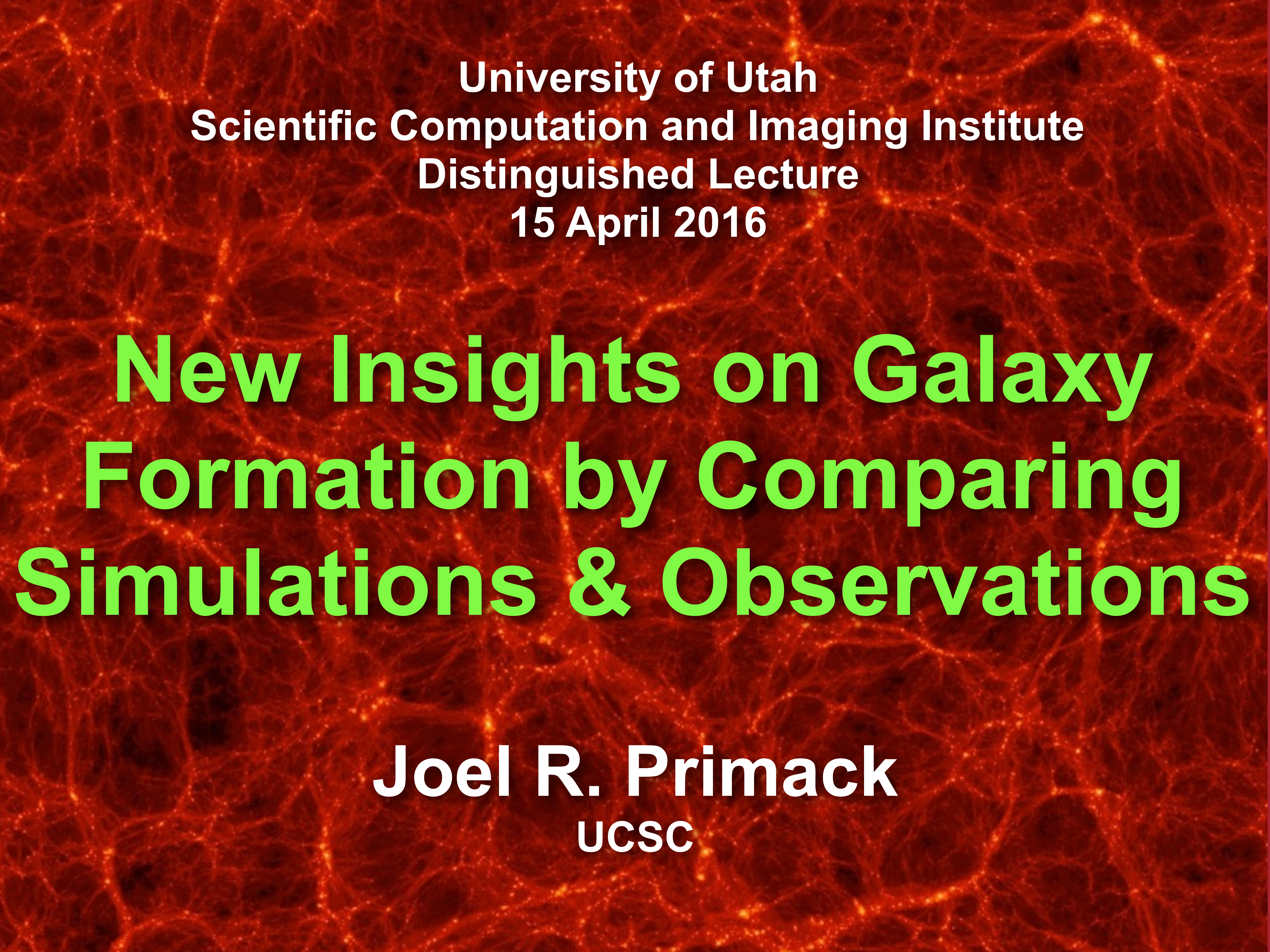


University of Utah
Scientific Computation and Imaging Institute
Distinguished Lecture
15 April 2016

New Insights on Galaxy Formation by Comparing Simulations & Observations

Joel R. Primack
UCSC

Outline

- Introduction - Large-Scale Simulations and Galaxies
  - Planck Cosmology Simulations
  - Stellar Halo Accretion Rate Coevolution (SHARC)
- 3 Aspects of Star-Forming Galaxies Seen in CANDELS
  - Giant Clumps
  - Compaction
  - Elongation
- Comparing with Cosmological Galaxy Simulations
  - Adaptive Refinement Tree hydro simulations
  - AGORA Galaxy Simulation Comparison Project

CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

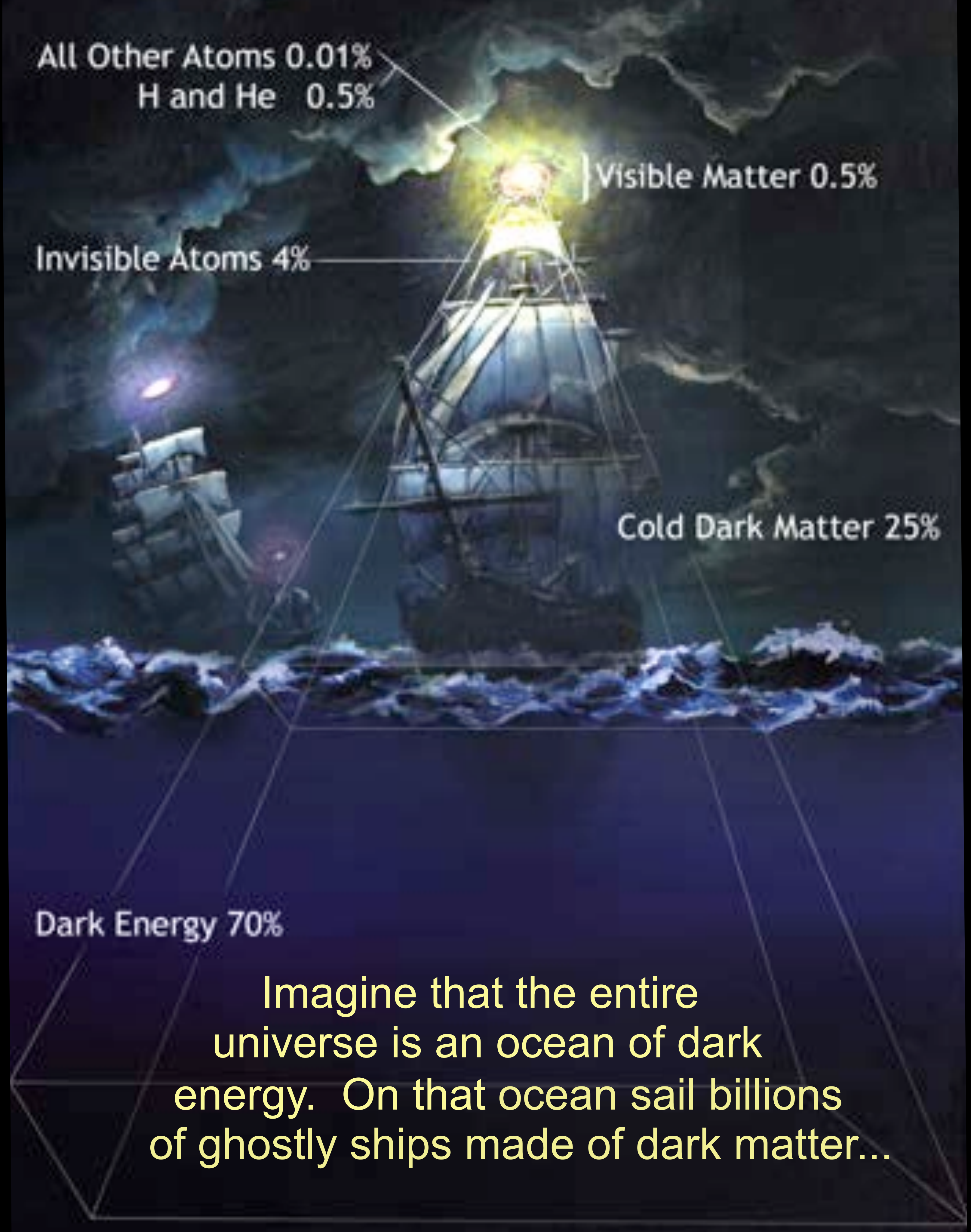
Cosmological Simulations

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 and dark matter halo properties, basis for semi-analytic models

Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids, mock galaxy images and spectra including stellar evolution and dust effects

Matter and Energy Content of the Universe



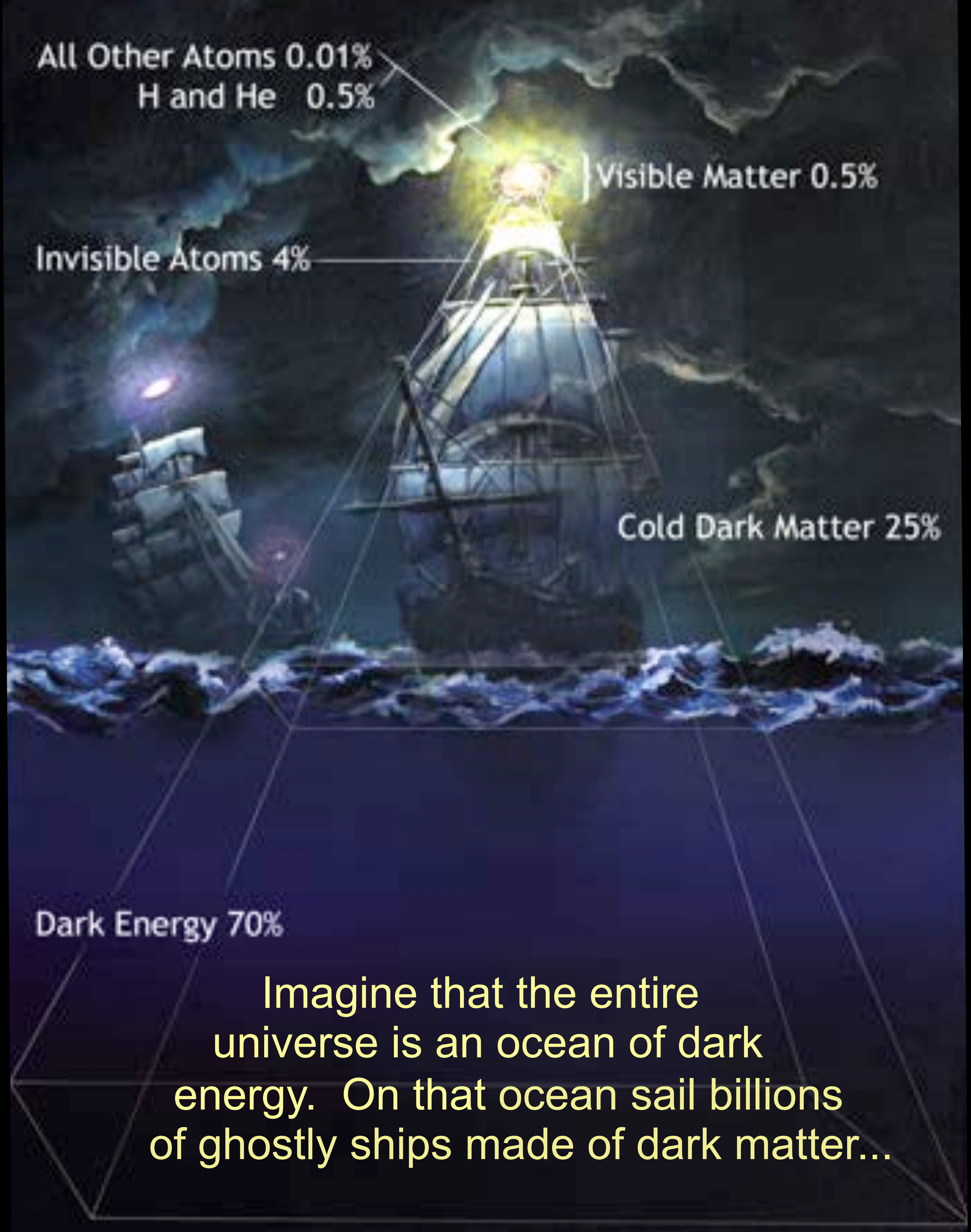
Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

Matter and Energy Content of the Universe

Dark Matter Ships

on a

Dark Energy Ocean



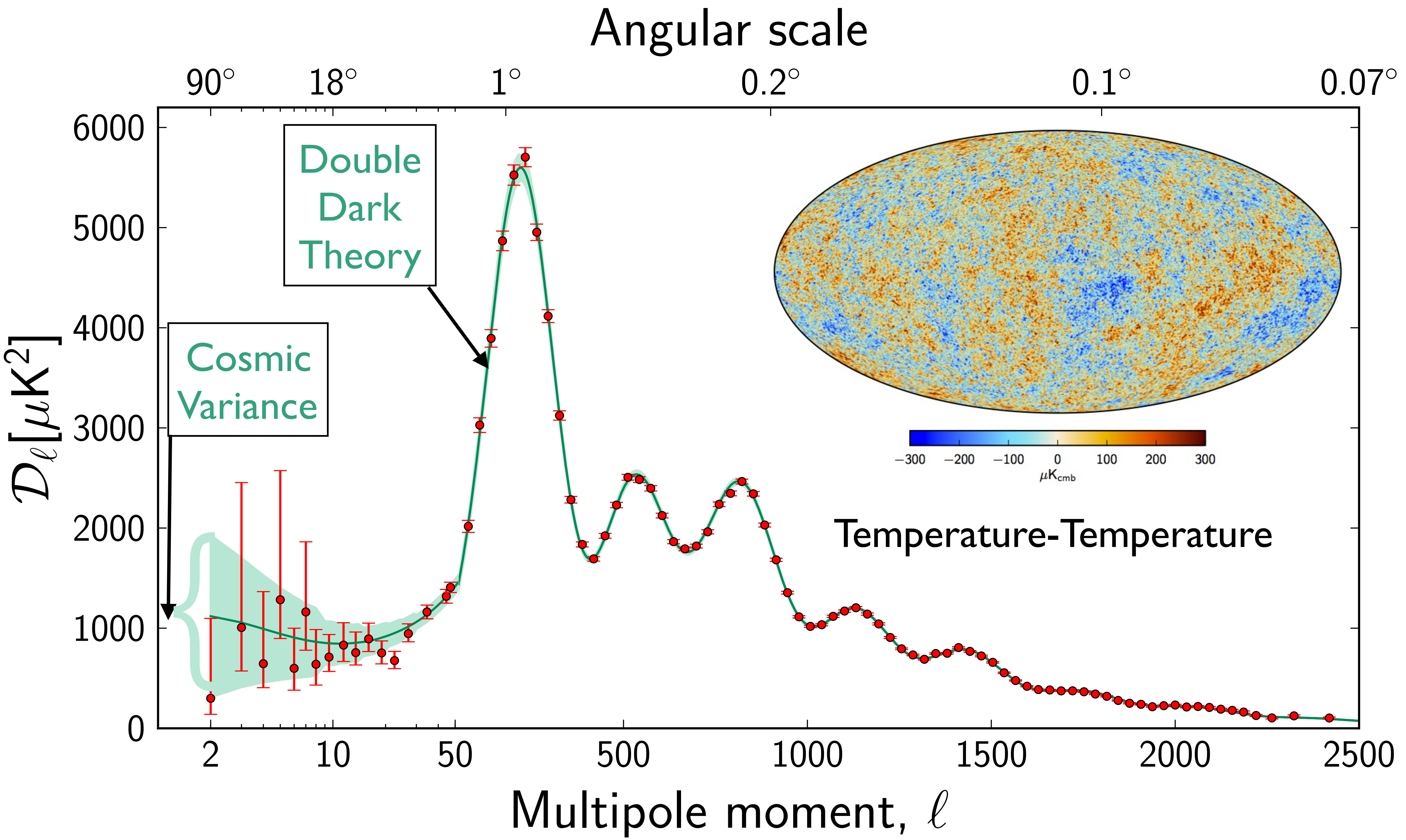
Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

