakthroughs for even larger telescopes.

As a TASC graduate student, you will contribute significantly to world-class, cutting-edge discoveries while positioning yourself to follow previous UCSC students who have gone on to become Hubble Fellows, Keck Fellows, Chandra Fellows, and junior faculty at excellent institutions.

Doug Lin
Astronomy & Astrophysics

Planet and star formation; accretion disks; stellar dynamics

Piero Madau
Astronomy & Astrophysics

Cosmology and high-energy astrophysics

Francis Nimmo
Earth and Planetary Sciences

Structure and evolution of rocky and icy planets

Joel Primack
Physics

Cosmology; galaxy formation; dark matter

Stefano Profumo
Physics

High-energy and particle astrophysics; dark matter

Enrico Ramirez-Ruiz
Astronomy & Astrophysics

High-energy astrophysics; stellar explosions; GRBs; accretion disks

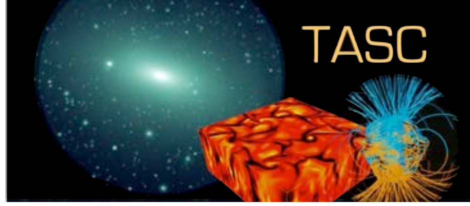
Adriane Steinacker
Astronomy & Astrophysics

Formation of planetary systems; solar system dynamics.

Stan Woosley
Astronomy & Astrophysics

Nuclear astrophysics; supernovae; gamma ray bursts; nucleosynthesis

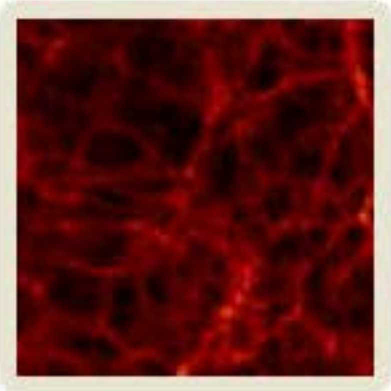
HOW TO APPLY: submit all applications to the Graduate Division of the University of California at Santa Cruz (http://graddiv.ucsc.edu/admissions). Apply to the UCSC department of your choice but indicate your interest in TASC in the application. All TASC-oriented applications will be reviewed jointly. Also send a separate letter of interest to Maria Sliwinski (sliwinsk@ucsc.edu), TASC graduate program advisor, 201 Interdisciplinary Sciences Bldg., UC Santa Cruz, Santa Cruz CA 95064. For further information see http://astro.ucsc.edu/tasc



Theoretical Astrophysics Santa Cruz

Big Data and Machine Learning

Our faculty lead and are engaged in the next big data projects of Astronomy -- HSC/Subaru, LSST, DESI -- and are advancing machine learning algorithms to glean the science them.



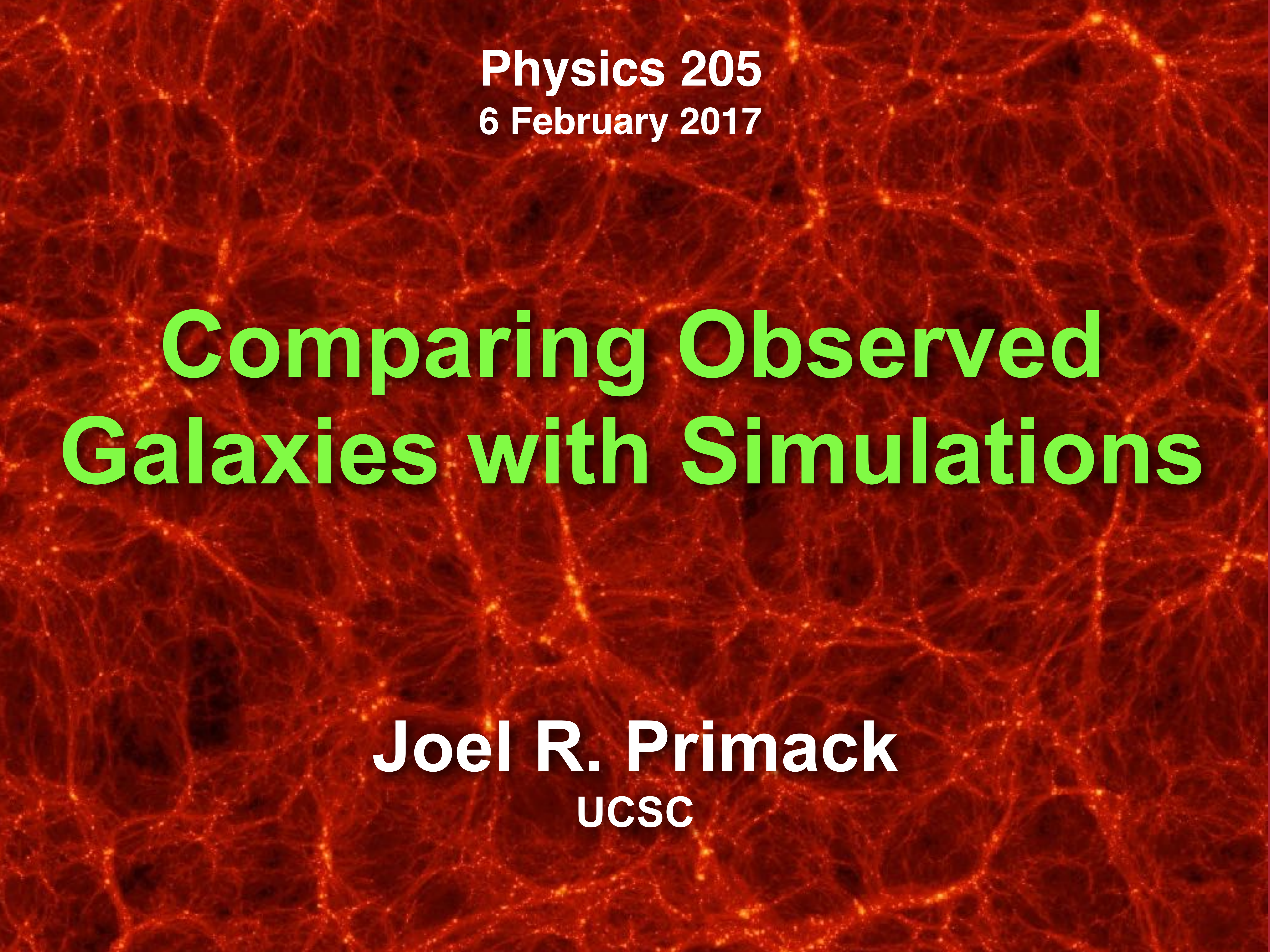
Supercomputing

Largest group of computational astrophysics faculty in the world, exploring fundamental questions in astrophysics through the use of supercomputers at the UC Santa Cruz.

Cosmic contributions

UCSC Astronomy and Astrophysics faculty are heavily involved with scientific planning for NASA's next generation of space-borne observatories, including the James Webb Space Telescope and the Wide Field Infrared Survey Telescope.

HOW TO APPLY: submit all applications to the Graduate Division of the University of California at Santa Cruz (http://graddiv.ucsc.edu/admissions). Apply to the UCSC department of your choice but indicate your interest in TASC in the application. All TASC-oriented applications will be reviewed jointly. Also send a separate letter of interest to Maria Sliwinski (sliwinsk@ucsc.edu), TASC graduate program advisor, 201 Interdisciplinary Sciences Bldg., UC Santa Cruz, Santa Cruz CA 95064. For further information see http://astro.ucsc.edu/tasc



Physics 205
6 February 2017

Comparing Observed Galaxies with Simulations

Joel R. Primack
UCSC


Hubble Space Telescope Ultra Deep Field - ACS
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

Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

Dark Matter Ships

on a

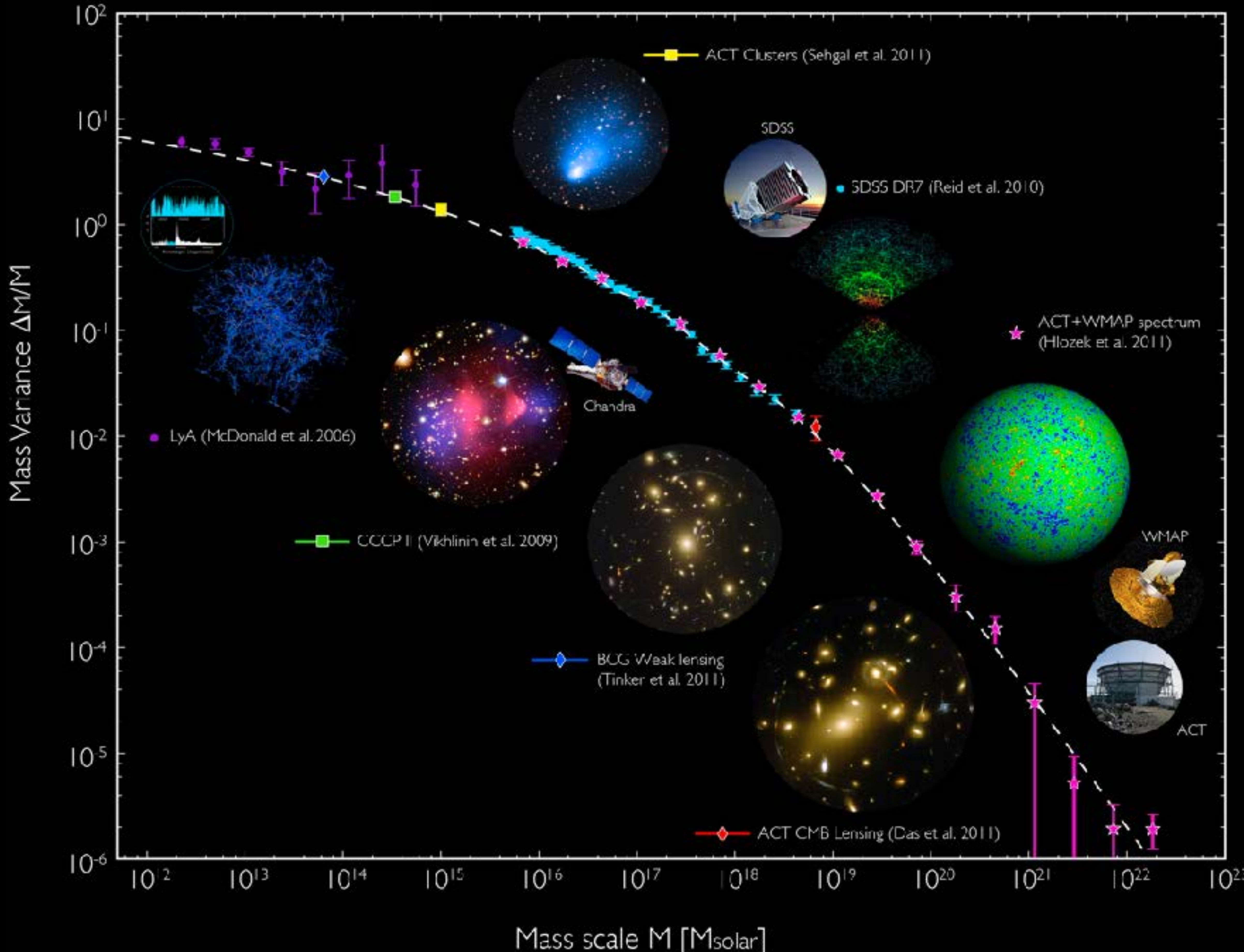
Dark Energy Ocean

Matter and Energy Content of the Universe

ΛCDM

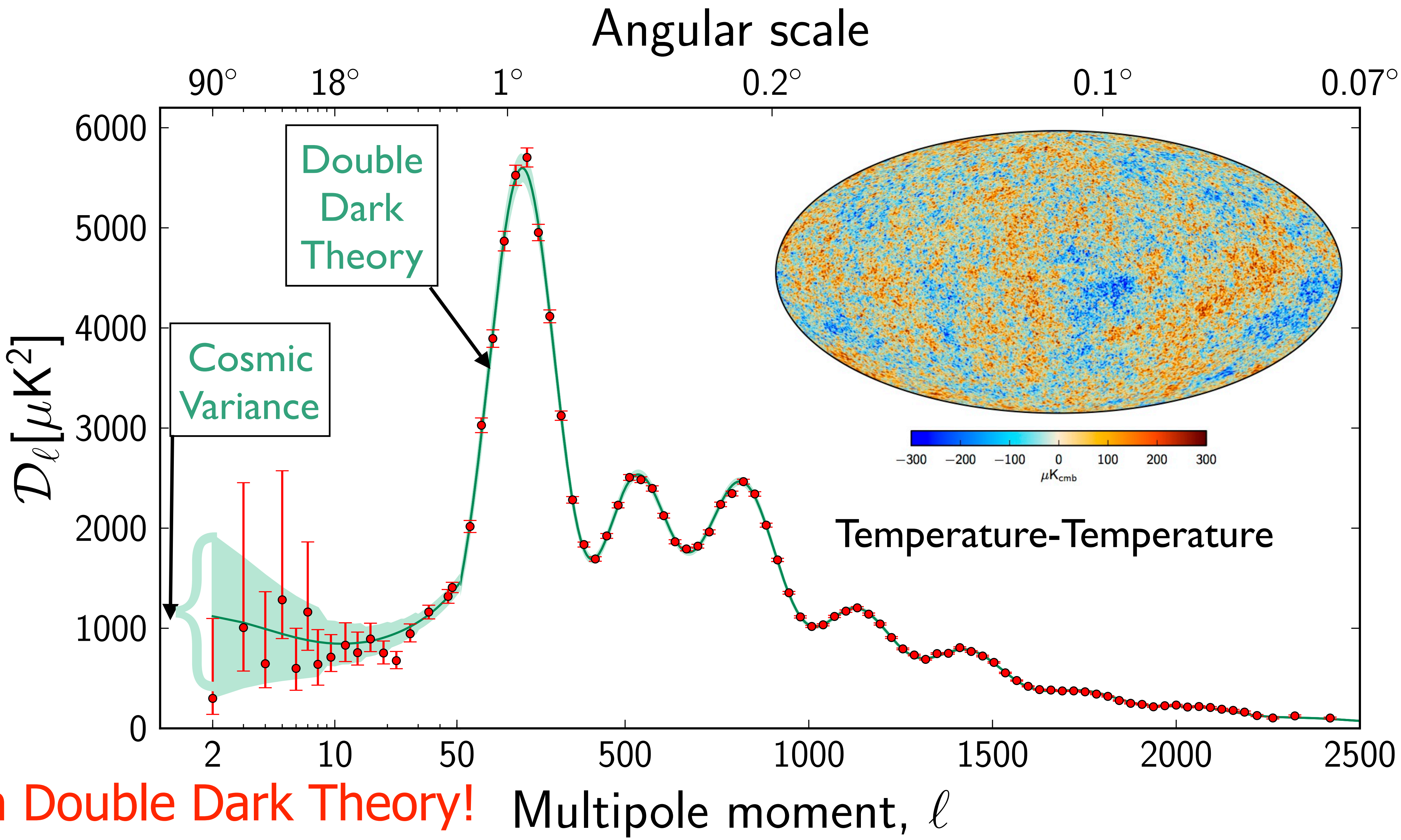
Double Dark Theory

Matter Distribution Agrees with Double Dark Theory!

