Physics 205

6 February 2017

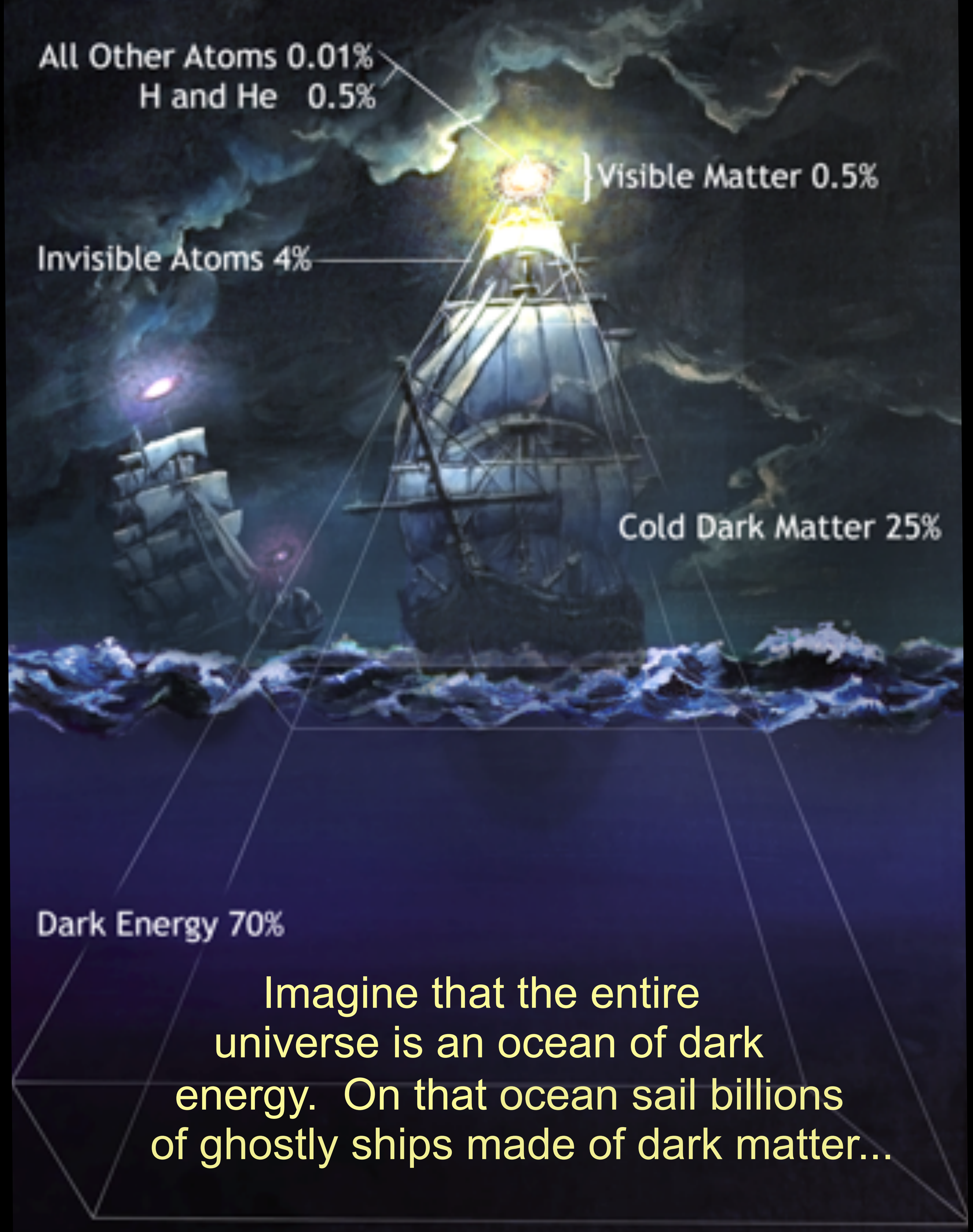
Comparing Observed Galaxies with Simulations

Joel R. Primack

UCSC

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.

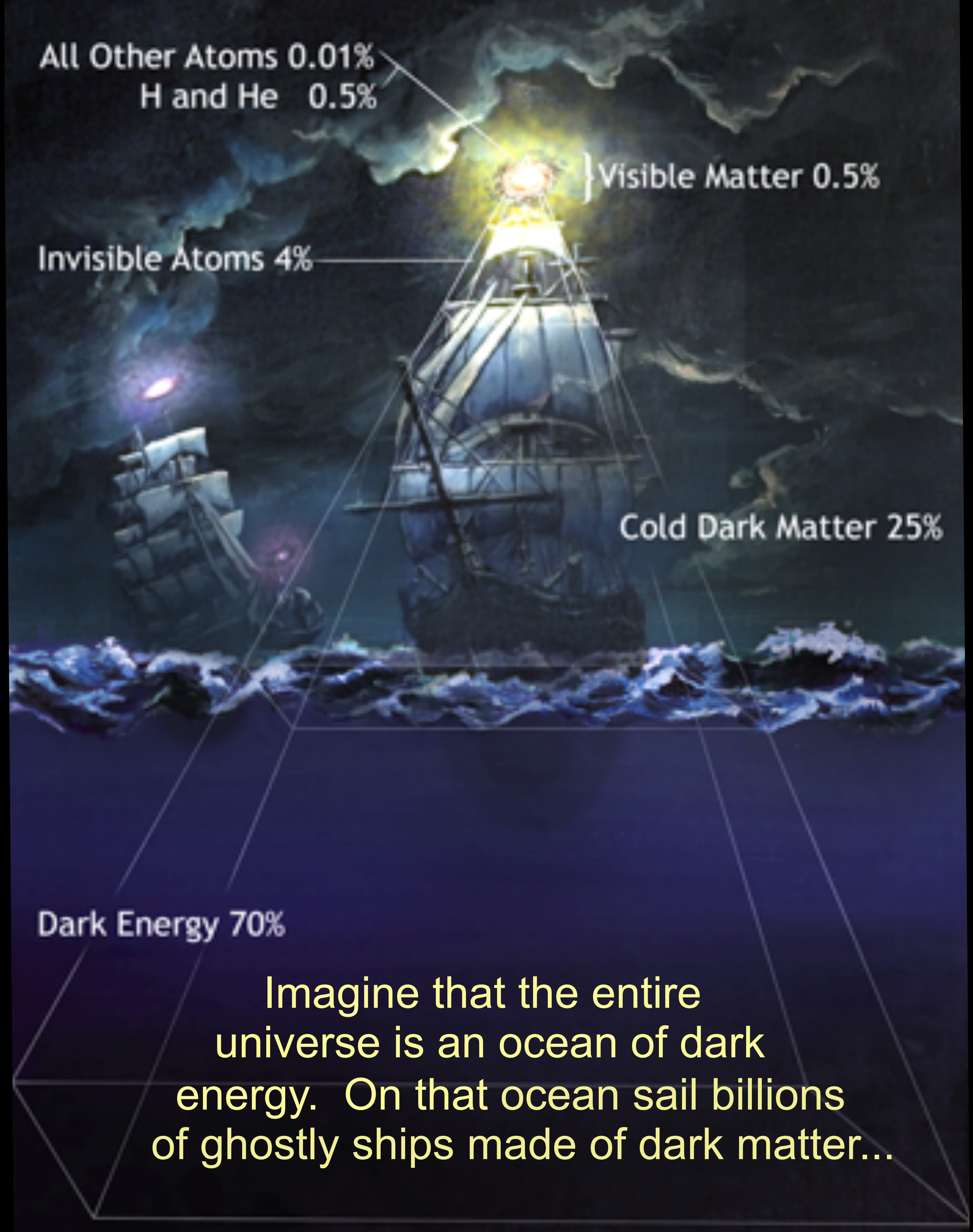


Matter and Energy Content of the Universe

Dark Matter Ships

on a

Dark Energy Ocean

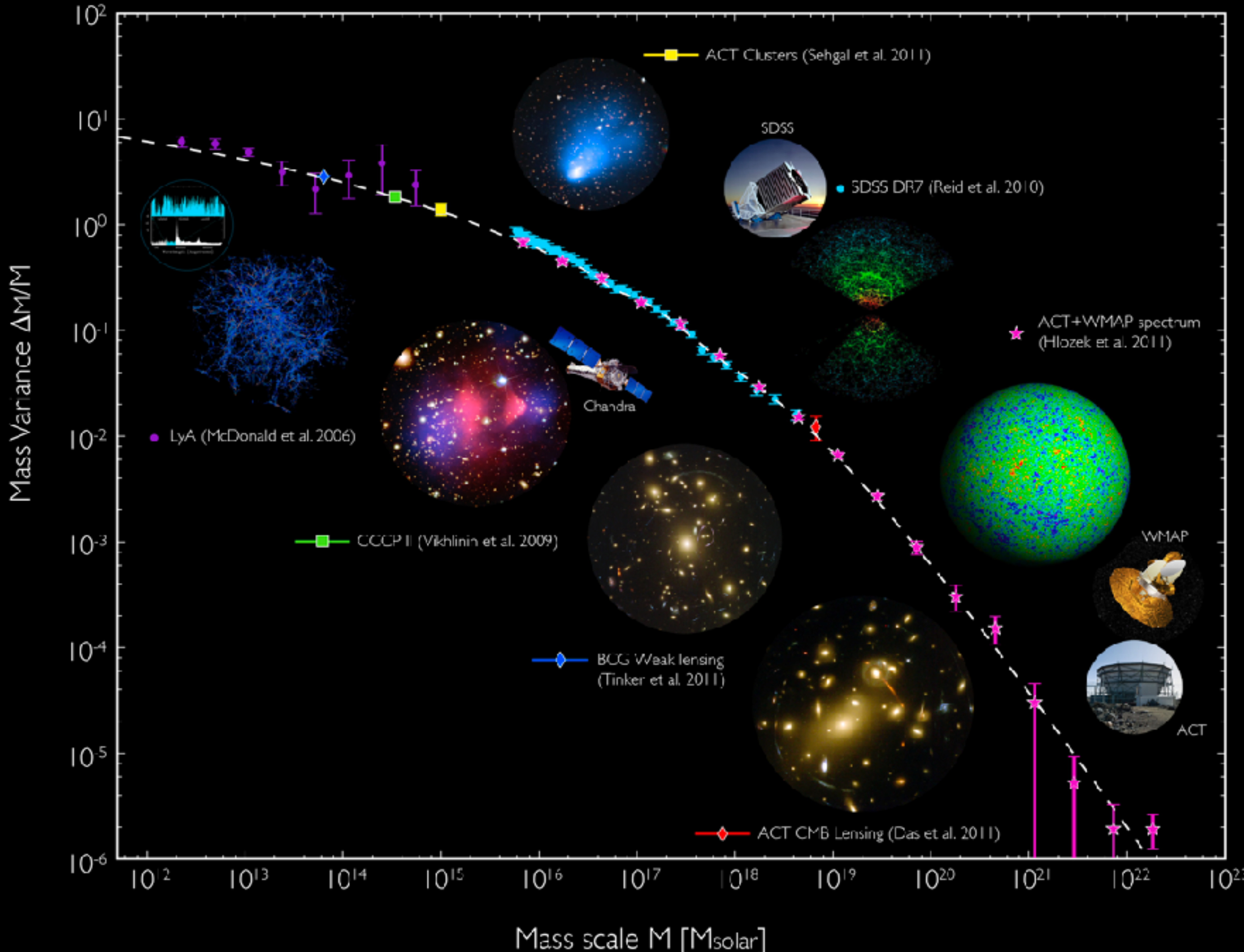


Matter and Energy Content of the Universe

ΛCDM

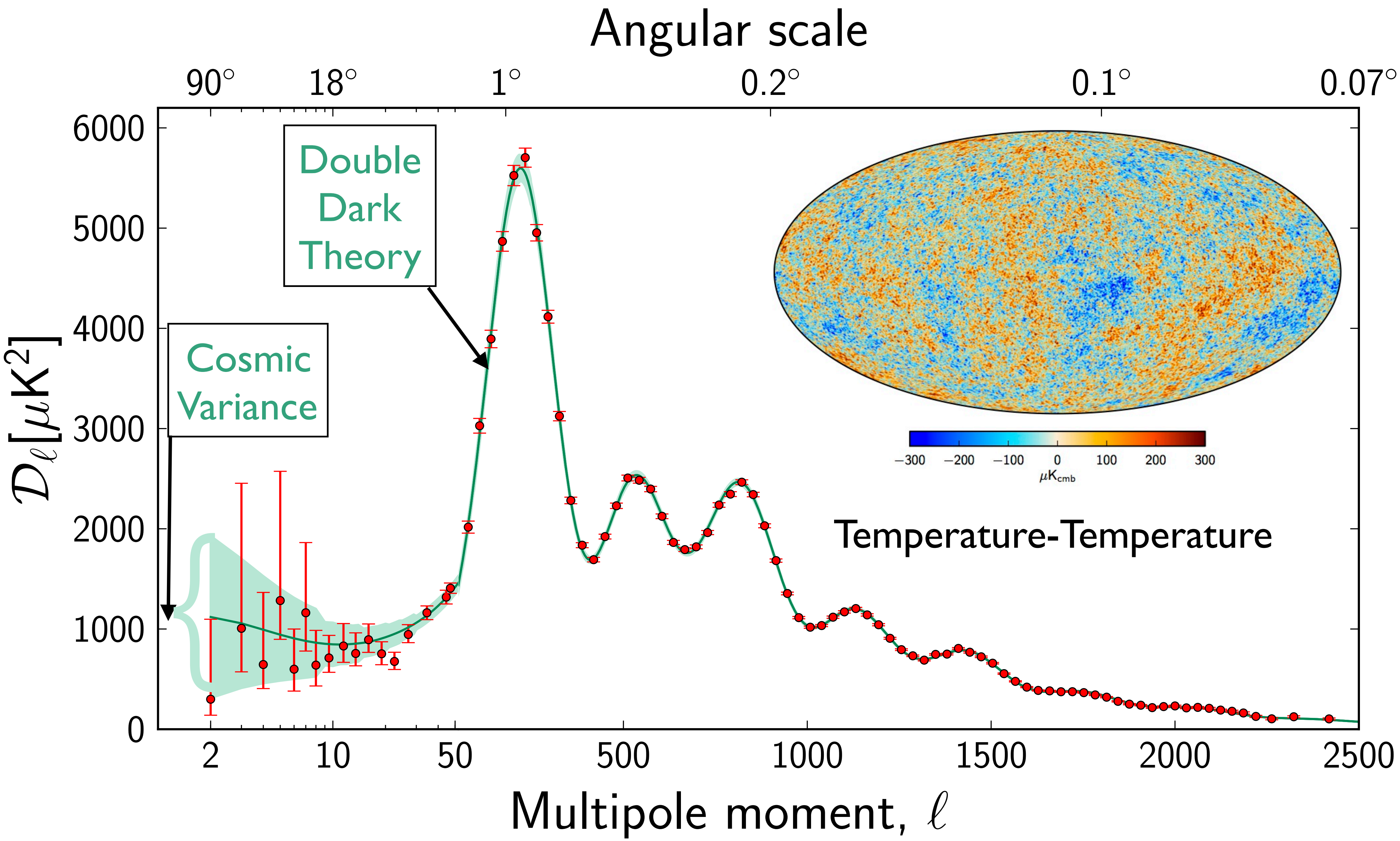
Double Dark Theory

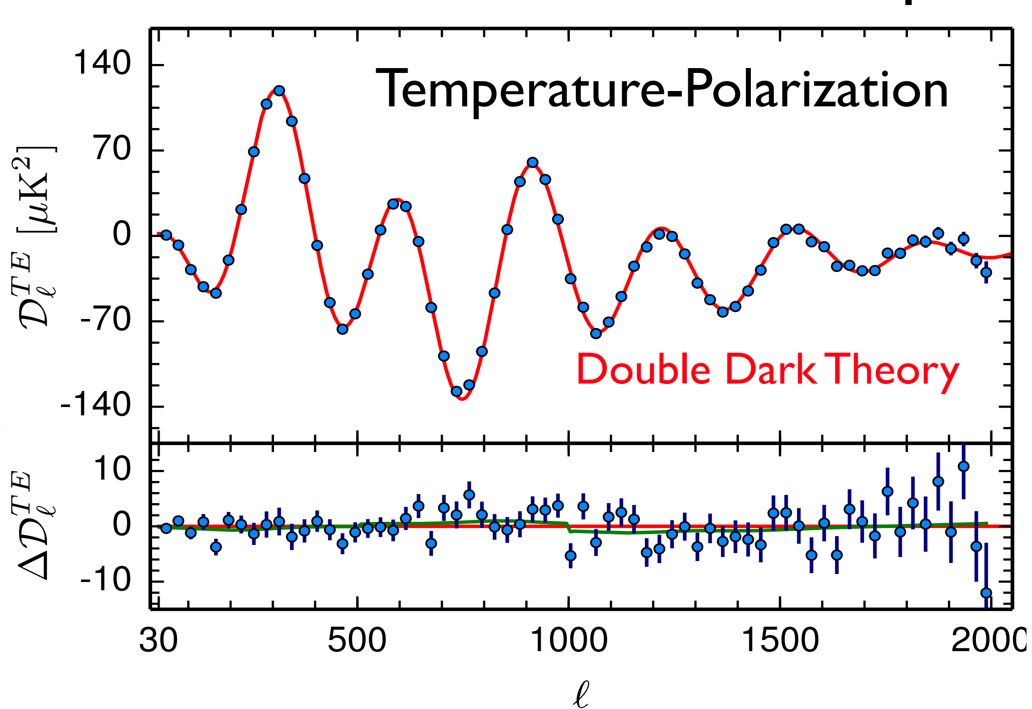
Matter Distribution Agrees with Double Dark Theory!