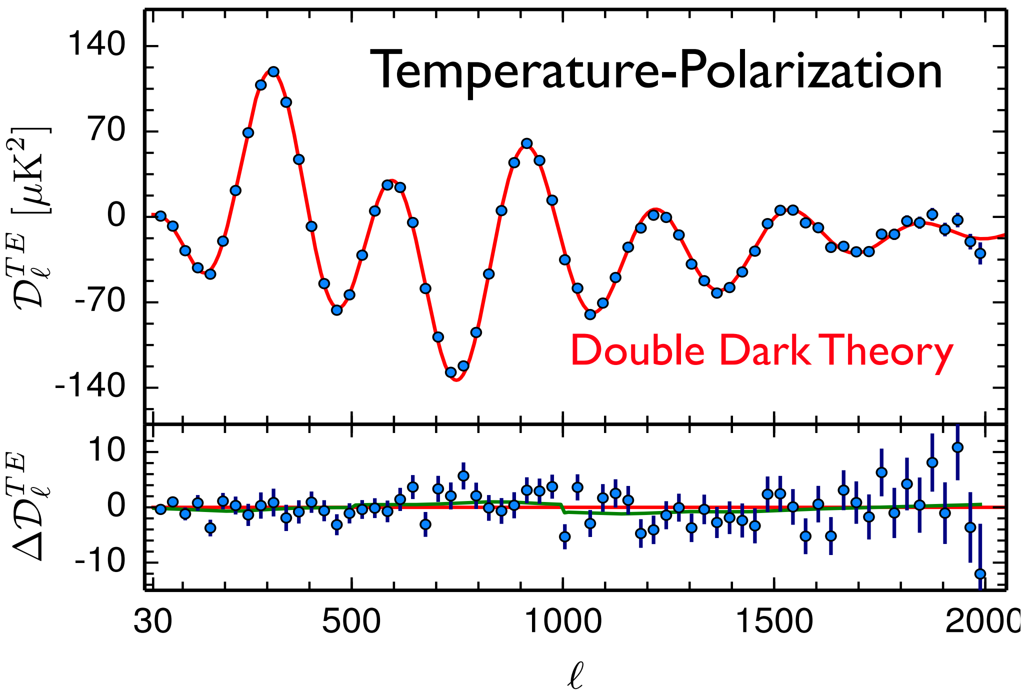
ΛCDM

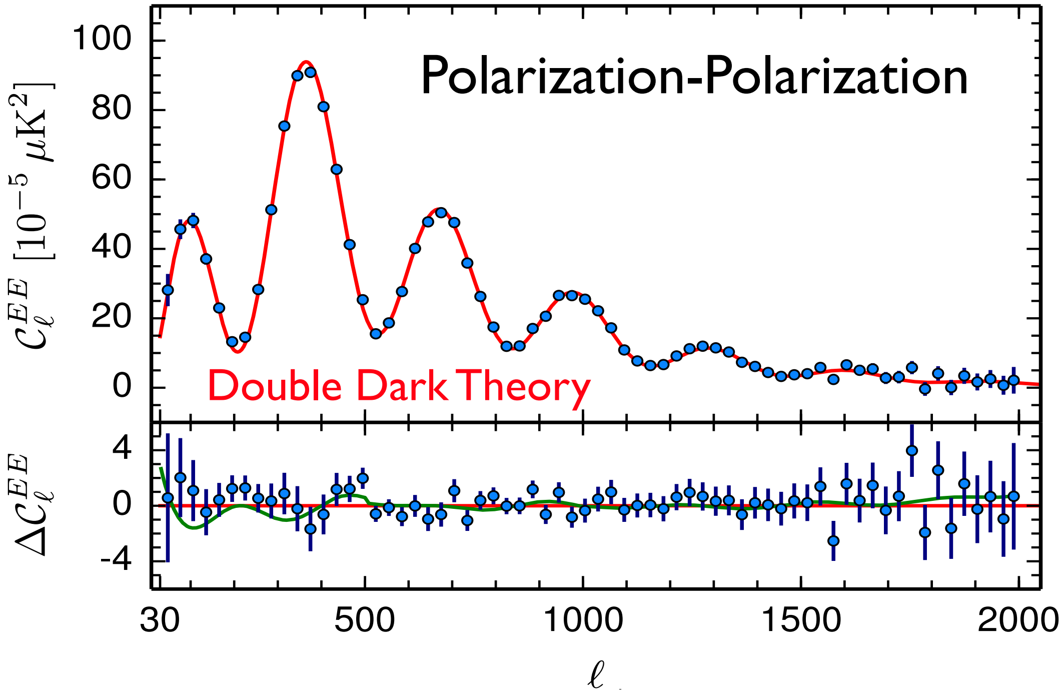
Double Dark Theory

European Space Agency PLANCK Satellite Data

Released February 9, 2015





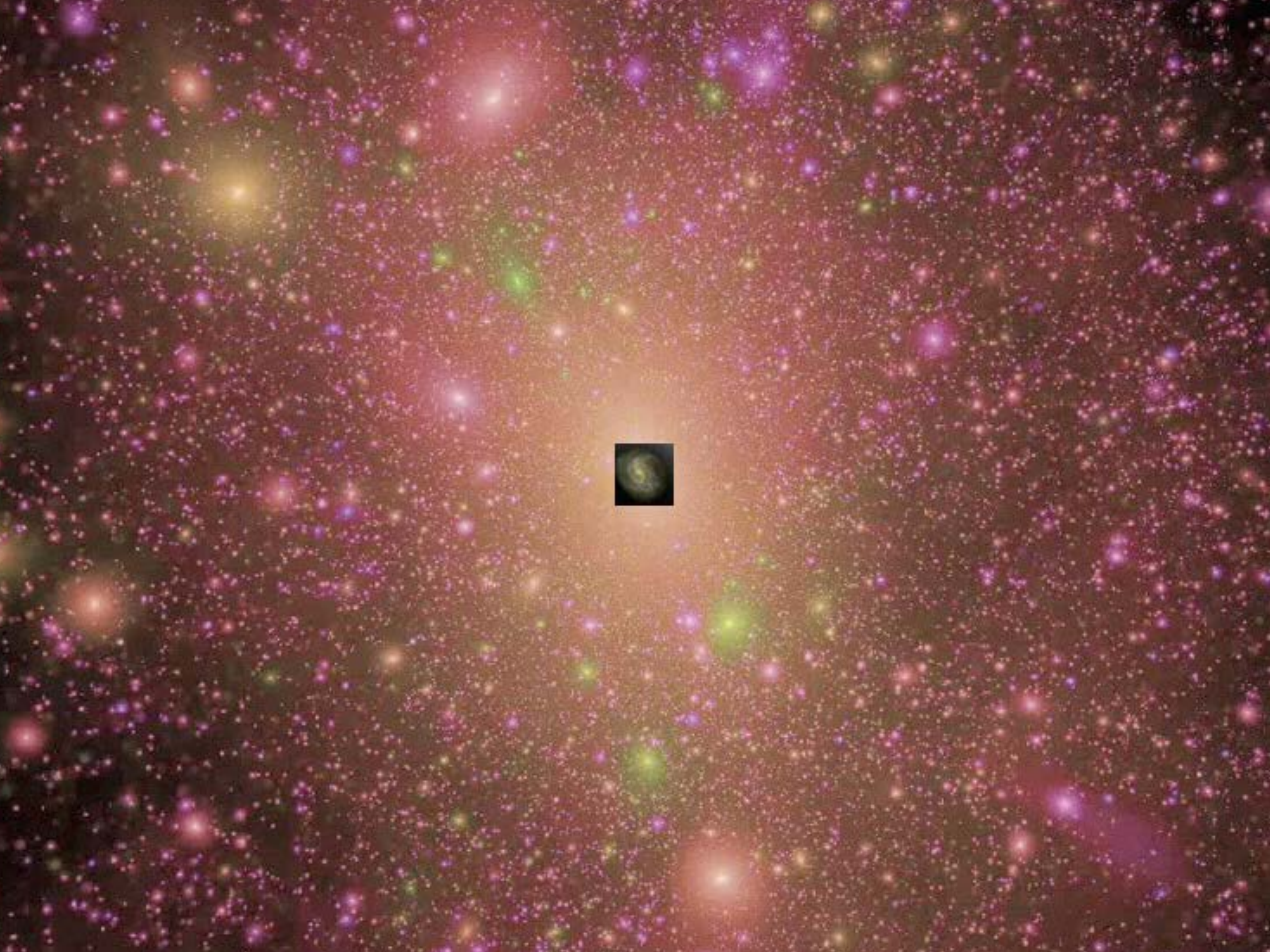


Aquarius Simulation

Volker Springel

Milky Way
100,000 light years

Milky Way Dark Matter Halo
1.5 million light years

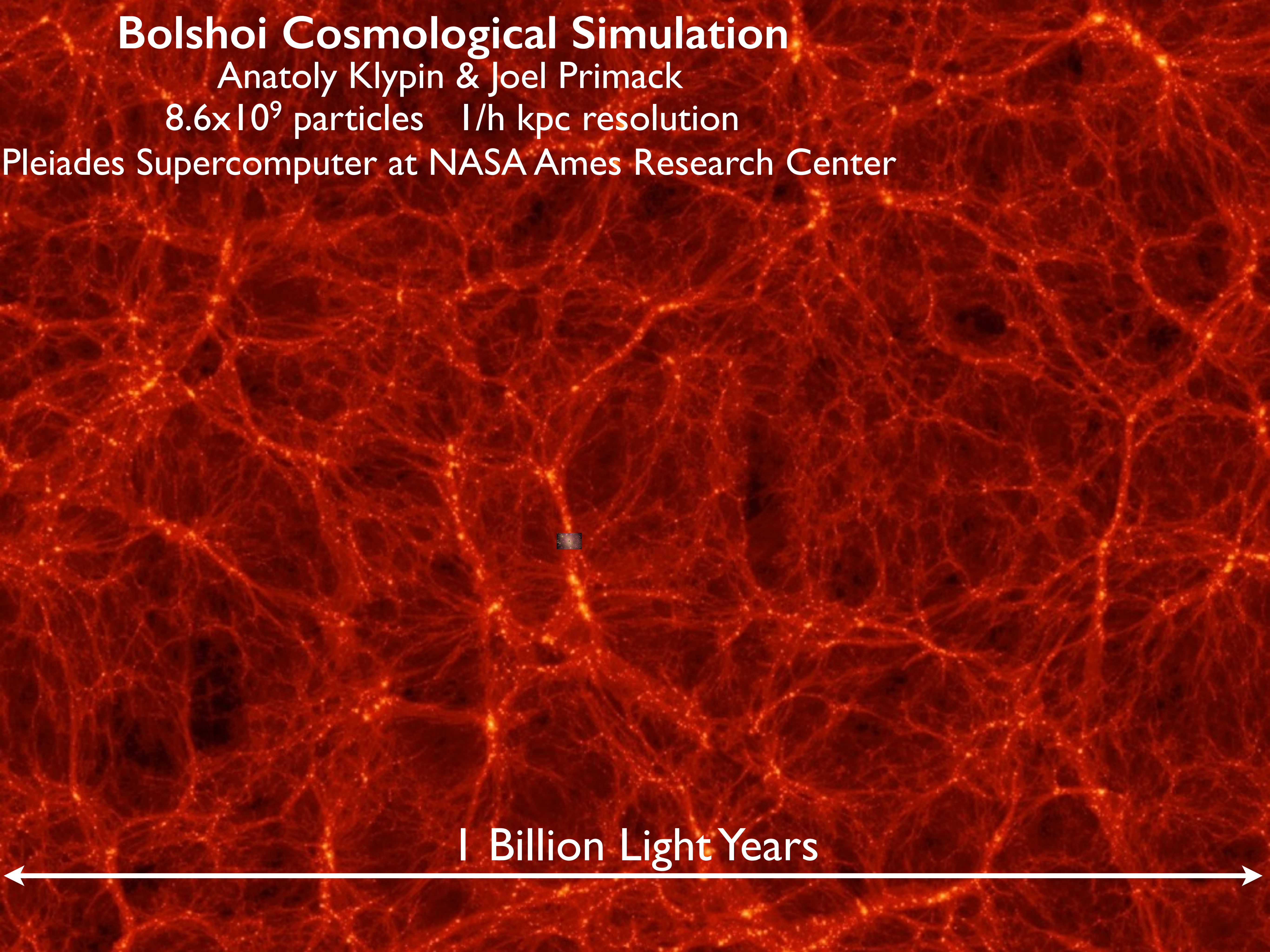


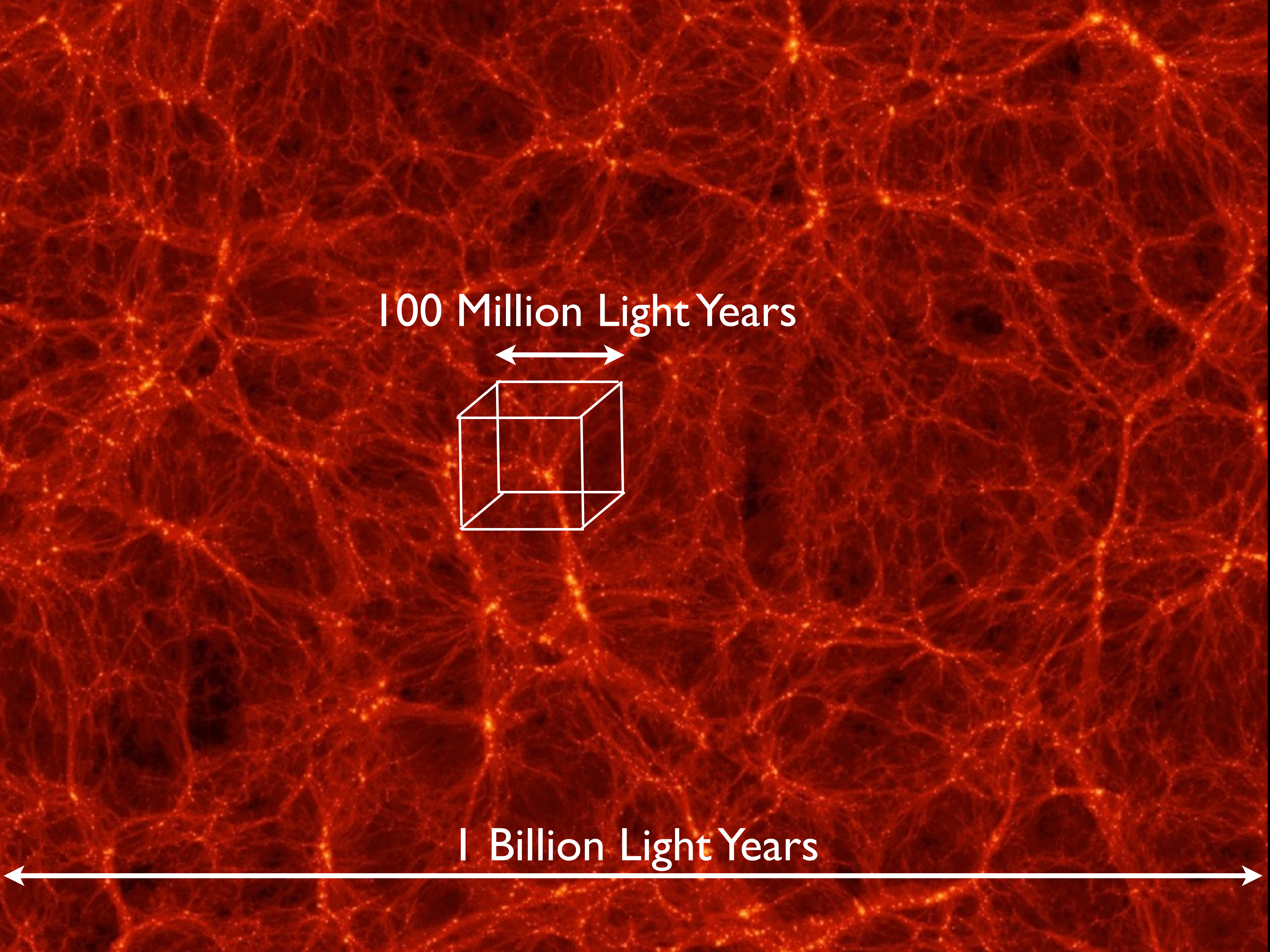
Bolshoi Cosmological Simulation

Anatoly Klypin & Joel Primack

8.6x10^9 particles   1/h kpc resolution

Pleiades Supercomputer at NASA Ames Research Center




100 Million Light Years
1 Billion Light Years

How the Halo of the Big Cluster Formed

100 Million Light Years

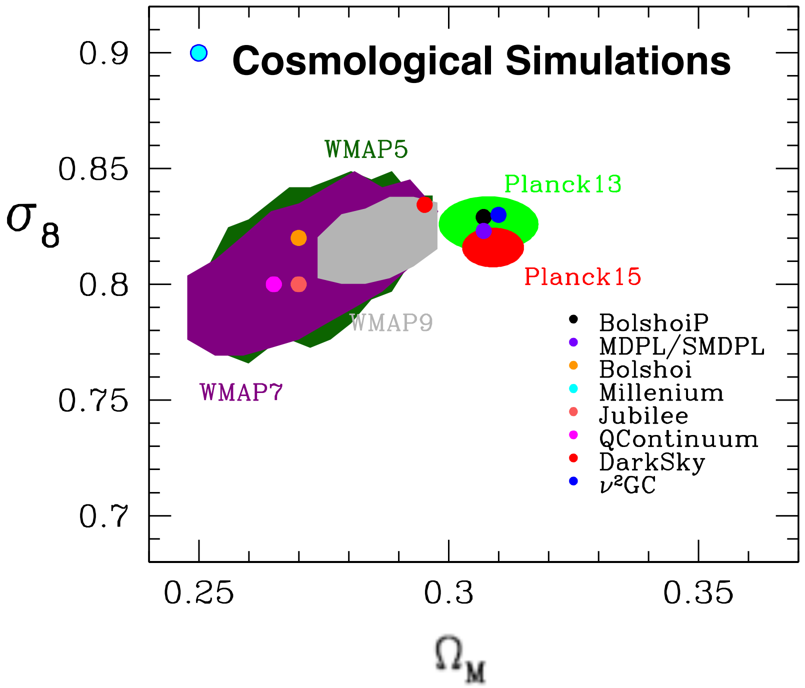
Bolshoi-Planck
Cosmological Simulation

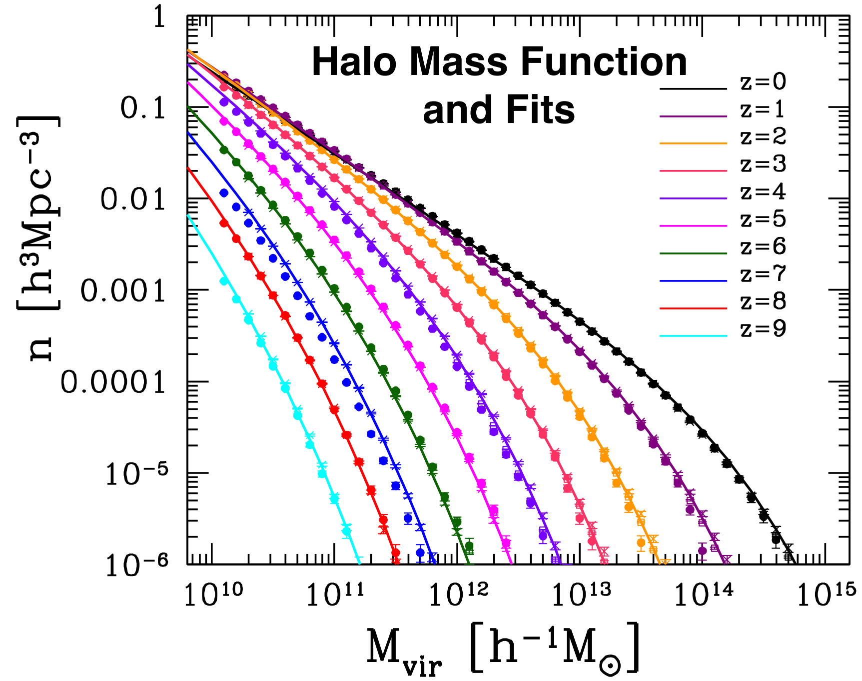
Merger Tree of a Large Halo

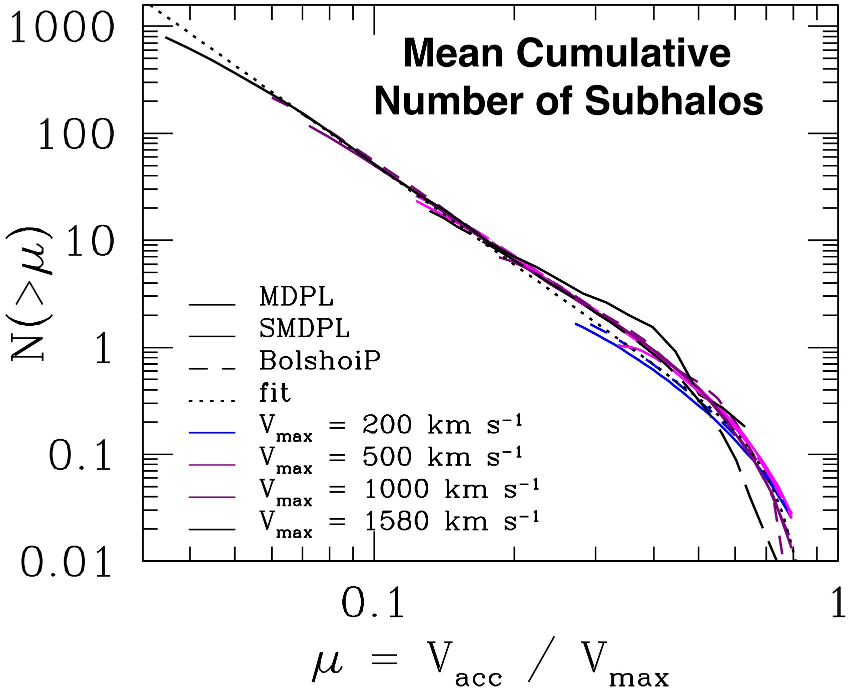
Peter Behroozi & Christoph Lee

Halo and Subhalo Demographics with Planck Cosmological Parameters: Bolshoi-Planck and MultiDark-Planck Simulations

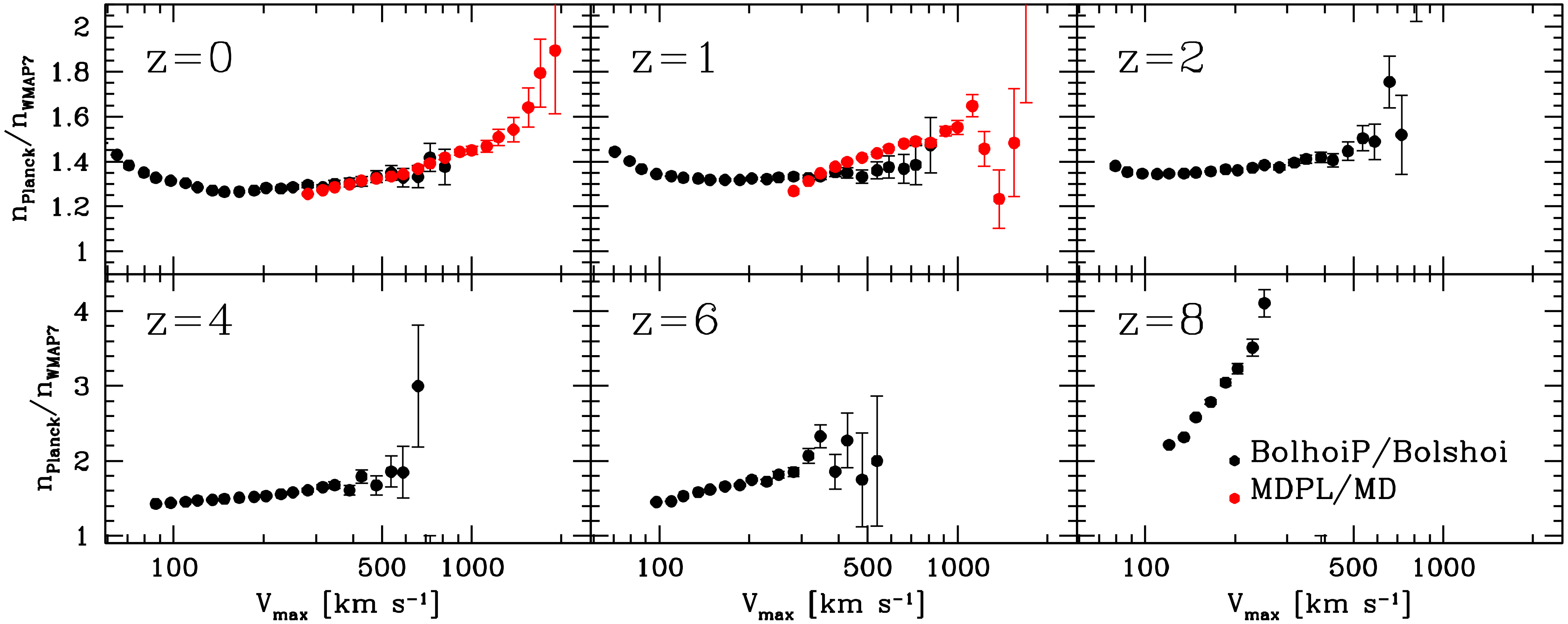
Aldo Rodrìguez-Puebla, Peter Behroozi, Joel Primack, Anatoly Klypin, Christoph Lee, Doug Hellinger







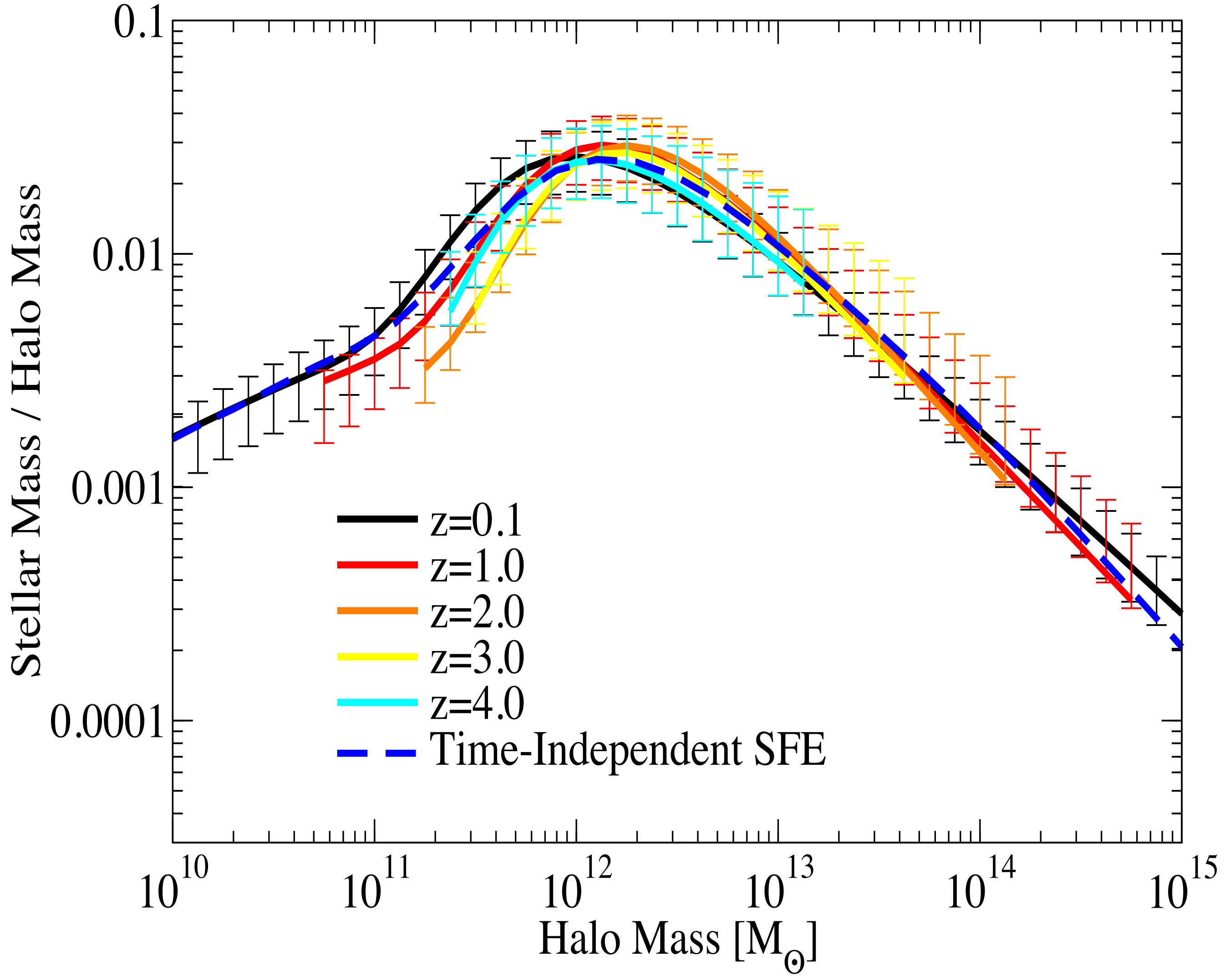
Number Density of Halos: Planck / WMAP7



There are many more halos with the Planck cosmology, especially at high masses and redshifts.