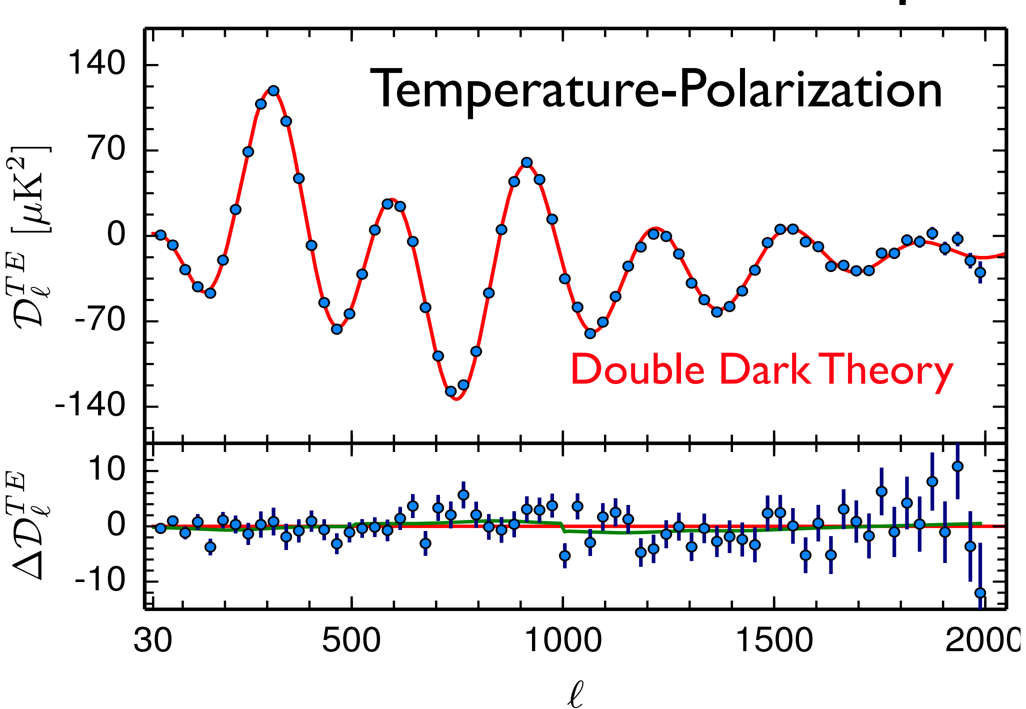


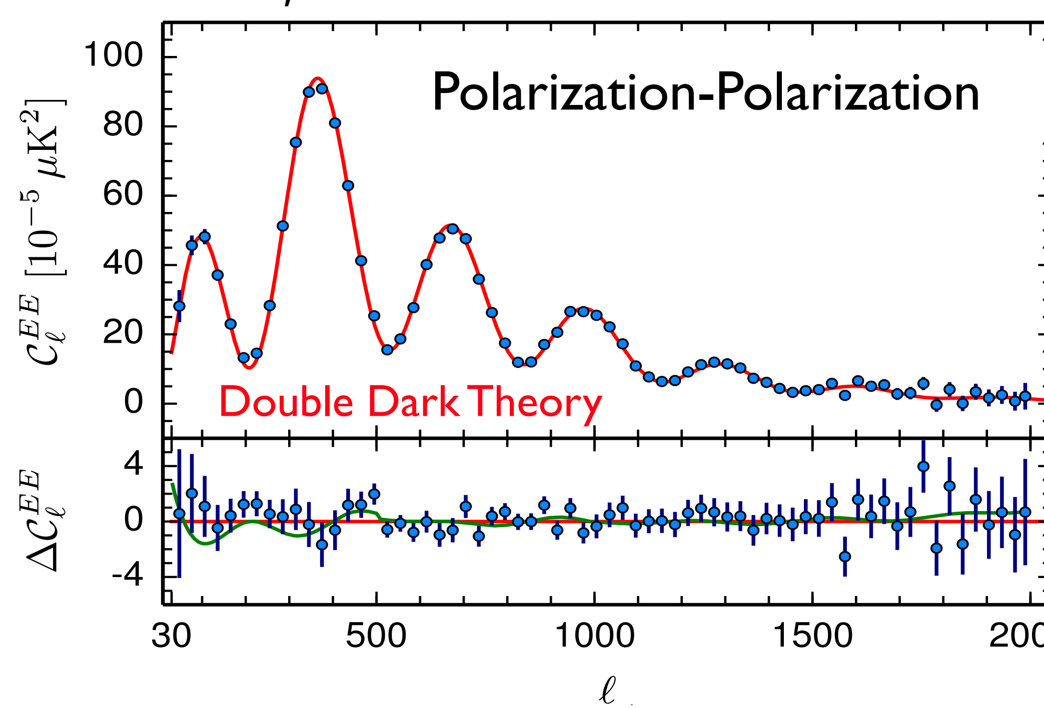
European Space Agency PLANCK Satellite Data

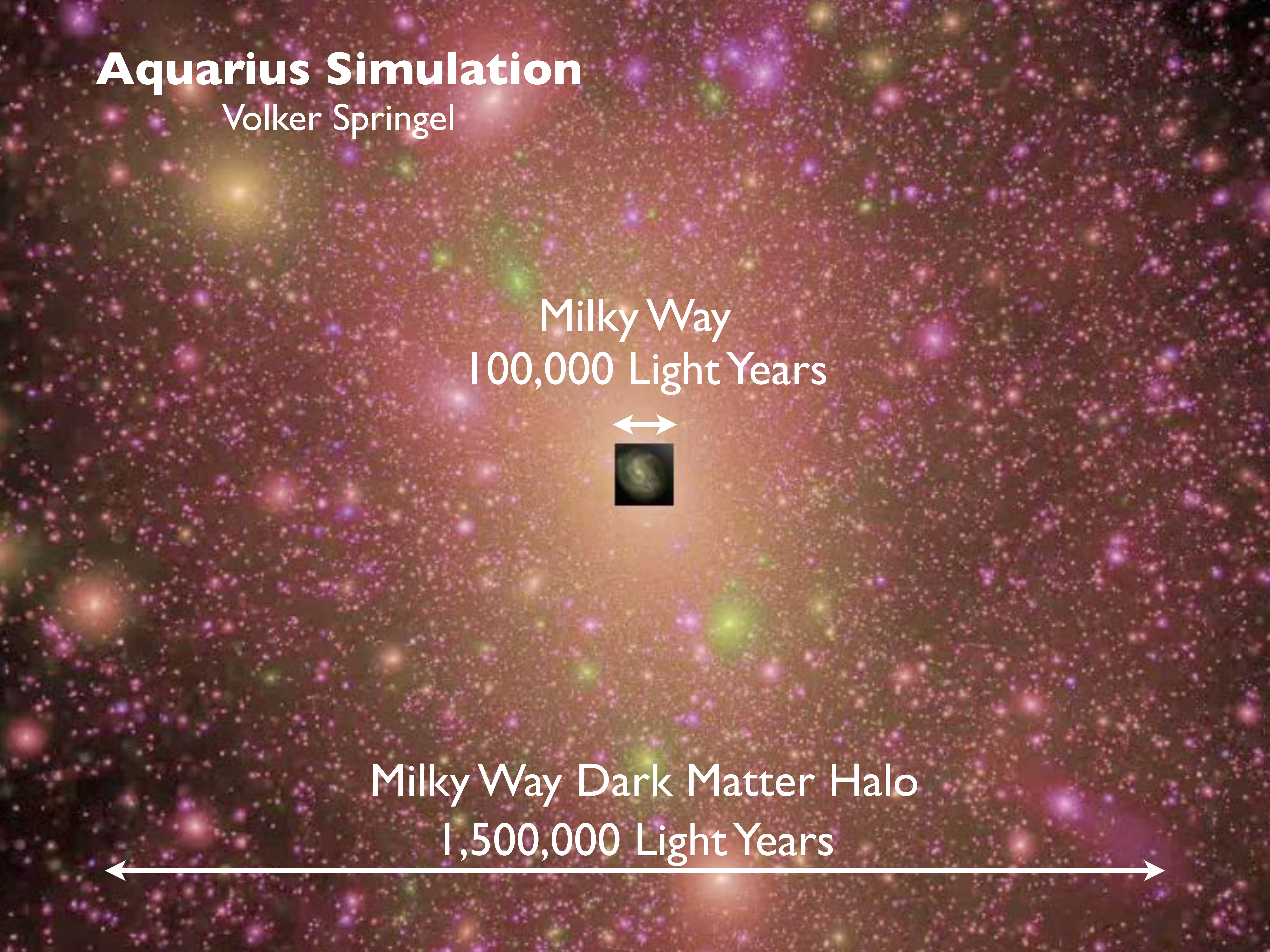
Released February 9, 2015

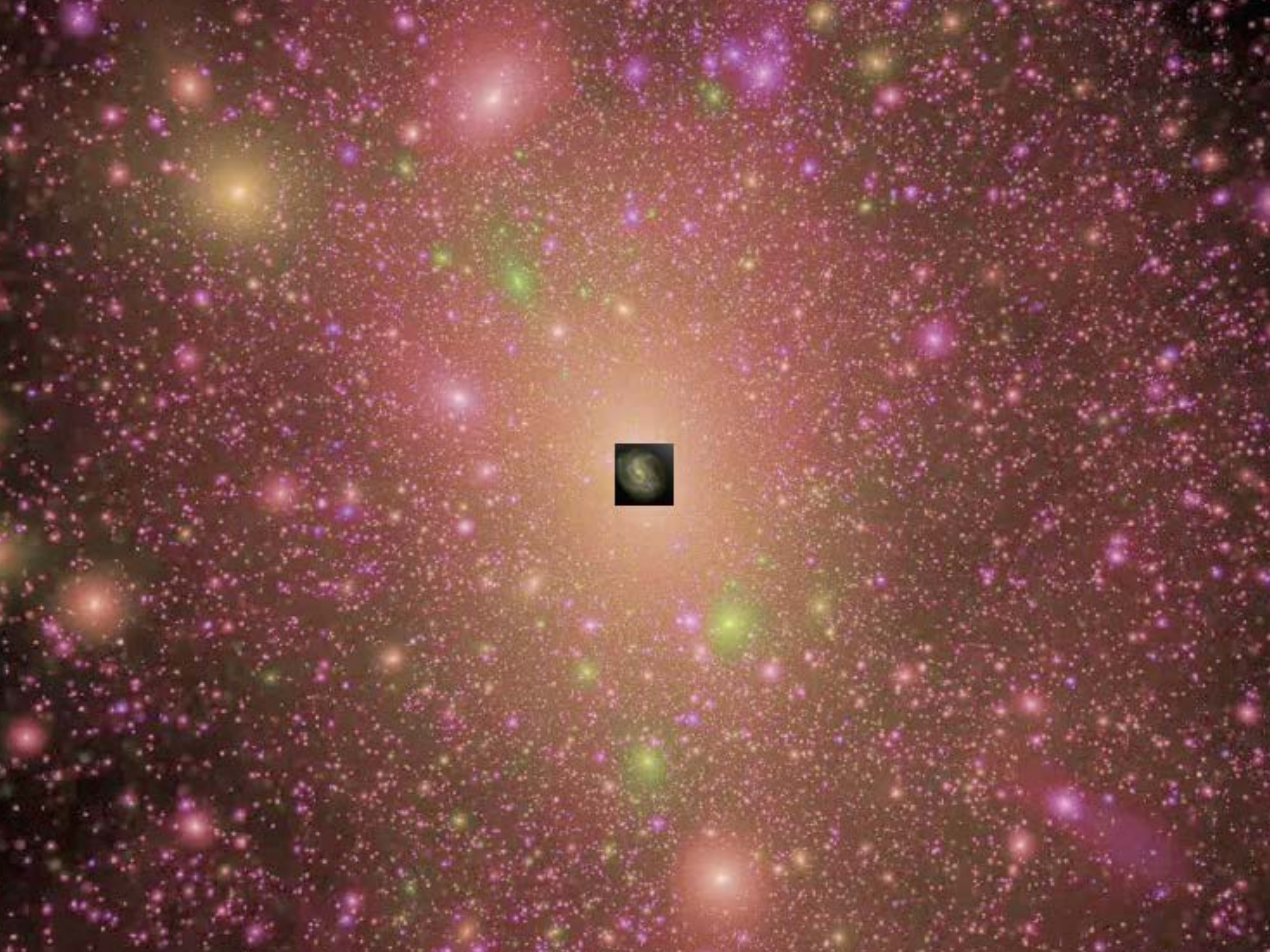


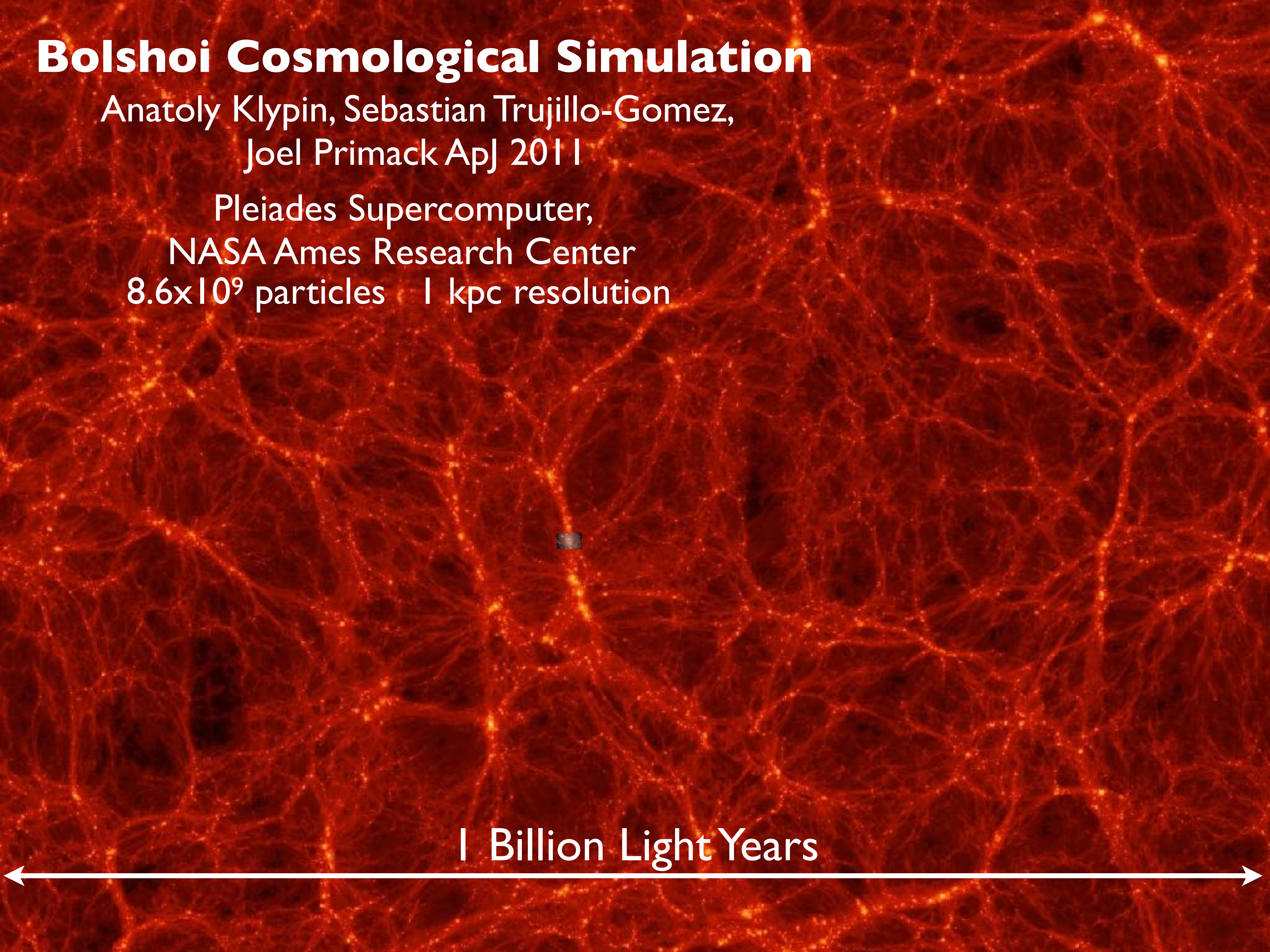
Agrees with Double Dark Theory!