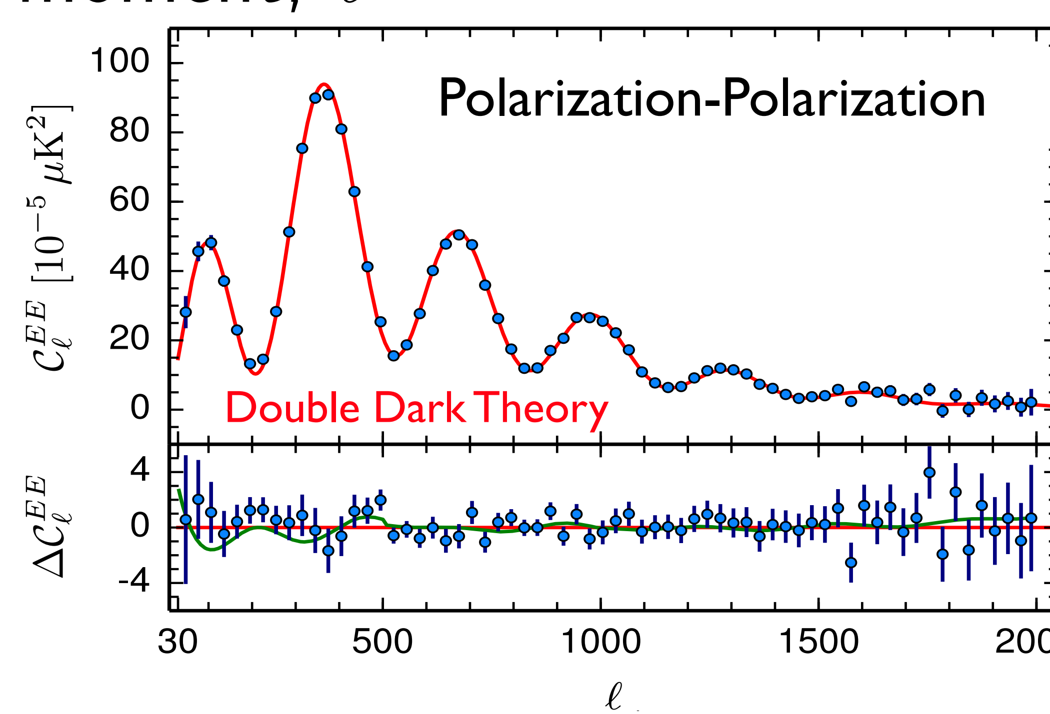


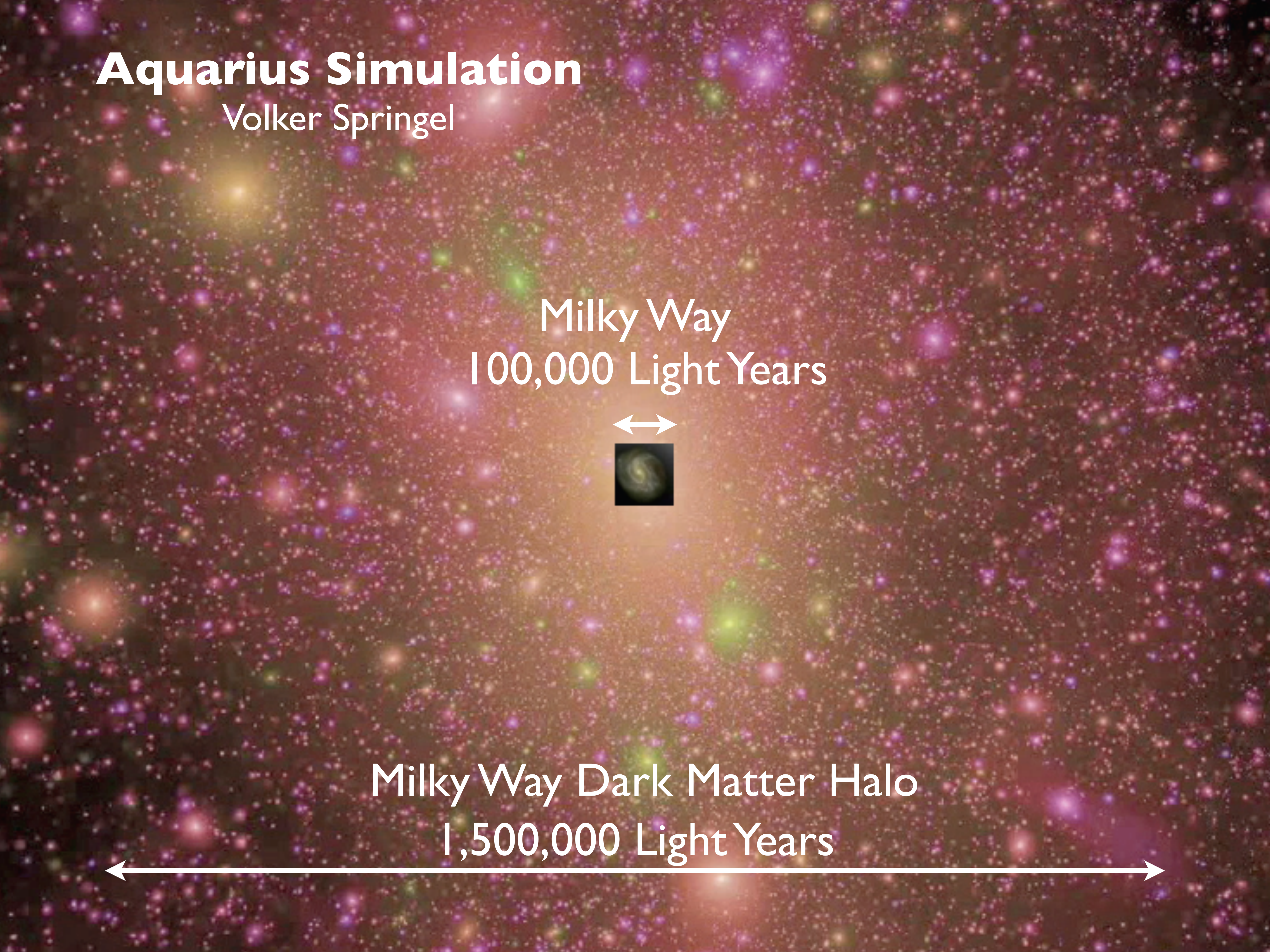
European Space Agency PLANCK Satellite Data

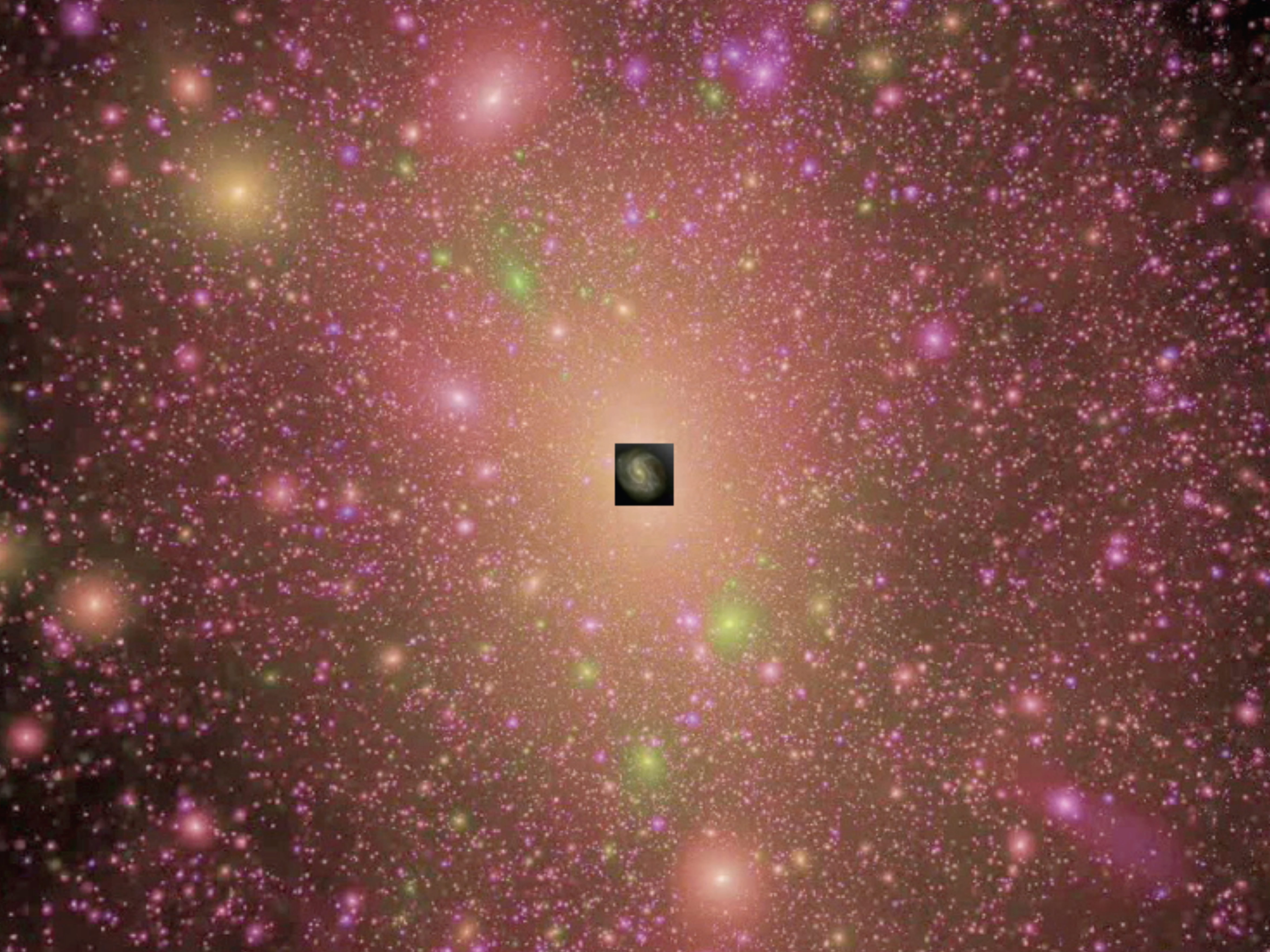
Released February 9, 2015

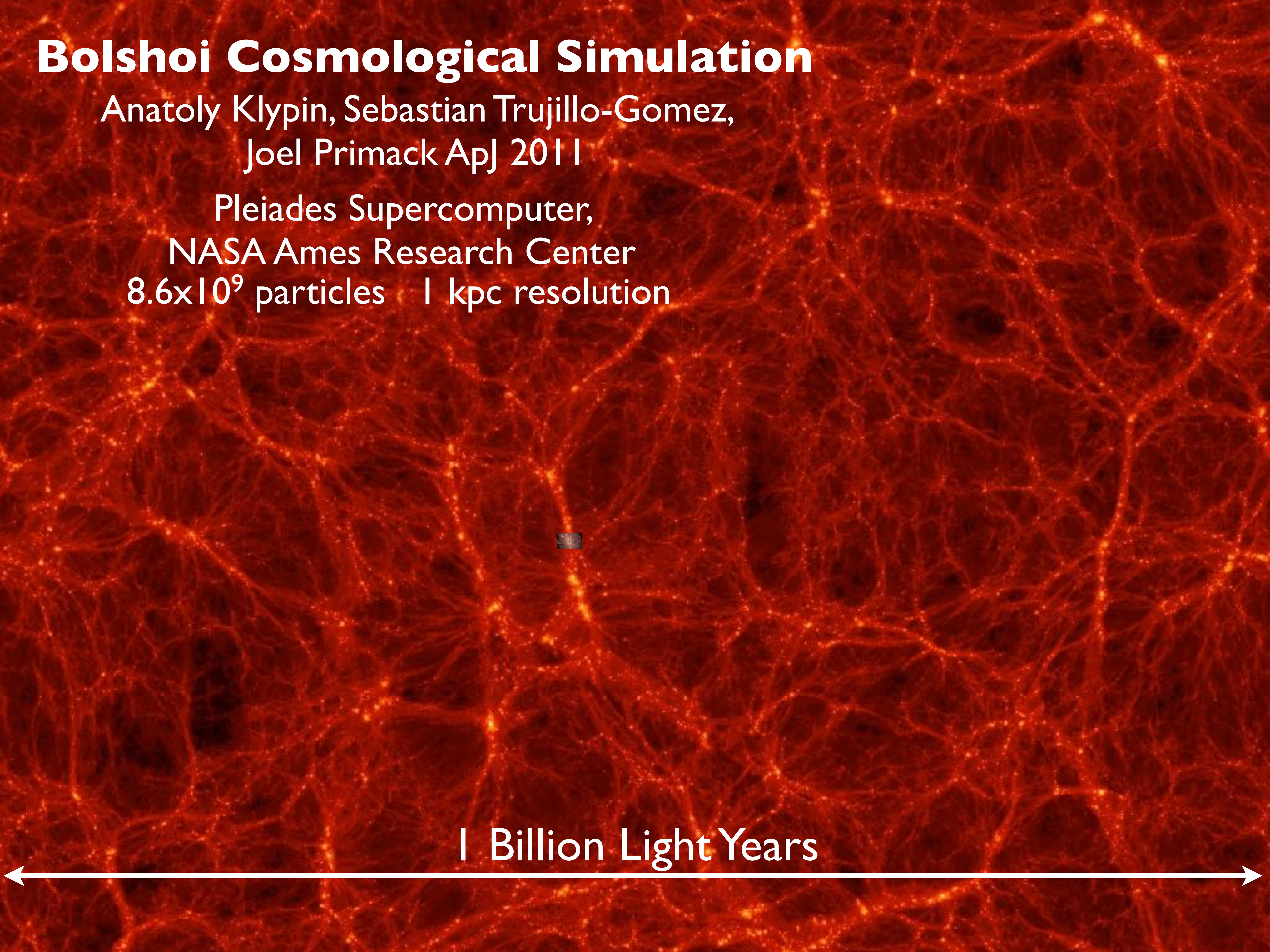




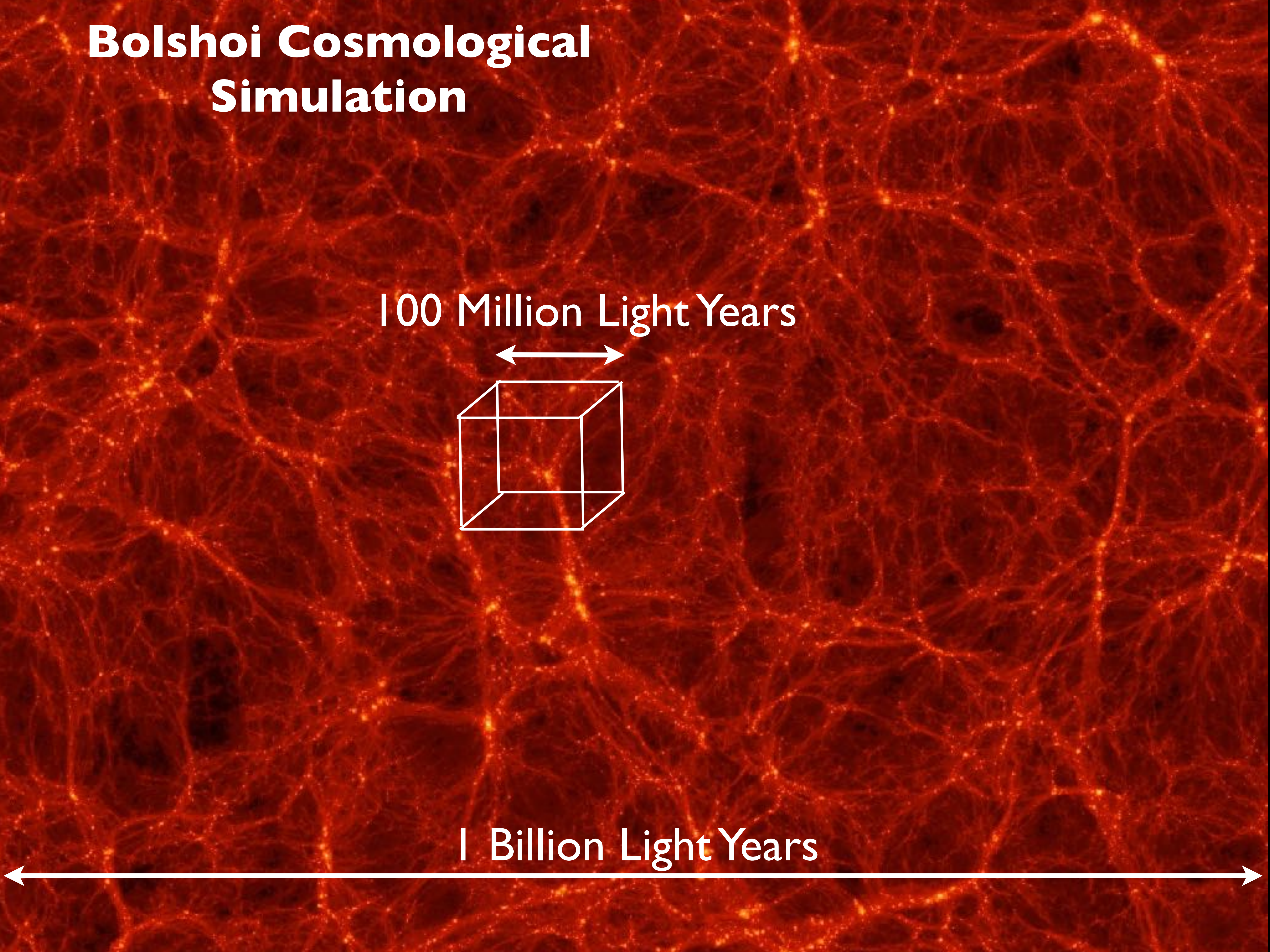



Aquarius Simulation
Volker Springel
Milky Way
100,000 Light Years
Milky Way Dark Matter Halo
1,500,000 Light Years




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



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.