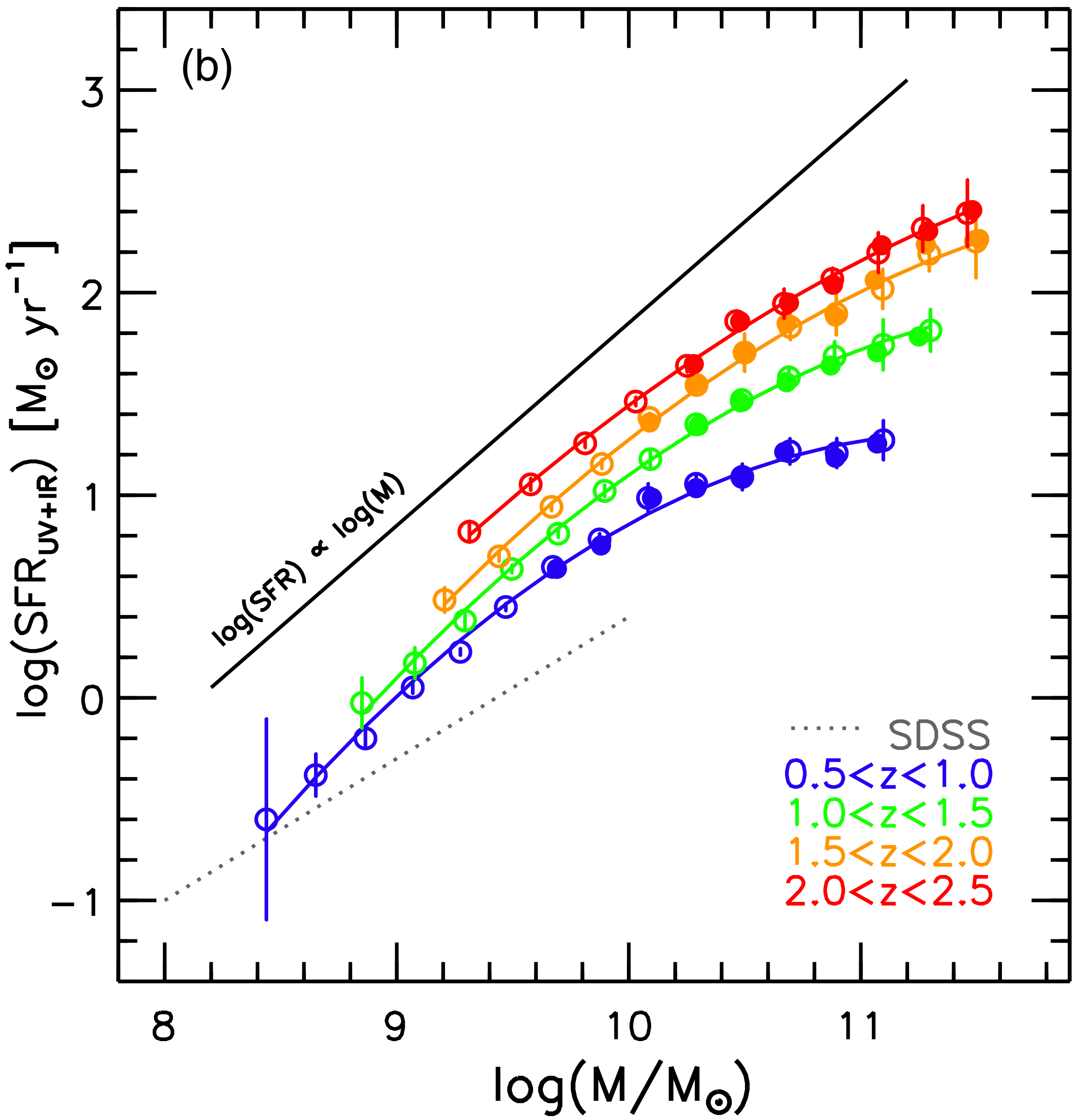
We have now released the halo catalogs and merger trees from all our new cosmological simulations. The paper includes Appendices with instructions for reading these files.

Relationship Between Galaxy Stellar Mass and Halo Mass



The stellar mass to halo mass ratio at multiple redshifts as derived from observations compared to the Bolshoi cosmological simulation. Error bars show 1σ uncertainties. A time-independent Star Formation Efficiency predicts a roughly **time-independent stellar mass to halo mass relationship**. (Behroozi, Wechsler, Conroy, ApJL 2013)

Star-forming Galaxies Lie on a "Main Sequence"

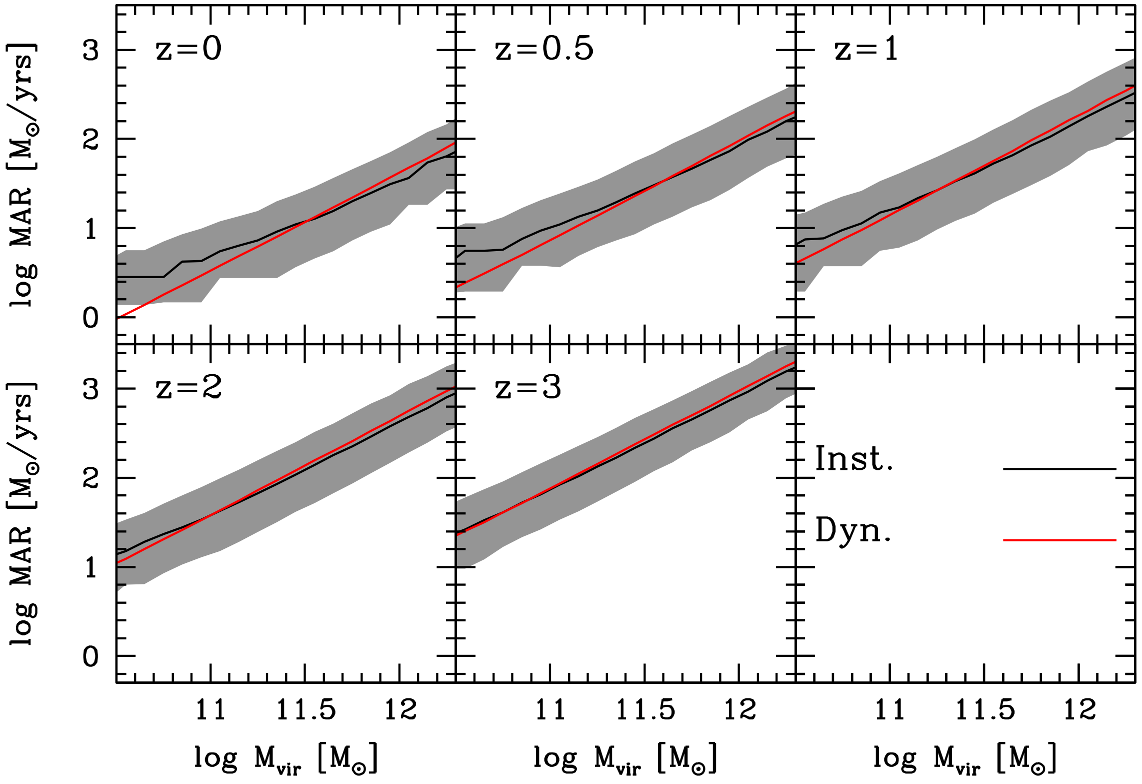


Just as the properties of hydrogen-burning stars are controlled by their mass, **the galaxy star formation rate (SFR) is approximately proportional to the stellar mass**, with the proportionality constant increasing with redshift up to about *z* = 2.5. (Whitaker et al. ApJ 2014)

Is Main Sequence SFR Controlled by Halo Mass Accretion?

by Aldo Rodríguez-Puebla, Joel Primack, Peter Behroozi, Sandra Faber MNRAS 2016

Halo mass accretion rates z=0 to 3



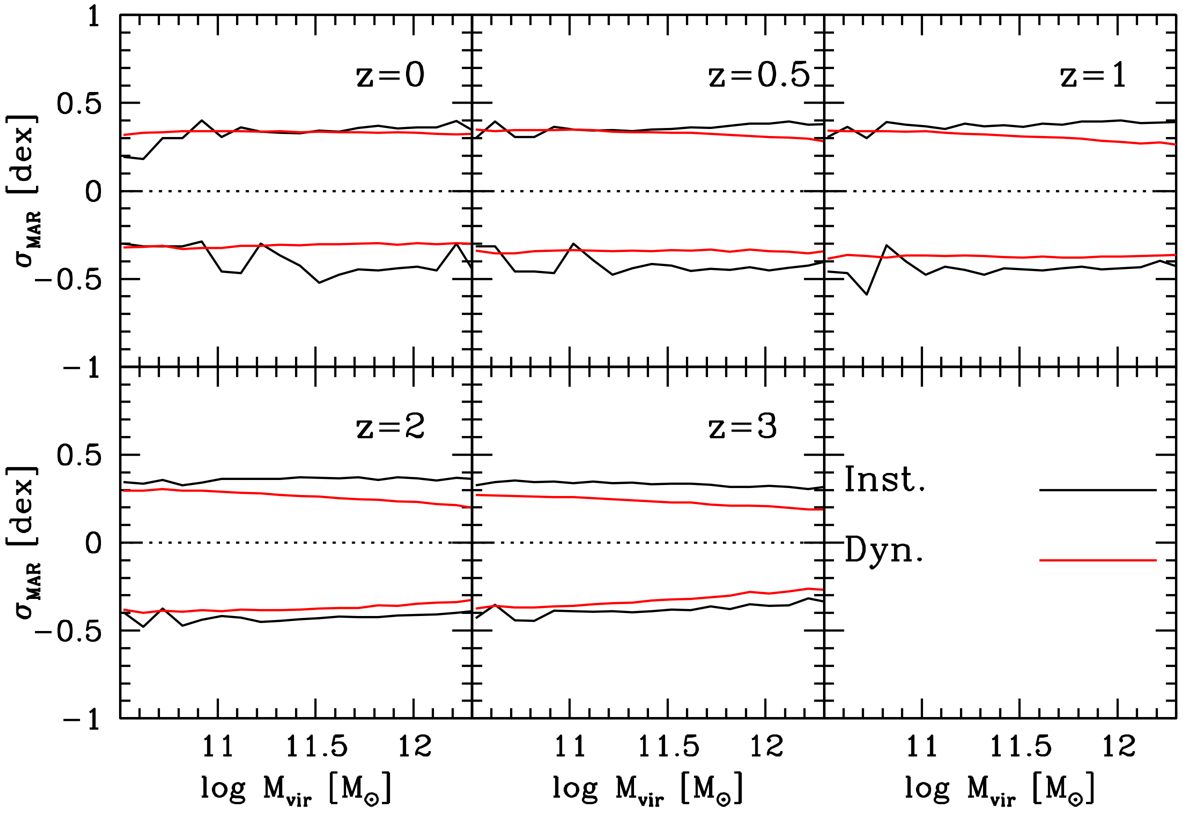
$$\frac{dM_*}{dt} = \frac{\partial M_*(M_{\rm vir}(t),z)}{\partial M_{\rm vir}}\frac{dM_{\rm vir}}{dt} + \frac{\partial M_*(M_{\rm vir}(t),z)}{\partial z}\frac{dz}{dt}$$

but if the M_*–$M_{\rm vir}$ relation is independent of redshift then the stellar mass of a central galaxy formed in a halo of mass $M_{\rm vir}(t)$ is $M_* = M_*(M_{\rm vir}(t))$. From this relation star formation rates are given simply by

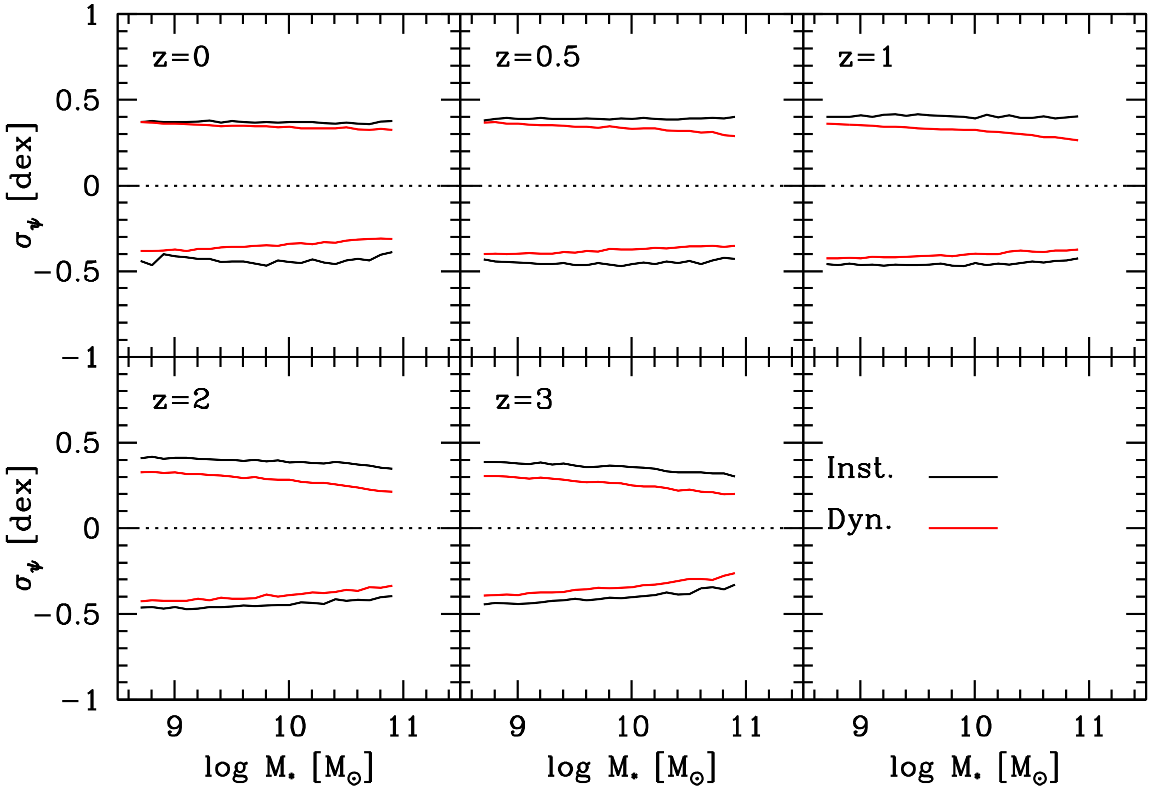
$$\frac{dM_*}{dt} = f_* \frac{d\log M_*}{d\log M_{\rm vir}}\frac{dM_{\rm vir}}{dt},$$

where $f_* = M_*/M_{\rm vir}$. We call this **Stellar-Halo Accretion Rate Coevolution (SHARC)** if true halo-by-halo.

Scatter of halo mass accretion rates



Implied scatter of star formation rates

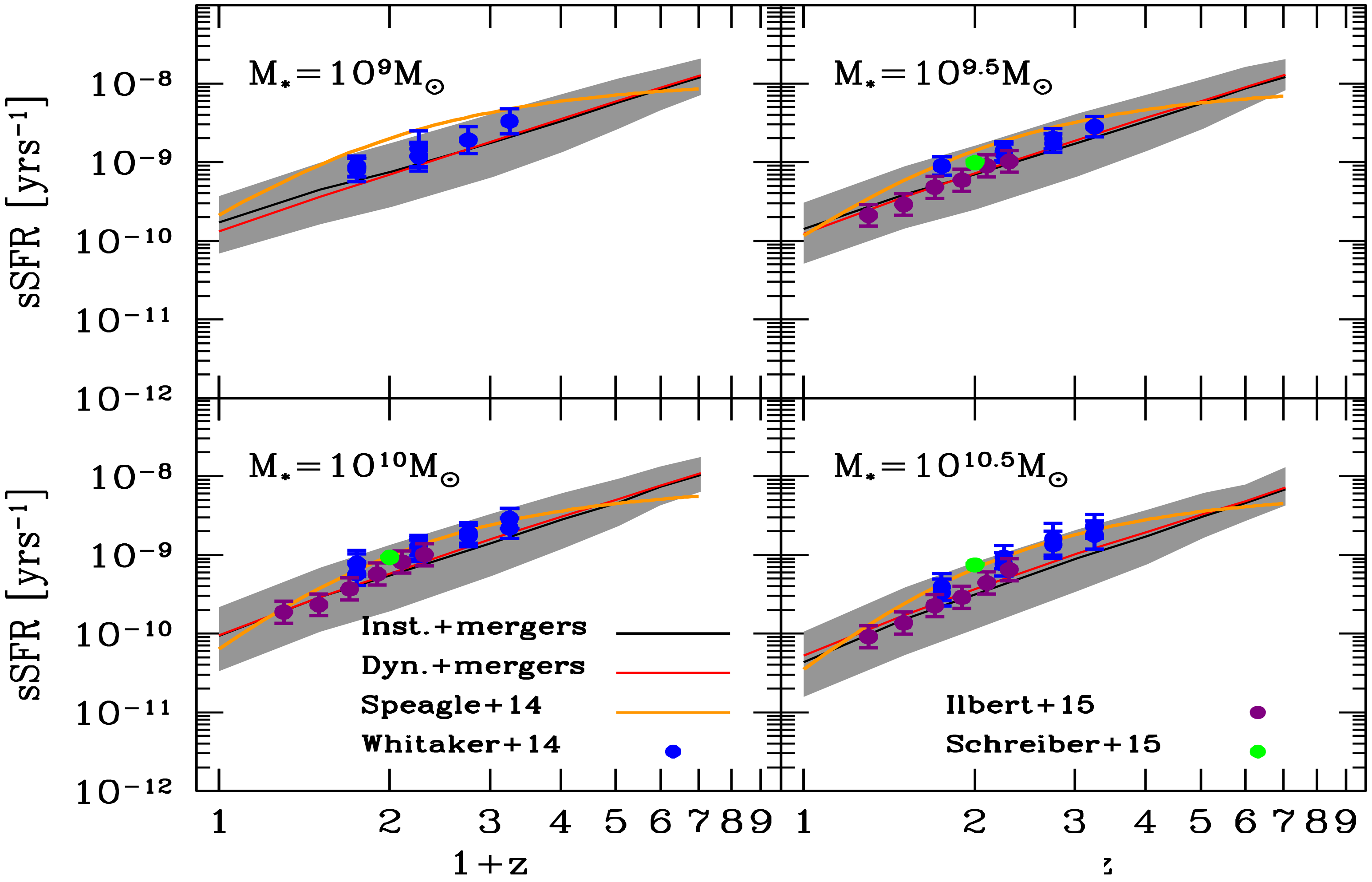


Consistent with observations!

Is Main Sequence SFR Controlled by Halo Mass Accretion?

by Aldo Rodríguez-Puebla, Joel Primack, Peter Behroozi, Sandra Faber MNRAS 2016

SHARC correctly predicts star formation rates to z ~ 4



SHARC predicts "Age Matching" (blue galaxies in accreting halos) and "Galaxy Conformity" at low z ✓

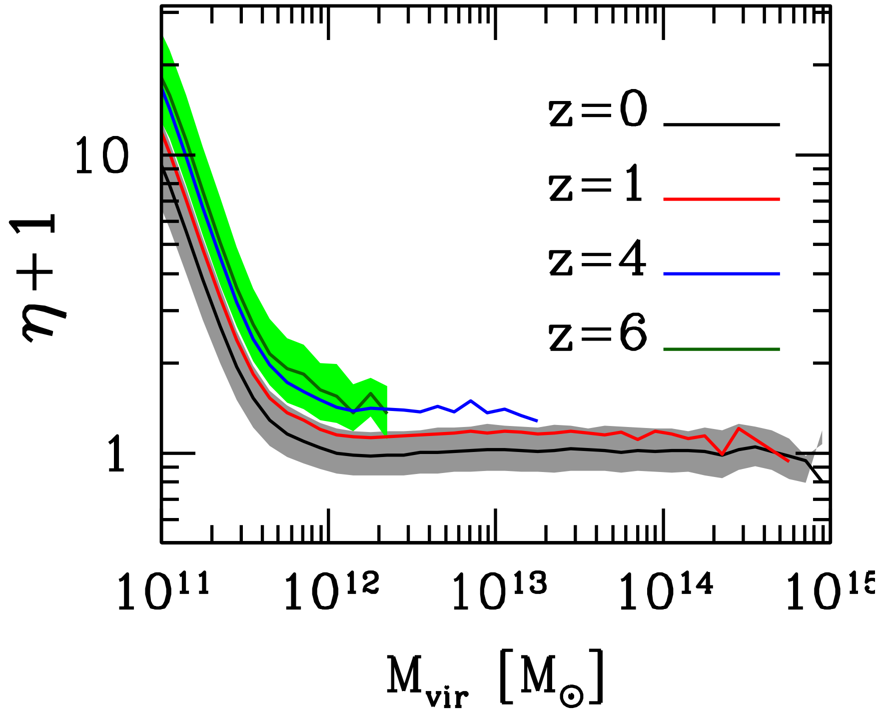
Open Questions:

Extend SHARC to higher-mass galaxies

Check predicted correlations vs. observations at higher z

Can SHARC be used to measure growth rate of halos from the observed star formation rate, as a dark energy vs. gravity test?