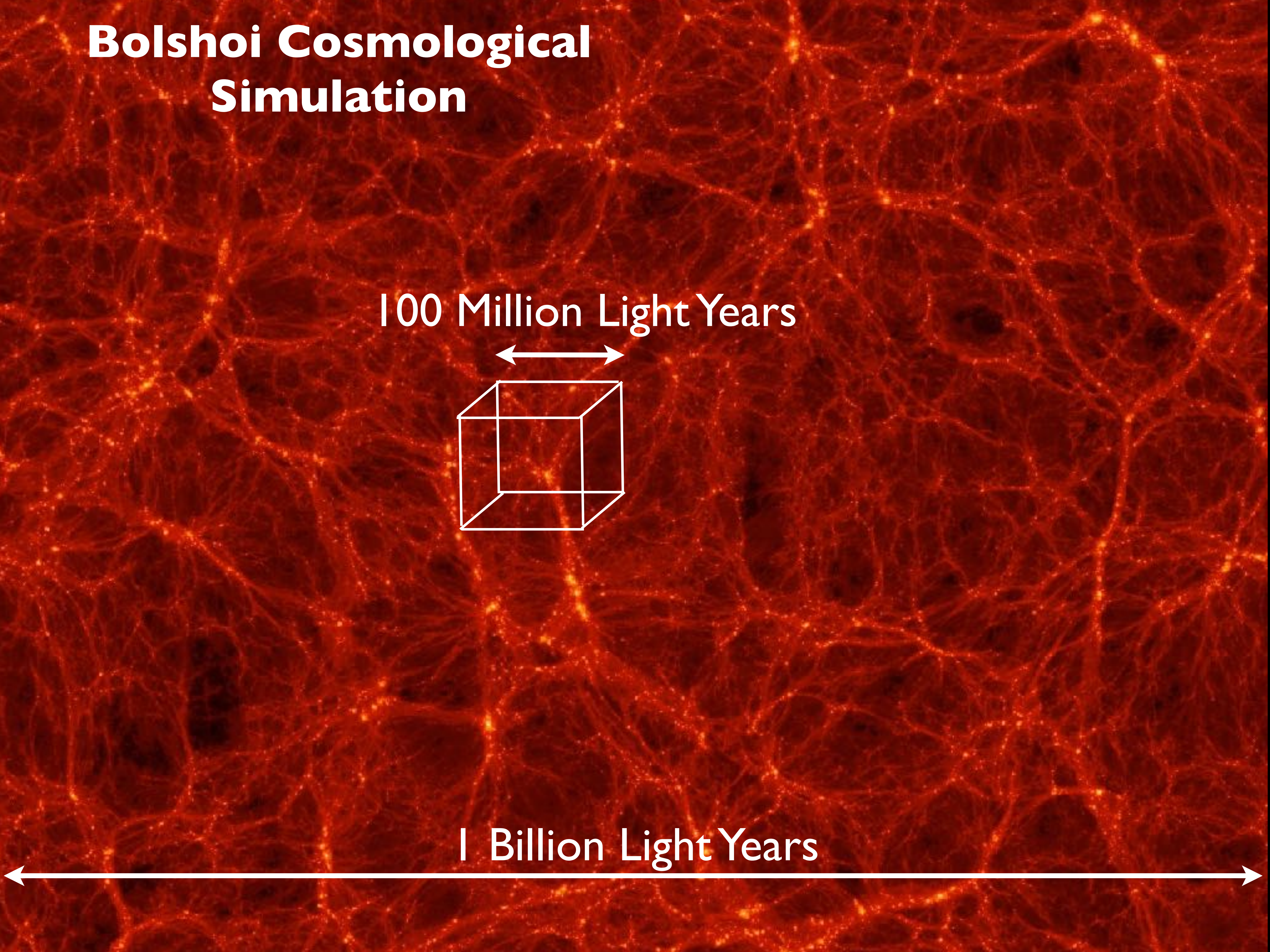





Aquarius Simulation
Volker Springel
Milky Way
100,000 Light Years
Milky Way Dark Matter Halo
1,500,000 Light Years




Bolshoi Cosmological Simulation
Anatoly Klypin, Sebastian Trujillo-Gomez,
Joel Primack ApJ 2011
Pleiades Supercomputer,
NASA Ames Research Center
8.6x10^9 particles   1 kpc resolution
1 Billion Light Years


Bolshoi Cosmological Simulation
100 Million Light Years
1 Billion Light Years

How the Halo of the Big Cluster Formed

100 Million Light Years

Bolshoi-Planck Cosmological Simulation

Merger Tree of a Large Halo

Structure Formation Methodology

- Starting from the Big Bang, we simulate the evolution of a representative part of the universe according to the Double Dark theory to see if the end result matches what astronomers actually observe.

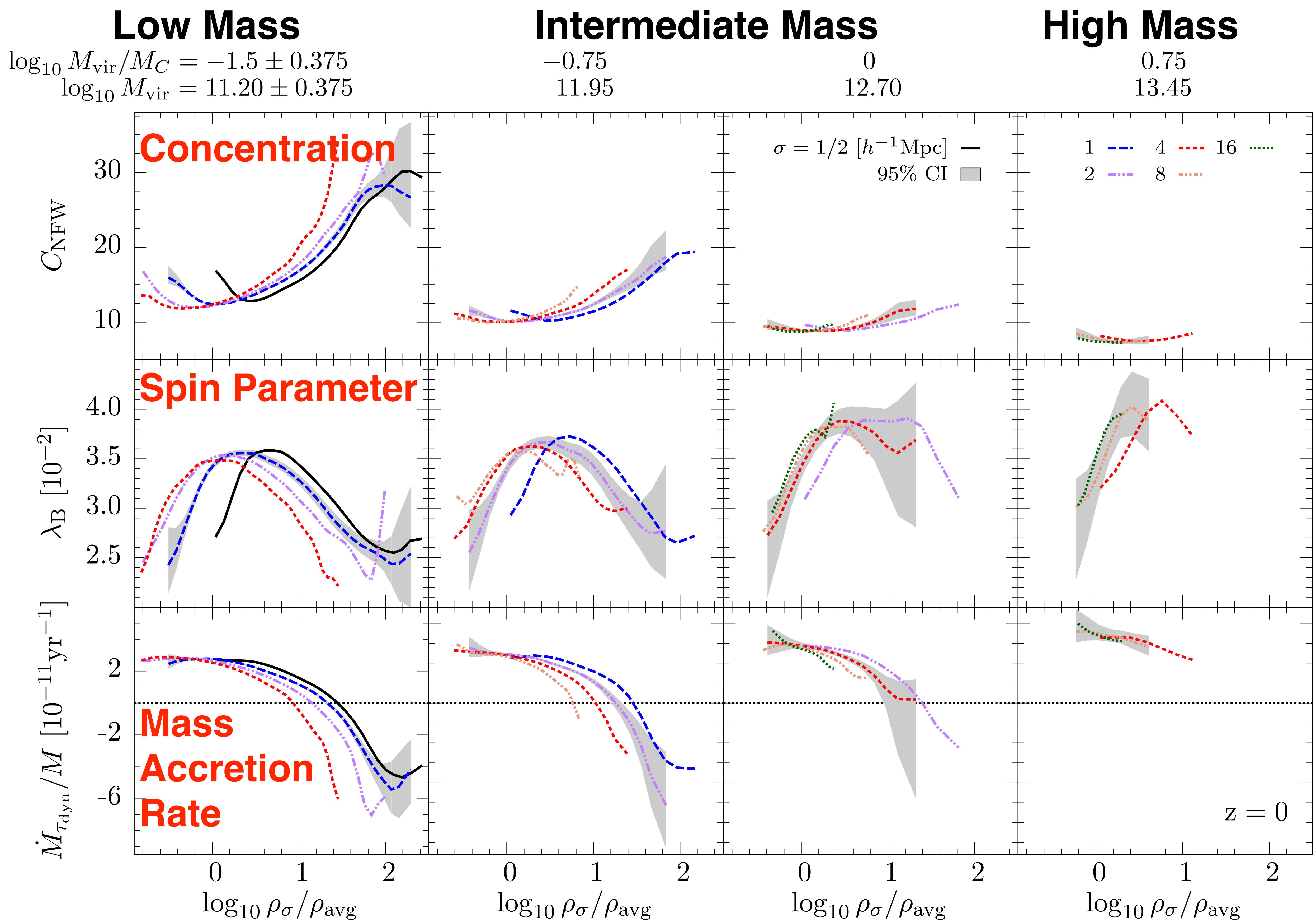
Structure Formation Methodology

- Starting from the Big Bang, we simulate the evolution of a representative part of the universe according to the Double Dark theory to see if the end result matches what astronomers actually observe.
- On the large scale the simulations produce a universe just like the one we live in. We're always looking for new phenomena to predict — every one of which tests the whole theory!

Properties of Dark Matter Haloes: Local Environment Density

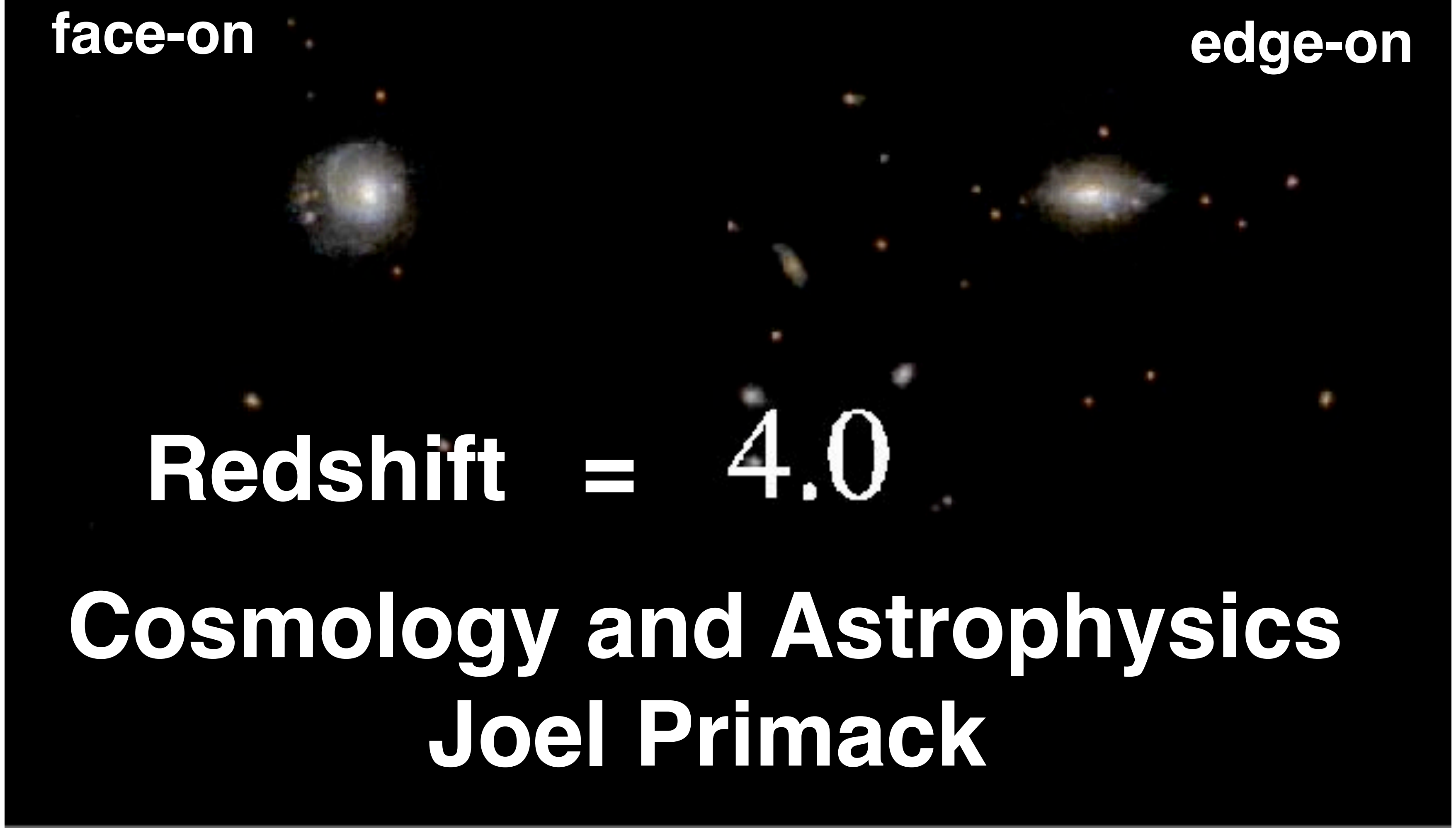
Christoph T. Lee, Joel R. Primack, Peter Behroozi, Aldo Rodríguez-Puebla, Doug Hellinger, Avishai Dekel

MNRAS 2017



Structure Formation Methodology

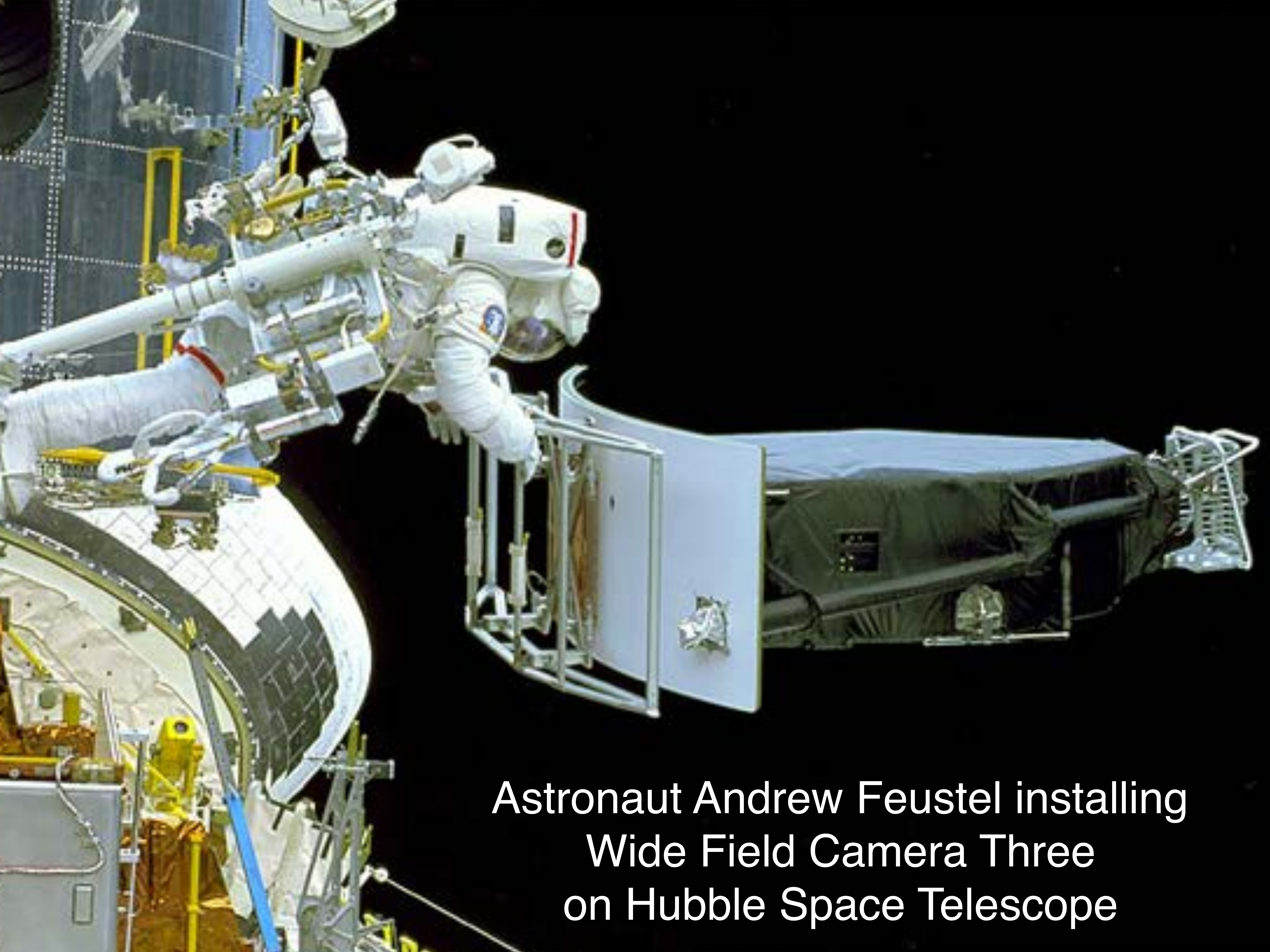
- Starting from the Big Bang, we simulate the evolution of a representative part of the universe according to the Double Dark theory to see if the end result matches what astronomers actually observe.
- On the large scale the simulations produce a universe just like the one we live in. We're always looking for new phenomena to predict — every one of which tests the theory!
- But the way individual galaxies form is only partly understood because it depends on the interactions of the ordinary atomic matter, as well as the dark matter and dark energy, to form stars and black holes. We need help from observations.