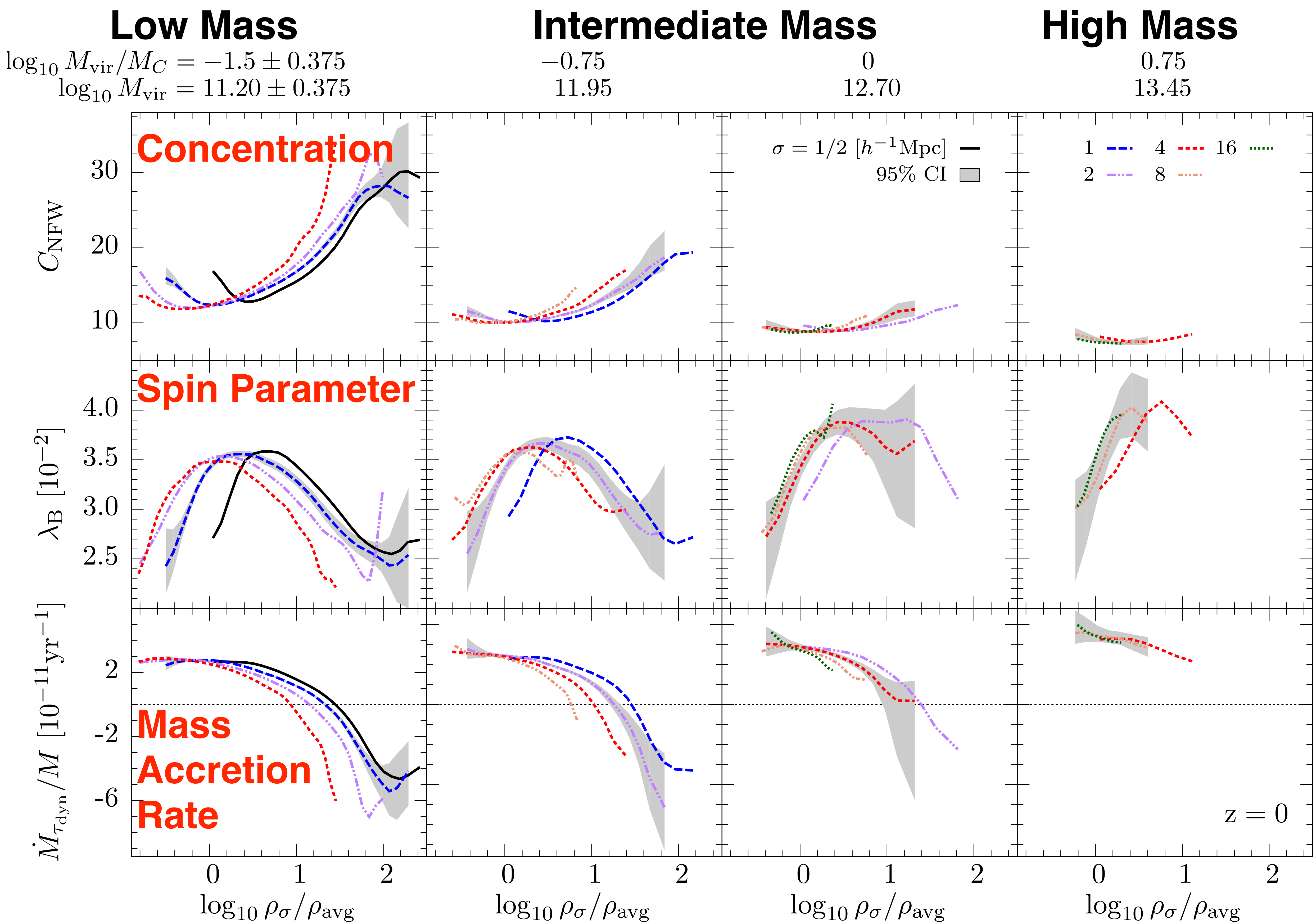
Structure Formation Methodology

- 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

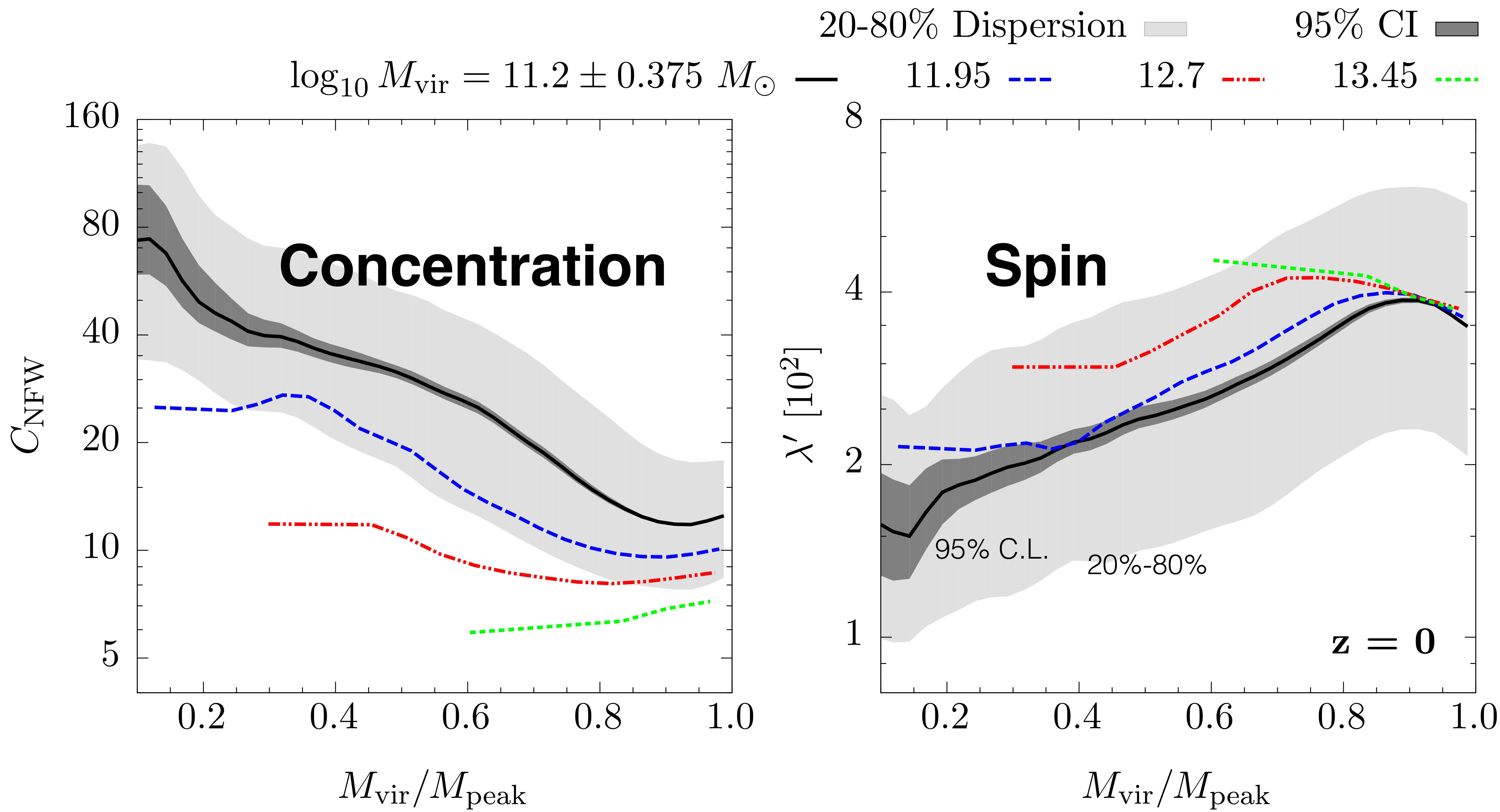
MNRAS 2017



Properties of Dark Matter Haloes: Causes & Effects of Mass Loss

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

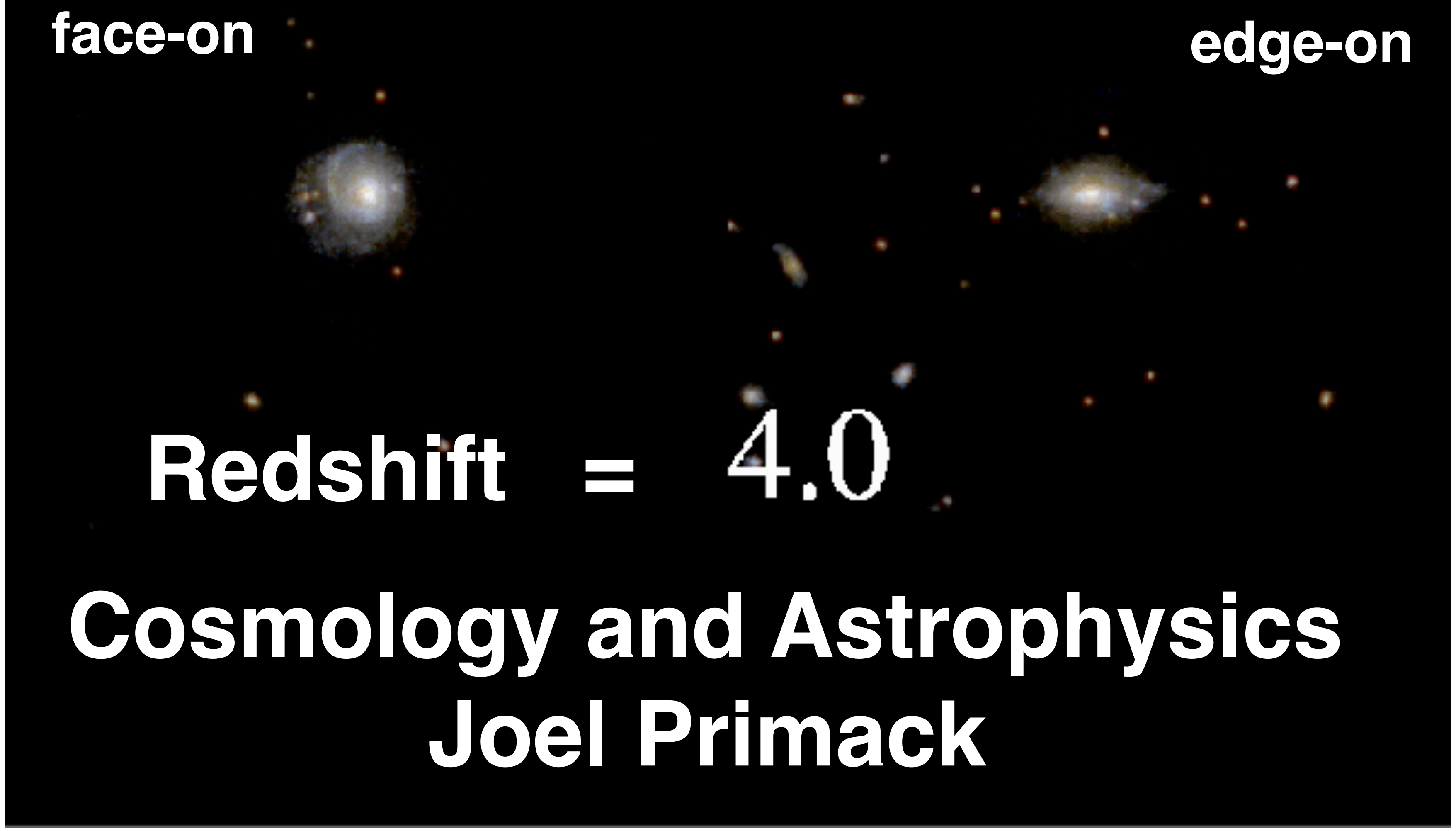
to be submitted to MNRAS



- **Most low mass halos in dense regions are significantly stripped**
- **Halos that have lost 5-15% of their mass relative to M_{peak} have lower C, higher λ**
- **Halos that have lost more than 25% of their mass have higher C and lower λ**

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.



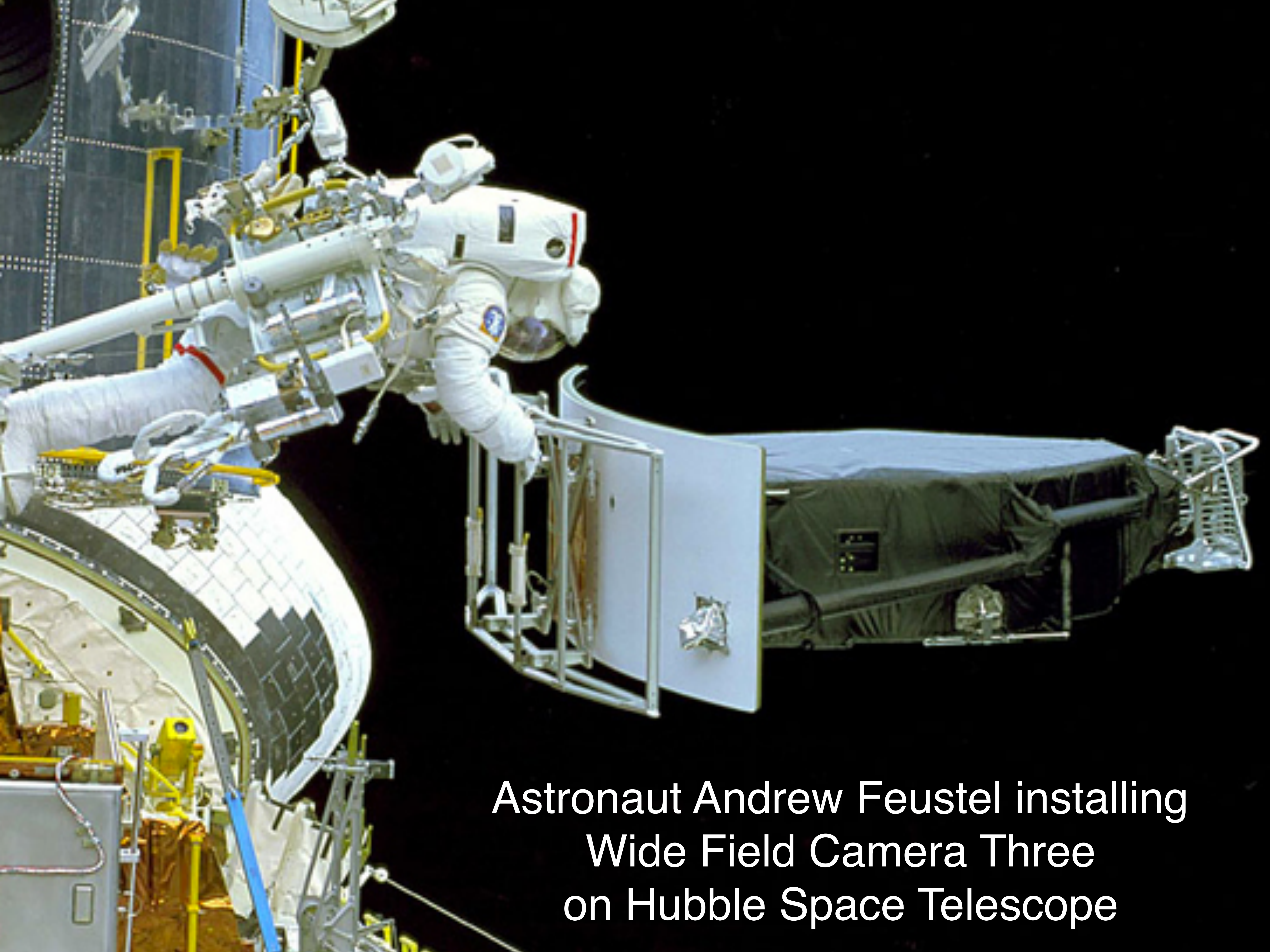
- **Bolshoi** - best cosmological simulations using the latest cosmological parameters.
- Largest suite of **high-resolution zoom-in hydrodynamic galaxy simulations** compared with observations by CANDELS, the largest-ever Hubble Space Telescope project.
- Dust absorption and re-radiation of starlight 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.

CANDELS

Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

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

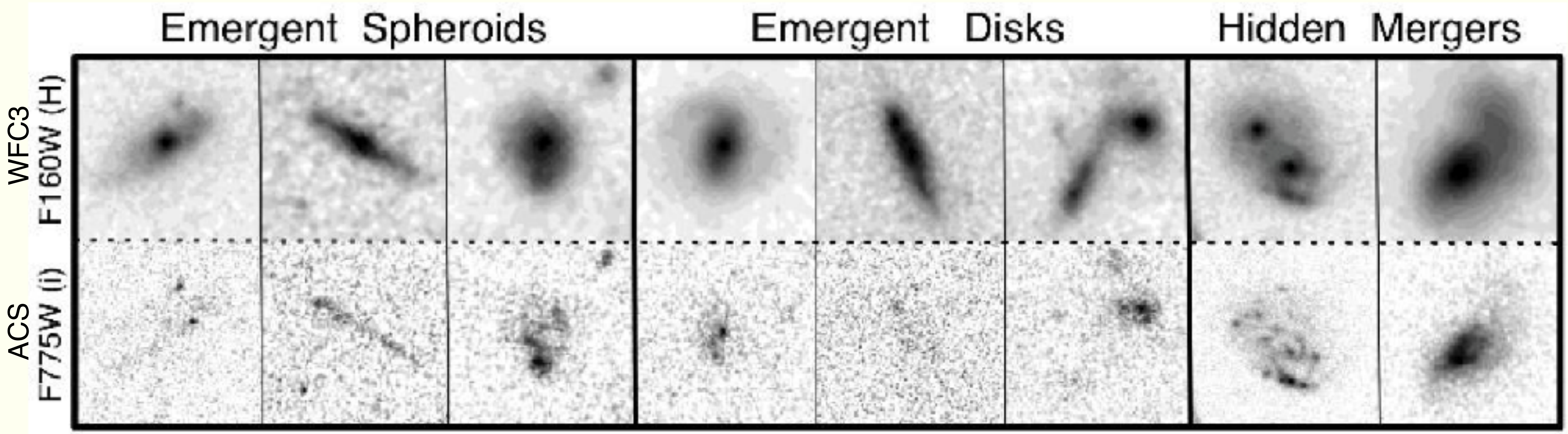
} Challenge for Observers & Simulators!