We put SHARC in "bathtub" equilibrium models of galaxy formation & predicted mass loading and metallicity evolution



Net mass loading factor η from an equilibrium bathtub model (E+SHARC)

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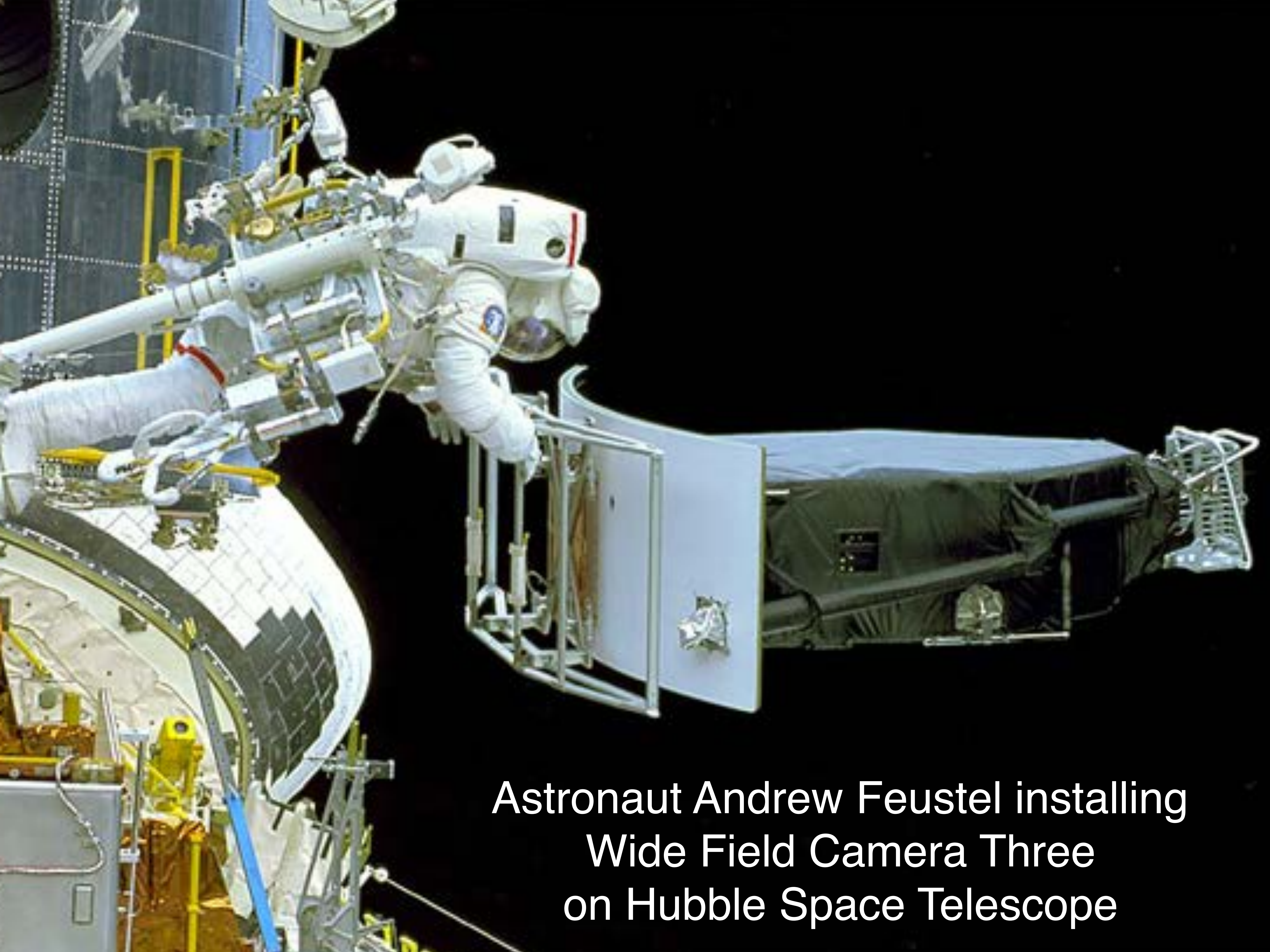
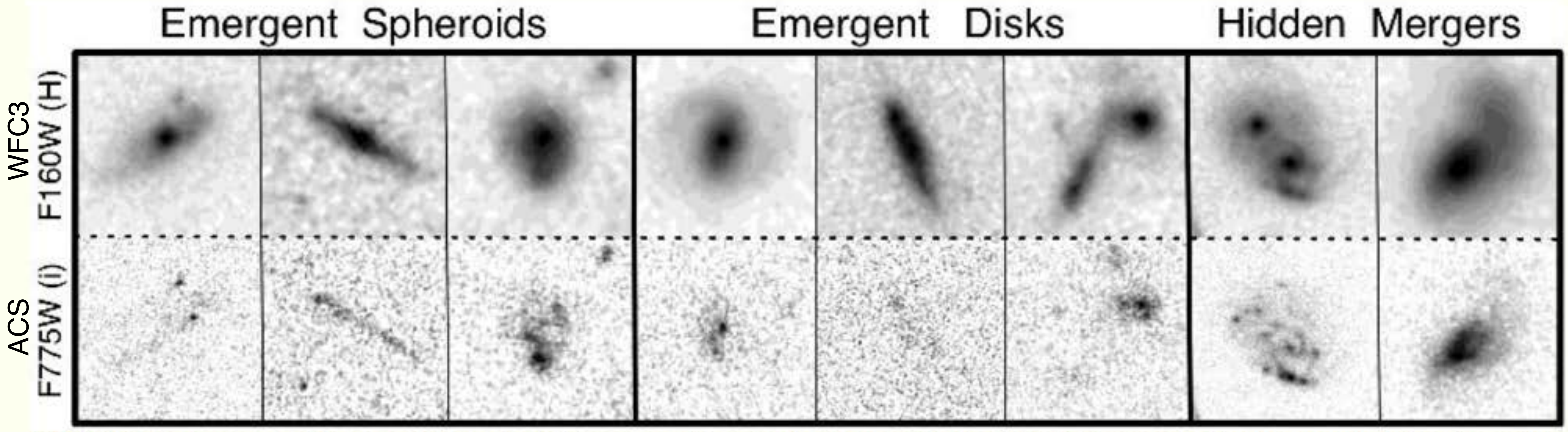


Astronaut Andrew Feustel installing
Wide Field Camera Three
on Hubble Space Telescope

The CANDELS Survey

candels.ucolick.org



CANDELS: A Cosmic Odyssey

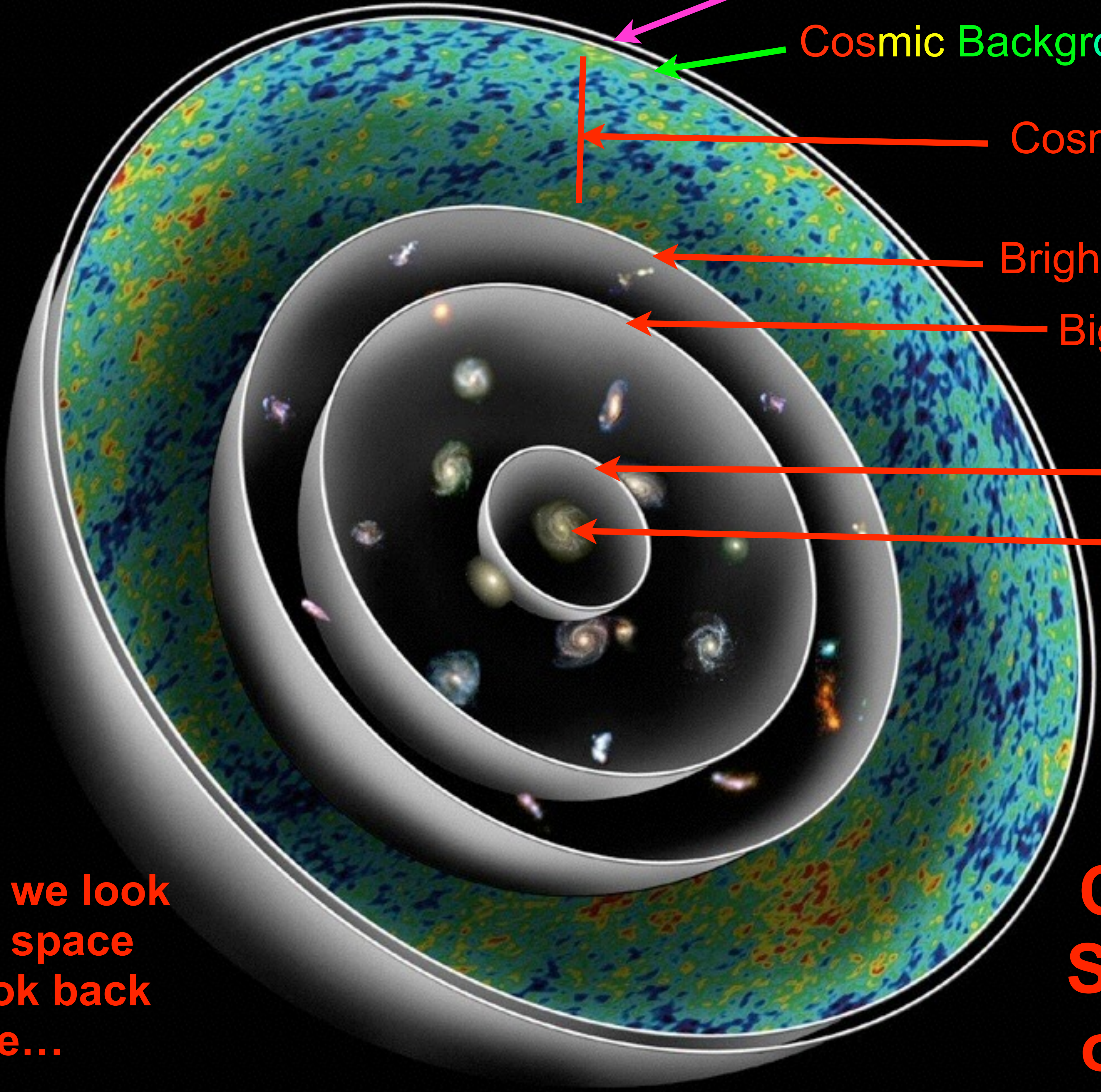
(blue 0.4 μm)$(1+z)$ = 1.6 μm @ $z = 3$

(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.

Cosmic Spheres of Time



Cosmic Horizon (The Big Bang)

Cosmic Background Radiation

Cosmic Dark Ages

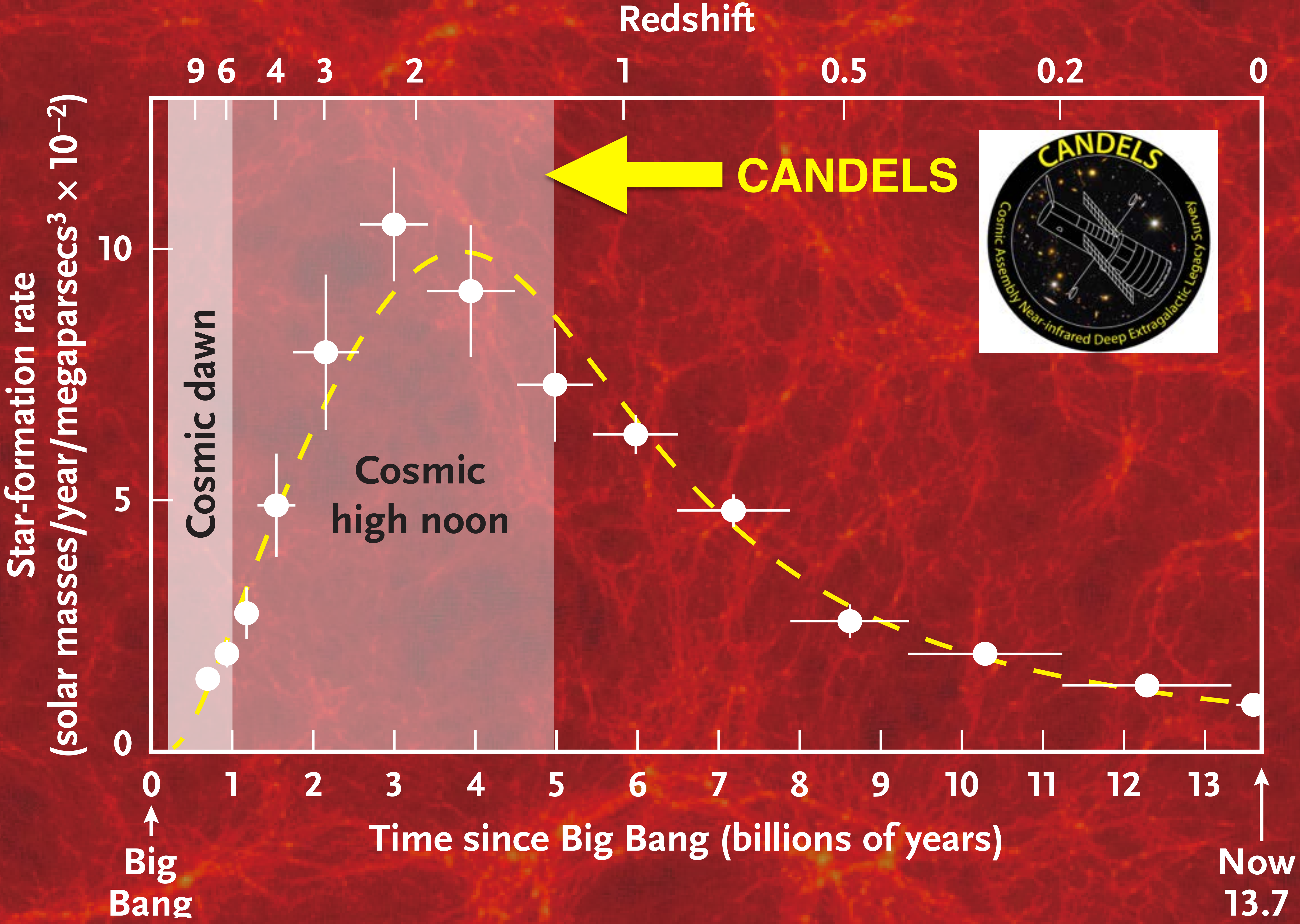
Bright Galaxies Form

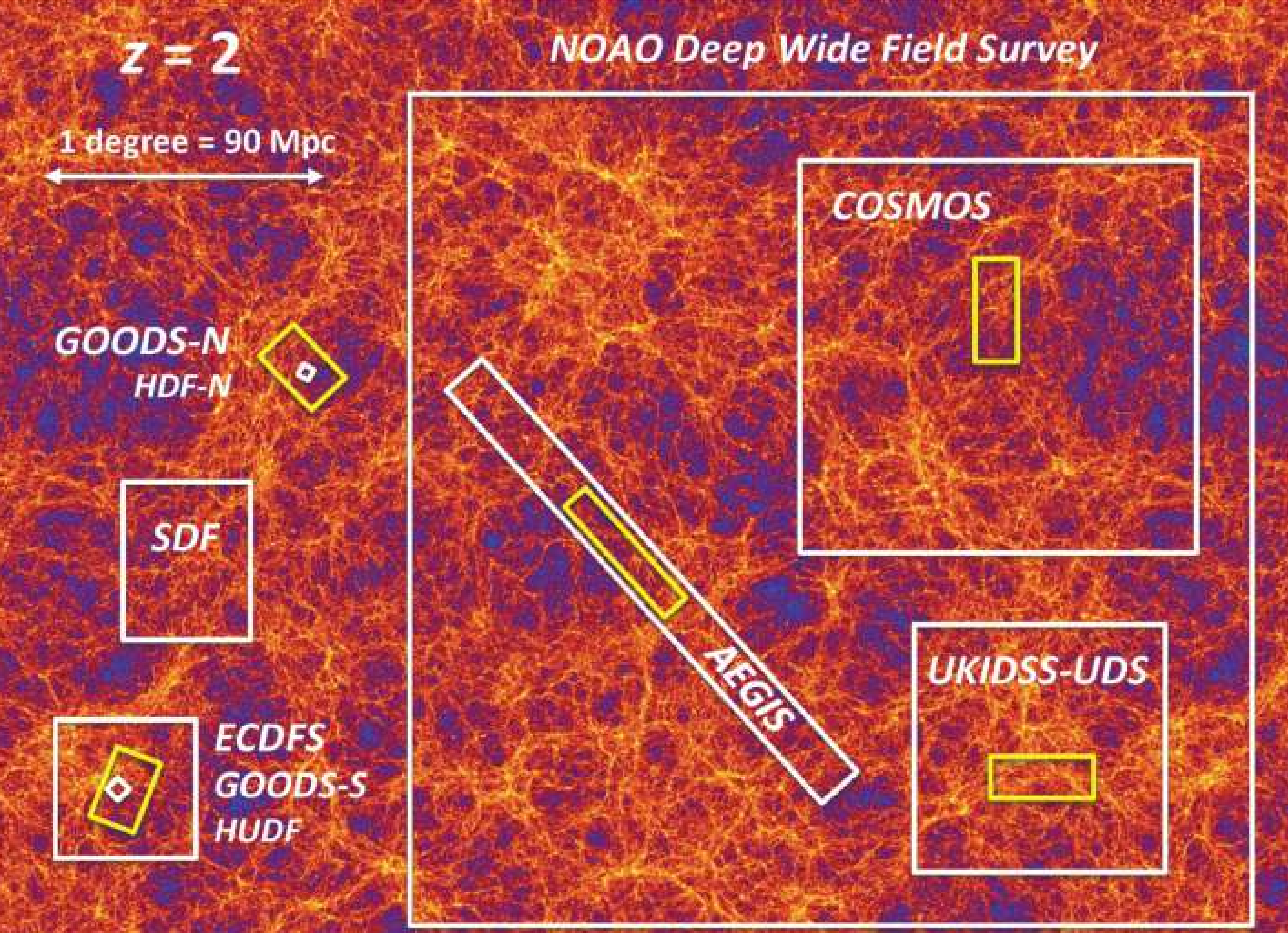
Big Galaxies Form

Earth Forms

Today

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


Redshift
9
6
4
3
2
1
0.5
0.2
0
Star-formation rate
(solar masses/year/megaparsecs^3 × 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

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 and dark matter halo properties, basis for semi-analytic models

Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids, mock galaxy images and spectra including stellar evolution and dust effects

Galaxy Hydro Simulations: 2 Approaches

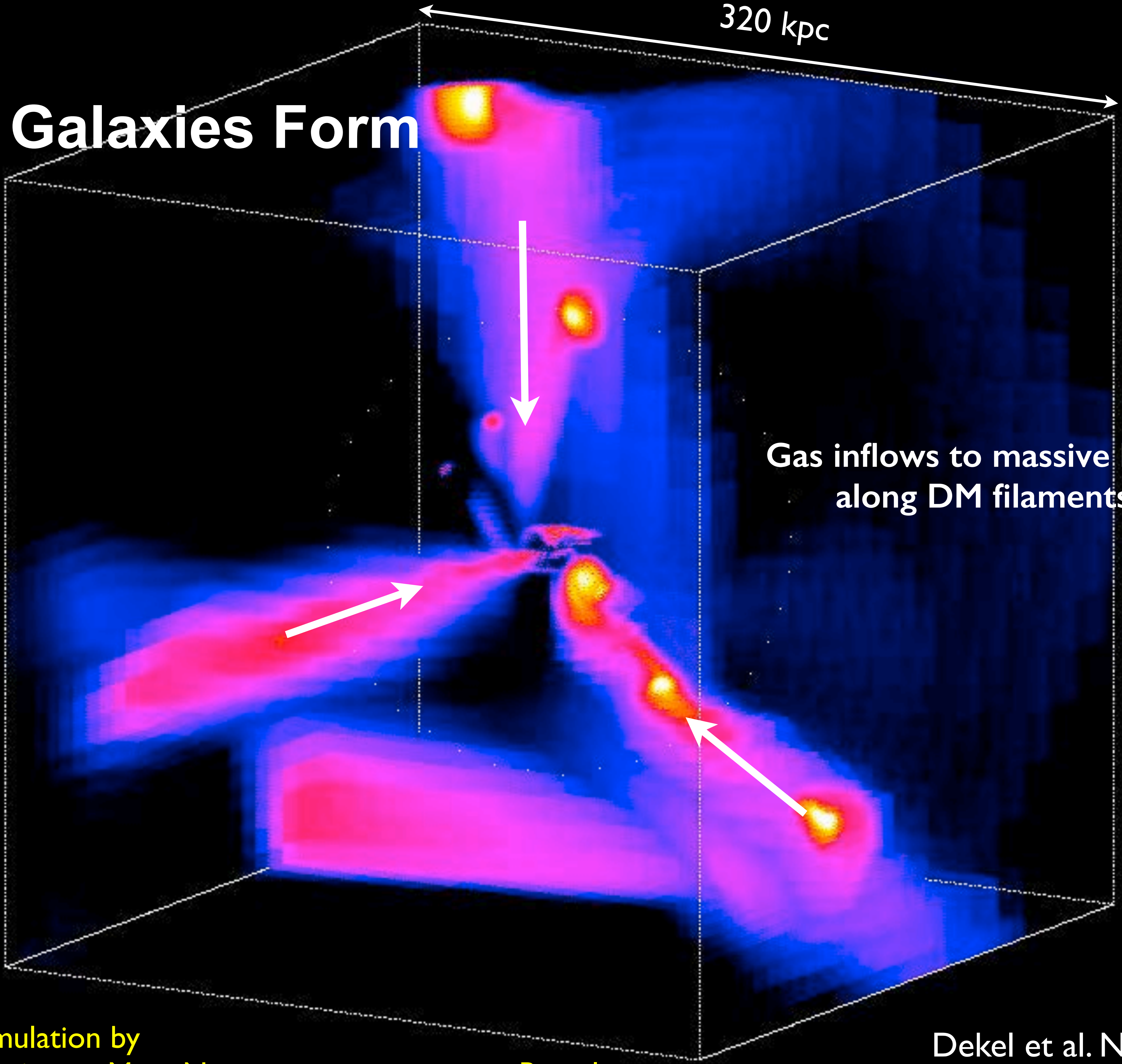
1. Low resolution (~ kpc)

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)

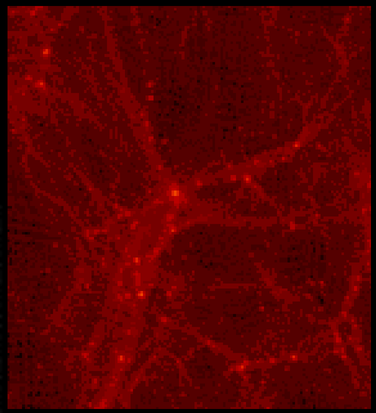
2. High resolution (~10s of pc) ← THIS TALK

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: we can't run statistical galaxy samples, so we model galaxy population evolution using simulation insights in semi-analytic models (SAMs).
Examples: ART and FIRE simulation suites, AGORA simulation comparison project.