- **Bolshoi** - best cosmological simulations using the latest cosmological parameters.
- Largest suite of **high-resolution zoom-in hydrodynamic galaxy simulations** compared with observations by CANDELS, the largest-ever Hubble Space Telescope project.
- Dust absorption and re-radiation of starlight in simulated galaxies using my group's **Sunrise** code used to make realistic images from our simulations.
- New methods for **comparison of simulated galaxies with observations**, including **Deep Learning** methods. Explain observed **galaxy clumps**, **compaction**, **elongation**.
- Co-leading with Piero Madau the Assembling Galaxies of Resolved Anatomy (**AGORA**) **international collaboration** to run and compare high-resolution galaxy simulations.

- 3 Aspects of Star-Forming Galaxies Seen in CANDELS
  - Compaction
  - Elongation
  - Clumps

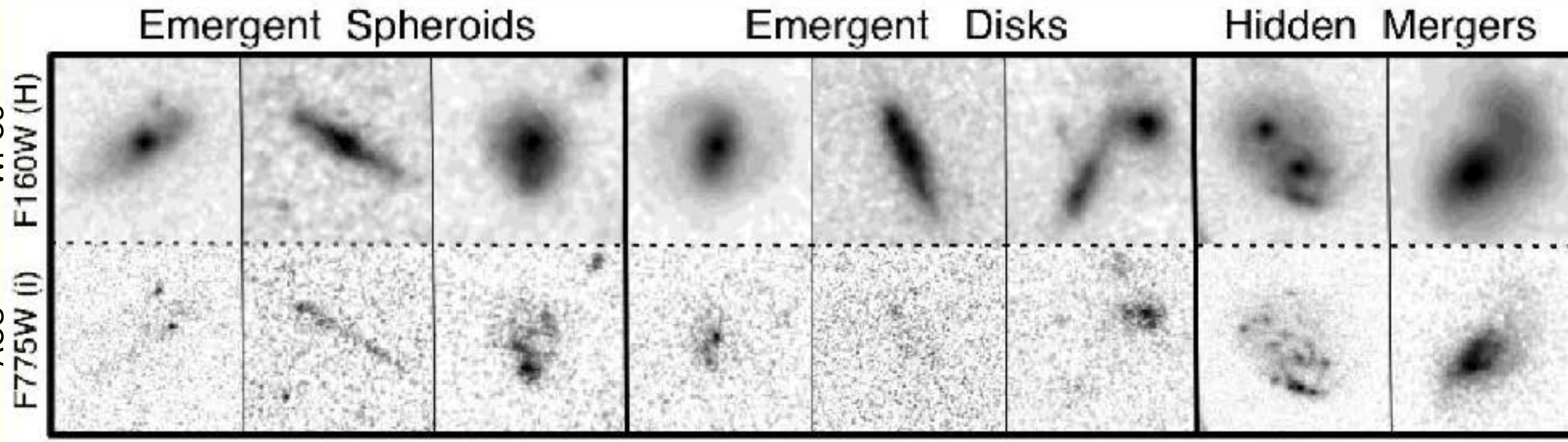
} Challenge for Observers & Simulators!



Astronaut Andrew Feustel installing
Wide Field Camera Three
on Hubble Space Telescope

The CANDELS Survey

candels.ucolick.org



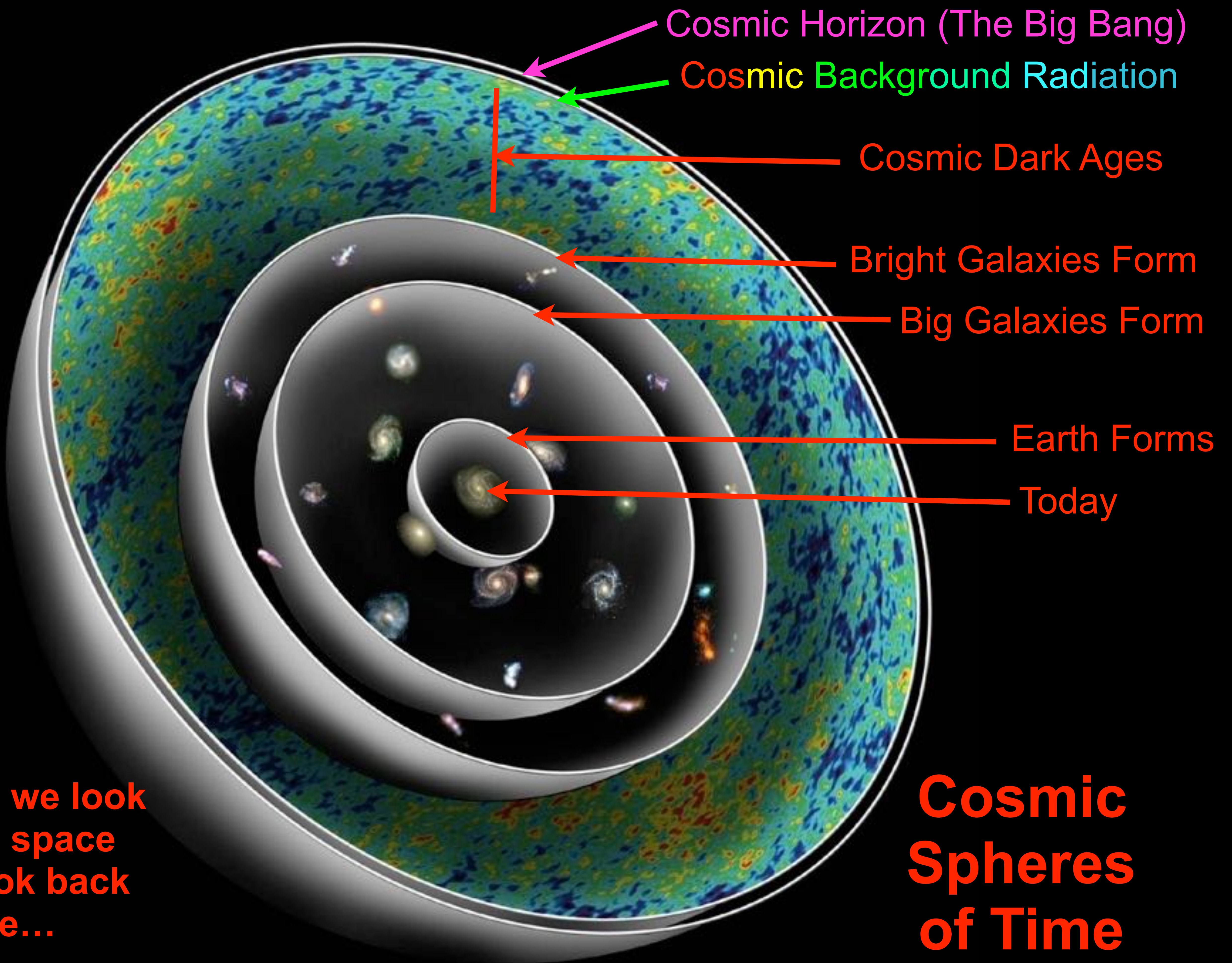
CANDELS: A Cosmic Odyssey

(blue 0.4 μm)(1+z) = 1.6 μm @ z = 3

(red 0.7 μm)(1+z) = 1.6 μm @ z = 2.3

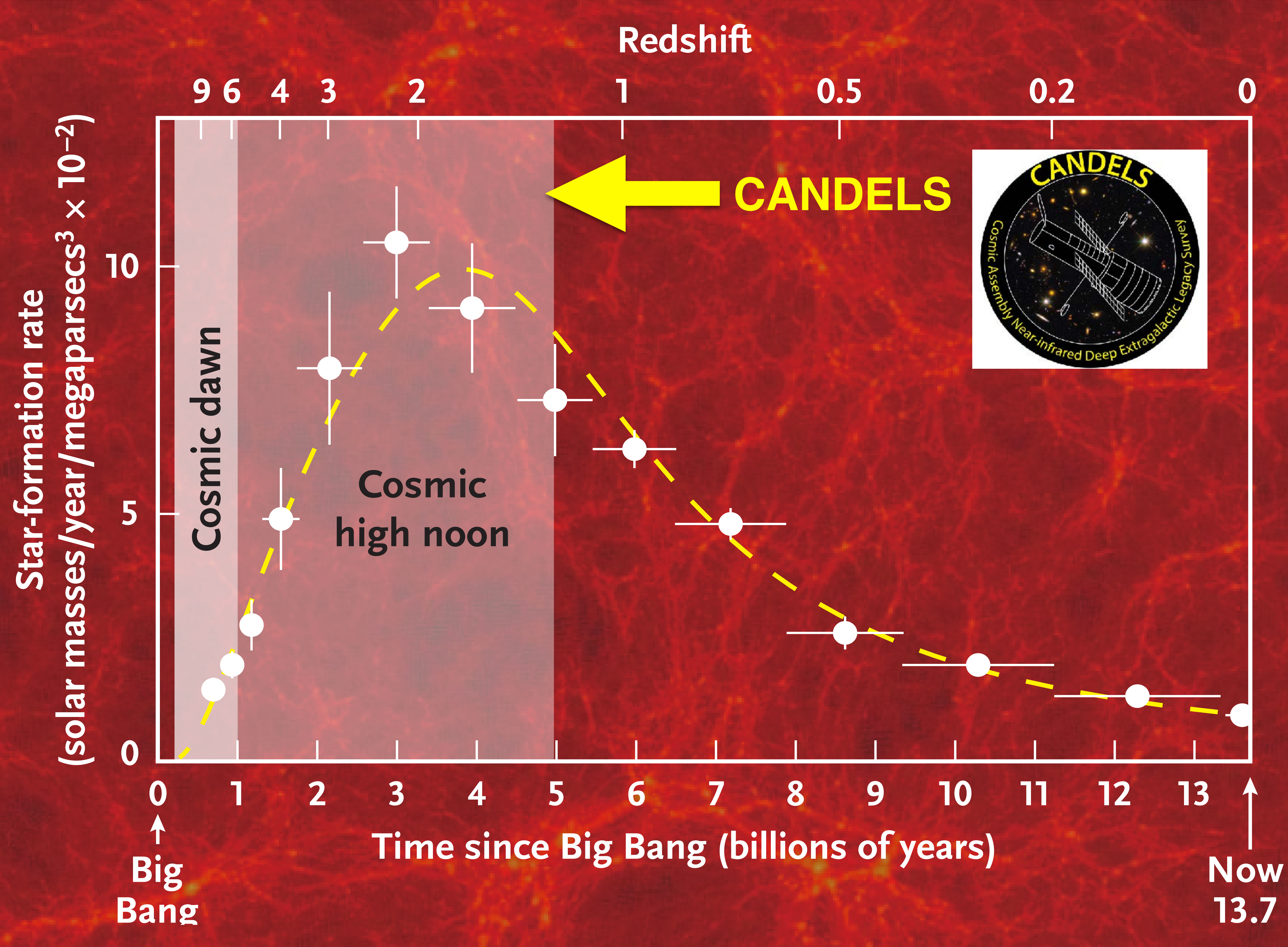
CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

- 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.
- CANDELS will exploit this new lookback power to construct a "cosmic movie" of galaxy evolution that follows the life histories of galaxies from infancy to the present time. This work will cap Hubble's revolutionary series of discoveries on cosmic evolution and bequeath a legacy of precious data to future generations of astronomers.



When we look out in space we look back in time…

Cosmic Spheres of Time



Redshift
9 6 4 3 2 1 0.5 0.2 0
Star-formation rate
(solar masses/year/megaparsecs³ × 10⁻²)
0
5
10
Cosmic dawn
Cosmic high noon
CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Time since Big Bang (billions of years)
Big Bang
Now 13.7

Galaxy Hydro Simulations: 2 Approaches

1. Low resolution (~ kpc)

Advantages: it's possible to simulate many galaxies and study galaxy populations and their interactions with CGM & IGM.

Disadvantages: since feedback &winds are "tuned," we learn little about how galaxies themselves evolve, and cannot compare in detail with high-z galaxy images and spectra.

Examples: Overwhelmingly Large Simulations (OWLs, EAGLE), AREPO simulations in 100 Mpc box (Illustris).

2. High resolution (~10s of pc) ← THIS TALK

Advantages: it's possible to compare in detail with high-z galaxy images and spectra, to discover how galaxies evolve, morphological drivers (e.g., galaxy shapes, clumps and other instabilities, origins of galactic spheroids, quenching). Radiative pressure & AGN feedbacks essential?

Disadvantages: statistical galaxy samples take too much computer time; can we model galaxy population evolution using simulation insights in semi-analytic models (SAMs)?