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

The CANDELS Survey

candels.ucolick.org



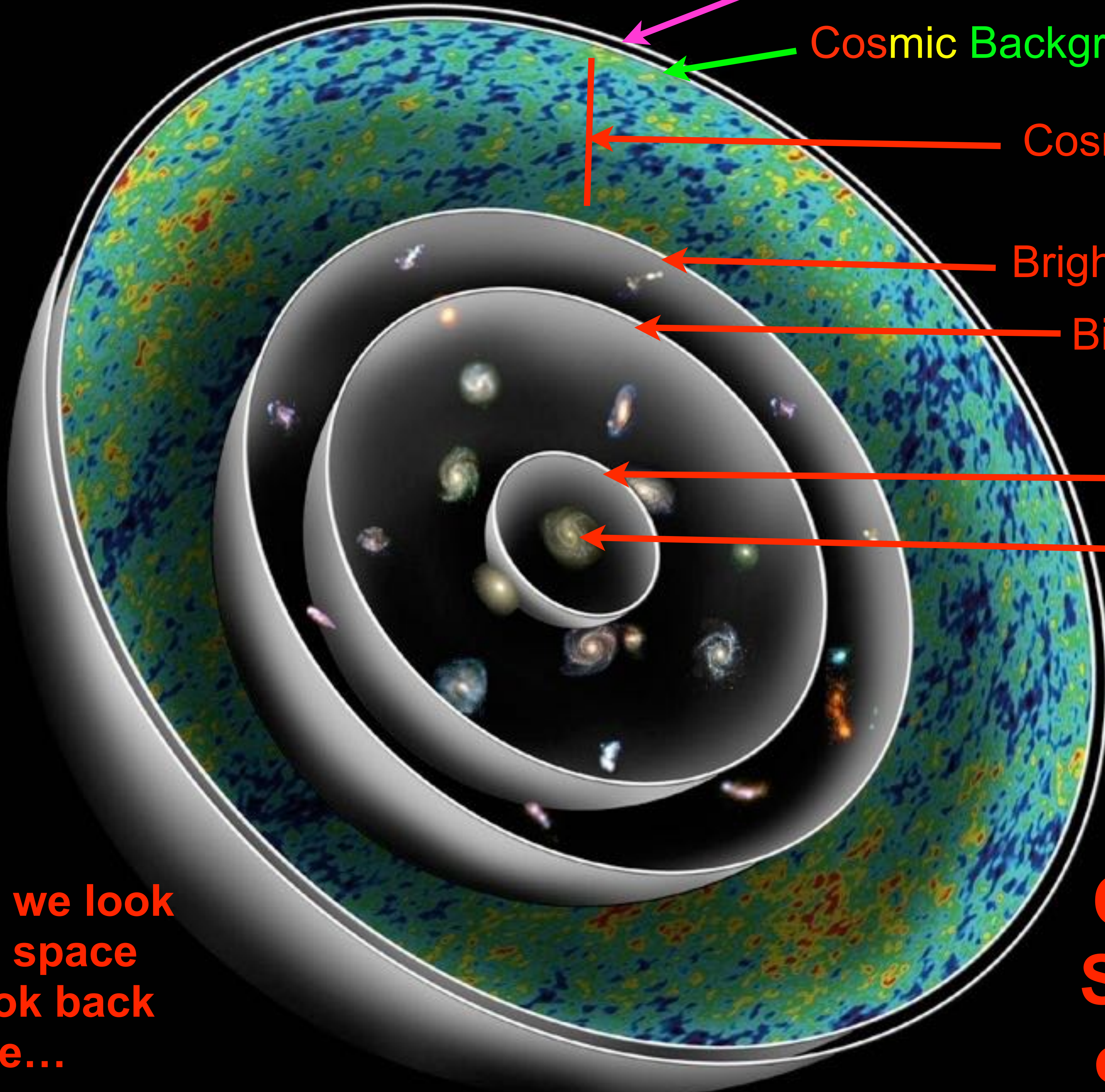
CANDELS: A Cosmic Odyssey

(blue 0.4 μm)(1+z) = 1.6 μm @ z = 3

(red 0.7 μm)(1+z) = 1.6 μm @ z = 2.3

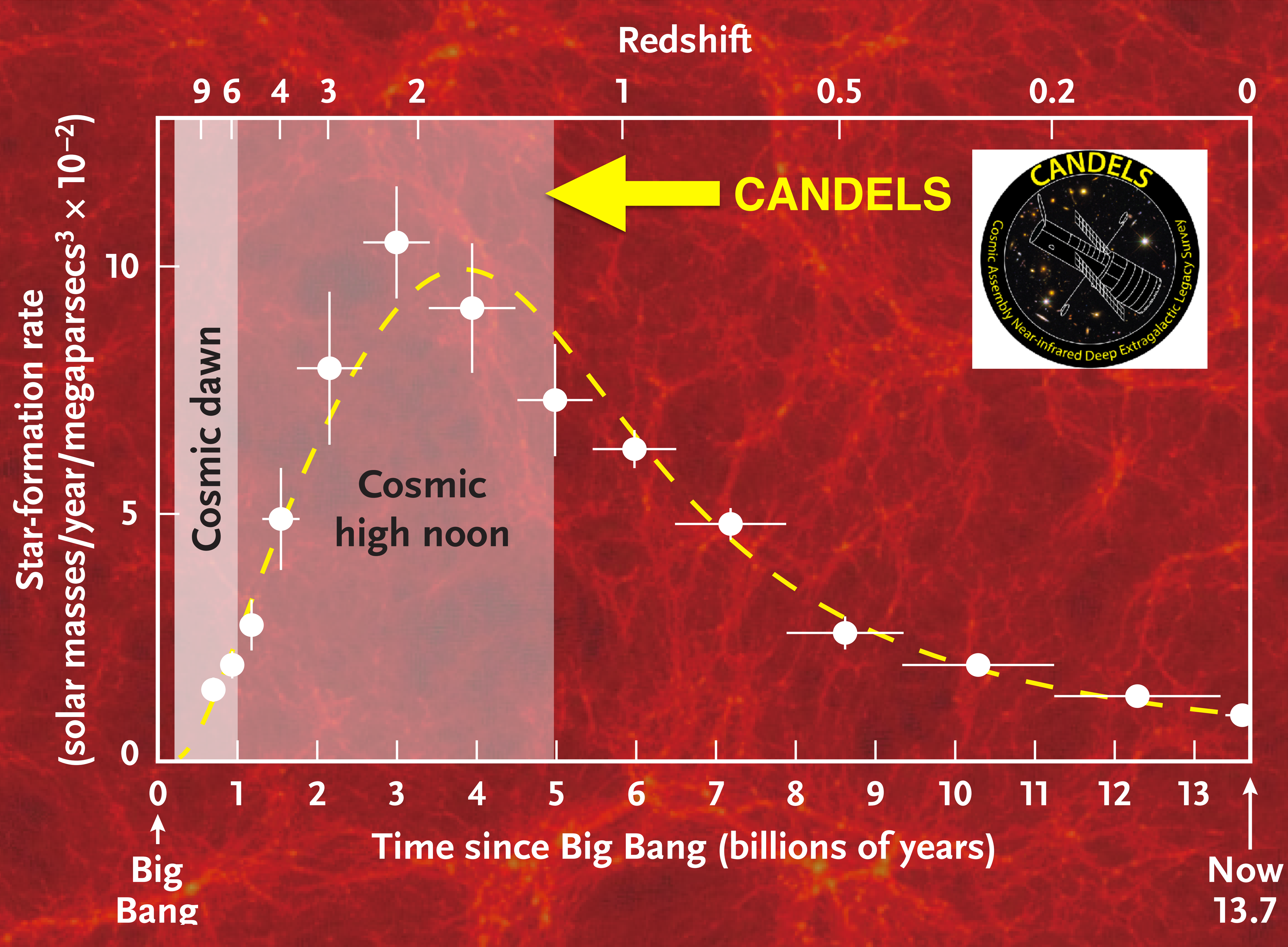
CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

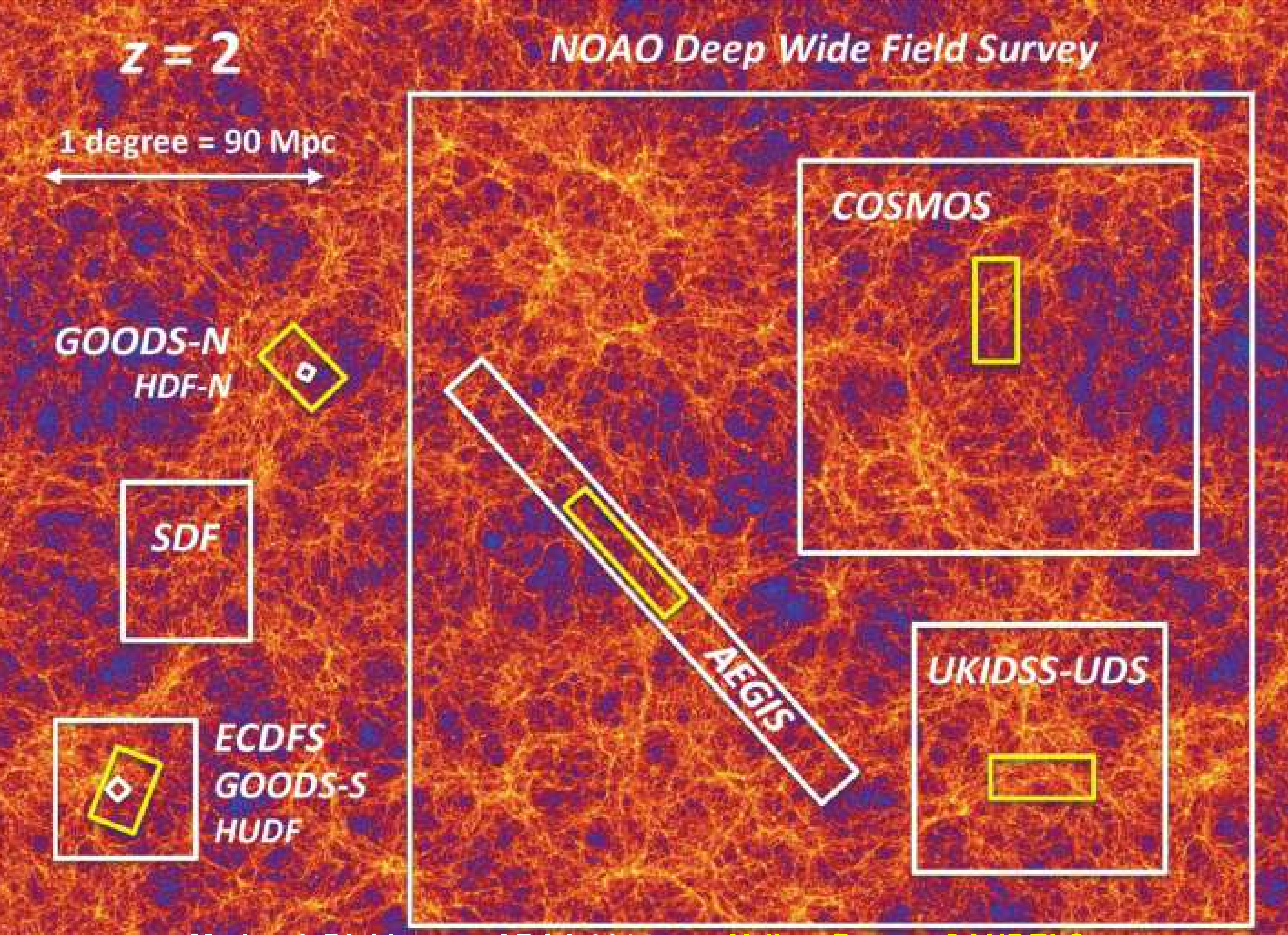
- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared 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
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



Madau & Dickinson - ARAA 2014 Yellow Boxes: CANDELS

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

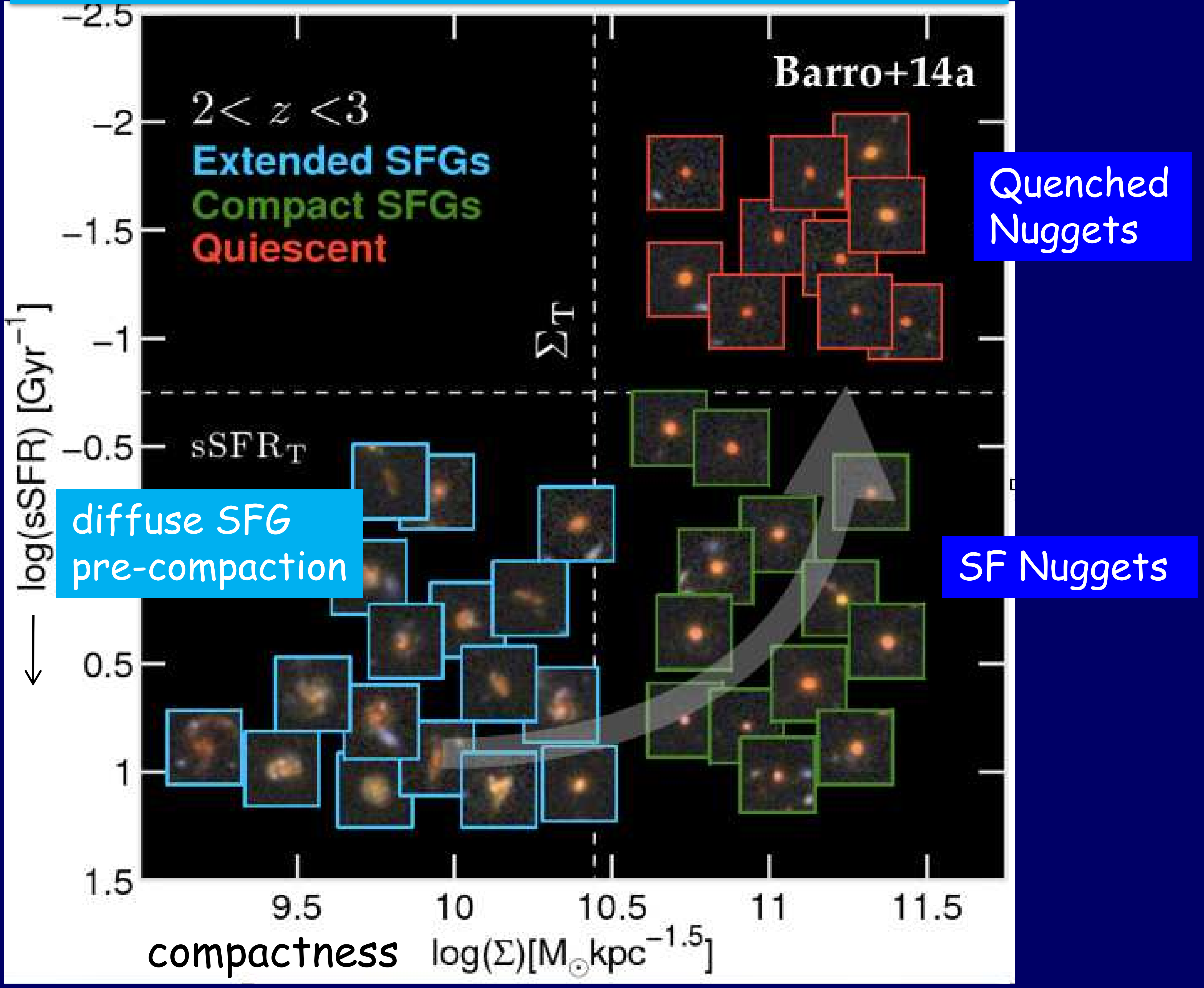
Advantages: it's possible to compare in detail with high-z galaxy images and spectra, to discover how galaxies evolve, morphological drivers (e.g., galaxy shapes, clumps and other instabilities, origins of galactic spheroids, quenching). Radiative pressure & AGN feedbacks essential?
Disadvantages: statistical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

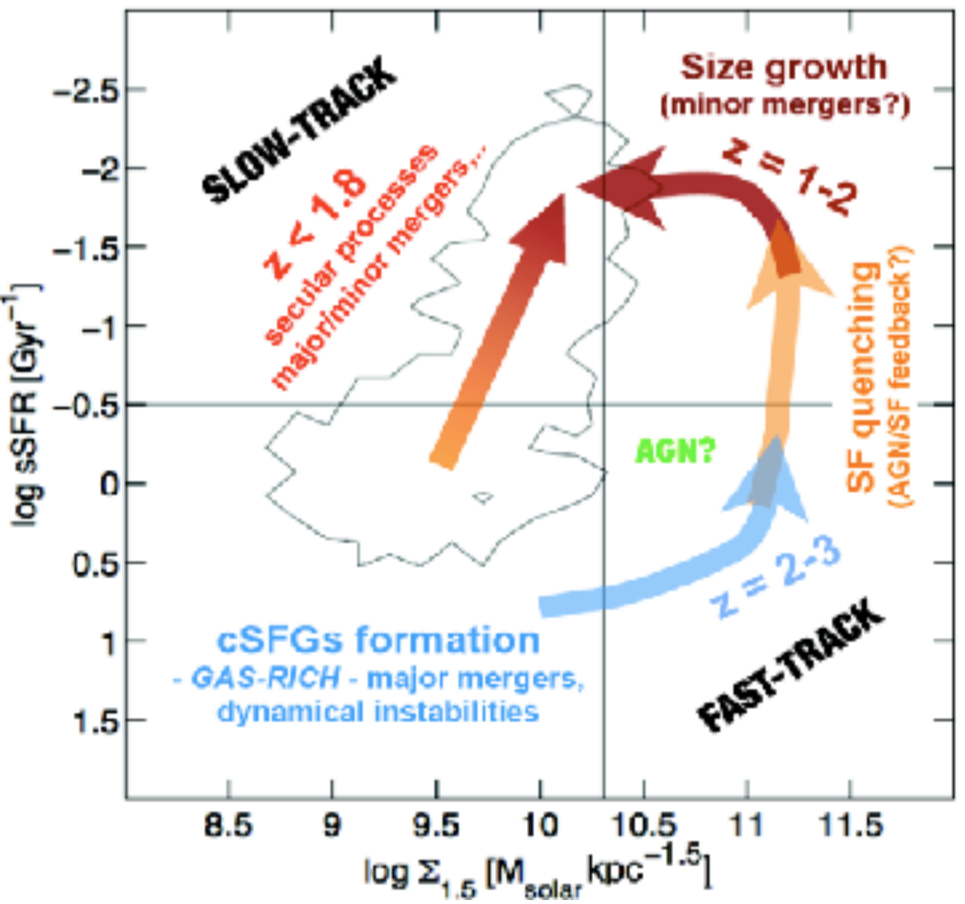
Our hydroART cosmological zoom-in simulations produce all of these phenomena!