How Galaxies Form



Gas inflows to massive halos
along DM filaments



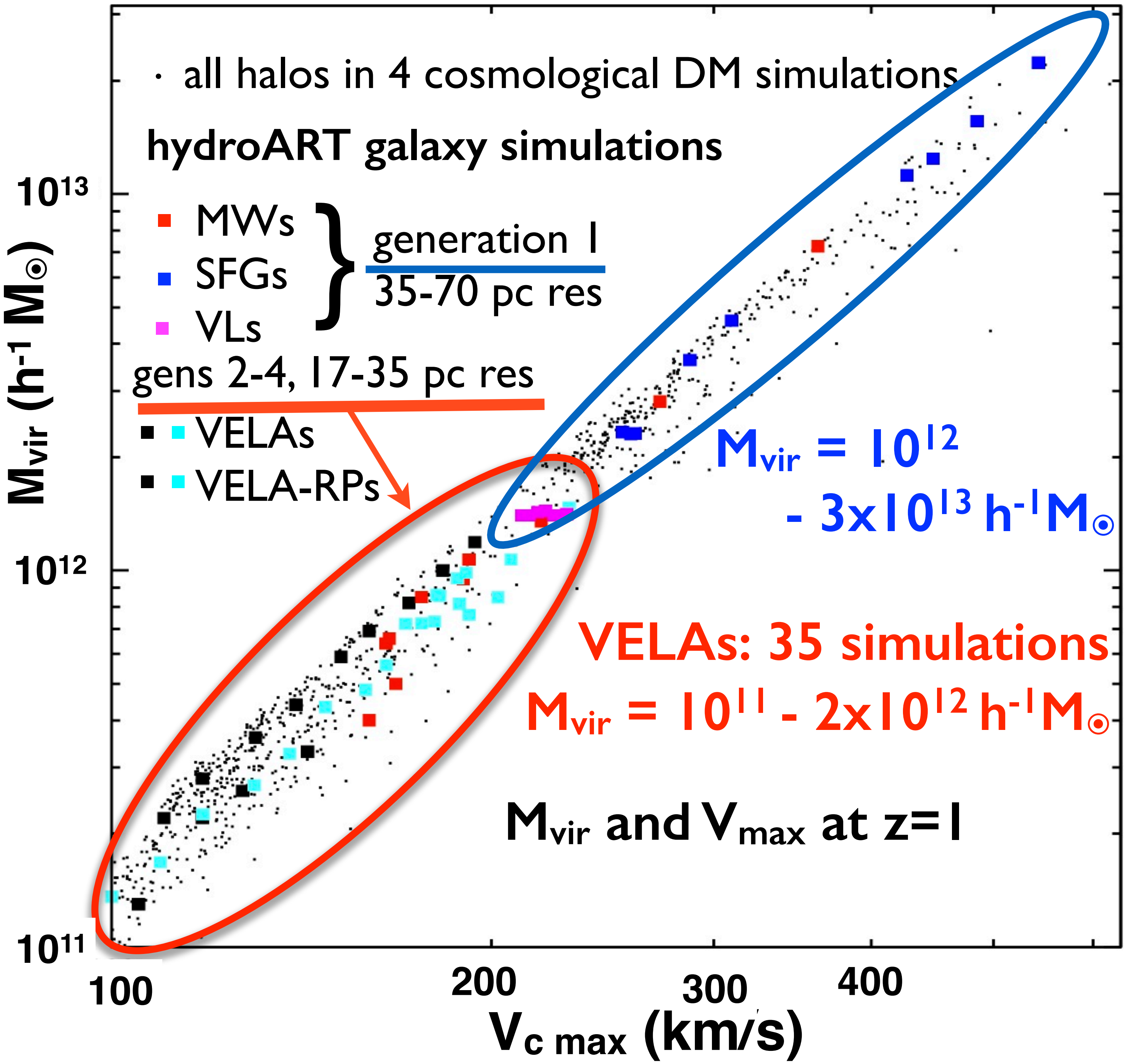
RAMSES simulation by
Romain Teyssier on Mare Nostrum supercomputer, Barcelona

Dekel et al. Nature 2009

4 Generations of hydroART simulations

ART code: Andrey Kravtsov, Anatoly Klypin, Daniel Ceverino

Simulations: Ceverino; Analysis: Ceverino, Hebrew U & UCSC



Gen 1: higher masses

Generations 2,3,4: VELA

same 35 initial conditions

17-35 pc best resolution

$M_{DM} = 8\times10^4\ M_\odot$

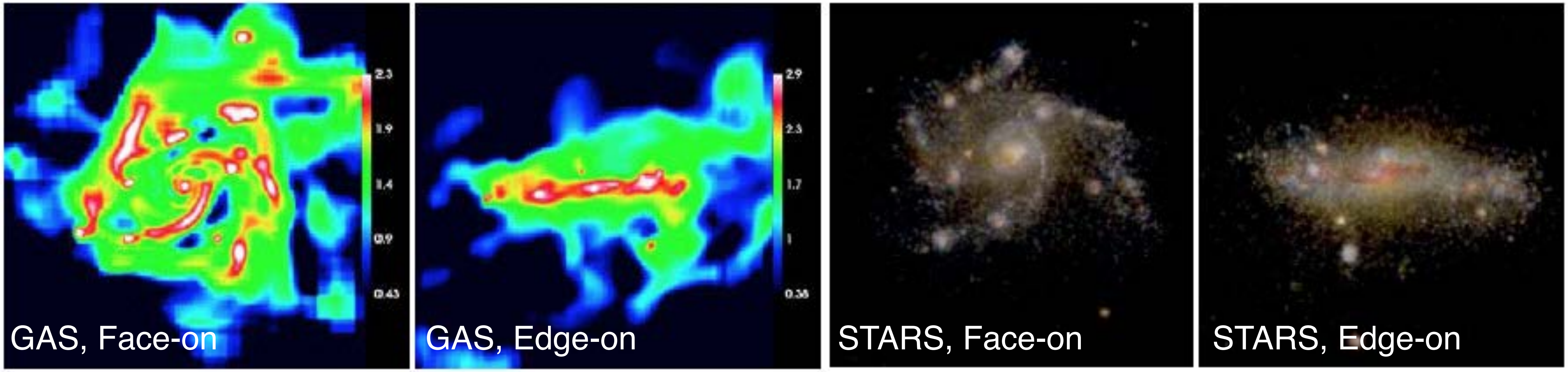
$M_{star} = 10^3\ M_\odot$

Gen 2: SN Feedback

Gen 3: SN+UV Rad Pressure

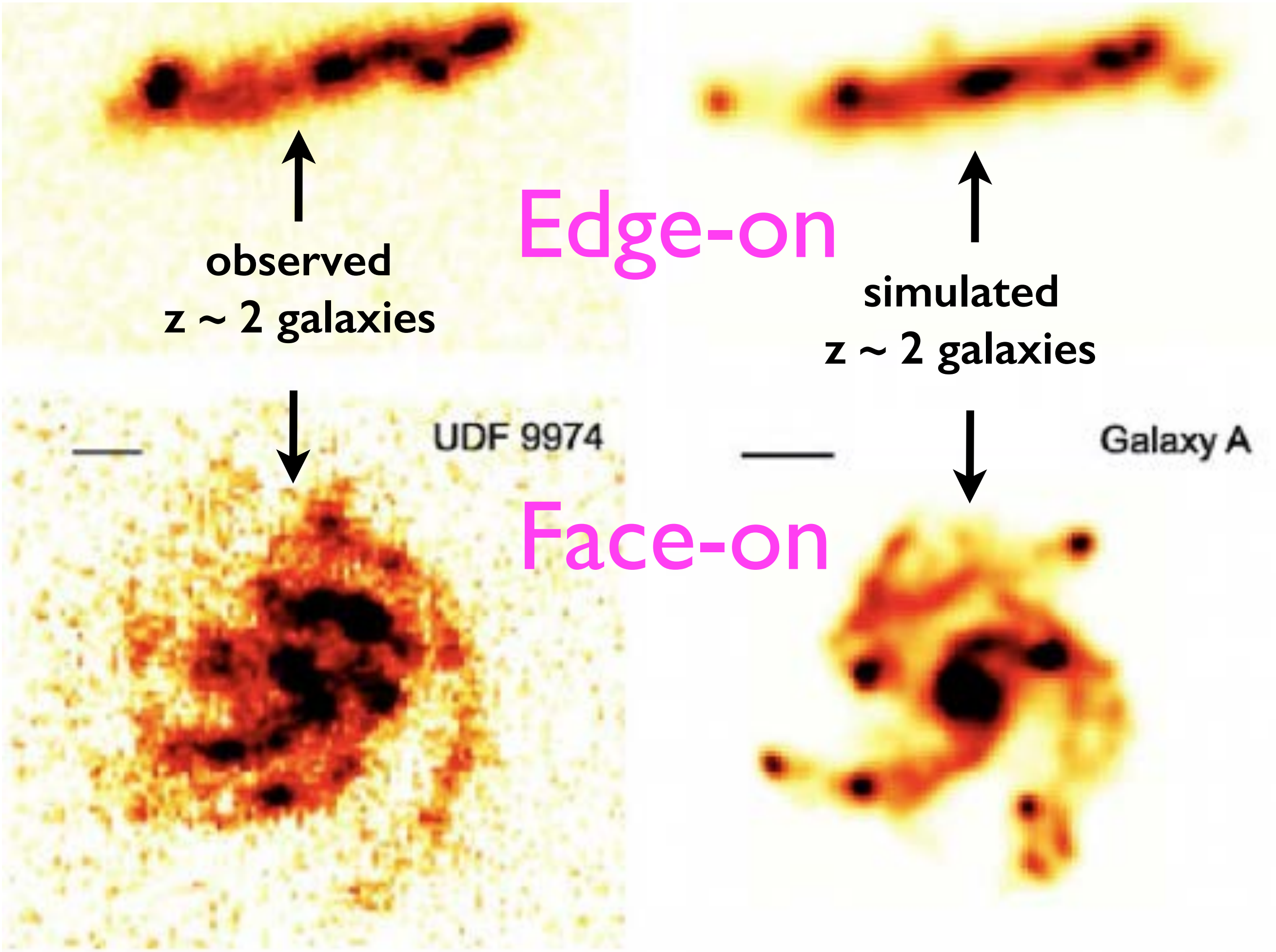
Gen 4: SN+UV/IR Rad Pressure

These were stopped at z ~ 1 to save cpu time.



Clumpy Galaxies in hydroART Generation 1 Simulations

Figure 1: Violently unstable disks in $\sim 10^{11} M_\odot$ halos with $\sim 10^{9} M_\odot$ clumps at $z = 2.3$: (a) face-on, (b) edge-on (Ceverino et al. 2009, resolution 70 pc, images 10 kpc across). RGB color images of the same simulated galaxy through dust using *Sunrise*: (c) face-on, (d) edge-on, illustrating how the clumps can be reddened and obscured when viewed edge-on.



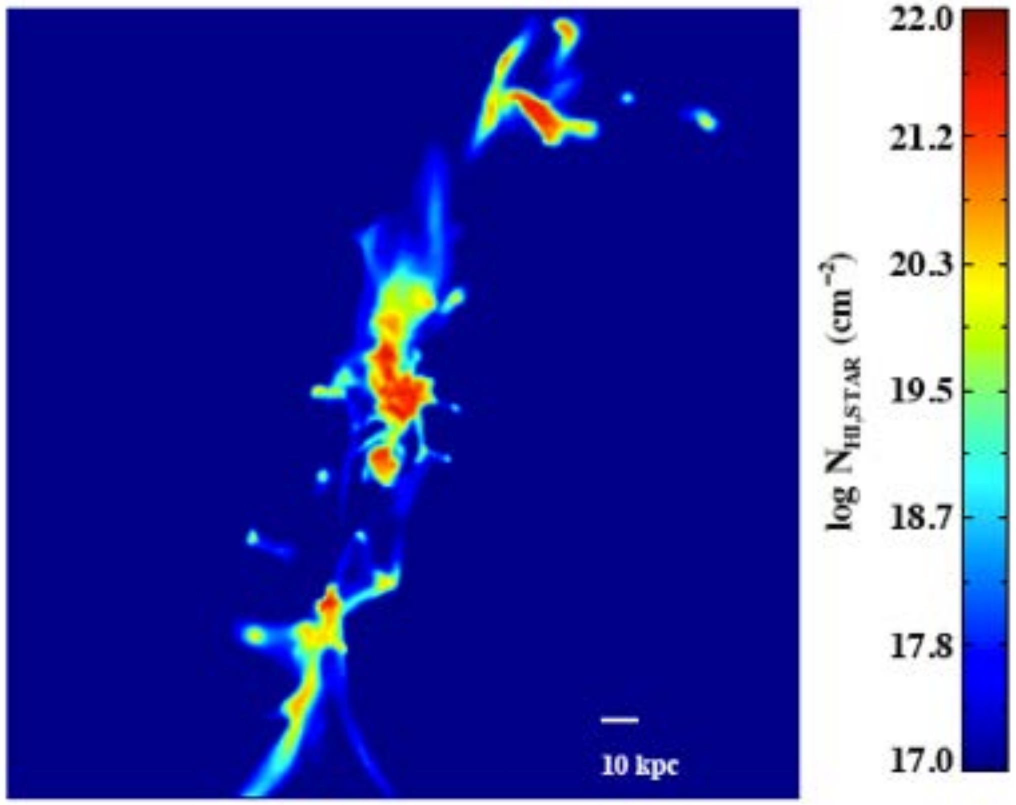
observed
z ~ 2 galaxies

Edge-on

simulated
z ~ 2 galaxies

Face-on

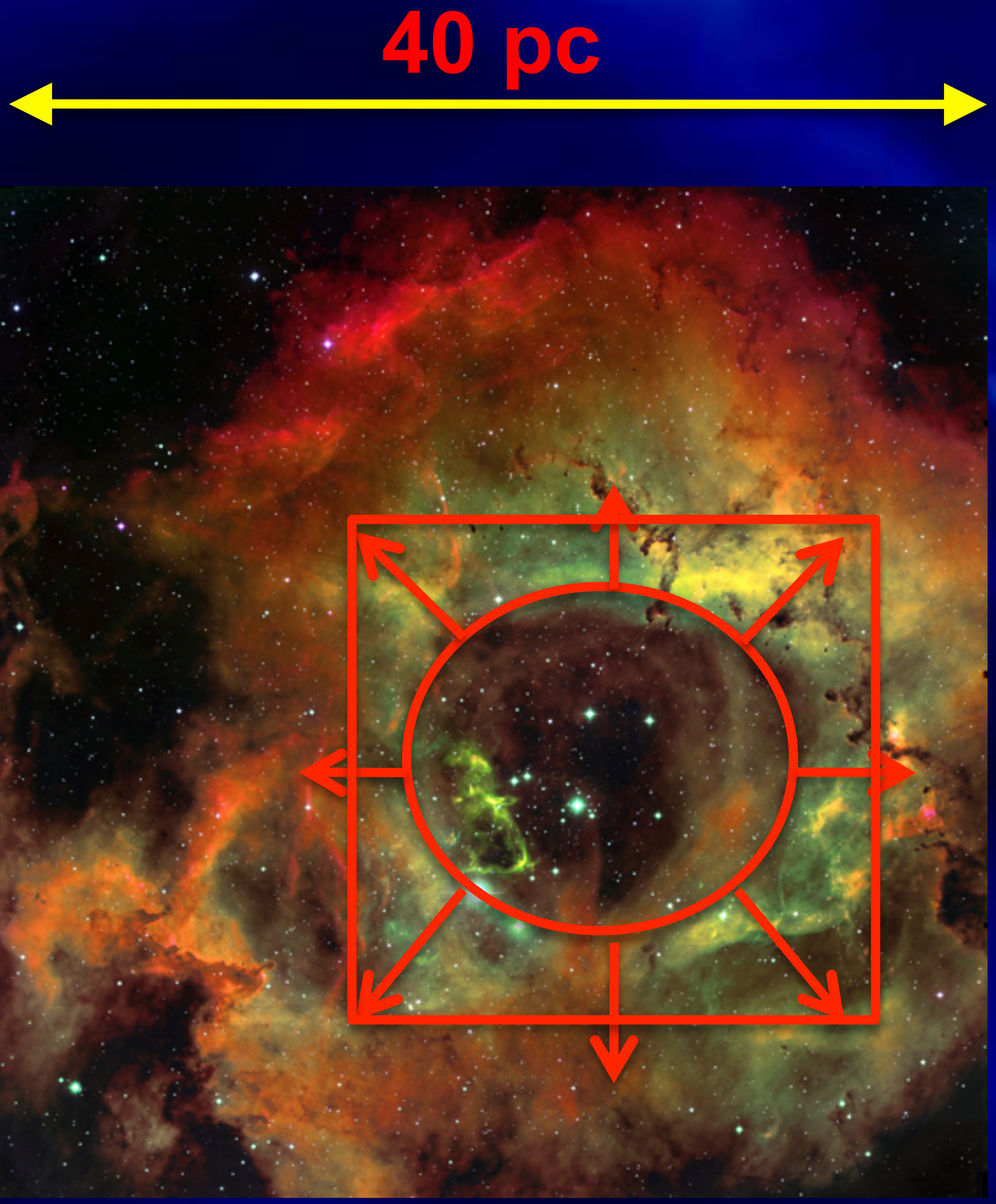
Ly alpha blobs from same simulation



Fumagalli, Prochaska, Kasen, Dekel, Ceverino, & Primack 2011

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

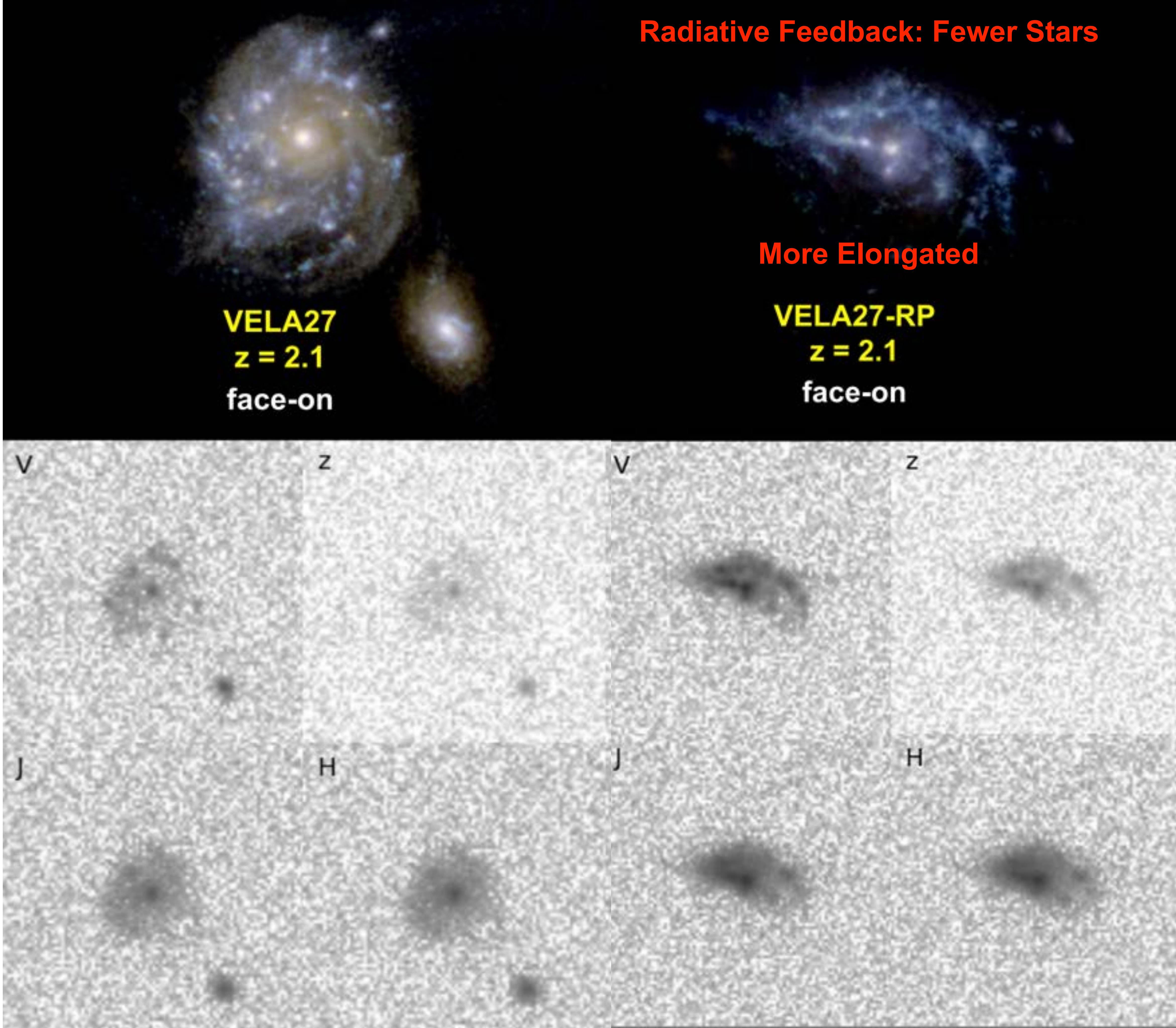
Simulated Galaxy 10 billion years ago

as it would appear nearby to our eyes

CANDELized

as it would appear to Hubble's ACS visual camera

as it would appear to Hubble's WFC3 infrared camera



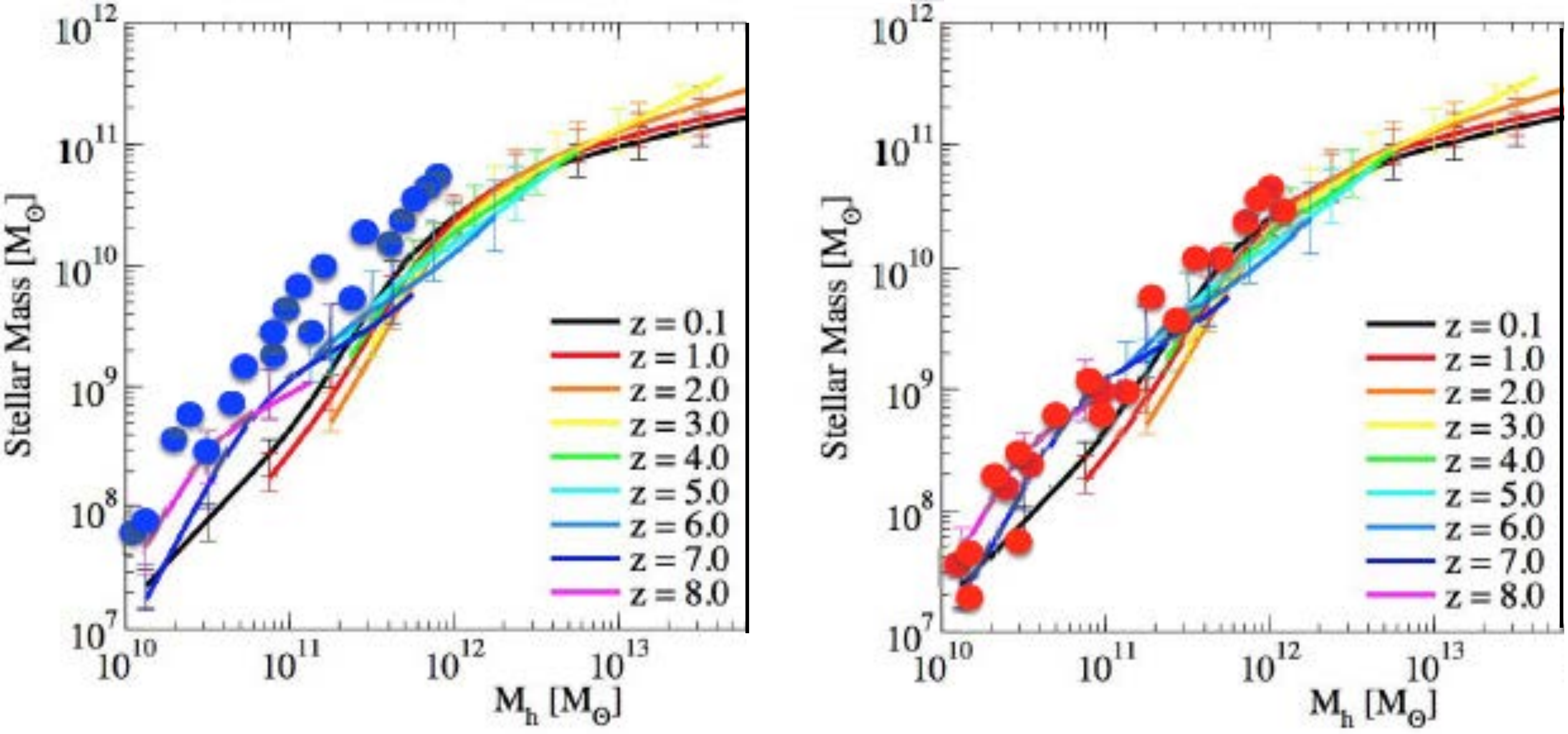
Radiative Feedback: Fewer Stars

More Elongated

Radiative Feedback Decreases Star Formation, Improving Agreement with Observations