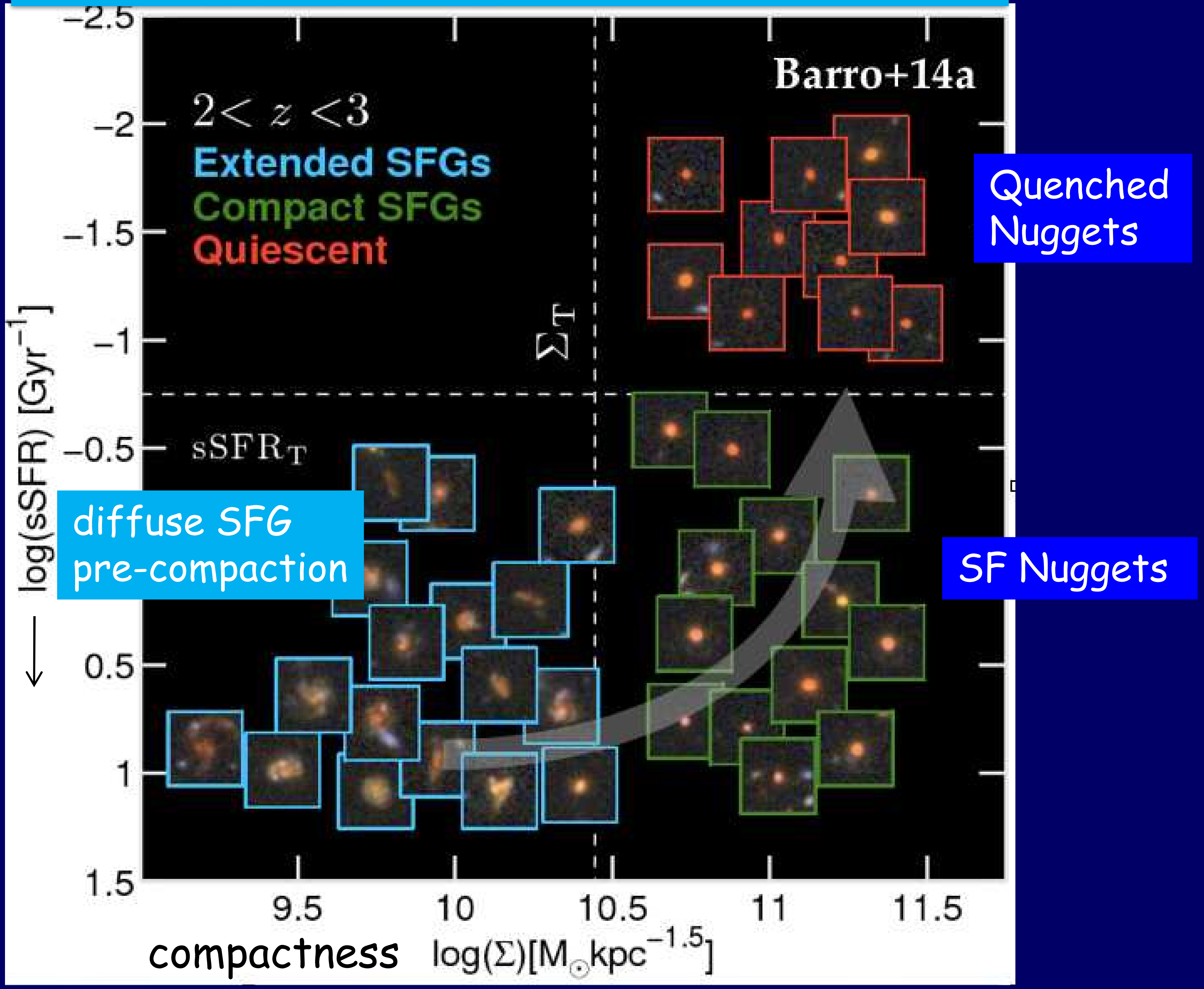
Examples: ART/VELA and FIRE simulation suites, AGORA simulation comparison project.

- 3 Aspects of Star-Forming Galaxies Seen in CANDELS
  - Compaction
  - Elongation
  - Clumps

} Challenge for Observers & Simulators!

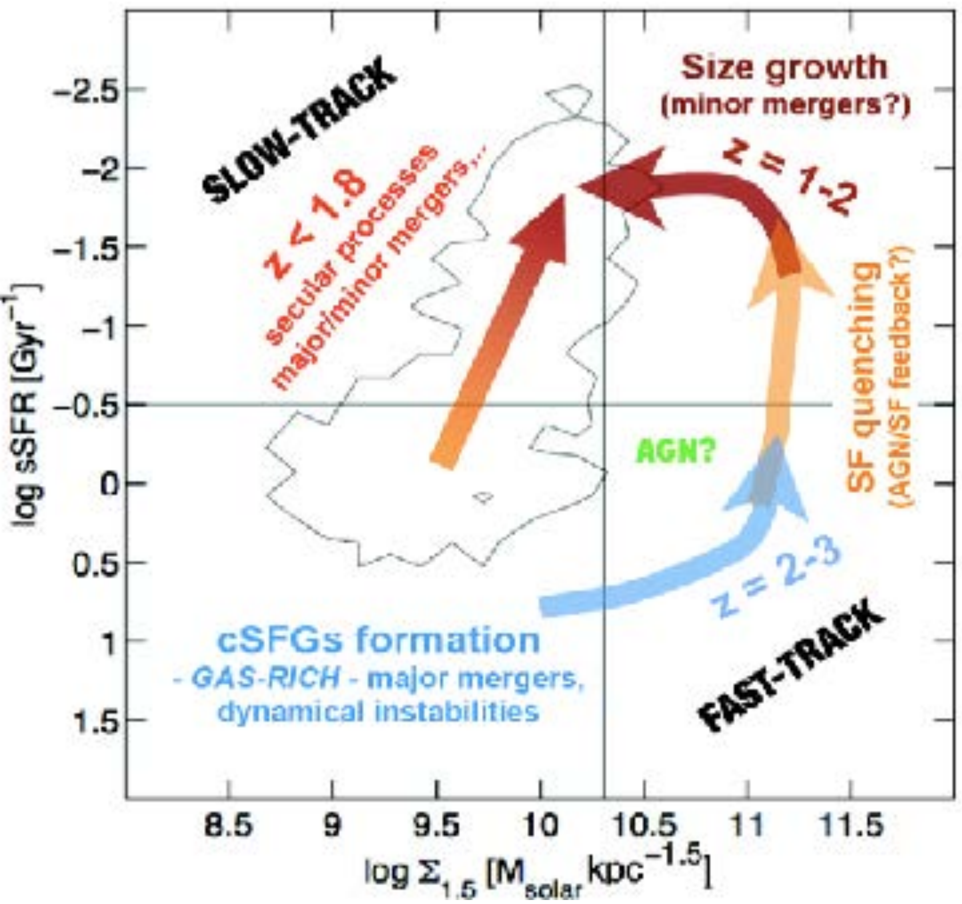
Our hydroART cosmological zoom-in simulations produce all of these phenomena!

The Fast Track of Galaxy Evolution



Ceverino+ RP simulations analyzed by Zolotov, Dekel, Tweed, Mandelker, Ceverino, & Primack MNRAS 2015

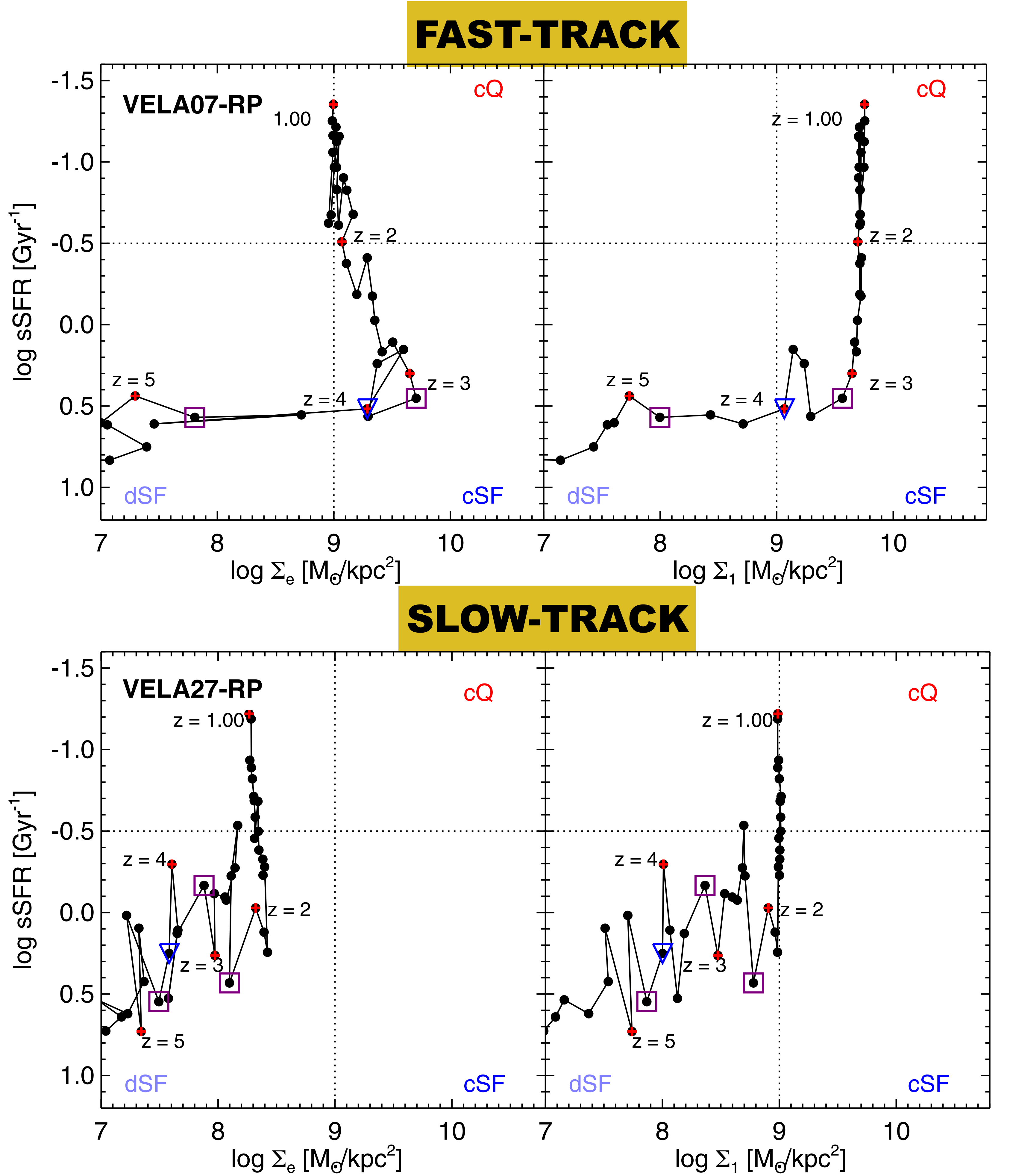
Barro+ (CANDELS) 2013



COMPACTION —>

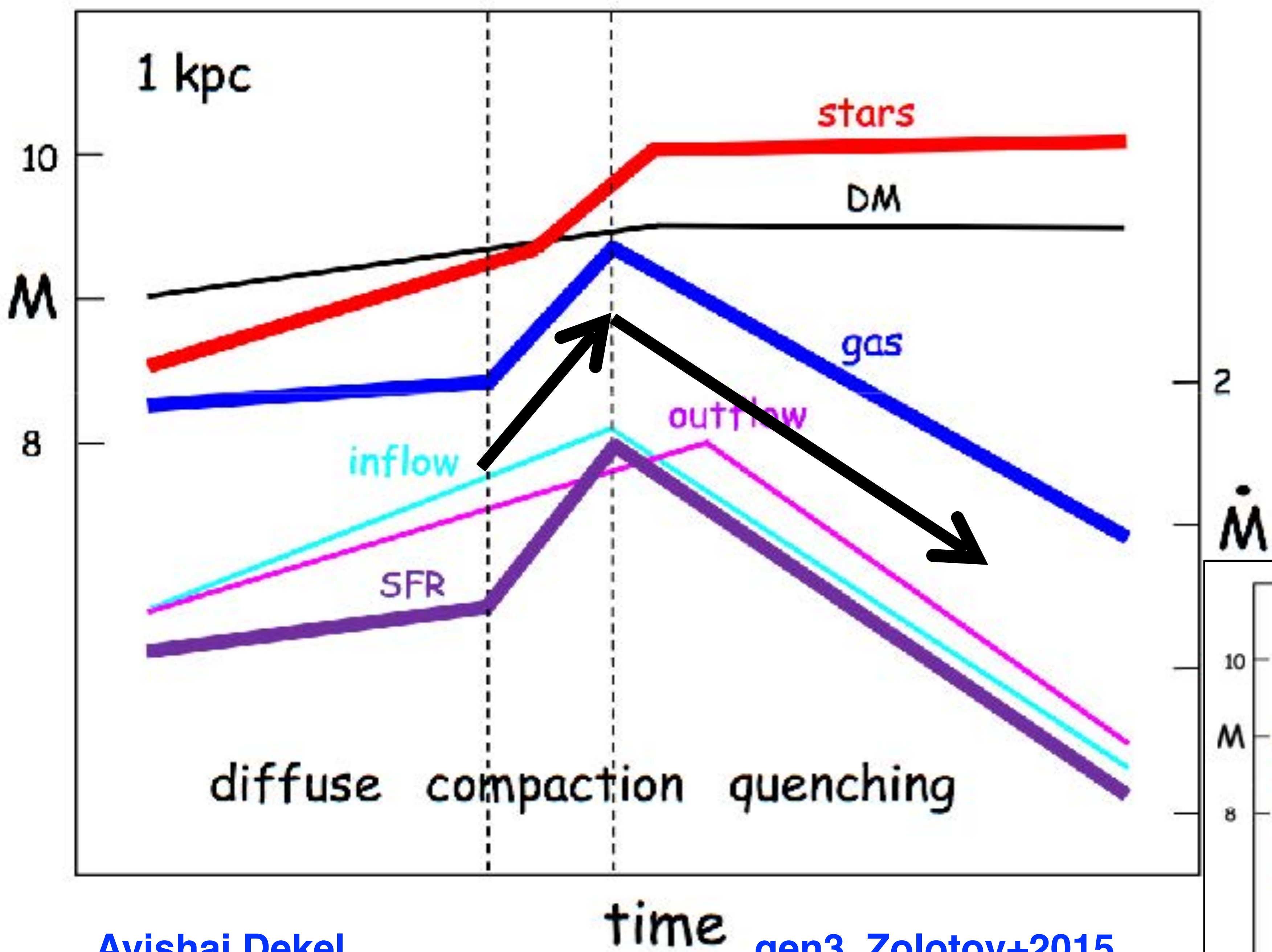
major merger

minor merger



Zolotov+2015

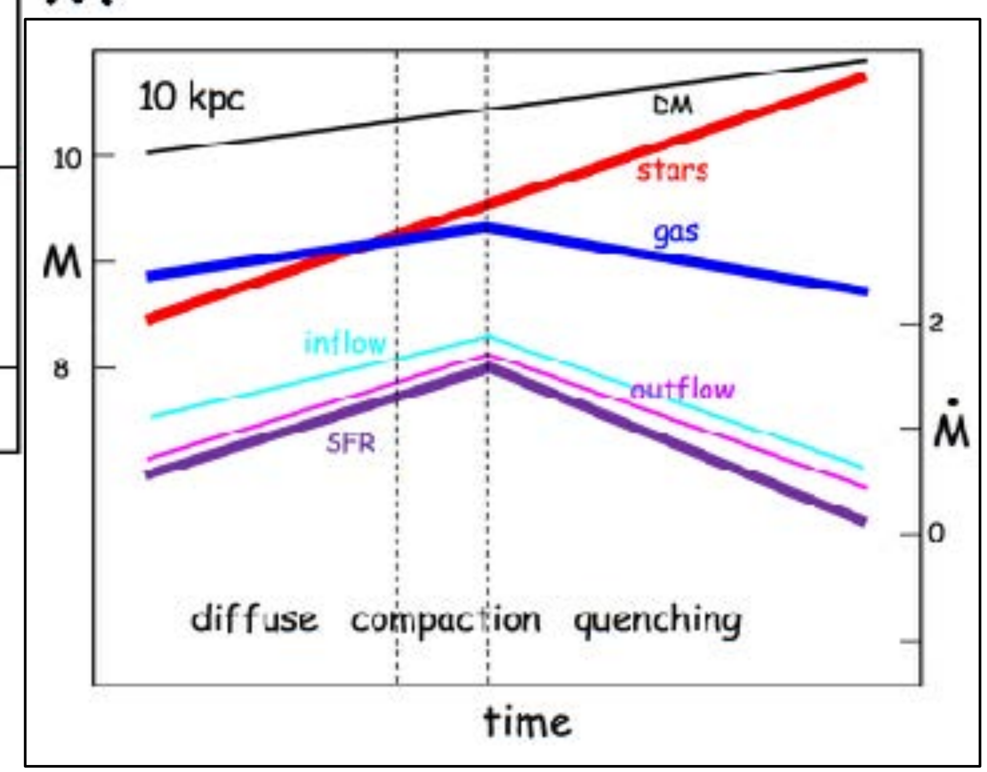
Compaction and Quenching in the Inner 1 kpc