The Fast Track of Galaxy Evolution



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

Barro+ (CANDELS) 2013

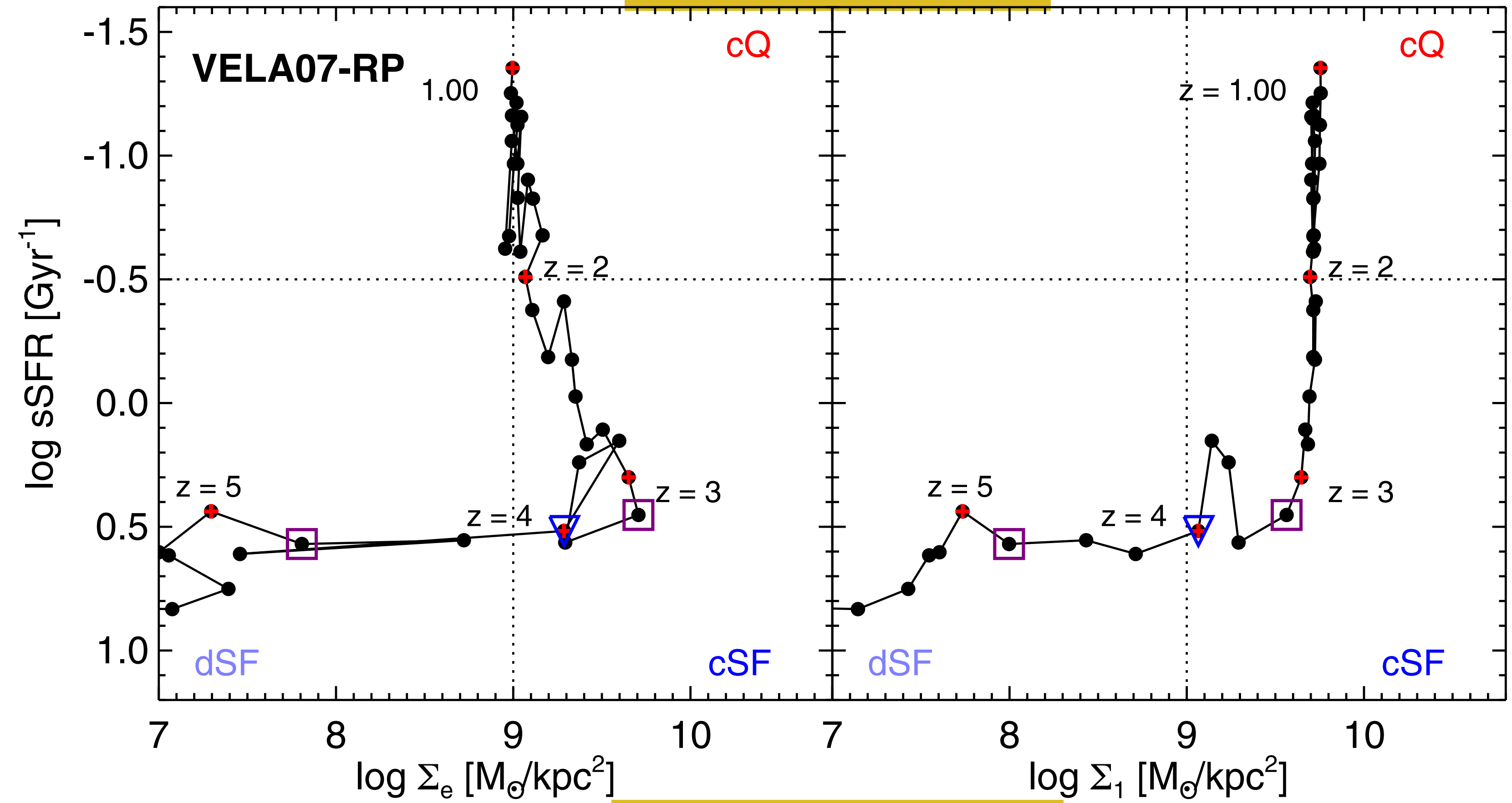


COMPACTION —>

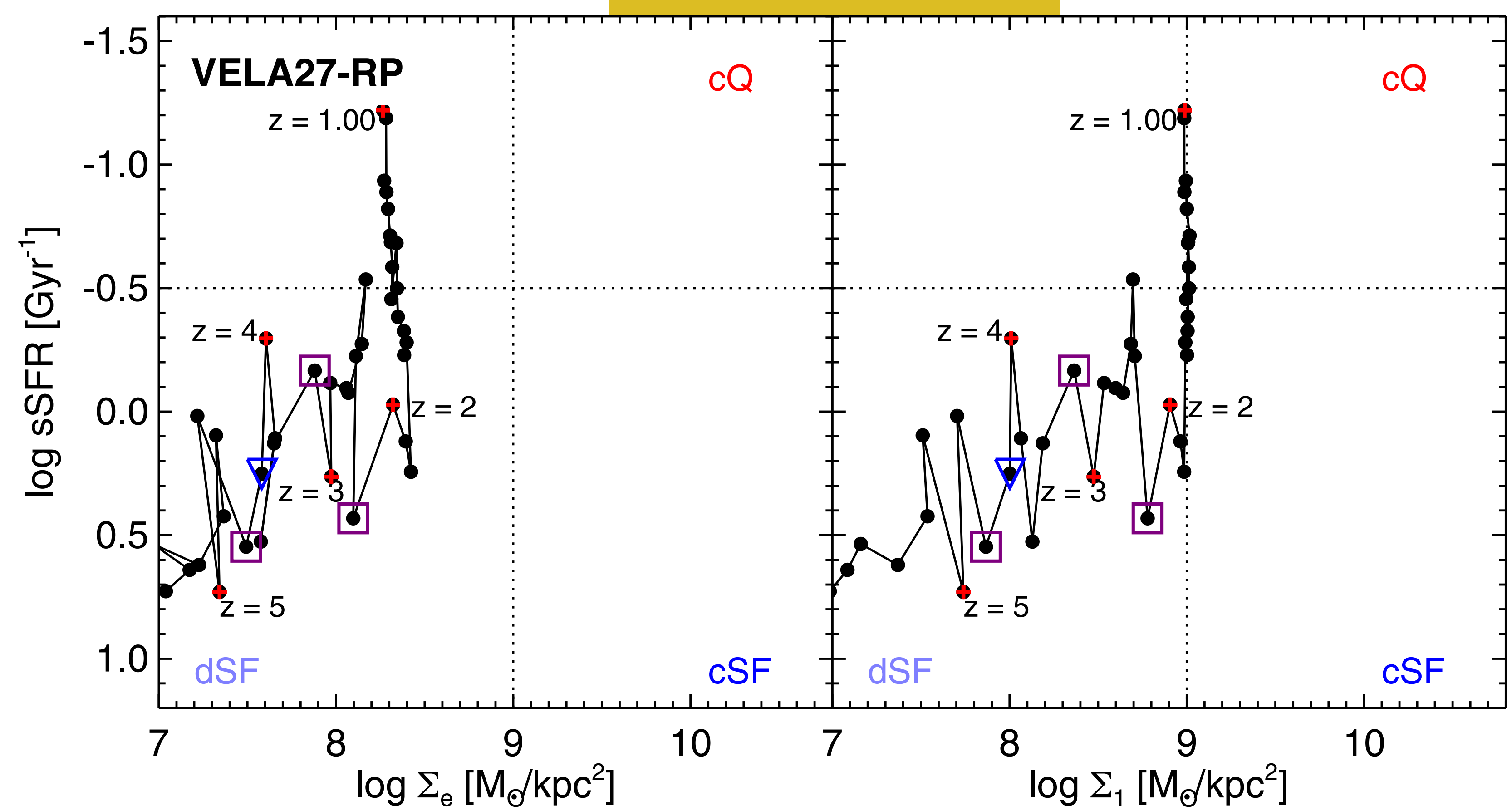
major merger

minor merger

FAST-TRACK

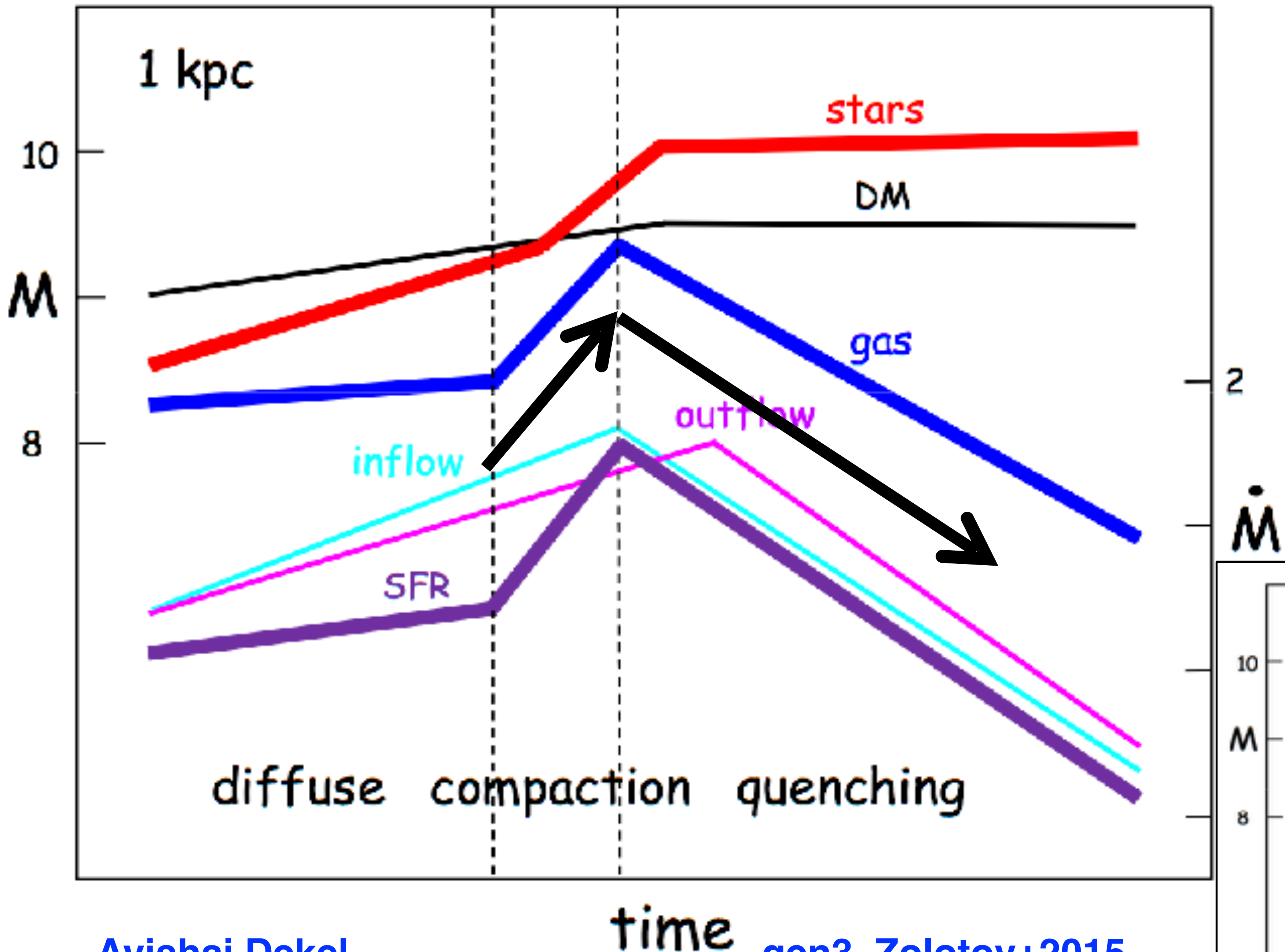


SLOW-TRACK



Zolotov+2015

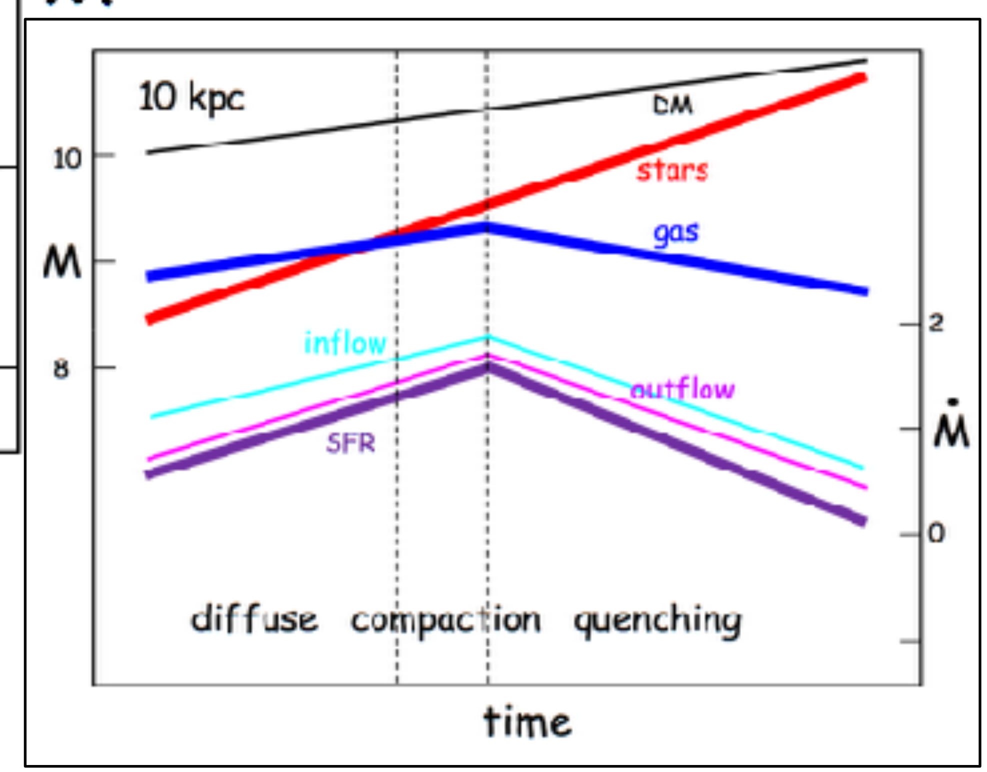
Compaction and Quenching in the Inner 1 kpc



Avishai Dekel

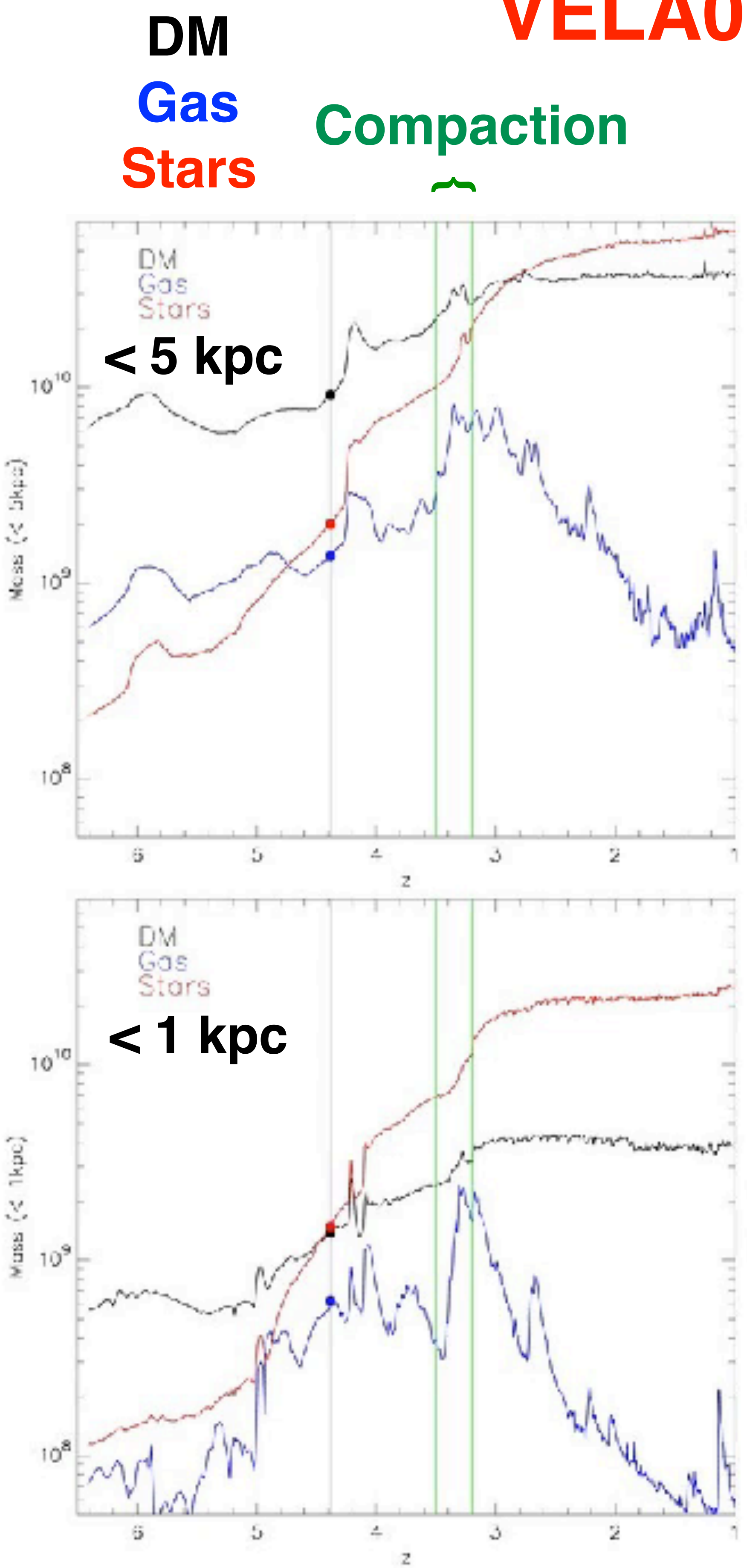
gen3 Zolotov+2015

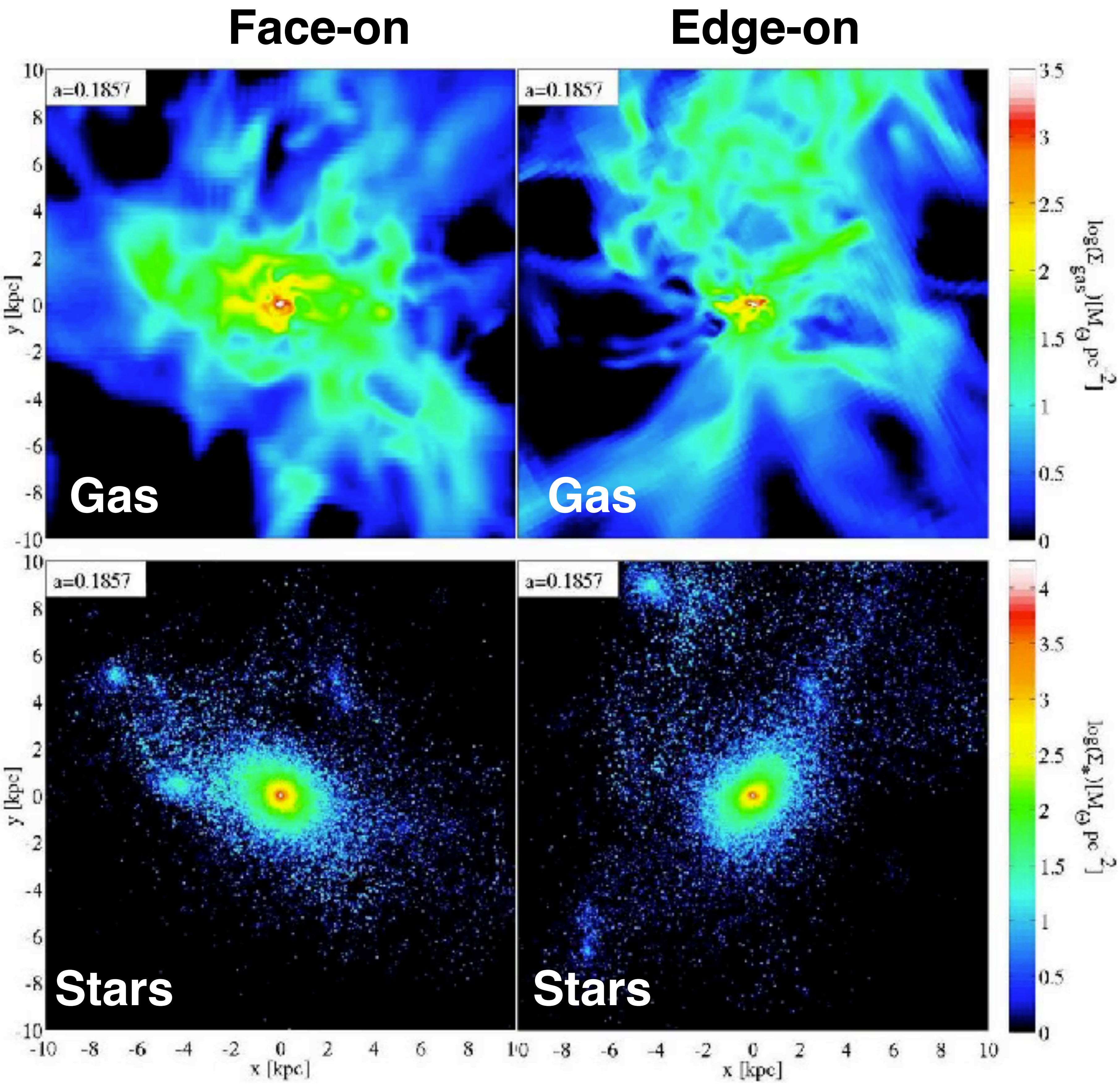
Inner 10 kpc



VELA07-RP Animations z = 4.4 to 2.3

Daniel Ceverino, Nir Mandelker

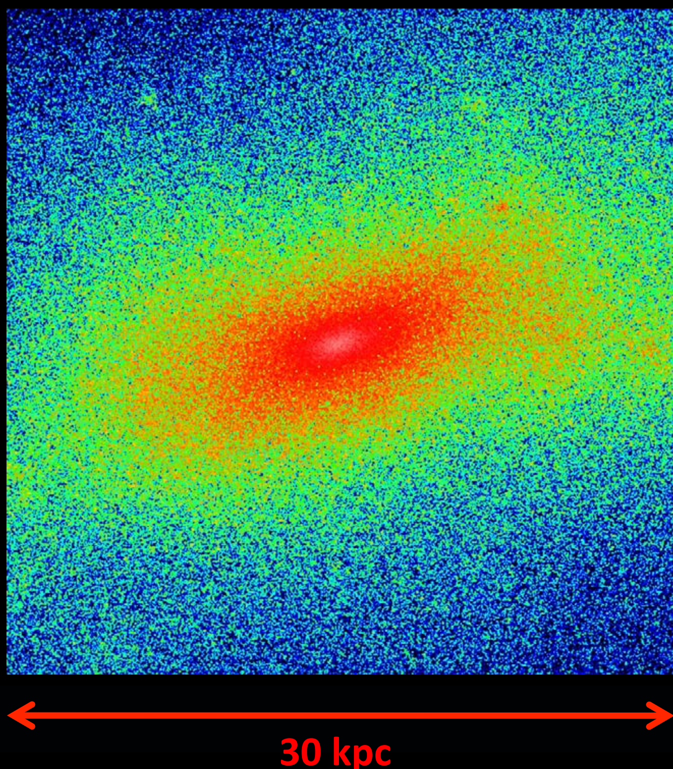


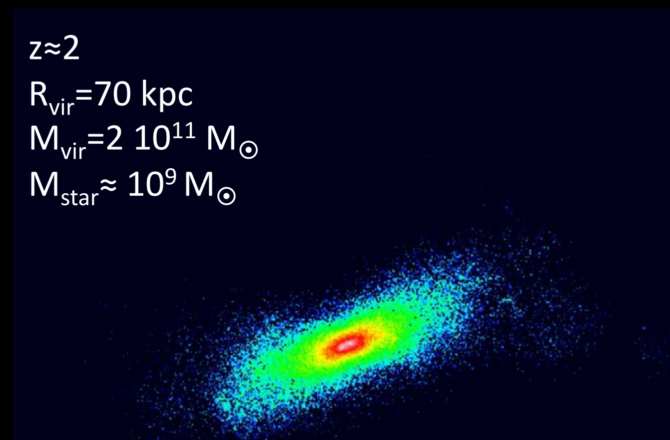


Our cosmological zoom-in simulations often produce elongated galaxies like observed ones. The elongated distribution of stars follows the elongated inner dark matter halo.