SNe Feedback (Gen 2)

SNe & Radiative Feedback (Gen 3)

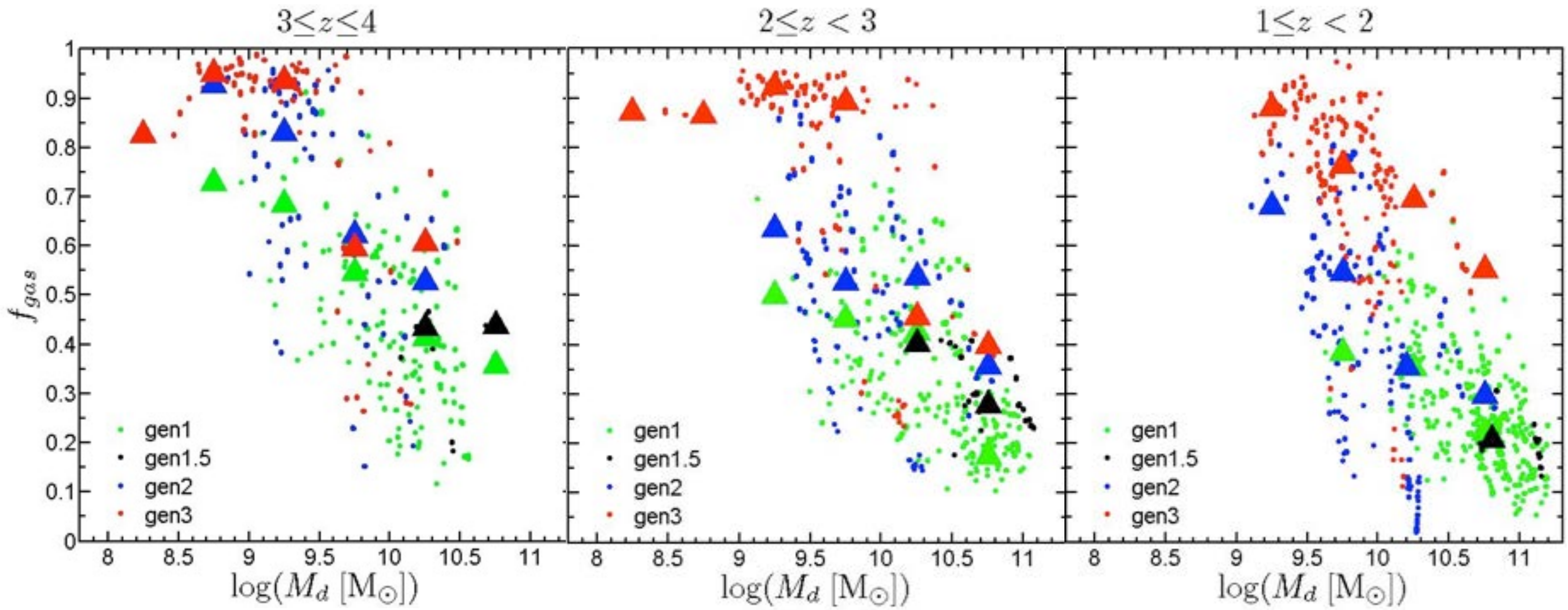


Stellar Mass - Halo Mass Relation from Abundance Matching - Behroozi, Wechsler, Conroy ApJ 2013

Daniel Ceverino

Stellar Mass is still a bit too high in UV RP simulations.

DISK COLD GAS FRACTIONS
in 3 generations of hydroART simulations



large triangles are medians

Nir Mandelker
Hebrew University

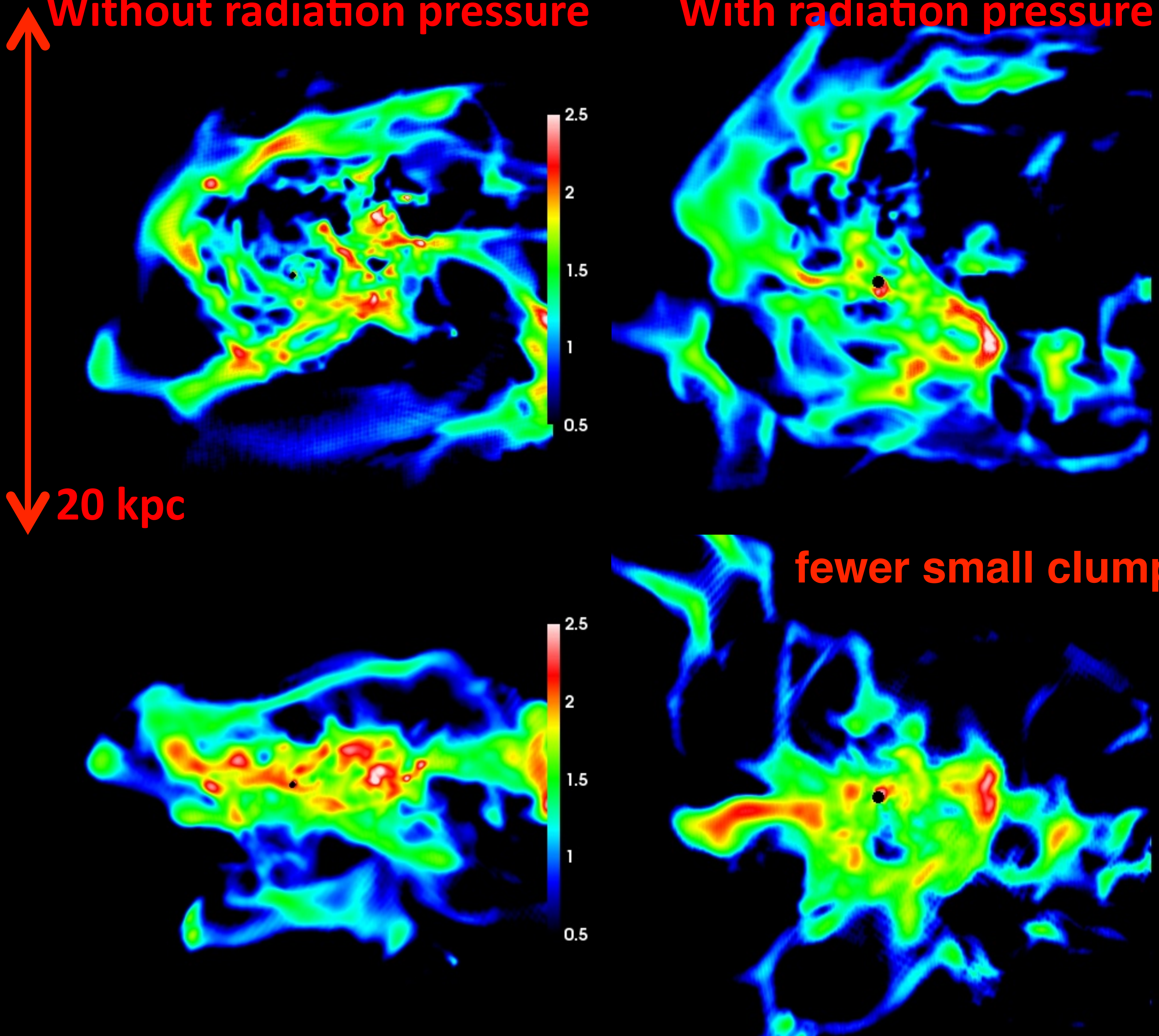
- ▲ gen1 - 35-70 pc resolution, $M_{halo} = 10^{12} - 10^{13}\ M_{sun}$ @z=1
- ▲ gen1.5 (same, lower SFR)
- ▲ gen2 - 15-30 pc resolution, $M_{halo} = 10^{11} - 2\times10^{12}\ M_{sun}$ @z=1
- ▲ gen3 - same as gen2, with Radiative Pressure Feedback

much higher f_{gas} at $z \lesssim 3$

Gas distributions

Without radiation pressure

With radiation pressure



20 kpc

fewer small clumps

Gas face-on

Gas edge-on

Daniel Ceverino

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

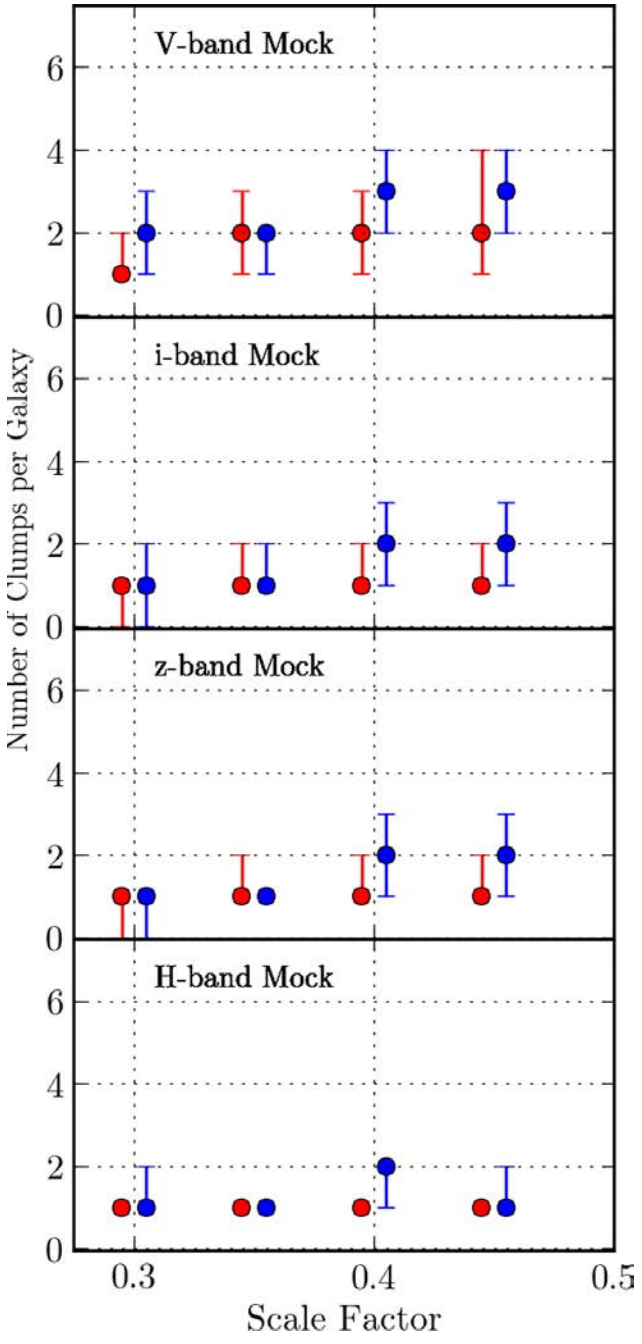
MNRAS **444,** 1389–1399 (2014) doi:10.1093/mnras/stu1534

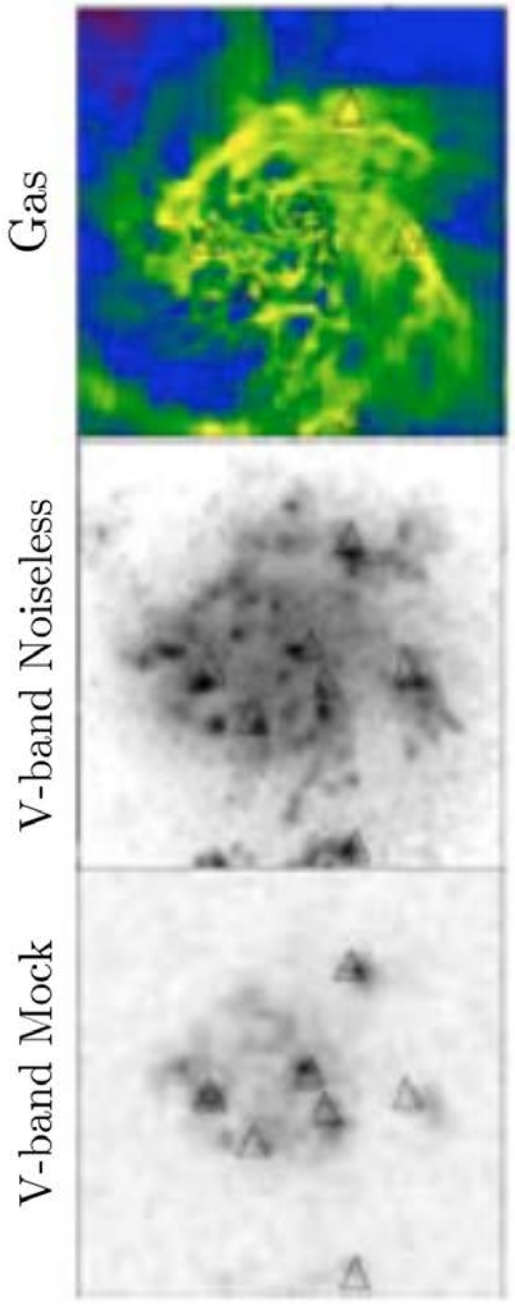
Star formation and clumps in cosmological galaxy simulations with radiation pressure feedback

Christopher E. Moody, Yicheng Guo, Nir Mandelker, Daniel Ceverino, Mark Mozena, David C. Koo, Avishai Dekel and Joel Primack

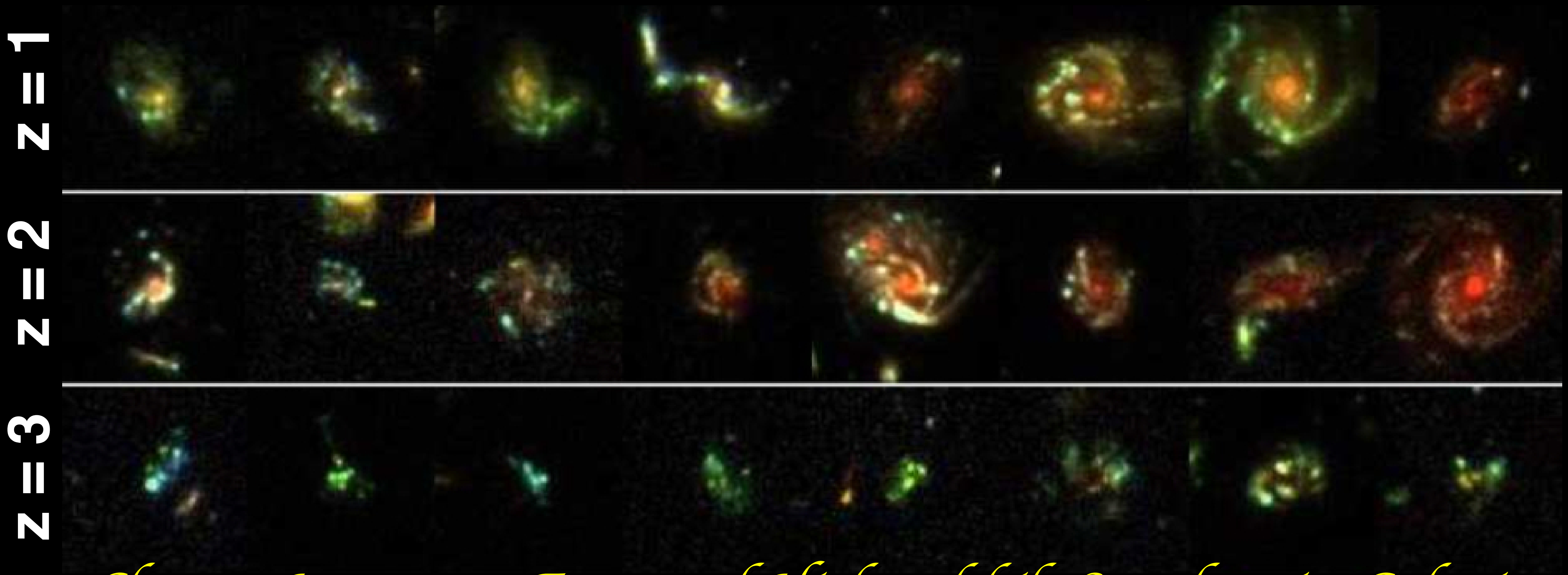
In simulations with RP the average number of low-mass clumps falls dramatically. Only clumps with stellar masses $M_{\rm clump}/M_{\rm disc} \leq 5$ per cent are impacted by the inclusion of RP, and RP and no-RP clump counts above this range are comparable. By creating mock *Hubble Space Telescope* observations we find that the number of clumps is slightly reduced in simulations with RP. However, since massive clumps survive the inclusion of RP and are found in our mock observations, we do not find a disagreement between simulations of our clumpy galaxies and observations of clumpy galaxies. We demonstrate that clumps found in any single gas, stellar, or mock observation image are not necessarily clumps found in another map, and that there are few clumps common to multiple maps.

		$f_{\rm clumpy}$ $z = 3.0$–2.3	$f_{\rm clumpy}$ $z = 2.3$–1.9	$f_{\rm clumpy}$ $z = 1.9$–1.5
No-RP	●	0.32	0.53	0.64
RP	●	0.24	0.48	0.54





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

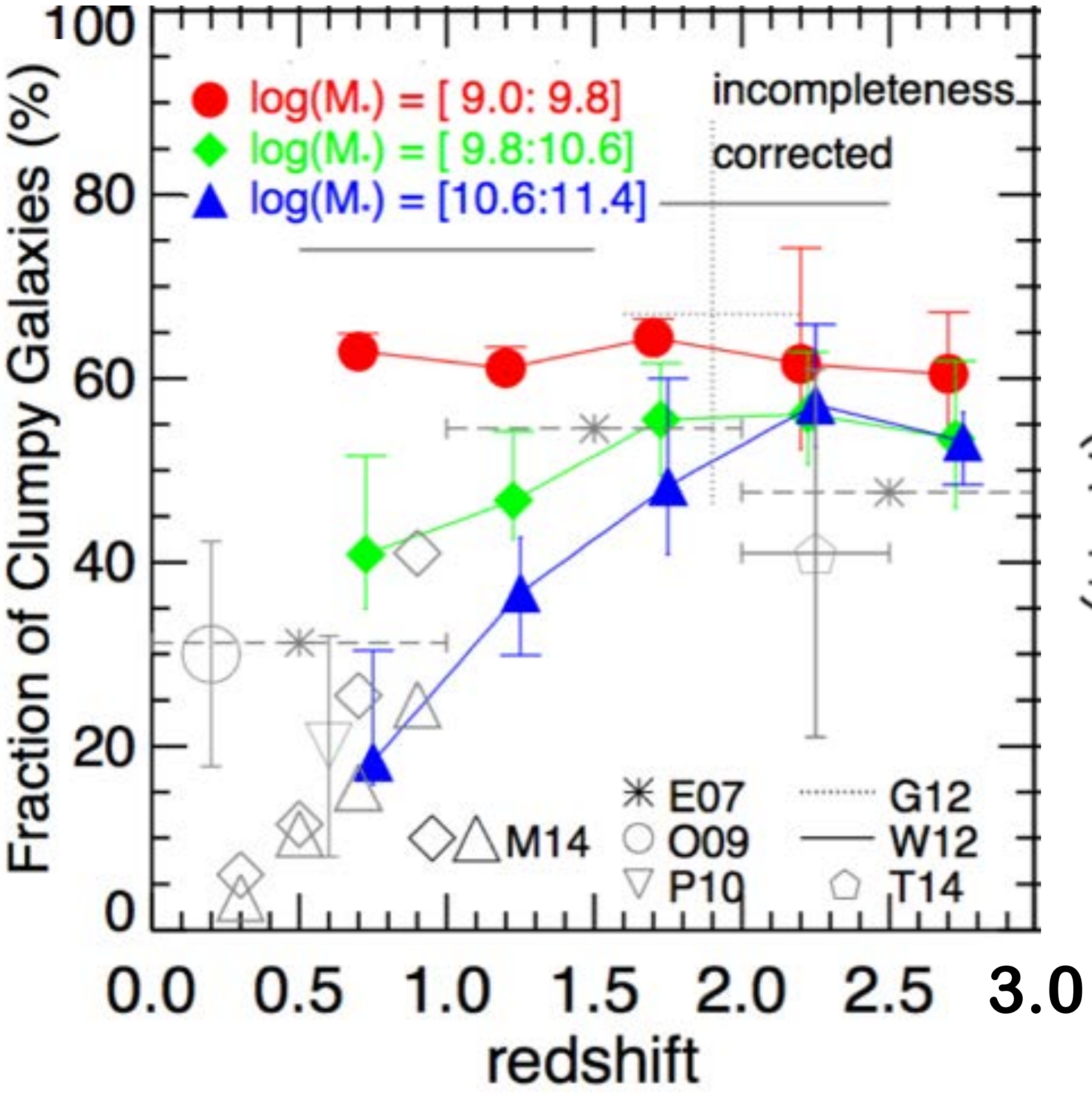
About 60% of star-forming galaxies are clumpy at z ~ 2.5.

The evolution of the clump fraction is mass-dependent.