Avishai Dekel

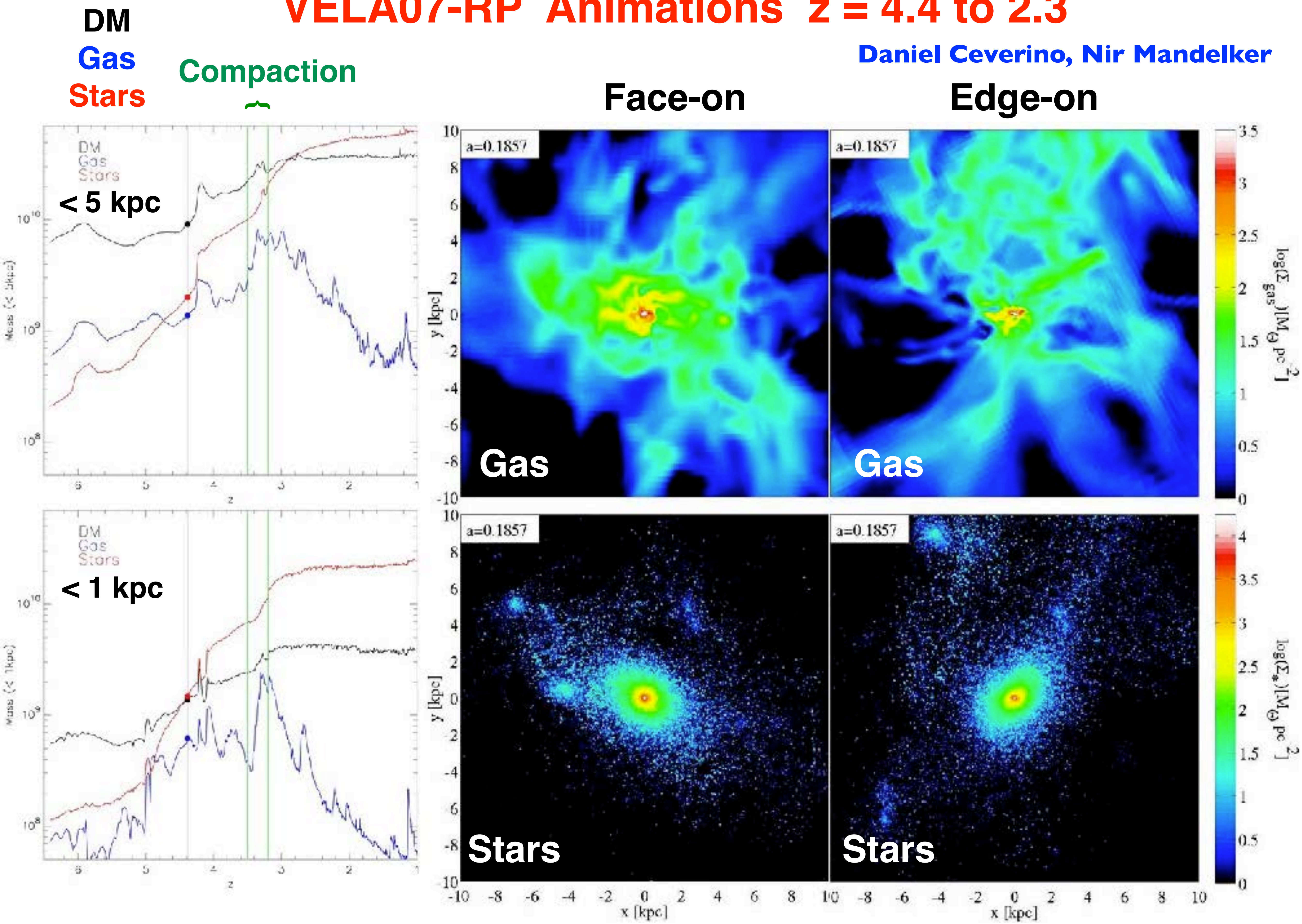
gen3 Zolotov+2015

Inner 10 kpc

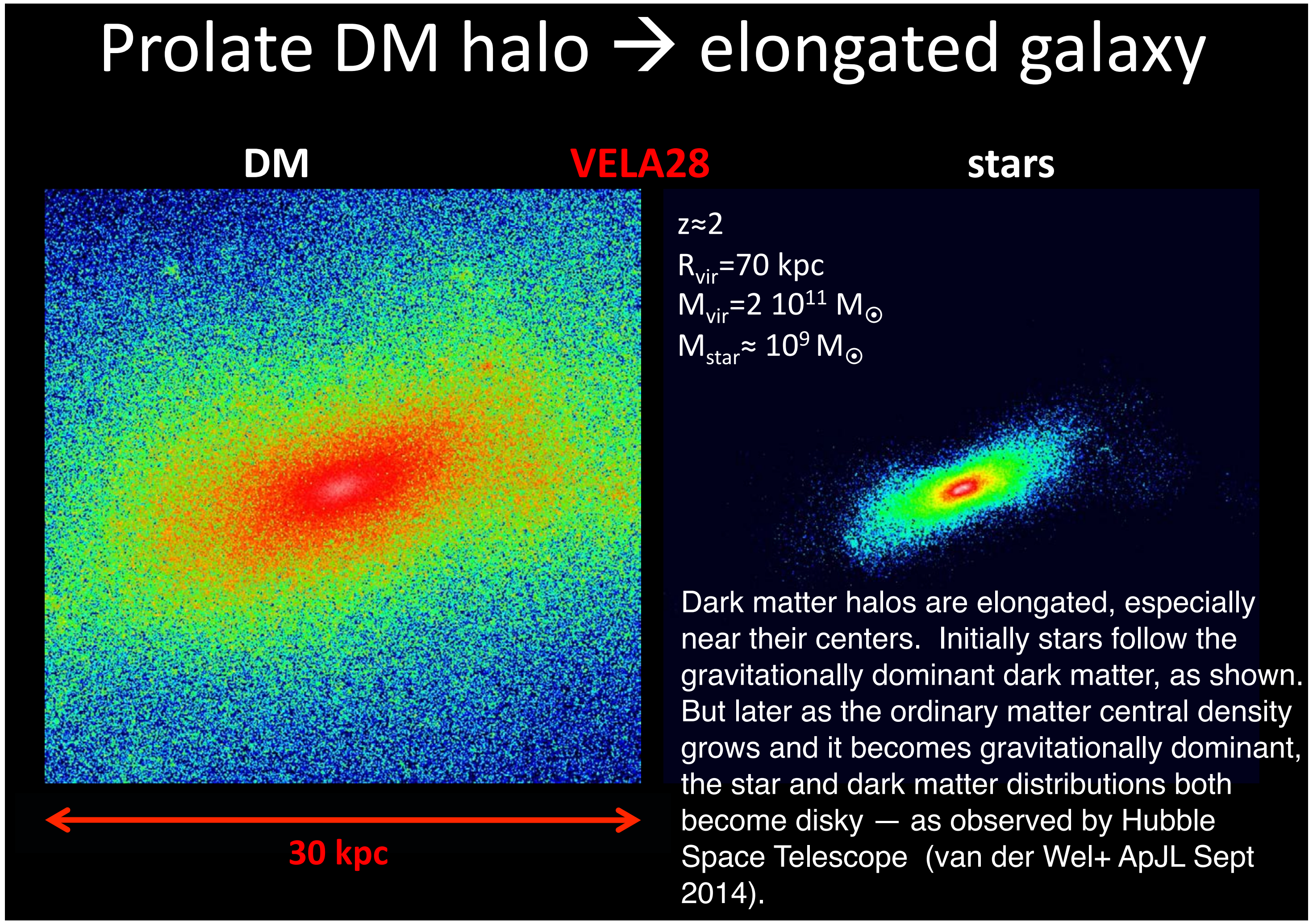


VELA07-RP Animations z = 4.4 to 2.3

Daniel Ceverino, Nir Mandelker



Our cosmological zoom-in simulations often produce elongated galaxies like observed ones. The elongated distribution of stars follows the elongated inner dark matter halo.



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **453,** 408–413 (2015)

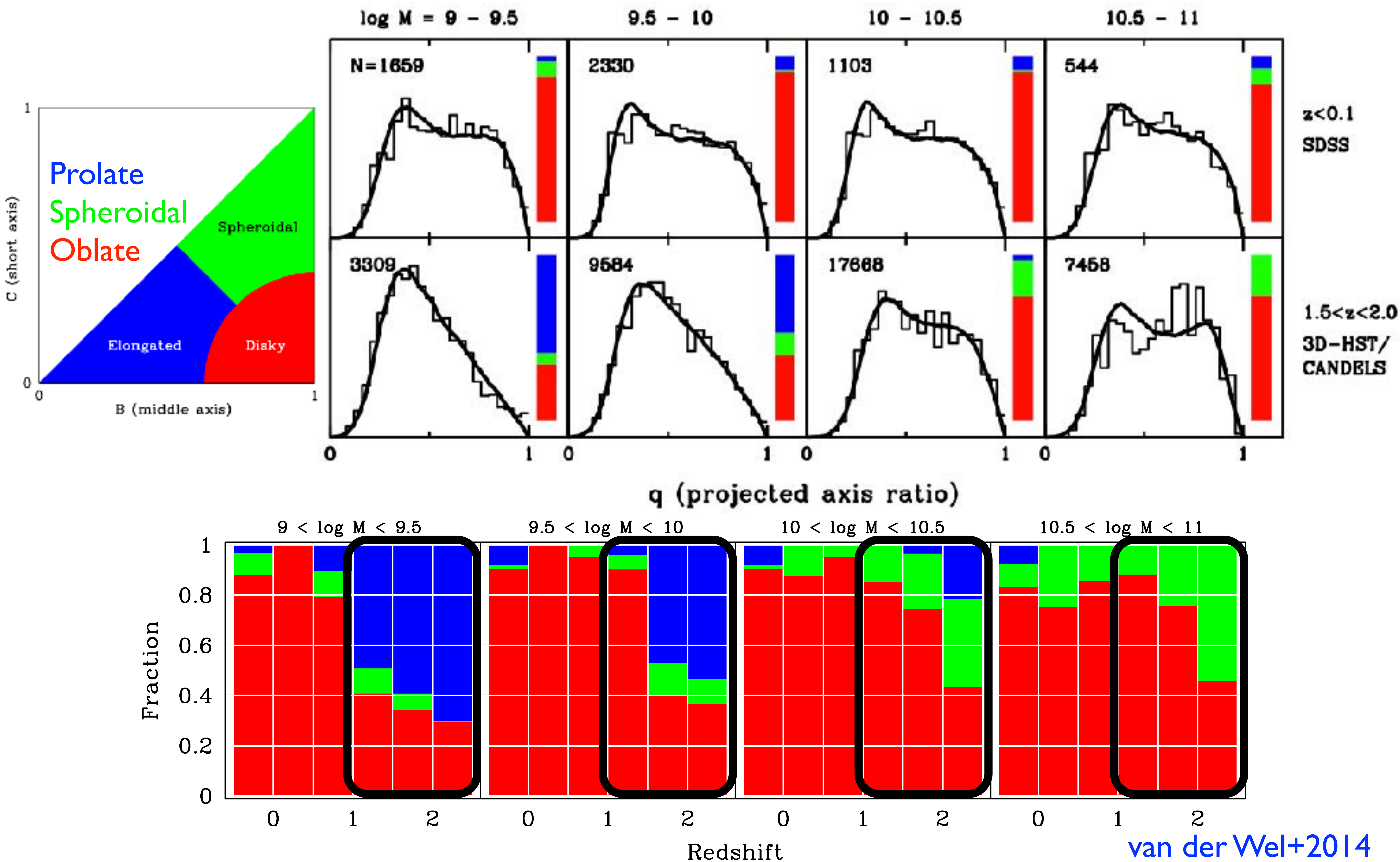
Formation of elongated galaxies with low masses at high redshift

Daniel Ceverino, Joel Primack and Avishai Dekel

ABSTRACT

We report the identification of elongated (triaxial or prolate) galaxies in cosmological simulations at z ~ 2. These are preferentially low-mass galaxies ($M_* \leq 10^{9.5}$ $M_\odot$), residing in dark matter (DM) haloes with strongly elongated inner parts, a common feature of high-redshift DM haloes in the cold dark matter cosmology. A large population of elongated galaxies produces a very asymmetric distribution of projected axis ratios, as observed in high-z galaxy surveys. This indicates that the majority of the galaxies at high redshifts are not discs or spheroids but rather galaxies with elongated morphologies