Prolate DM halo → elongated galaxy

DM VELA28 stars





z≈2, R_{vir}=70 kpc, $M_{vir}=2\ 10^{11}\ M_\odot$, $M_{star} \approx 10^9\ M_\odot$

Dark matter halos are elongated, especially near their centers. Initially stars follow the gravitationally dominant dark matter, as shown. But later as the ordinary matter central density grows and it becomes gravitationally dominant, the star and dark matter distributions both become disky — as observed by Hubble Space Telescope (van der Wel+ ApJL Sept 2014).

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

Formation of elongated galaxies with low masses at high redshift

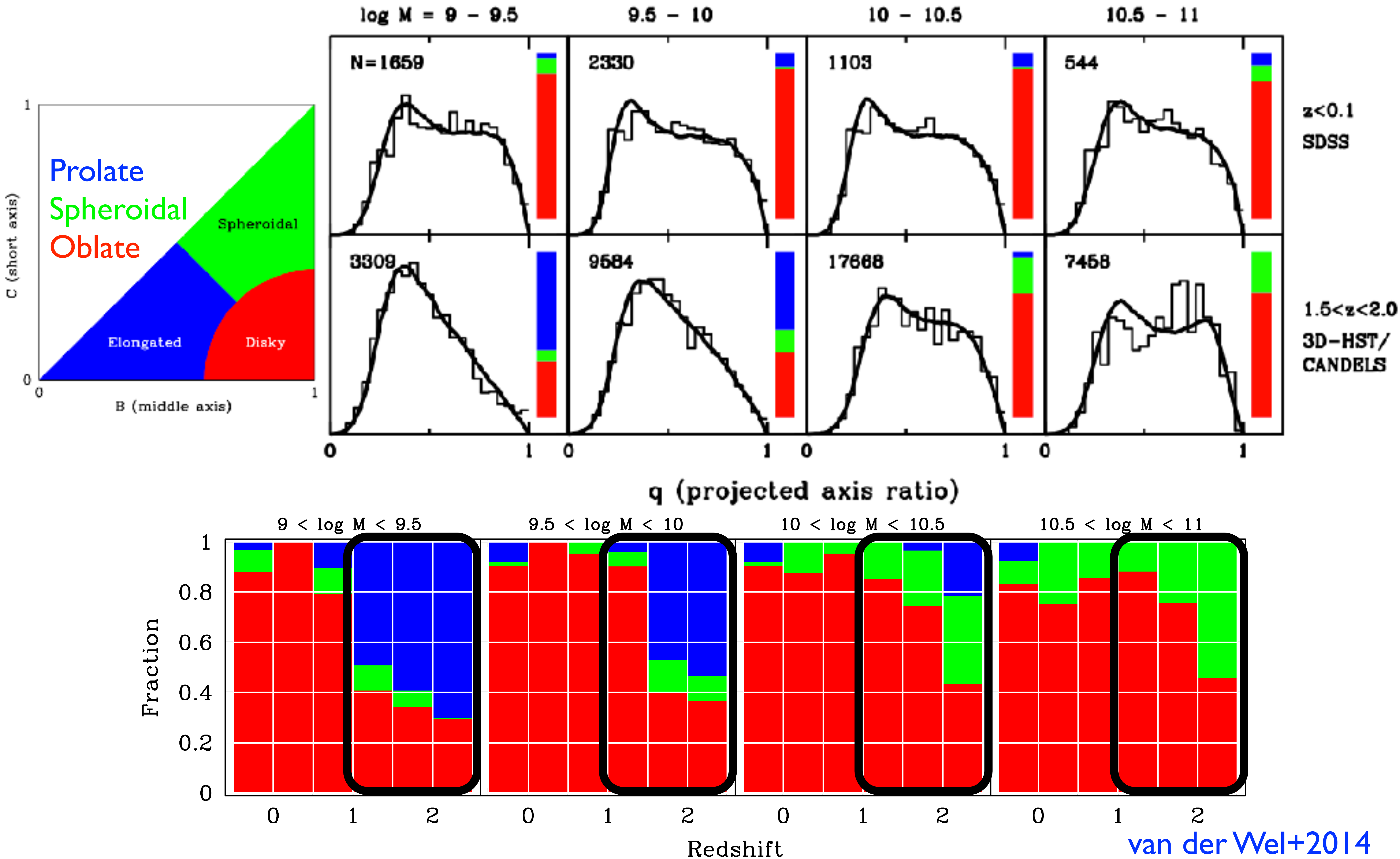
Daniel Ceverino, Joel Primack and Avishai Dekel

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

Nearby large galaxies are mostly disks and spheroids — but they start out looking more like pickles.

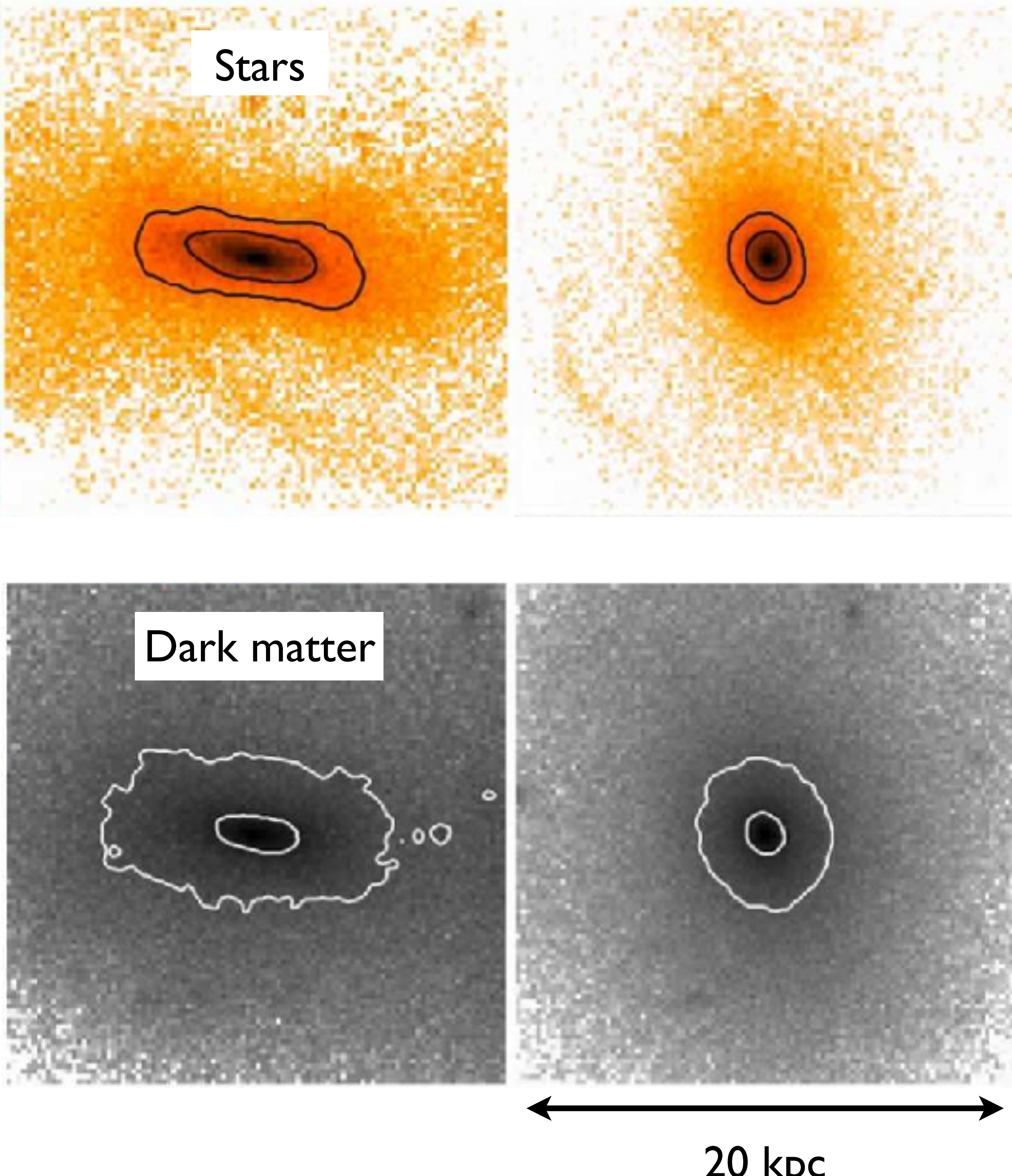
Prolate galaxies dominate at high redshift/low masses

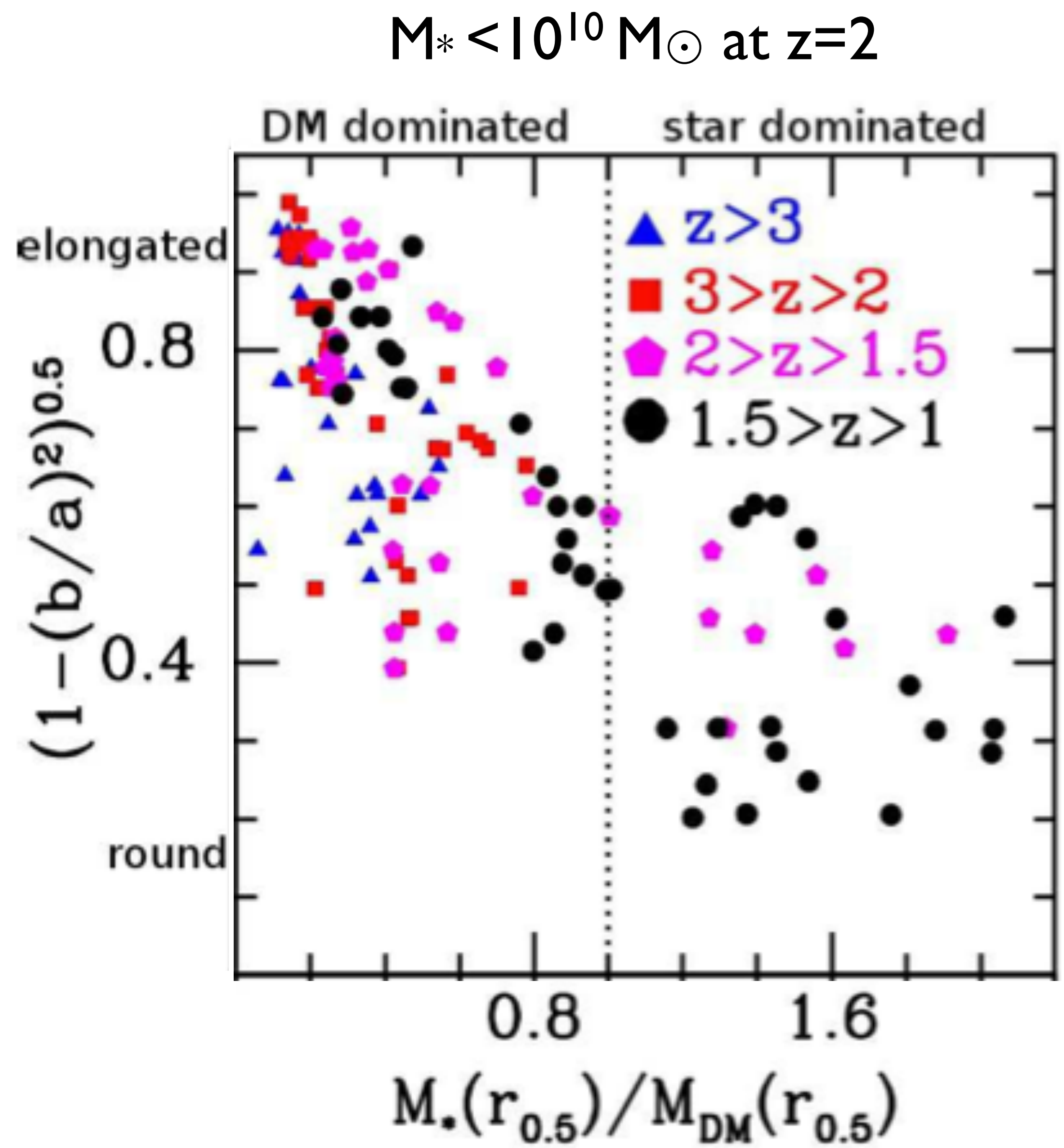


van der Wel+2014

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

Formation of elongated galaxies with low masses at high redshift





See also Tomassetti et al. 2016 MNRA

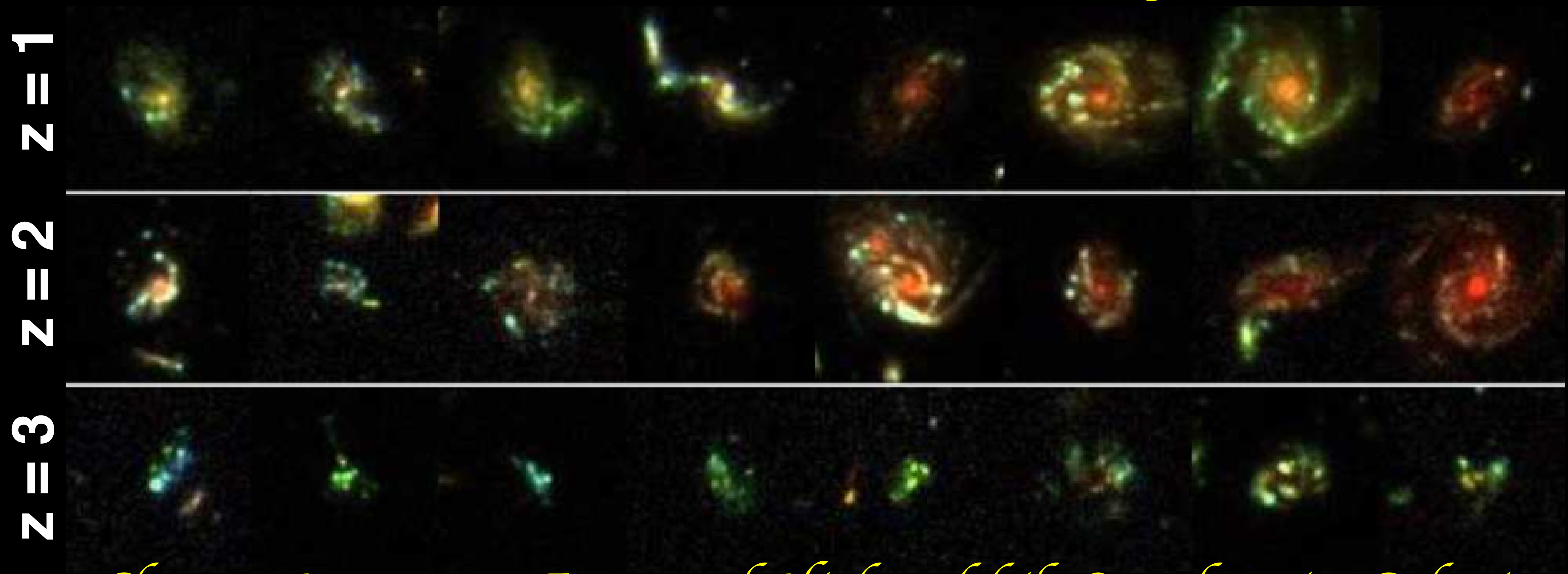
- 3 Aspects of Star-Forming Galaxies Seen in CANDELS
  - Compaction
  - Elongation
  - Clumps

} Challenge for Observers & Simulators!

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

Clumps remain a crucial challenge for simulators!

CLUMPS in CANDELS - Yicheng Guo



Clumps: Important Feature of High-redshift Star-formingGalaxies

- Seen in deep rest-frame UV (e.g., Elmegree+07, 09, Guo+12), rest-frame optical images (e.g., Forster Schreiber+11, Guo+12), and emission line maps (e.g, Genzel+08, 11)
- Span a wide redshift range: 0.5<z<5
- Typical stellar mass: 10^7~10^9 Msun, typical size: ~1 kpc
- Regions with blue UV—optical color and enhanced specific SFR (e.g., Guo+12, Wuyts+12)
- Many are in underlying disks, based on either morphological (e.g., Elmegreen+07,09) and kinematic (e.g., Genzel+11) analyses

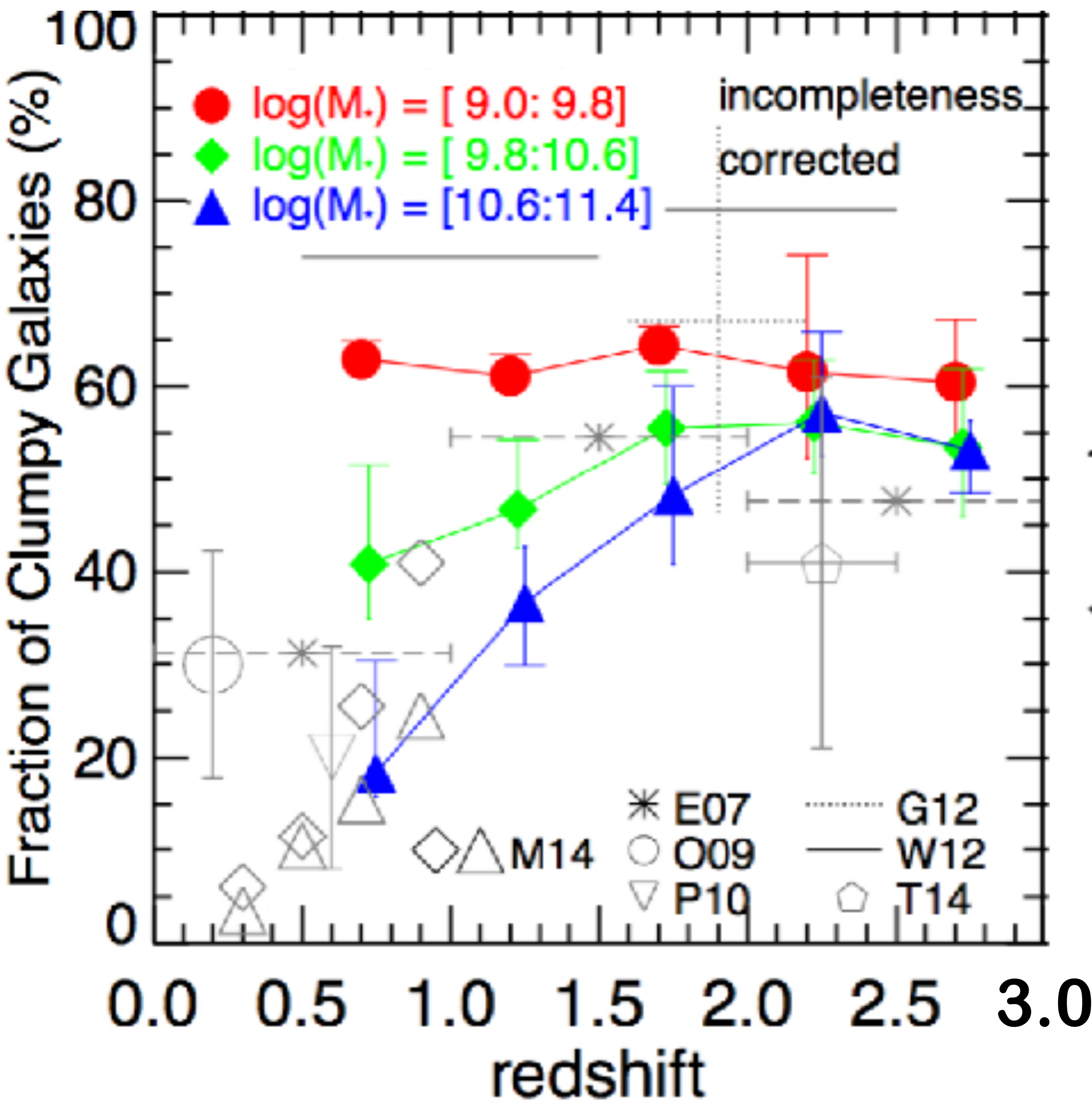
About 60% of star-forming galaxies are clumpy at z ~ 2.5.