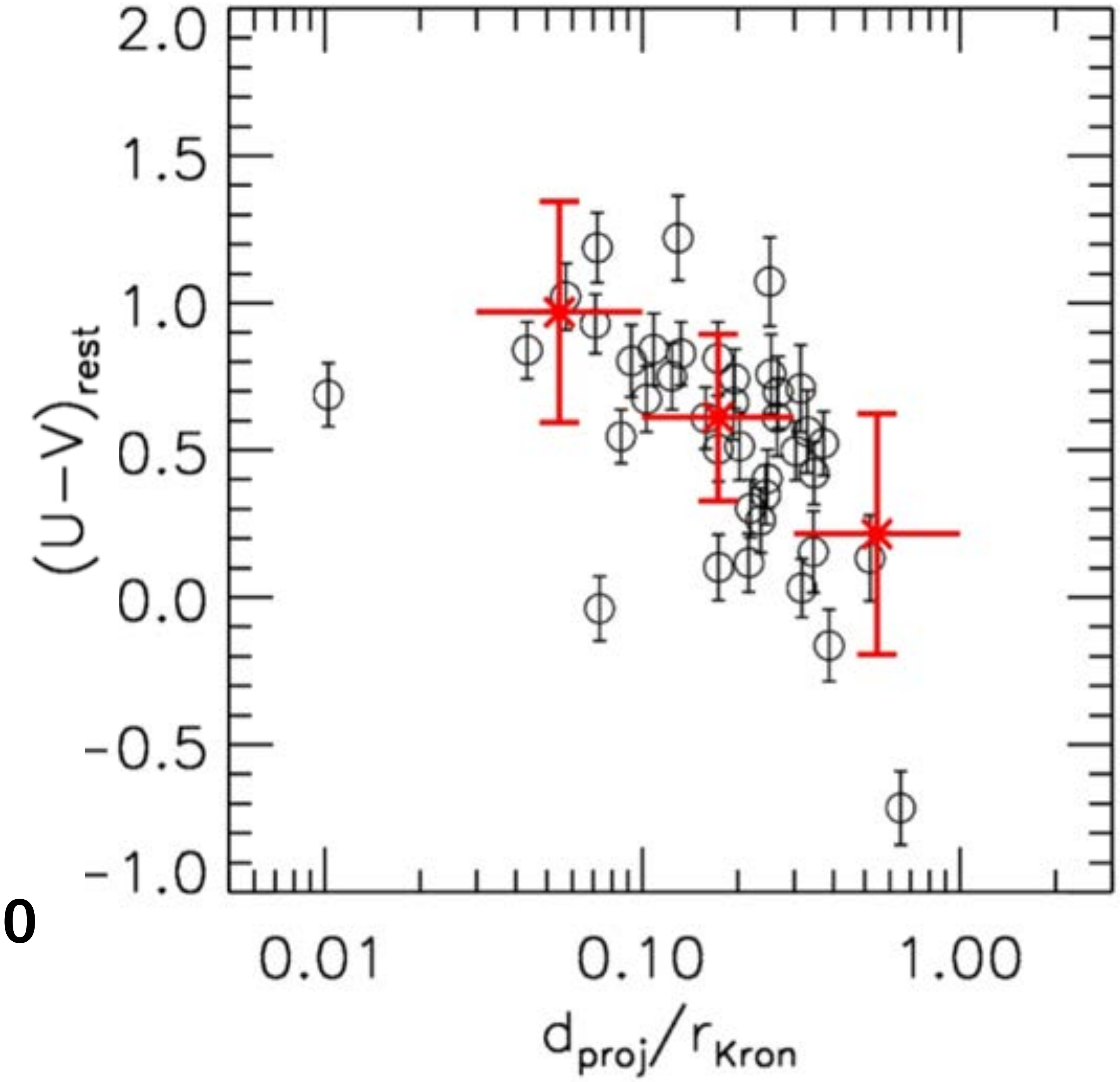
Clumps have radial variation of their UV-optical colors:

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

as clump radial migration predicts.



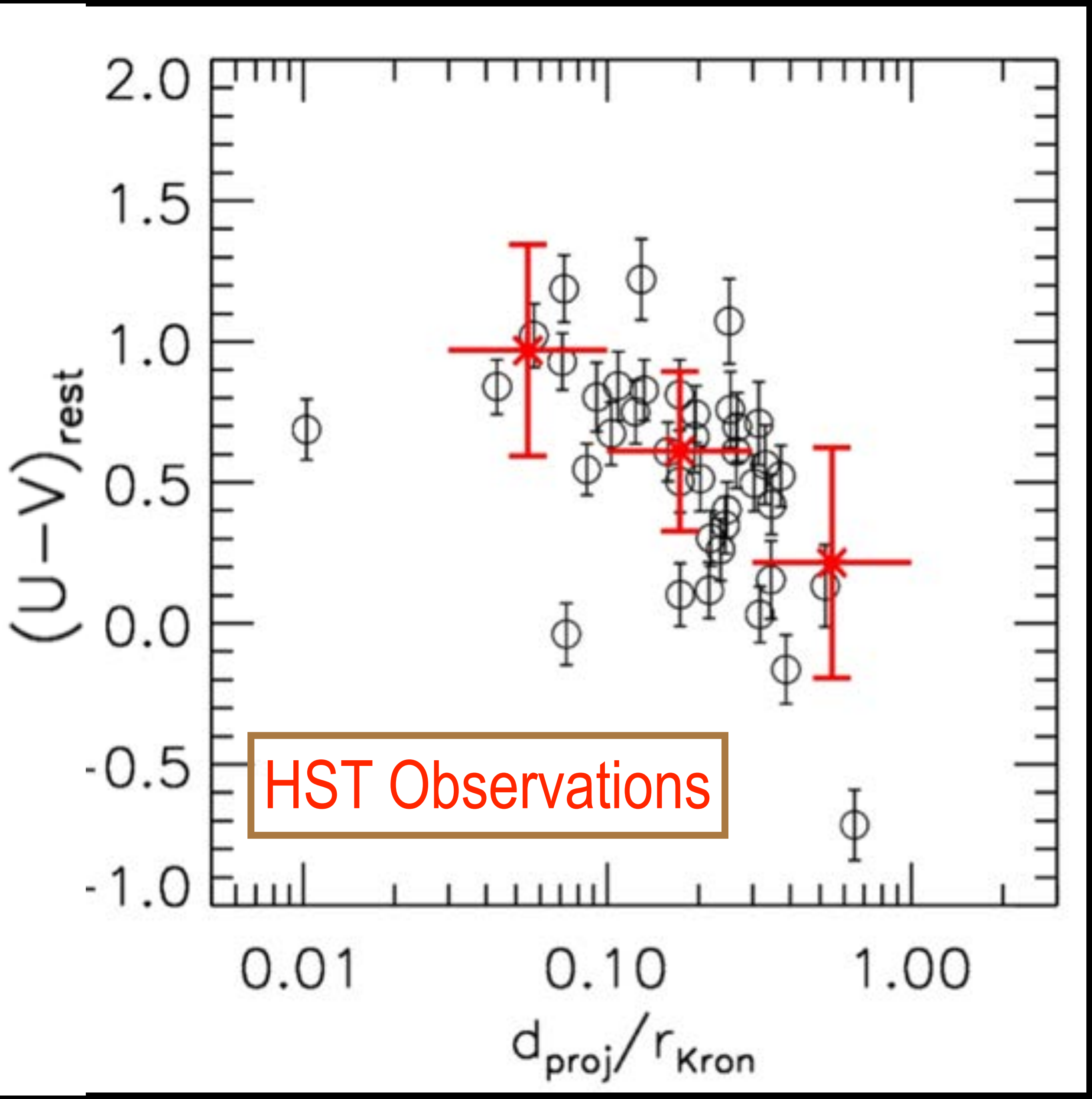
Yicheng Guo+2015



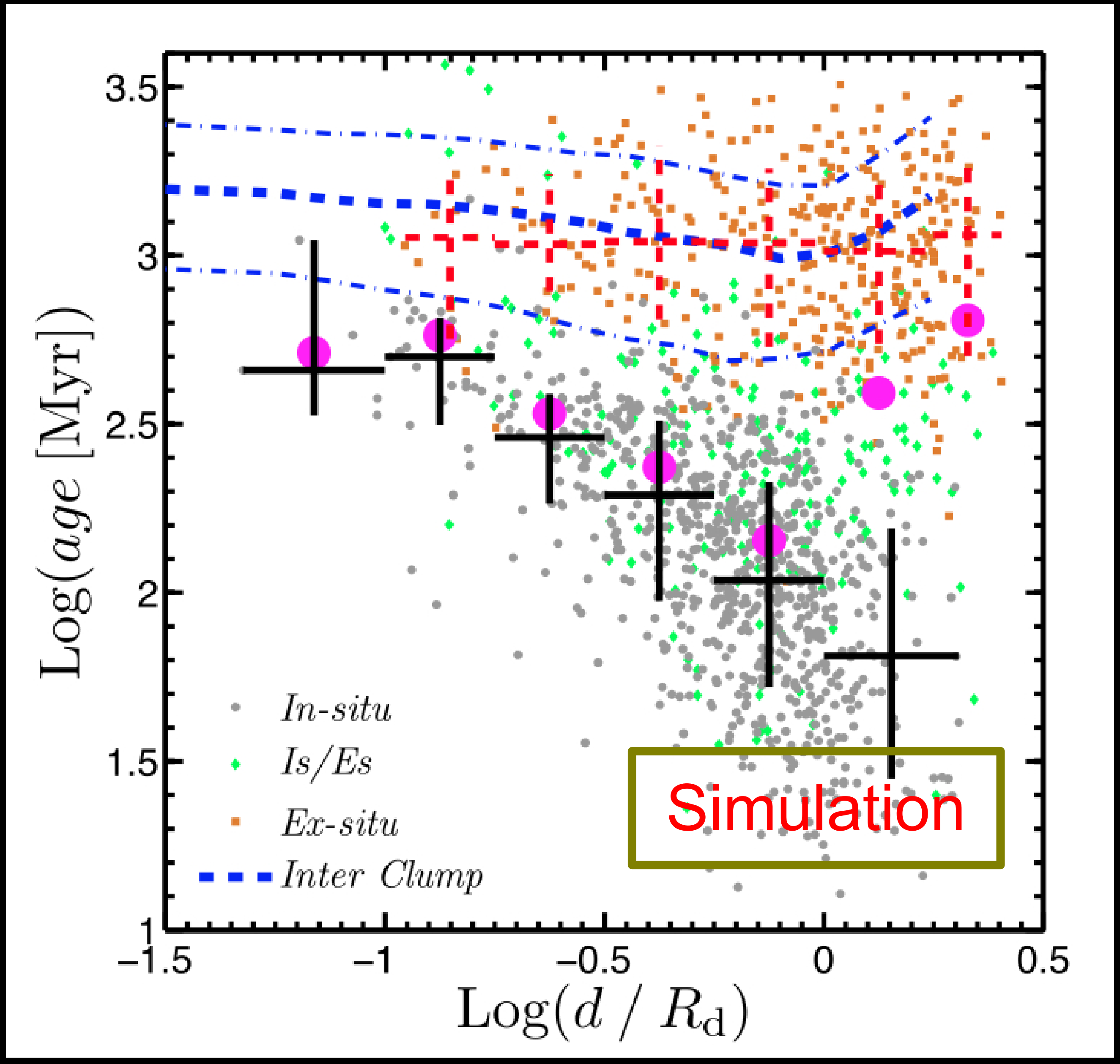
Yicheng Guo+2012

Radial Variations Consistent with the In-ward Migration Scenario: Clumps → Bulges

- Central clumps: less star formation, older, more dust, denser
- Outskirt clumps: more star formation, younger, less dust, less dense
- Similar trends seen in numerical simulations (Mandelker+14)



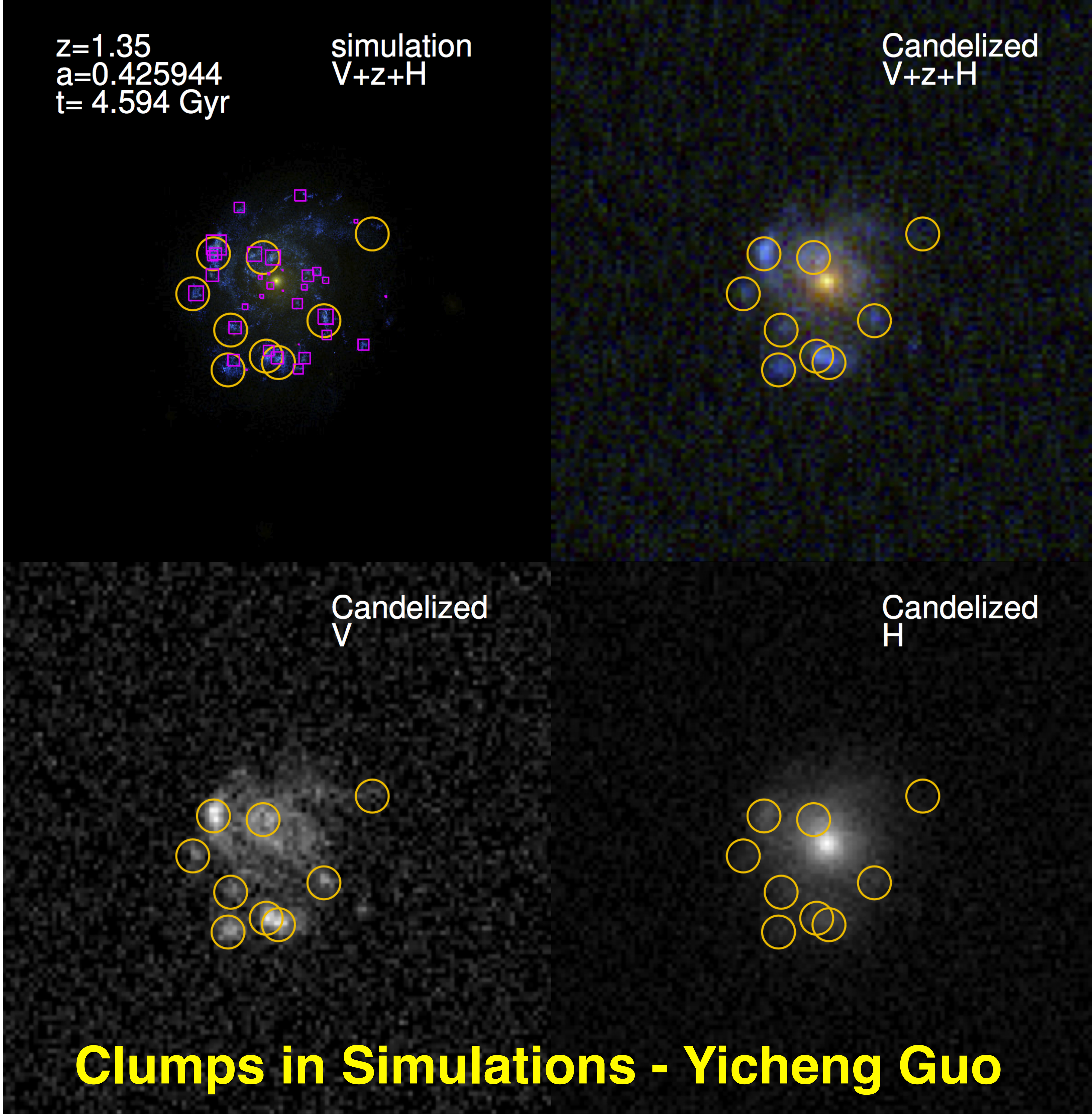
Guo+12



Mandelker+14

Comparing clumps in simulation

with clump finder on Candelized V & H bands



Clumps in Simulations - Yicheng Guo

Summary: tracing clumpy galaxies from z=3 to z=0.5

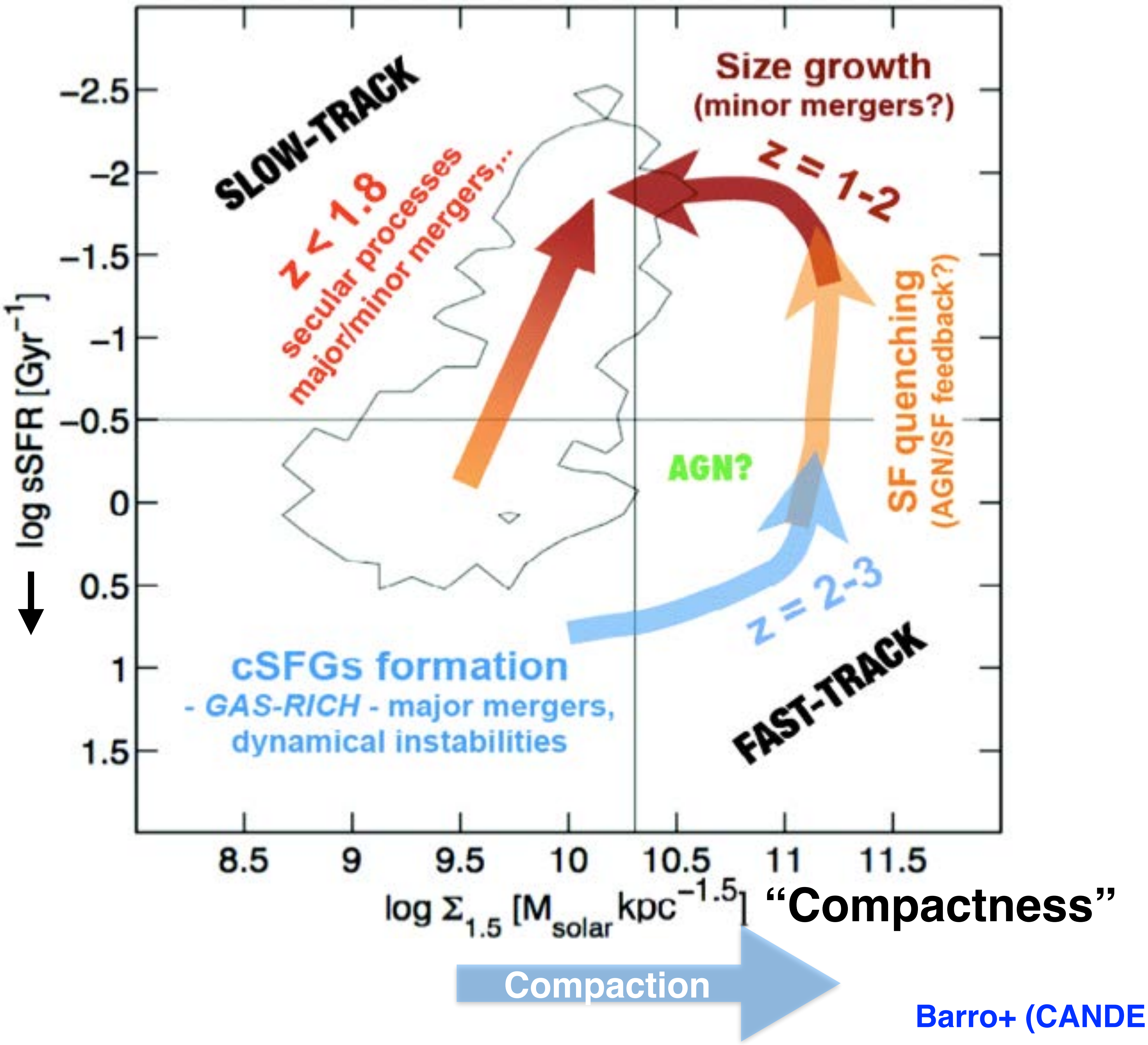
- Sub-structures (giant clumps) of galaxies are crucial to galaxy formation and evolution

- Clumpy fraction of star-forming galaxies from z=3 to z=0.5
  (1) About 60% of star-forming galaxies at z~3 are clumpy
  (2) The evolution of the clumpy fraction depends on the mass of the galaxies
  (3) Clump formation: VDI for massive galaxies, minor merger for intermediate-mass galaxies

- Physical properties of clumps and their variations at z~2
  (1) Clumps are blue regions with enhanced sSFR
  (2) Central clumps are redder, and outskirts clumps are bluer
  (3) Clump's radial variation is consistent with the in-ward migration scenario

- Using CANDELized simulations to study the nature of clumps
  (1) understand the completeness of clump detection
  (2) understand the observational effects and blending of clump detection
  (3) understand clump formation mechanisms