Prolate galaxies dominate at high redshift/low masses

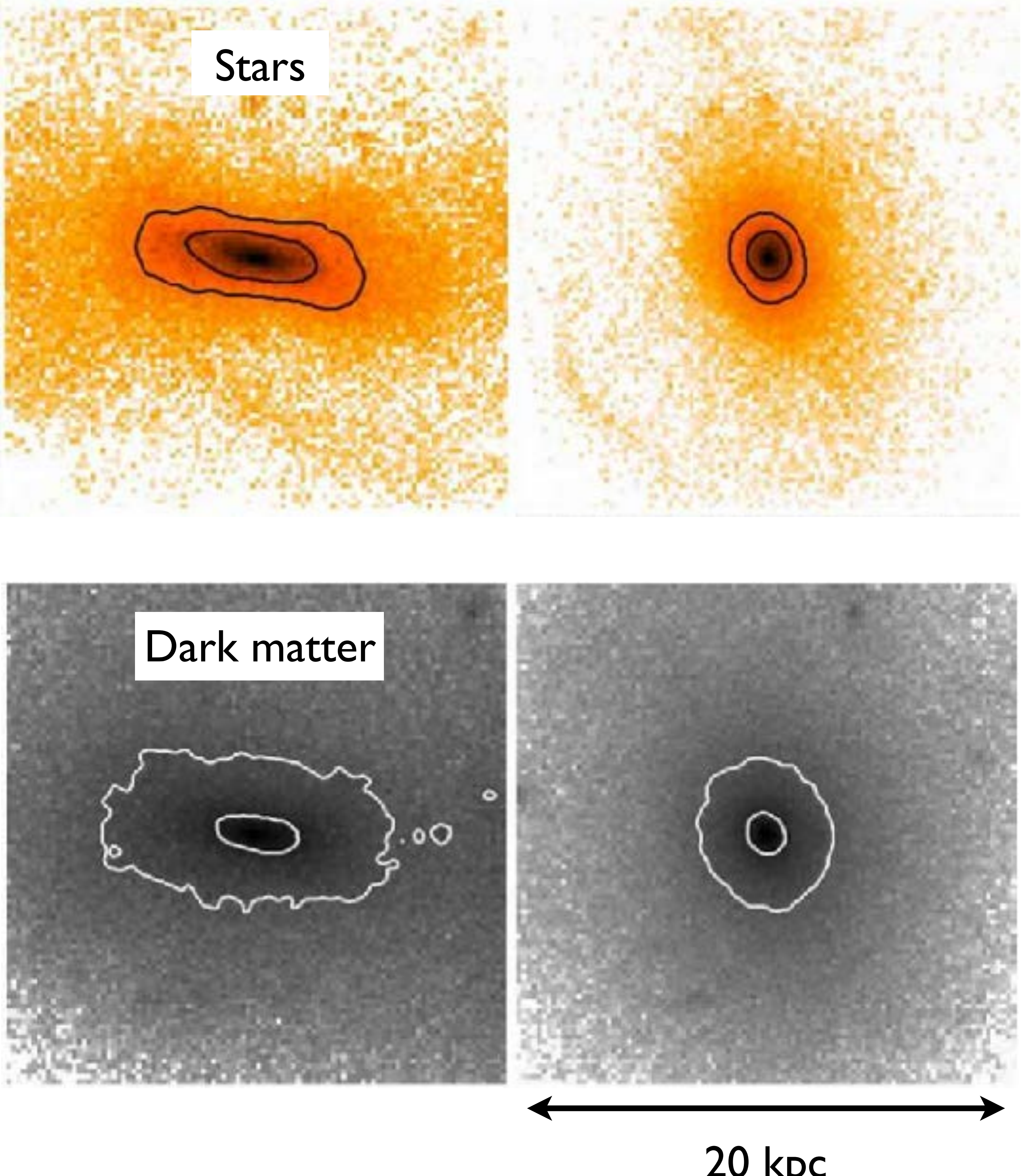


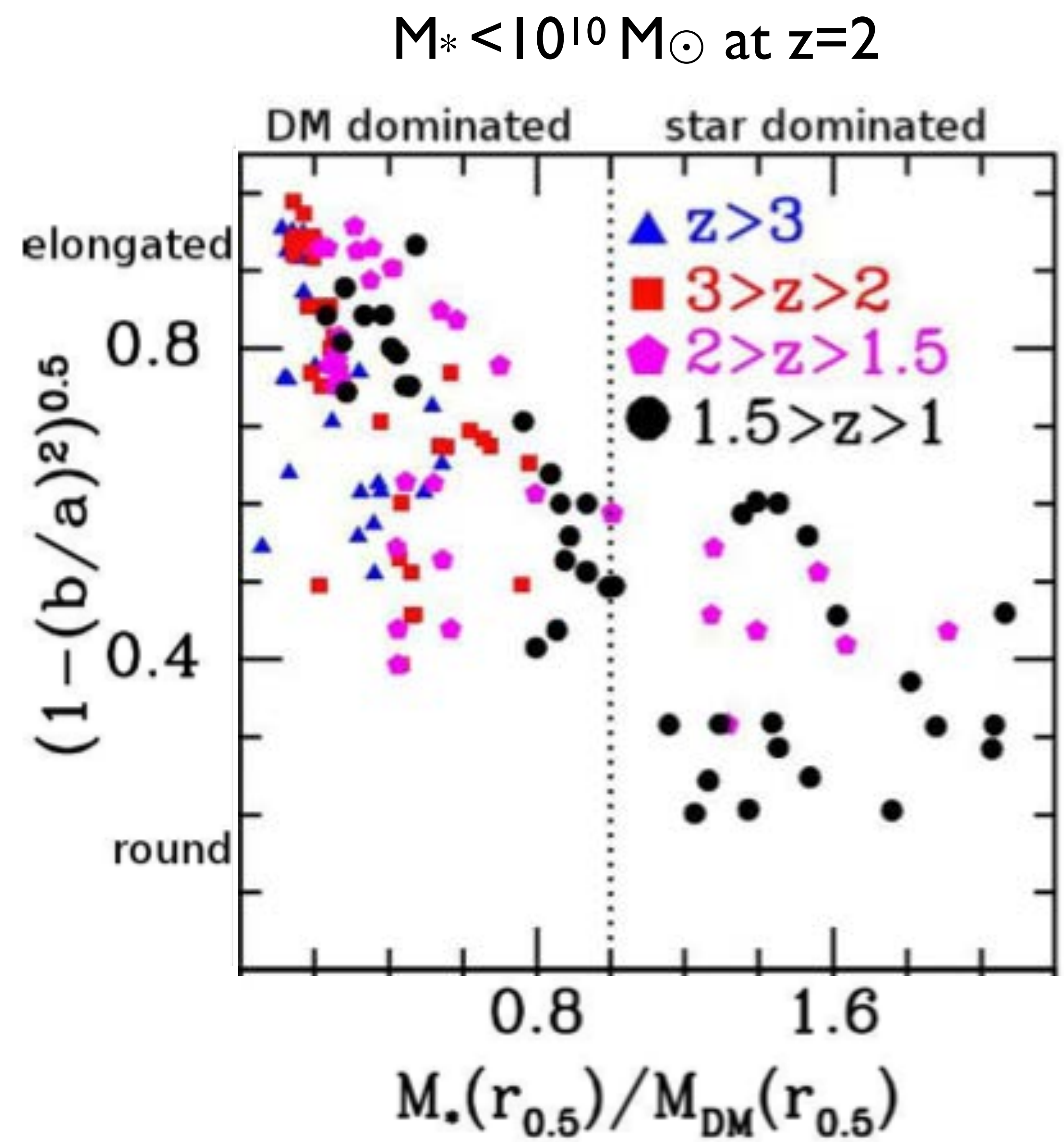
van der Wel+2014

See also WHEN DID ROUND DISK GALAXIES FORM? T. M. Takeuchi et. al ApJ 2015

In hydro sims, dark-matter dominated galaxies are prolate

Ceverino, Primack, Dekel MNRAS 453, 408 (2015)





Also Tomassetti et al. 2016 MNRAS, Zhang, Primack, et al. 2018

“Face Recognition for Galaxies”

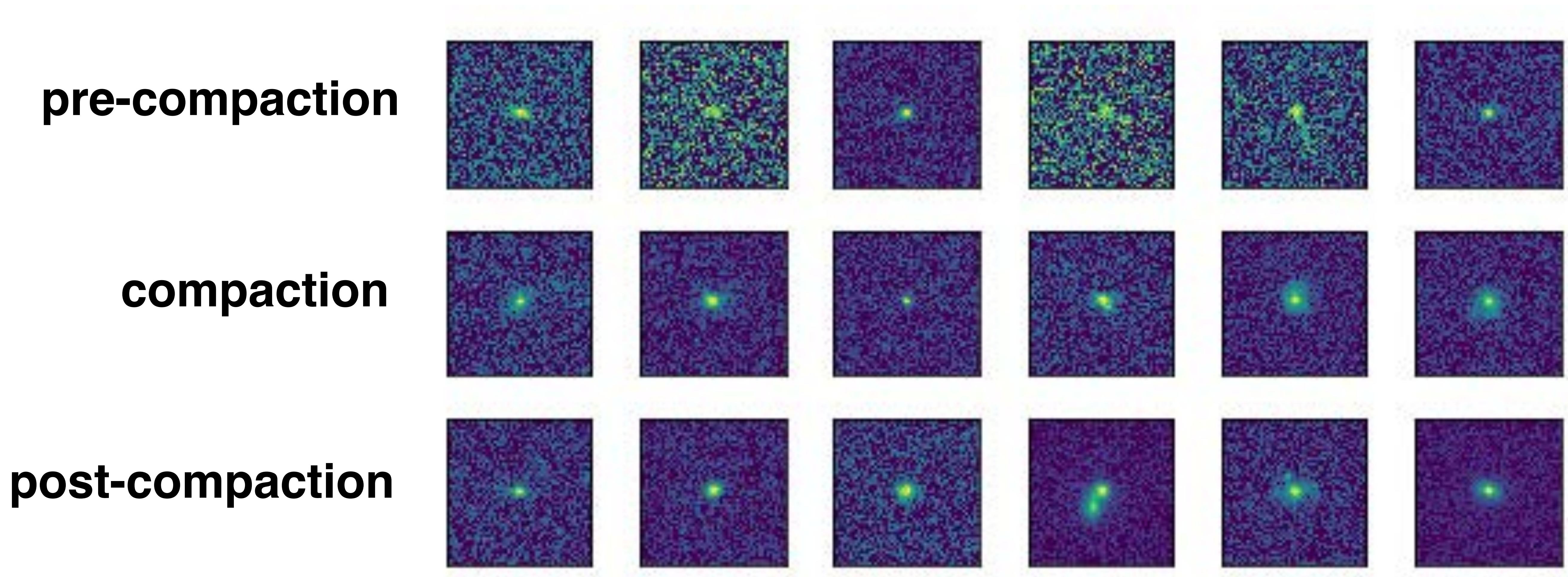
Detecting wet compaction at high redshift with deep learning

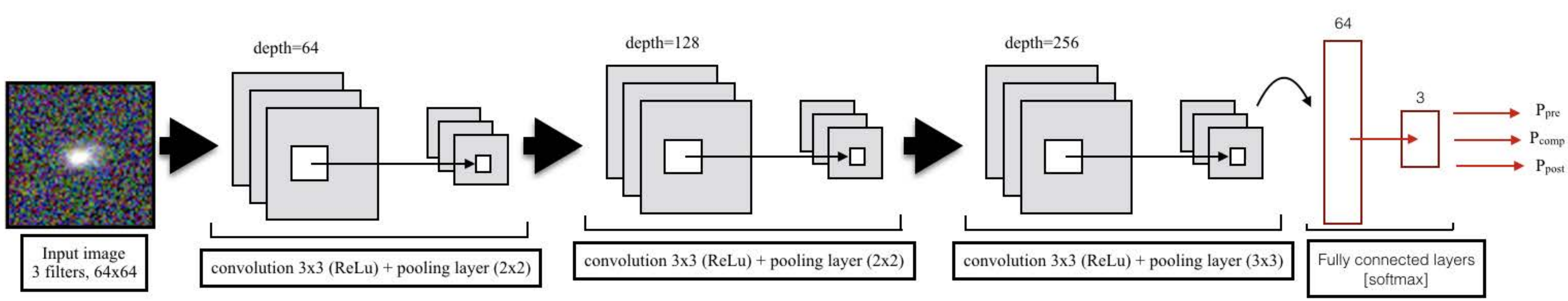
Marc Huertas-Company, Joel Primack, Avishai Dekel, David Koo, et al. 2018

ABSTRACT

We explore a new approach to classify galaxy images from deep surveys oriented towards detecting astrophysical processes calibrated on cosmological hydrodynamic galaxy simulations. To illustrate the methodology we focus on wet compaction. Recent theoretical and observational works have suggested that compact bulges at high redshift might be formed through gas inflows (wet compaction events) before quenching. We train a simple Convolutional Neural Network (CNN) with mock *CANDELized* images from our VELA zoom-in simulations that are selected for being in a wet-compaction phase according to the assembly history extracted from the simulation. We show that the CNN is able to retrieve a galaxy in the compaction phase within a time window of ±0.3 Hubble times based only on the pixels distribution. We then use the trained network to classify real galaxies from the CANDELS survey into three classes (pre-compaction, compaction and post-compaction). We find that compaction typically occurs at a characteristic stellar mass of $M^{*}{\sim}10^{9.5-10}$ solar masses all redshifts, as in the VELA simulations. The galaxies that are experiencing compaction in the CANDELS redshift range ($1 < z < 3$) are therefore typically the progenitors of $M^{*}{\sim}10^{10.5}$ solar mass galaxies at $z \sim 0$, like the Milky Way. The presented technique can be generalized to other processes and could constitute an alternative way of classifying galaxies in the era of massive imaging surveys and cosmological simulations, to help improve the comparison between theory and observations.

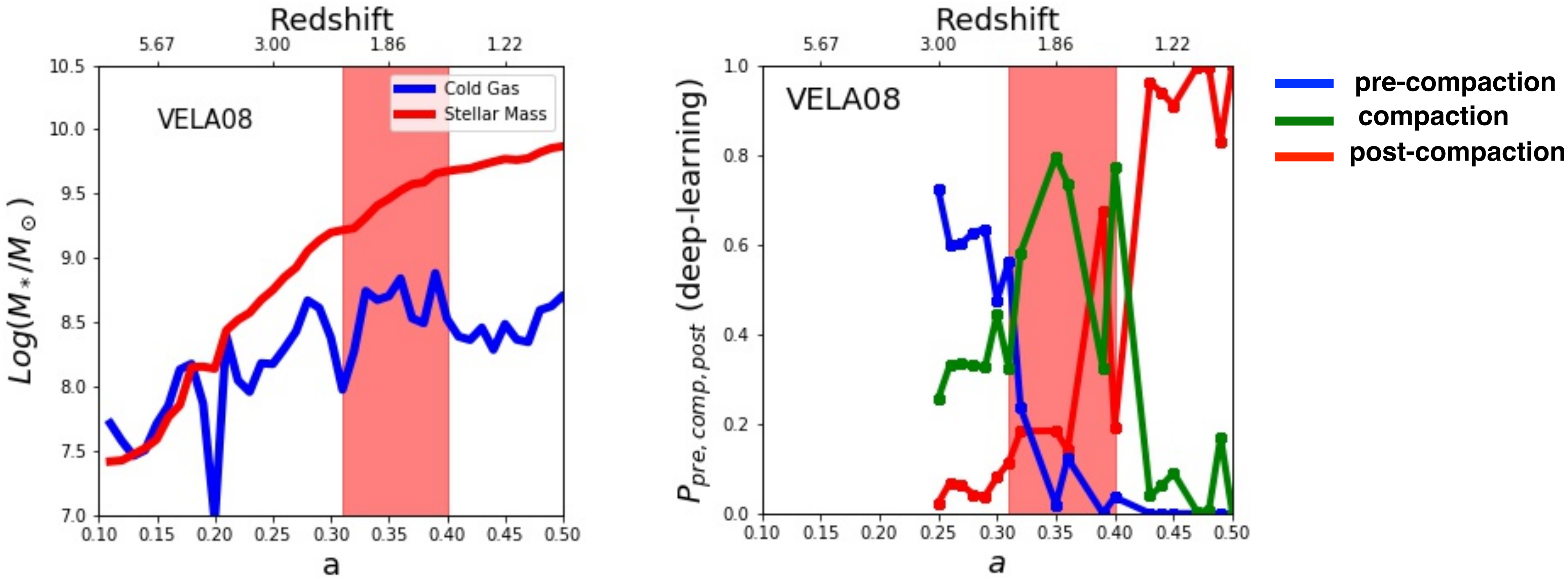
Examples of CANDELized simulated galaxy images



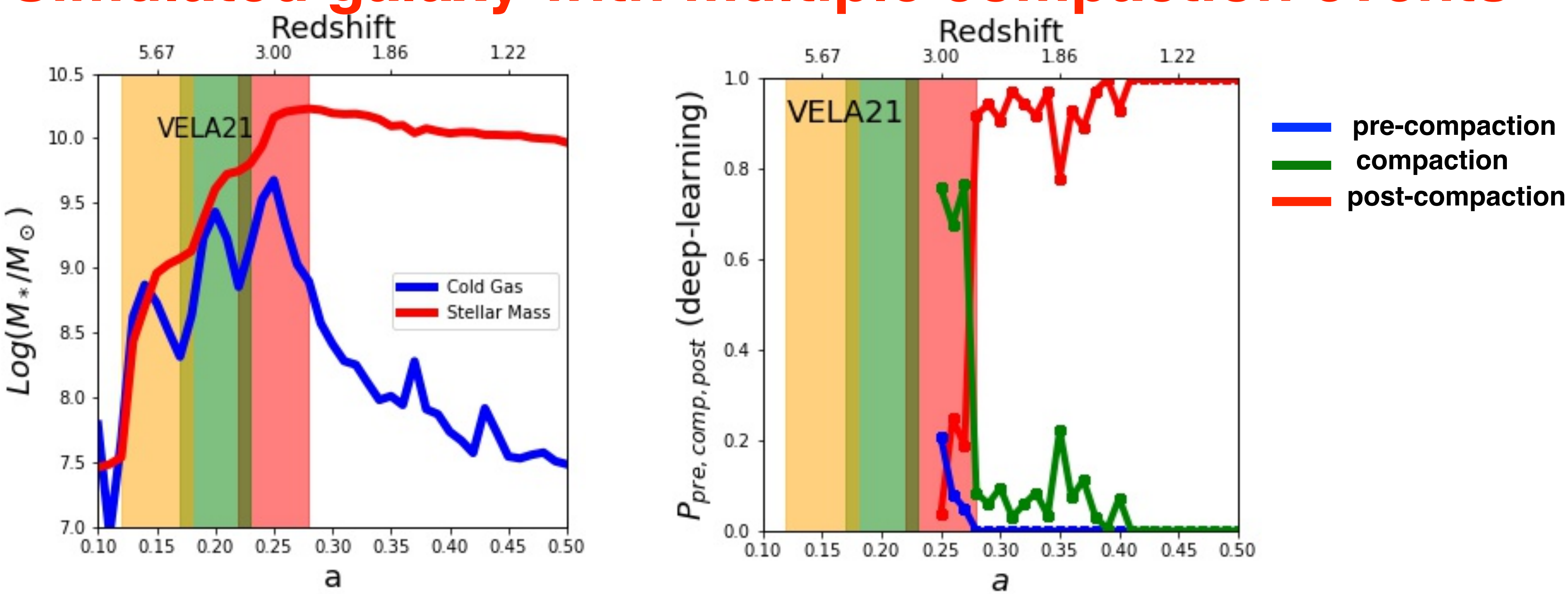


Architecture of the deep network used for classification in this work. The network is a standard and simple CNN configuration made of 3 convolutional layers followed by pooling and dropout.