The evolution of the clump fraction is mass-dependent.

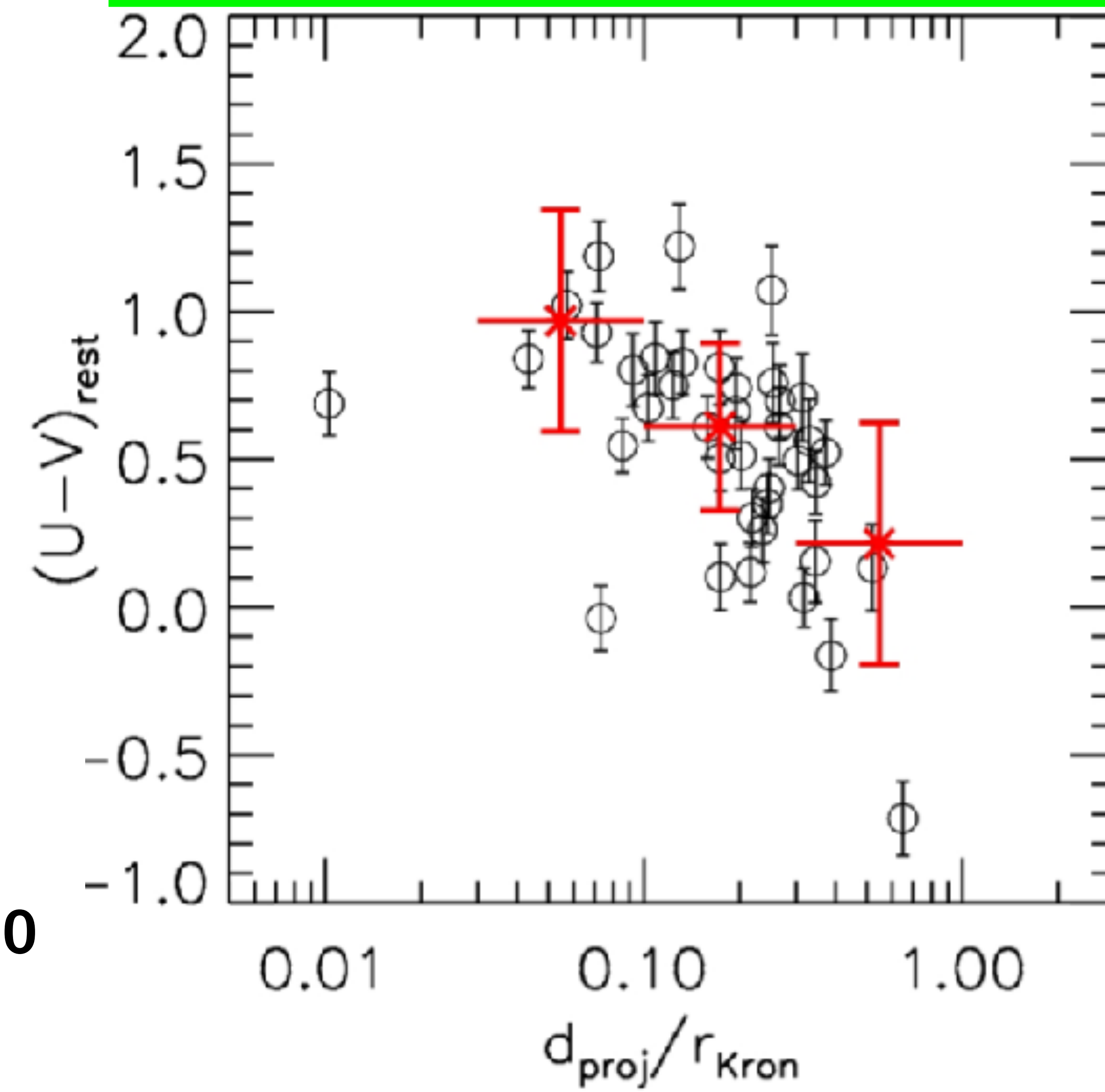
Clumps have radial variation of their UV-optical colors:

- outer clumps are bluer &
- central clumps are redder,

as clump radial migration predicts.

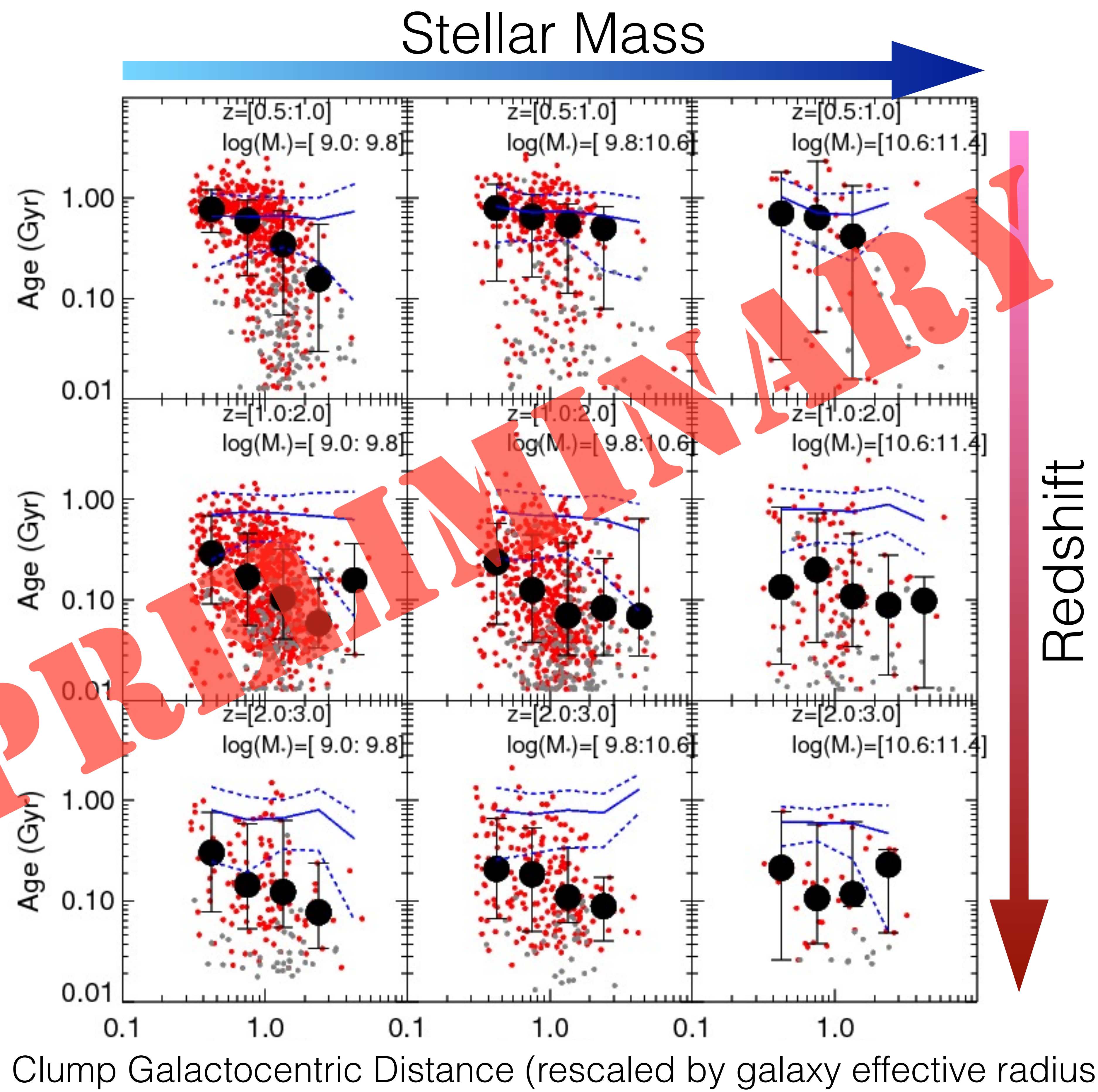


Yicheng Guo+2015



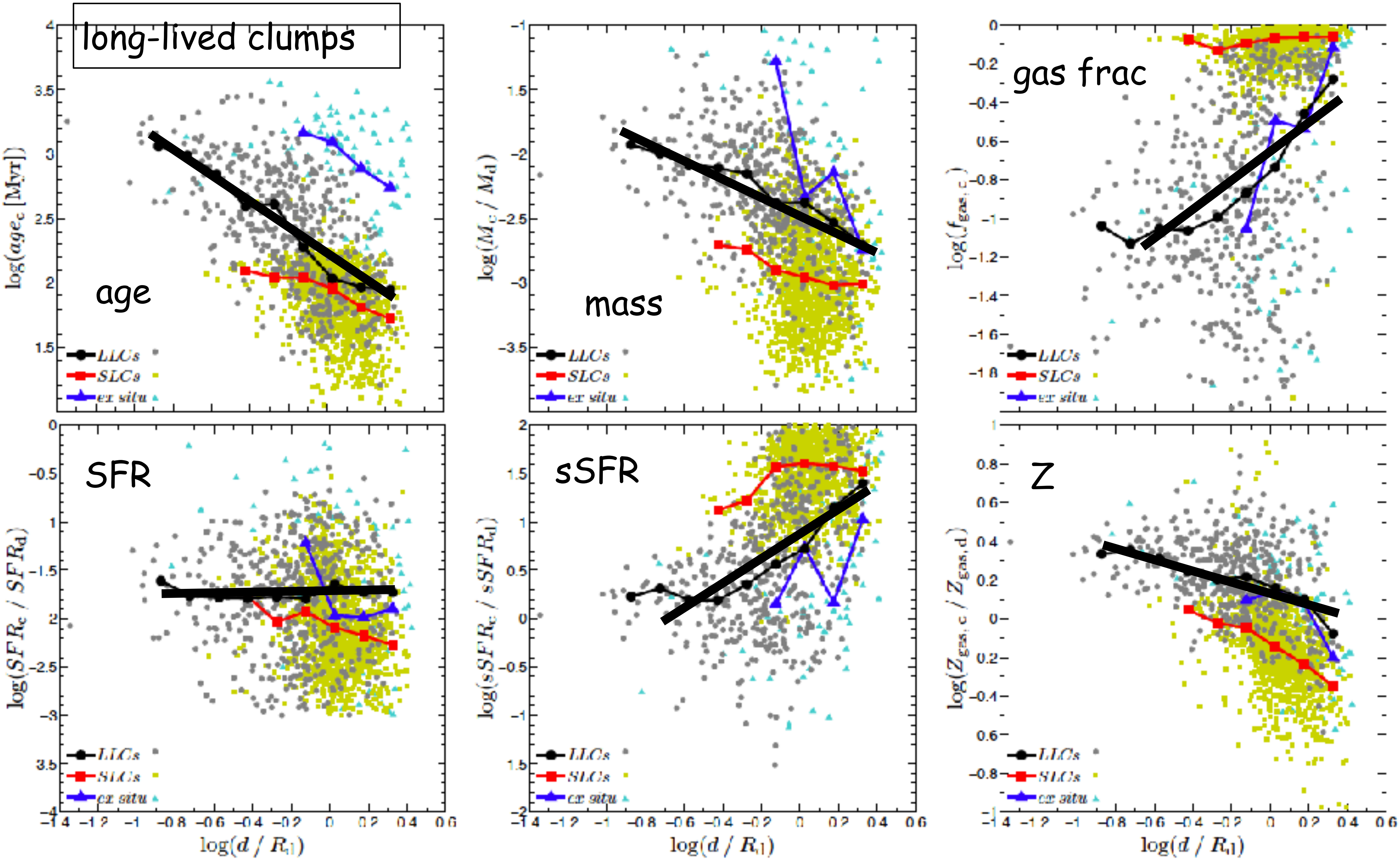
Yicheng Guo+2012

CLUMPS in CANDELS - Yicheng Guo



Predicted Gradients of Clump Properties

Mandelker+16 ART-AMR cosmological simulations, ~25pc resolution



Face Recognition for Galaxies

We propose to use **Deep Learning** (the Convolutional Neural Net method of machine learning, which has been so successful in face recognition and language translation) to discover what **information about active physical processes can be reliably extracted from images of galaxies**. We'll train a Deep Learning classifier using mock images from simulated galaxies paired with physical information from the simulations; then we'll see if the deep learning classifier can successfully predict values for the same properties from mock images for which we don't provide any physical information. If we are successful in extracting useful information from the simulations, we will apply the same method to observations to predict physical characteristics and processes in images of real galaxies. We are specifically interesting in identifying the underlying physical processes that lead to major morphological transformations, for example the formation of galactic spheroids.

This effort, led by our collaborator Dr. Marc Huertas-Company and partially funded by a grant from Google, draws inspiration from the winning solution of a 2015 competition in the machine learning community to best reproduce the Galaxy Zoo classifications of Sloan Digital Sky Survey (SDSS) galaxy images. The winning team used a Deep Learning algorithm to predict morphological parameters of the SDSS galaxies with nearly perfect accuracy. Working with the same algorithm, Dr. Huertas-Company led a collaboration to classify $\sim 50,000$ images of galaxies from the CANDELS survey. We are using the same algorithm to classify our mock images in order to compare them with observed galaxies.

DEEP-Theory Meeting   9 Jan 2017

Progress generating mock images and IFU data cubes from our Sunrise pipeline (Greg Snyder, Raymond Simons) Email 1/8 from Greg Snyder (STScI): I am pleased to report that I have finished creating Sunrise images on the entire suite of VELA Generation 3 simulations. There were 34 simulations that had enough snapshots to consider. I have copied them all to Pleiades and applied Raymond's speedy yt—>Sunrise extraction algorithm and our Sunrise imaging pipeline. I am finished with CANDELizing 75% of the sample and I expect to reach 100% by later this week, at which point I will copy out these files. One new improvement is that I have added filters for JWST's MIRI instrument in addition to NIRCAM and HST for the set of candelized images. MIRI (5-25 microns) will only make sense for the higher redshifts because we didn't do dust emission, but could help characterize shapes in the very early universe.

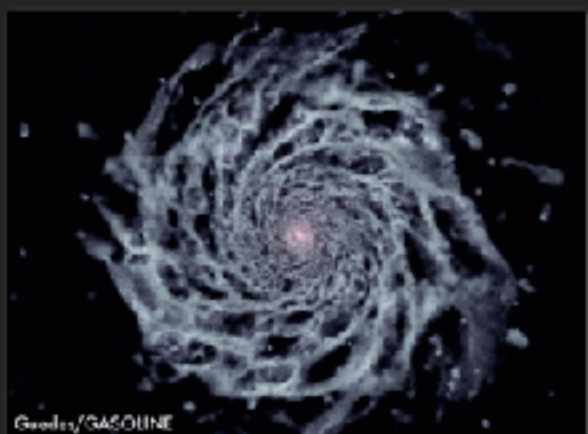
Analyzing these images for **clumps** (Yicheng Guo); measuring **GALFIT statistics** a, b, axis ratio b/a, Sersic index of CANDELized images (Yicheng and Vivian Tang) compared with high resolution images (Liz McGrath). R_{eff} **for SDSS galaxies as a function of density** (Christoph, Graham Vanbenthuysen).

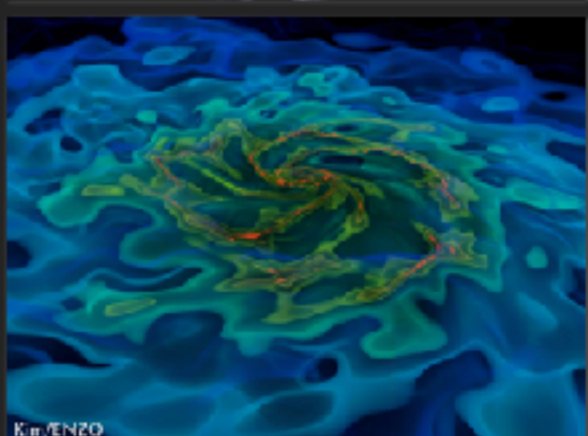
Preparing information for **Deep Learning** (**DL**) about the simulations using yt analysis of the saved timesteps (Sean Larkin, Fernando Caro, Christoph Lee) and using other methods (Nir Mandelker, Santi Roca-Fabrega) to see **whether giving the deep learning code this information in addition to mock images will allow the code to determine some of these phenomena from the images** at least in the best cases of inclination, resolution, and signal/noise (Marc Huertas-Company and team). **What data about the simulations should we give DL?**

AGORA Assembling Galaxies of Resolved Anatomy

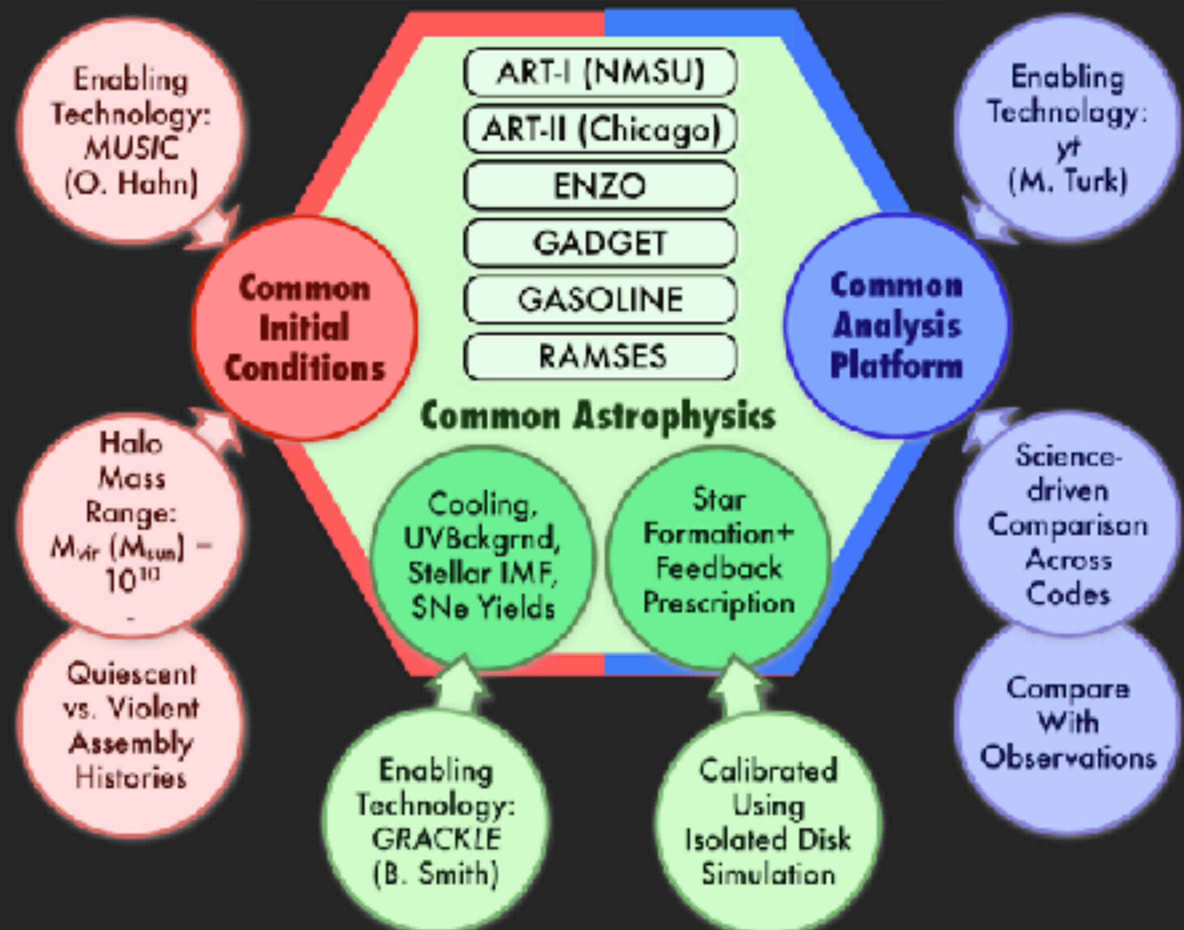
A High-resolution Galaxy Simulations Comparison Initiative: www.AGORAsimulations.org

High-res Galaxy Simulations





AGORA Comparison Infrastructure



AGORA Goal & Team

- GOAL: A collaborative, multi-platform study to raise the realism and predictive power of galaxy formation simulations
- TEAM: 140+ participants from 60+ institutions worldwide, as of August 2016
- DATA SHARING: Simulations outputs and analysis softwares will be shared with the community

- Contact: santacruzgalaxy@gmail.com
- AGORA First Light: Flagship paper by Ji-hoon Kim et al. (ApJS 2014)
- Project funded in part by:

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); Grackle
cooling function (based on ENZO and Eris cooling)

Tools to compare simulations based on *yt*, for all codes used in AGORA, with instantaneous visualization

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

www.AGORAsimulations.org

AGORA Isolated Disk Comparison

ApJ 2016

Milky Way-mass Disk Galaxy Formation with 80 pc Resolution

Summary of results:

- If carefully constrained, galaxy simulation codes agree well with one another despite having evolved largely independently for many years without cross-breedings
- Simulations are more sensitive to input physics than to intrinsic code differences.
- AGORA continues to promote collaborative and reproducible science in the community.

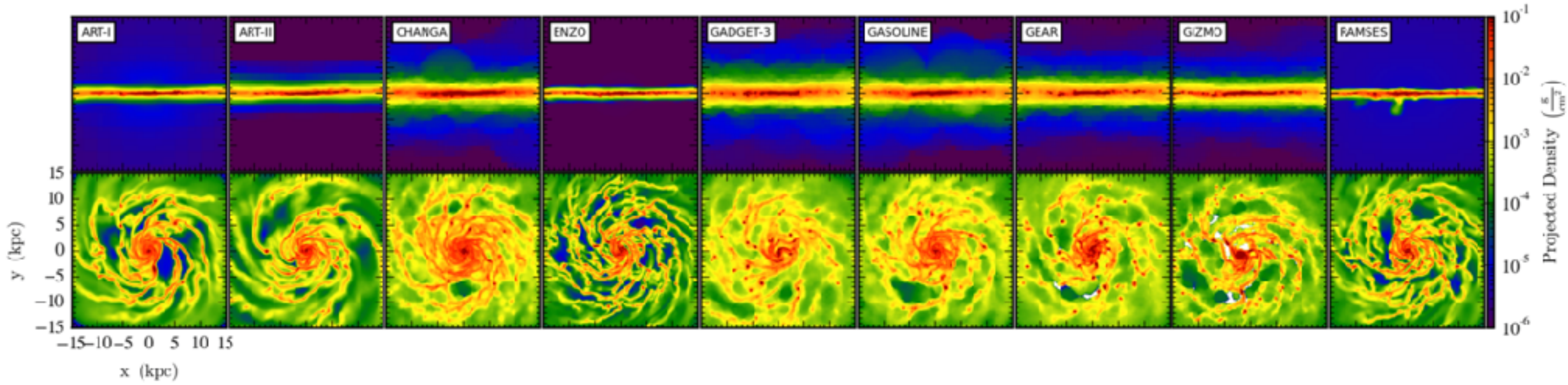


Figure 2. The 500 Myr composite snapshots of gas surface density from *Sim-1* with radiative gas cooling but without star formation or feedback. Each frame is centered on the location of maximum gas density within 1 kpc from the center of gas mass. Simulations performed by: Daniel Ceverino (ART-I), Robert Feldmann (ART-II), Spencer Wallace (CHANGA), Mike Butler (ENZO), Jun-Hwan Choi (GADGET-3), Ben Keller (GASOLINE), Yves Revaz (GEAR), Alessandro Lupi (GIZMO), and Romain Teyssier (RAMSES).

Website: AGORAsimulations.org

Summary

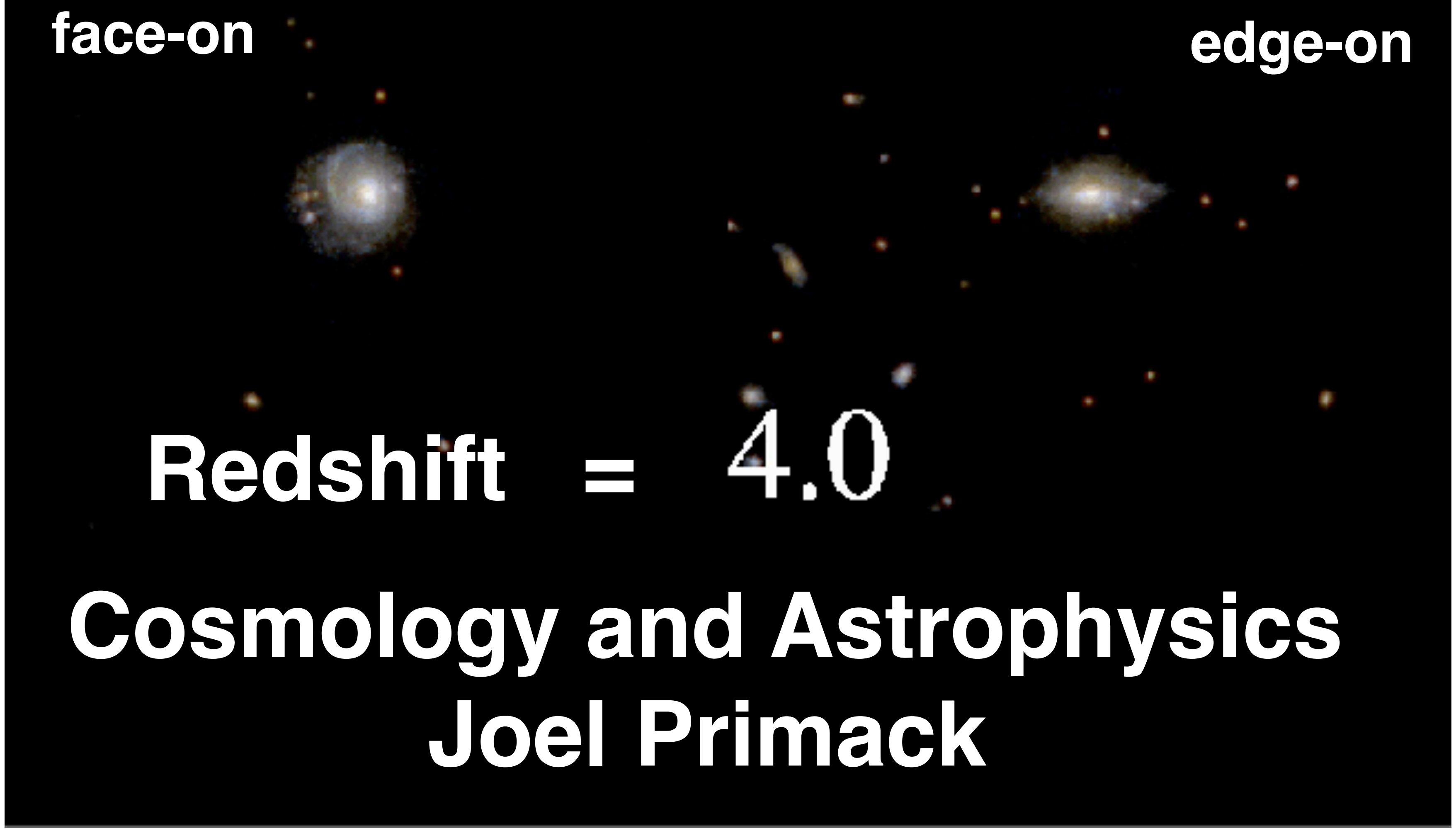
- Large-Scale Simulations and Galaxies
  - Planck Cosmology Simulations more halos at high M, z
  - Halo properties depend on environmental density
  - Stellar Halo Accretion Rate Coevolution (SHARC)
- 3 Aspects of Star-Forming Galaxies Seen in CANDELS
  - Compaction
  - Elongation
  - Giant Clumps

  } Our simulations help explain these phenomena

CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

- AGORA Galaxy Simulation Comparison Project
  - Understand different results from different codes, and raise the realism of all simulation codes

Thanks!!



- **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.

Joel Primack RECENT PhD STUDENTS

Rachel Somerville (PhD 1997) Jerusalem (postdoc) – Cambridge (postdoc) – Michigan (Asst. Prof.) – MPI Astronomy Heidelberg (Professor) – STScI/Johns Hopkins – Rutgers (Professor)
Michael Gross (PhD 1997) Goddard (postdoc) – UCSC (staff) – NASA Ames (staff)
James Bullock (PhD 1999) Ohio State – Harvard (Hubble Fellow) – UC Irvine (Professor)
Ari Maller (PhD 1999) Jerusalem – U Mass Amherst (postdoc) – CityTech CUNY (Assoc. Prof.)
Risa Wechsler (PhD 2001) Michigan – Chicago (Hubble Fellow) – Stanford U (Assoc. Prof.)
T. J. Cox (PhD 2004) Harvard (postdoc, Keck Fellow) – Carnegie Observatories (postdoc) – Data Scientist at Voxer, San Francisco
Patrik Jonsson (PhD 2004) UCSC (postdoc) – Harvard CfA (staff) – SpaceX senior programmer
Brandon Allgood (PhD 2005) – Numerate, Inc. (co-founder)
Matt Covington (PhD 2008) – analytic understanding of galaxy mergers, semi-analytic models of galaxy formation – U Minn (postdoc) – U Arkansas (Asst. Prof.)
Greg Novak (PhD 2008) – running and comparing galaxy merger simulations with observations – Princeton (postdoc) – Inst Astrophysique de Paris (postdoc) – Data Scientist at StichFix
Christy Pierce (PhD 2009) – AGN in galaxy mergers – Georgia Tech (postdoc) – teaching
Rudy Gilmore (PhD 2009) – WIMP properties and annihilation; extragalactic background light and gamma ray absorption – SISSA, Trieste, Italy (postdoc), Data Scientist at TrueCar, L.A.
Alberto Dominguez (PhD 2011) – UCR (postdoc), Clemson (postdoc), Madrid (postdoc)
Lauren Porter (PhD 2013) – semi-analytic predictions vs. observations — Data Sci at Groupon
Chris Moody – analysis of high-resolution galaxy simulations: galaxy morphology transformations (PhD 2014) – Data Scientist at Square, San Francisco

Joel Primack CURRENT PhD STUDENTS

Christoph Lee – galaxy morphology: simulations vs. observations
Viraj Pandya — semi-analytic models compared with observations
I would welcome additional graduate students

UCSC Cosmology & Galaxy Research Group 2017 – Prof. Joel Primack

UCSC Grad Students:

Christoph Lee christoph28@gmail.com 707-338-9543: Galaxy-Halo Connections, LSS, Halo Properties vs. Density, Stripping, SAM, Deep Learning & Galaxies

Viraj Pandya viraj.pandya@ucsc.edu 831-459-5722 (ISB 255): Galaxies and Cosmology

SIP students supervised by Christoph & Joel:

Austin Tuan (Phillips Academy, Andover, MA) austin.tuan99@gmail.com 408-831-8787: How Does Halo Radial Profile depend on stripping, environment, and other halo properties?

Max Untrecht (Woodside HS) max.untrecht@gmail.com: Halo Properties vs. Mass & Web

Undergraduate Astrophysics Students

Radu Dragomir (UCSC) rdragomi@ucsc.edu: Galaxy Properties from SDSS, Abundance Matching Dependence on Environment

Elliot Eckholm (UCSC) eeckholm@ucsc.edu 619-993-2120: 3D Viz of Cosmic Web & Halos

Sean Larkin (UCSC) sflarkin@ucsc.edu 949-439-7775: Deep Learning & Galaxy Simulations

Yifei Luo (Nanjing U, China) luoyifei54301@sina.com: Identifying SDSS PDGs (Disk Galaxies Without Classical Bulges) and Determining Their Mass, Environment, etc.

Tze Goh (Columbia) tpg2107@columbia.edu: Halo & Galaxy Properties in Small Cosmic Walls (Like Milky Way and Andromeda) and Other Cosmic Web Environments

Graham Vanbenthuysen (UCSC) gvanbent@ucsc.edu 916-508-0446: Galaxy Size vs. Local Density

Other Research Group Members

Miguel Aragon-Calvo (UNAM-Ensenada) miguel.angel.aragon.calvo@gmail.com: Spine of the Cosmic Web of Bolshoi-Planck simulation and SDSS

Peter Behroozi (UC Berkeley) pbehroozi@gmail.com: Galaxies, Galaxy-Halo Connection

Doug Hellinger hellinger.doug@gmail.com: DM Density & V per Voxel, Voids, Protoclusters

Nina McCurdy (Scientific Computing and Imaging Institute, U Utah) nina@cs.utah.edu: Visualizing Forming Galaxies & Dark Matter

Aldo Rodriguez-Puebla (UNAM) rodriguez.puebla@gmail.com: LSS, Galaxies

Paul Sutter (Ohio State) paul@pmsutter.com: Voids in SDSS and in Simulations

Vivian Tang (UCSC) drftingaway@yahoo.com: Shapes of Simulated Galaxies

Dekel Research Group, Hebrew University, Jerusalem

Avishai Dekel (HU) avishai.dekel@mail.huji.ac.il: Galaxy Formation

Santi Roca-Fabrega (HU postdoc) santi.roca@mail.huji.ac.il: galaxy simulations, and streams

Jonathan Freundlich (starting HU postdoc) observations of gas in high-z galaxies, theory

Hangzhou Jiang (starting HU postdoc) working on halos and subhalos

Nir Mandelker (Yale postdoc) nir.mandelker@yale.edu: galaxyVDI, stream instability

UCSC Observational Galaxy Research Group

Guillermo Barro (Berkeley) gbarro@ucolick.org: Galaxy Formation & Evolution, Compaction

Zhu Chen zhuchen@shnu.edu.cn: Galaxy Formation & Evolution

Sandra Faber faber@ucolick.org: Galaxy Formation & Evolution

Yicheng Guo ycguo@ucolick.org: Galaxy Formation & Evolution, Clumps

Marc Huertas-Company (Observatoire de Paris) marc.huertas@obspm.fr: Galaxy Image Analysis with Deep Learning

David Koo koo@ucolick.org: Galaxy Formation & Evolution

Hassen Yesuf hyesuf@ucolick.org: Galaxy Formation & Evolution, Winds

Joel Primack (UCSC) - New Insights on Galaxy Formation from Comparing Simulations and Observations

Computer simulations and theoretical understanding have now reached a stage where simulations are increasingly able to tackle the complexity of galaxy formation and evolution. This talk will start by summarizing new results from analysis of cosmic large scale structure simulations including Bolshoi-Planck and MultiDark-Planck [1,2], including the possibility that the star formation rate of many star-forming galaxies reflects their dark matter halo's mass accretion rate [3]. I will then describe successes and challenges of high-resolution hydrodynamic galaxy simulations in trying to understand the Hubble Space Telescope observations of galaxies during the period of most vigorous star formation (redshifts 1 to 3, "Cosmic High Noon") [4]. Most astronomers used to think that galaxies form as disks, that forming galaxies are pretty smooth, and that galaxies generally grow in radius as they grow in mass — but we are now learning that all these statements are questionable. The majority of star-forming galaxies at $z > 1$ apparently have mostly elongated (prolate) stellar distributions [5] rather than disks or spheroids, and our simulations may explain why [6,7]. A large fraction of star-forming galaxies at redshifts $1 < z < 3$ are found to have massive stellar clumps [8]; these originate from phenomena including disk instabilities in our simulations [9,10] and semi-analytic models [11,12], which also help to create compact spheroids ("nuggets") through galaxy compaction [13]. Our simulations rather accurately reproduce observed evolution of galaxies in radius [14] and time [15]. We are trying to understand how angular momentum evolves as gas falls toward the inner galaxy and becomes stars [16], and how disk galaxies decrease their velocity dispersion and settle into thin disks by the present epoch [17]. This talk will also describe the Assembling Galaxies of Resolved Anatomy (AGORA) program to run high-resolution simulations using as much as possible the same initial conditions, physical assumptions, and output analysis procedures. AGORA will systematically compare galaxy simulations using the main available computer codes with each other and with observations, and thus improve understanding of galaxy formation [18,19].

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[5] van der Wel et al. 2014, Geometry of Star-forming Galaxies from SDSS, 3D-HST, and CANDELS, http://adsabs.harvard.edu/abs/2014ApJ...792L...6V
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[8] Guo et al. 2014, Clumpy Galaxies in CANDELS, http://adsabs.harvard.edu/abs/2015ApJ...800...39G
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[18] Kim et al. 2014, The AGORA High-resolution Galaxy Simulations Comparison Project, http://adsabs.harvard.edu/abs/2014ApJS..210...14K
[19] Kim et al. 2016, The AGORA High-resolution Galaxy Simulations Comparison Project. II: Isolated Disk Test, ApJ submitted (http://adsabs.harvard.edu/abs/2016arXiv161003066K)

THANKS!