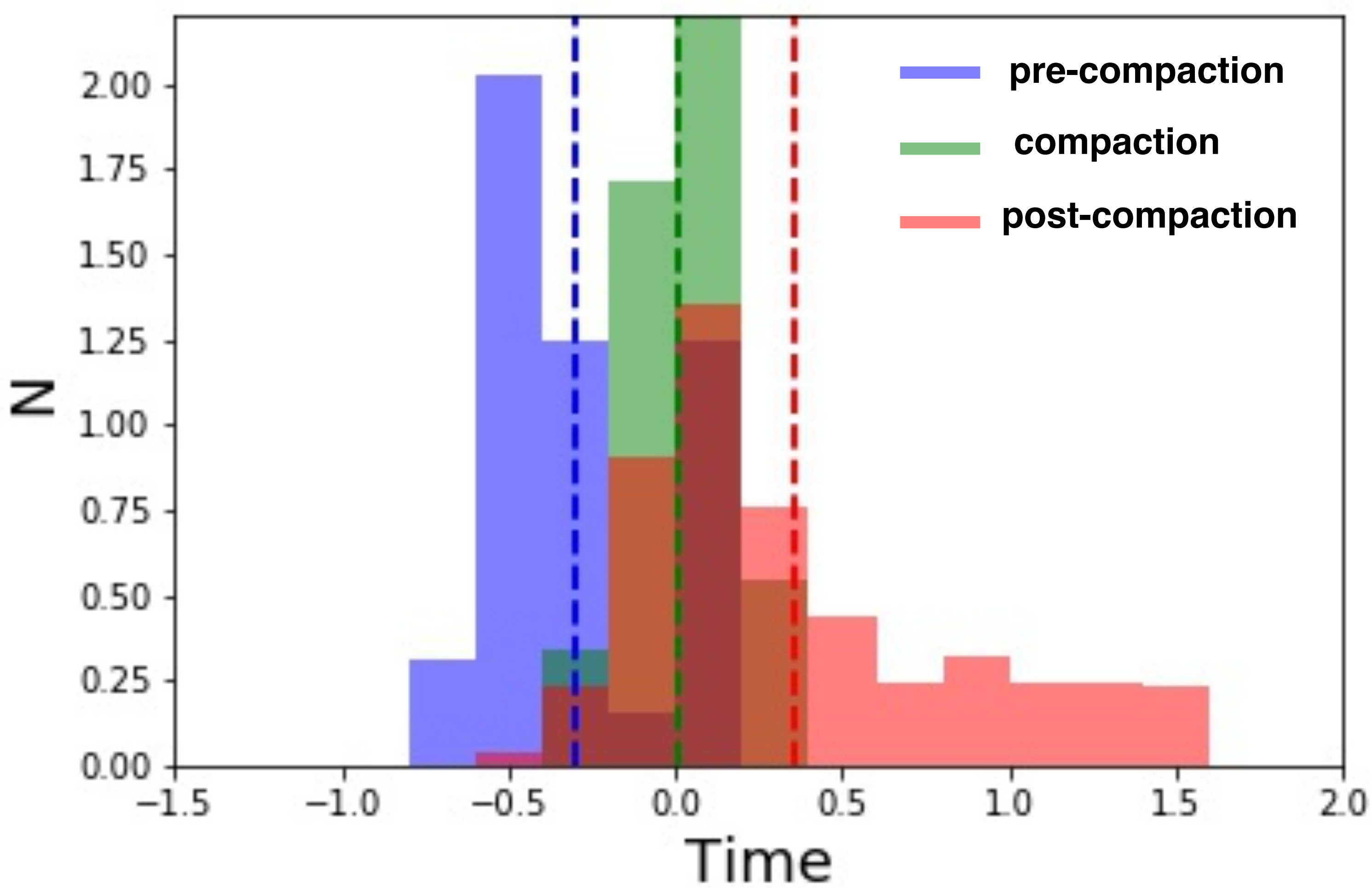
Simulated galaxy with single compaction event



Simulated galaxy with multiple compaction events

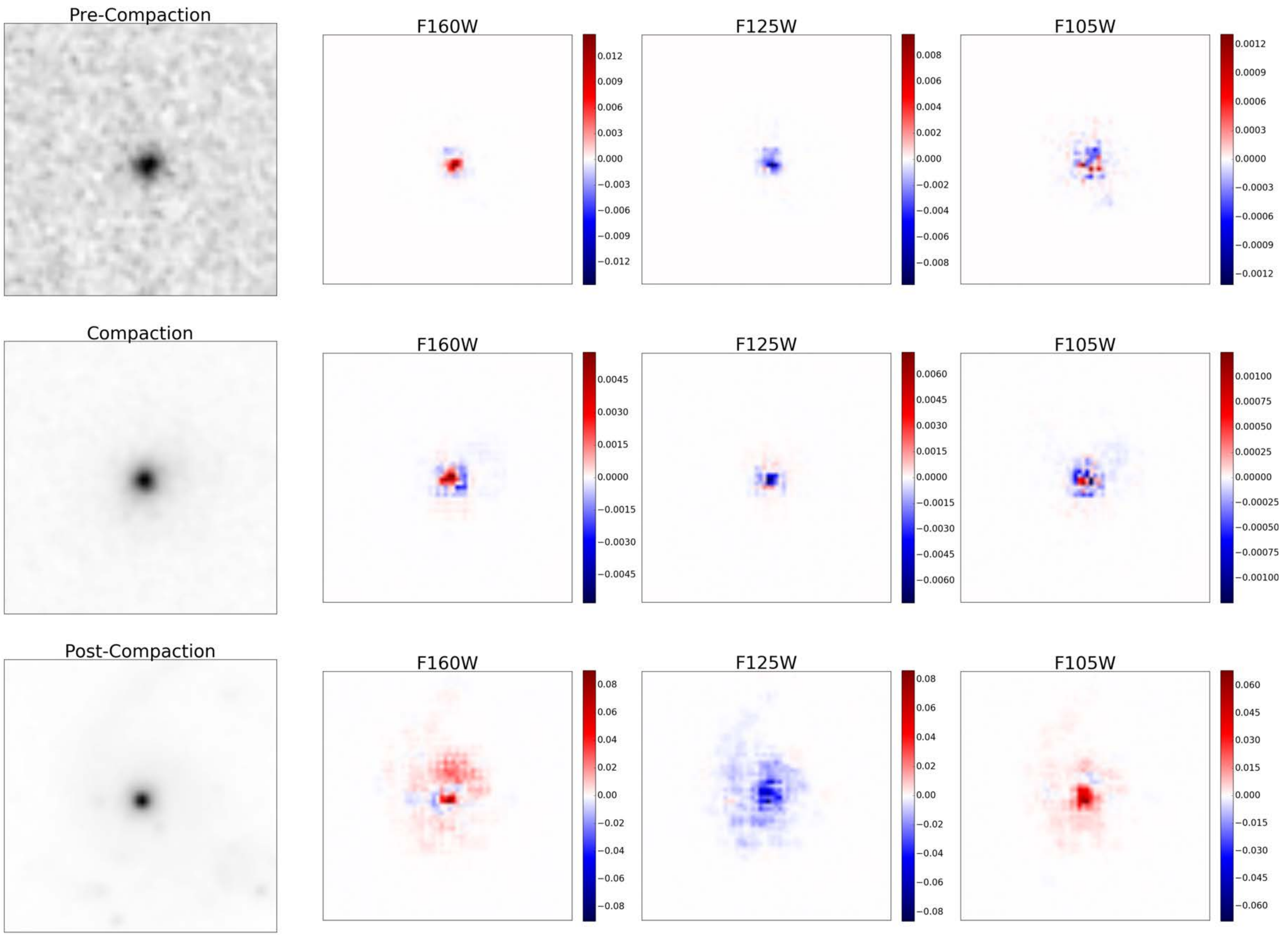


Testing the Trained Deep Learning Code

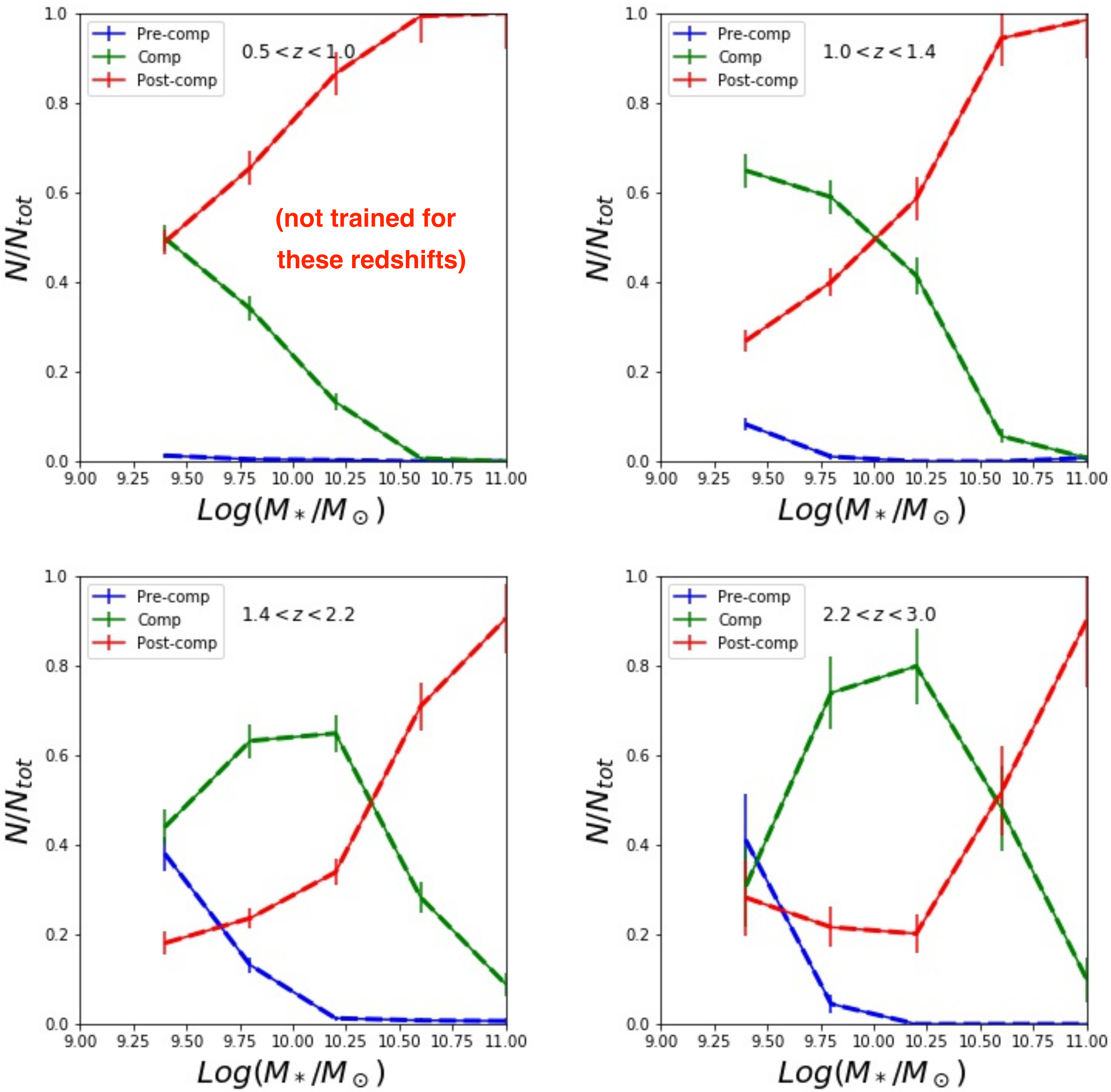


Observability of the compaction event with the calibrated classifier. The histograms show the distributions of time (relative to the Hubble time at the time of compaction). The dashed vertical lines show the average values for each class with the same color code. Despite some overlap, the classifier is able to establish temporal constraints on the different phases. Integrated gradient method shows that the classifier is using relevant pixels, not noise.

Integrated gradients output of the model. The left column is the original image and the other columns show the integrated gradients for the different wavelength filters. The network automatically detects the pixels belonging to the galaxy and used all of them to make the decisions.



Applying the Trained Deep Learning Code to CANDELS Galaxies



Stellar mass distributions of HST CANDELS galaxies in pre-compaction, compaction, and post-compaction phases in different redshift bins. The DL code correctly shows the temporal evolution. Galaxies in the compaction phase typically peak at stellar masses $10^{9.5-10}$ M_{sun} at all redshifts, as in the VELA simulations.

Computer vision and deep learning applied to simulations and imaging of galaxies and the evolving universe

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Large-scale simulations track the evolution of structure in the universe of dark energy and cold dark matter on scales of billions of light years

Cosmological zoom-in simulations model how individual galaxies evolve through the interaction of atomic matter, dark matter, and dark energy

Our VELA galaxy simulations agree with HST CANDELS observations that most galaxies start prolate, becoming spheroids or disks after compaction events

A deep learning code was trained with VELA galaxy images plus metadata describing whether they are pre-compaction, compaction, or post-compaction

The trained deep learning code was able to identify the compaction and post-compaction phases in CANDELized images

The trained deep learning code was also able to identify these phases in real HST CANDELS observations, finding that compaction occurred for stellar mass $10^{9.5\text{-}10}$ M_{sun}, as in the simulations — and James Webb Space Telescope will allow us to do even better