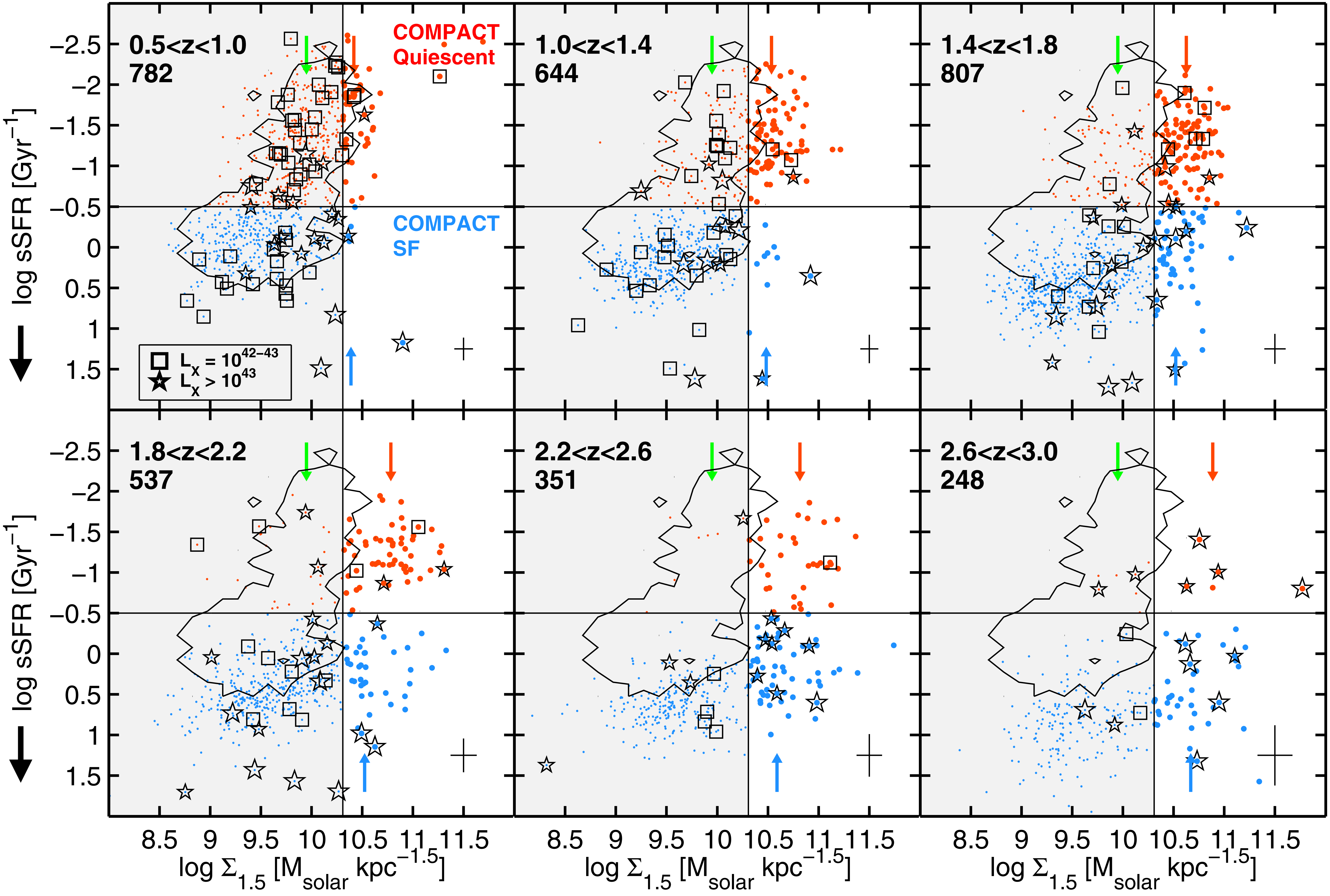
COMPACTION in CANDELS - Guillermo Barro



Barro+ (CANDELS) 2013

CANDELS: THE PROGENITORS OF COMPACT QUIESCENT GALAXIES AT z ~ 2

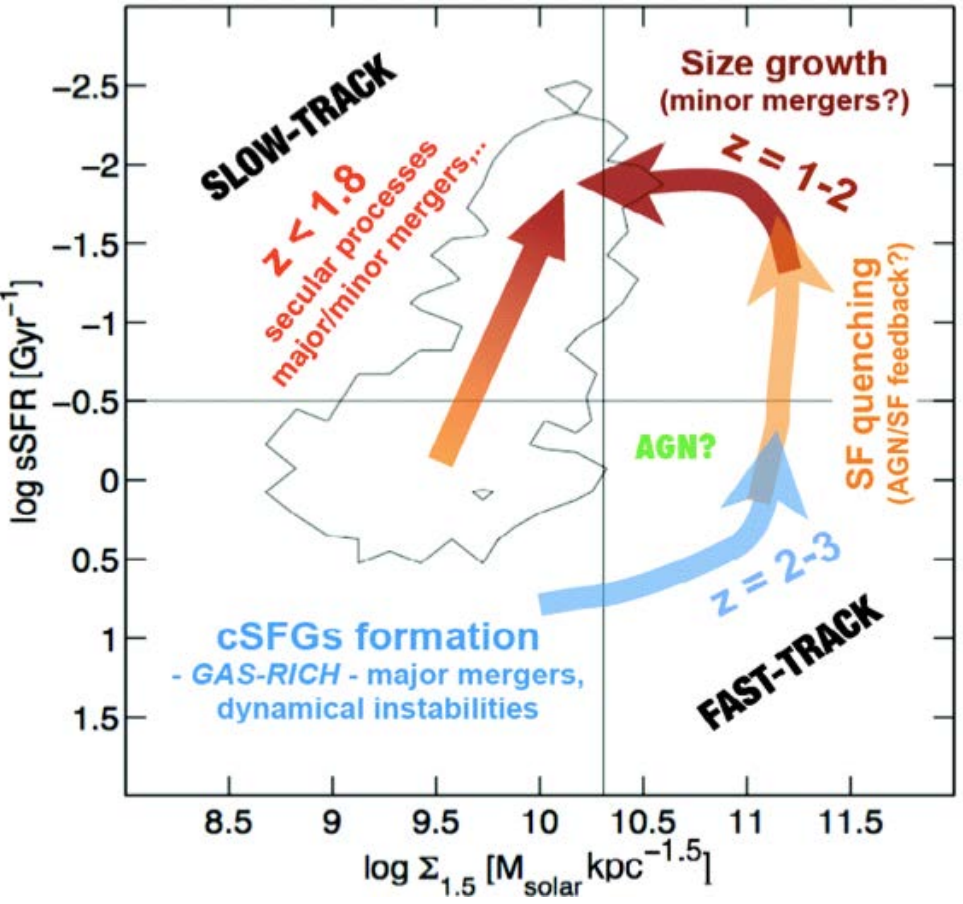
Guillermo Barro, S. M. Faber, Pablo G. Perez-Gonzalez, David C. Koo, et al.   ApJ 2013



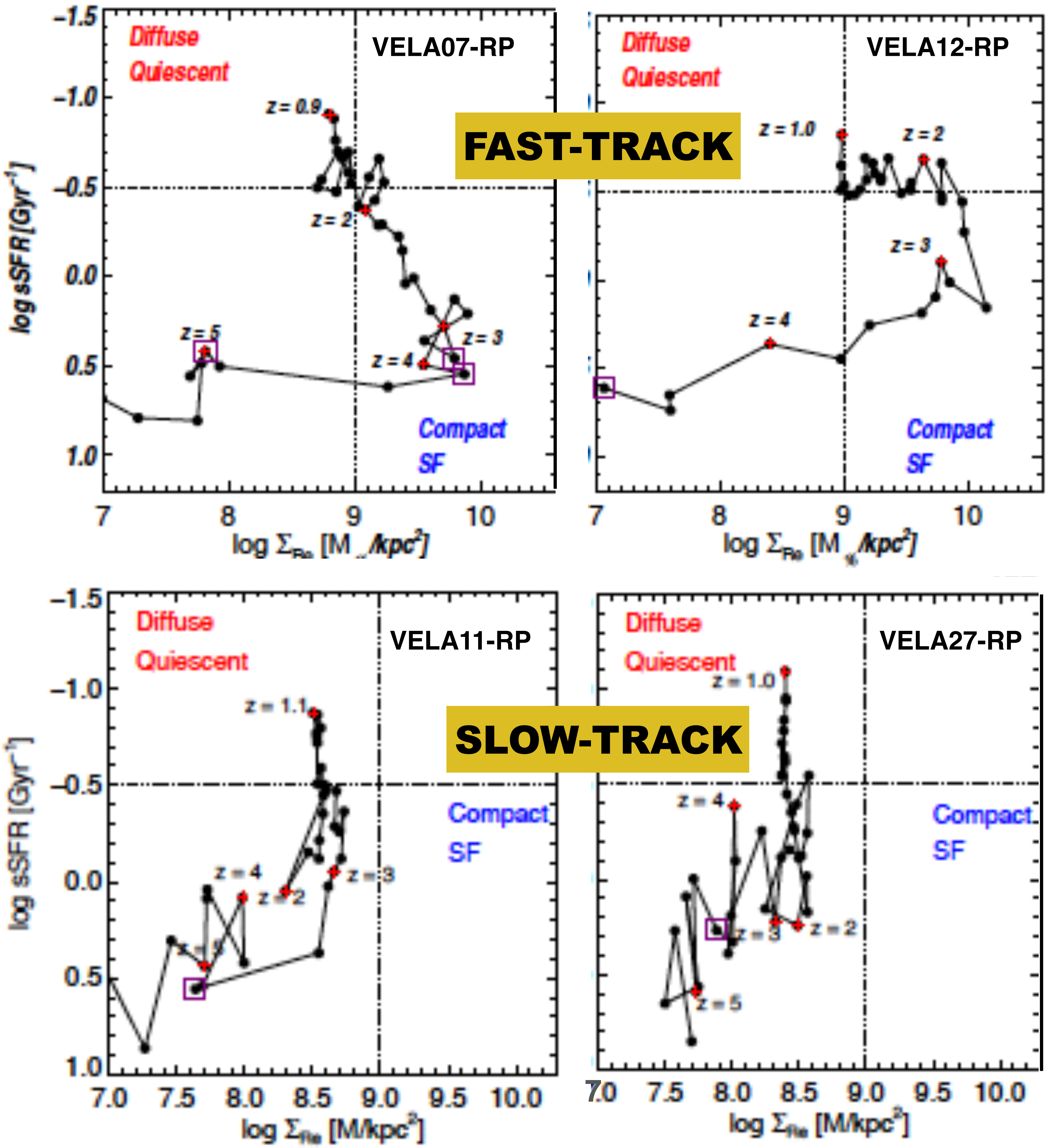
Evolution of sSFR vs. compactness ($\Sigma/r^{1.5}$) at $0.5 < z < 3$ in roughly equal comoving volumes.

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

Barro+ (CANDELS) 2013



COMPACTION —>



FAST-TRACK

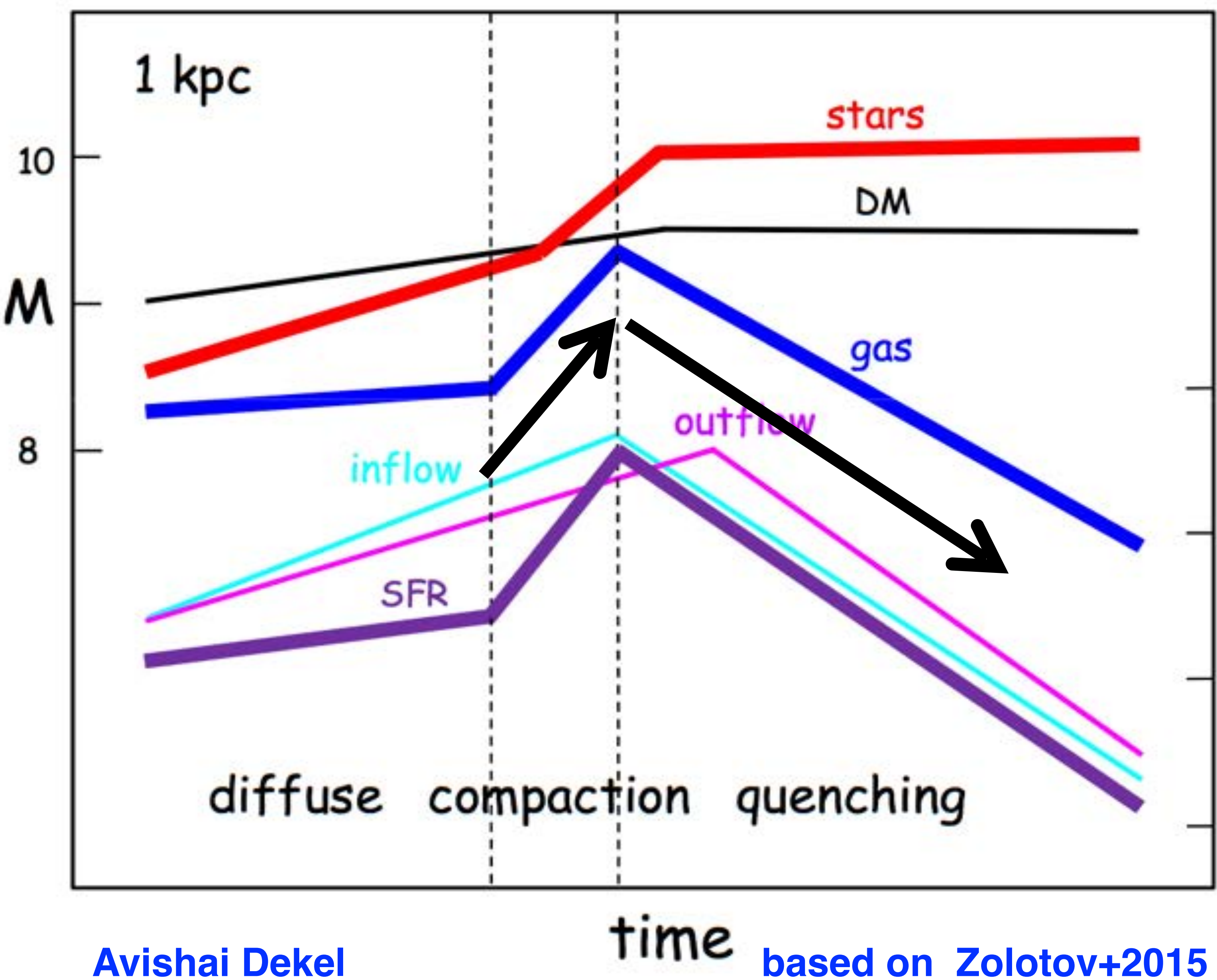
SLOW-TRACK

⊡ minor merger

⊡ major merger

Zolotov+2015

Compaction and Quenching in the Inner 1 kpc

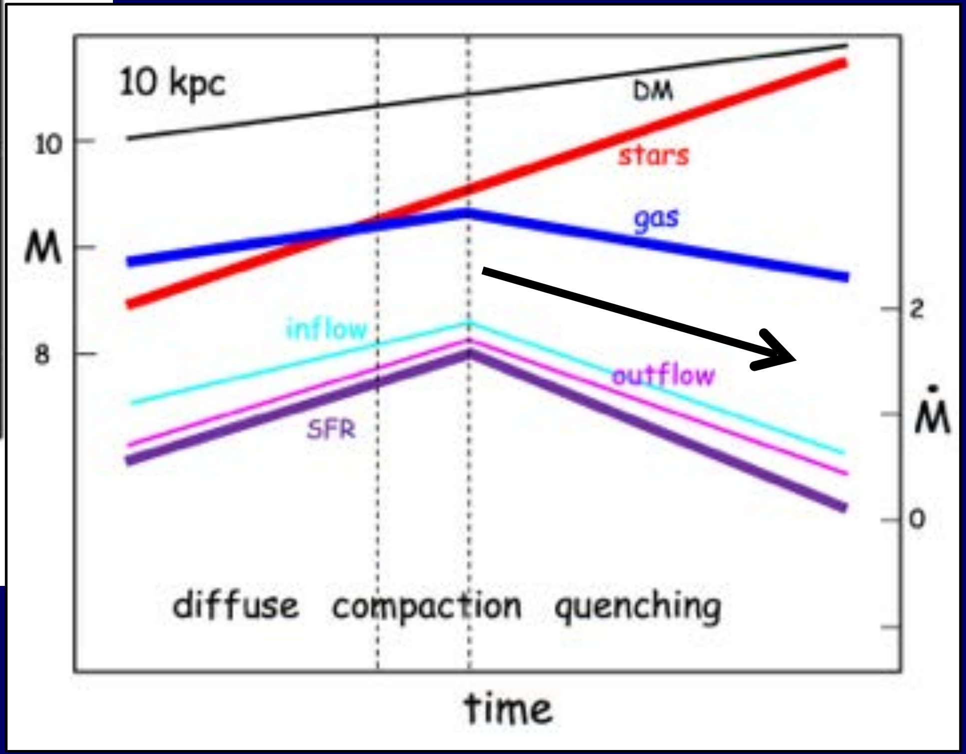


Avishai Dekel

based on Zolotov+2015

inner 1 kpc

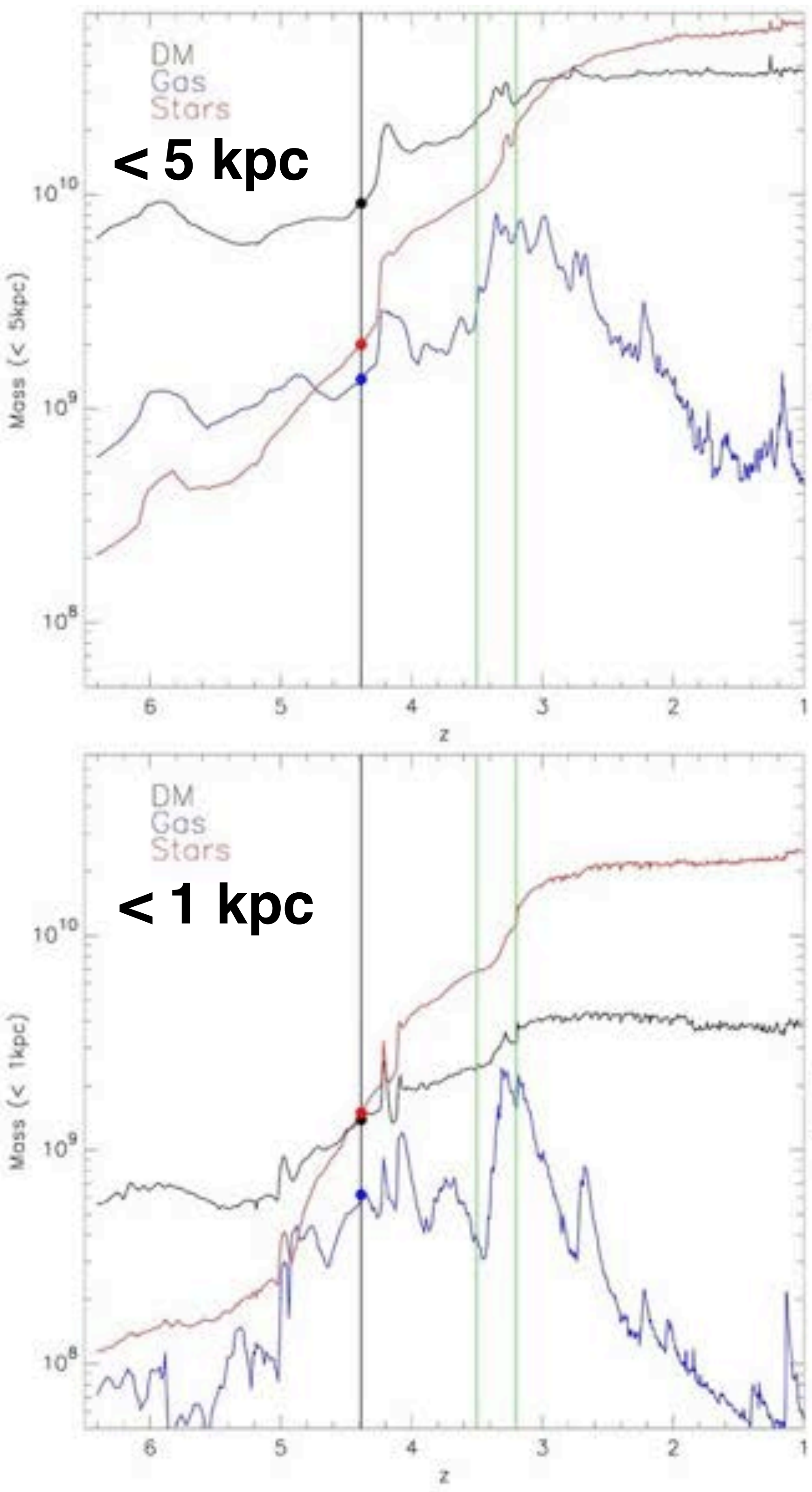
Inner 10 kpc



VELA07-RP Animations z = 4.4 to 2.3

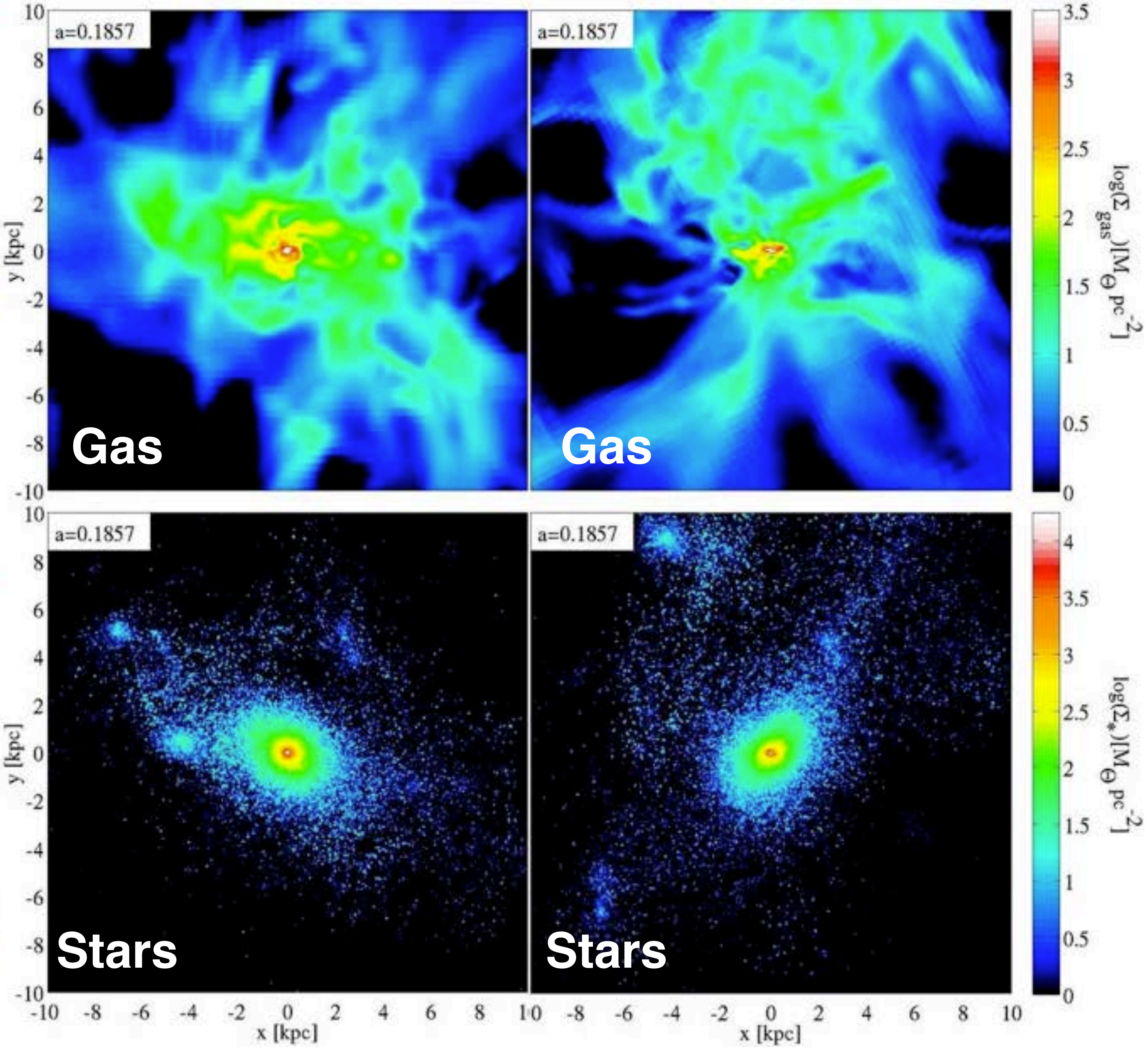
DM
Gas
Stars

Compaction

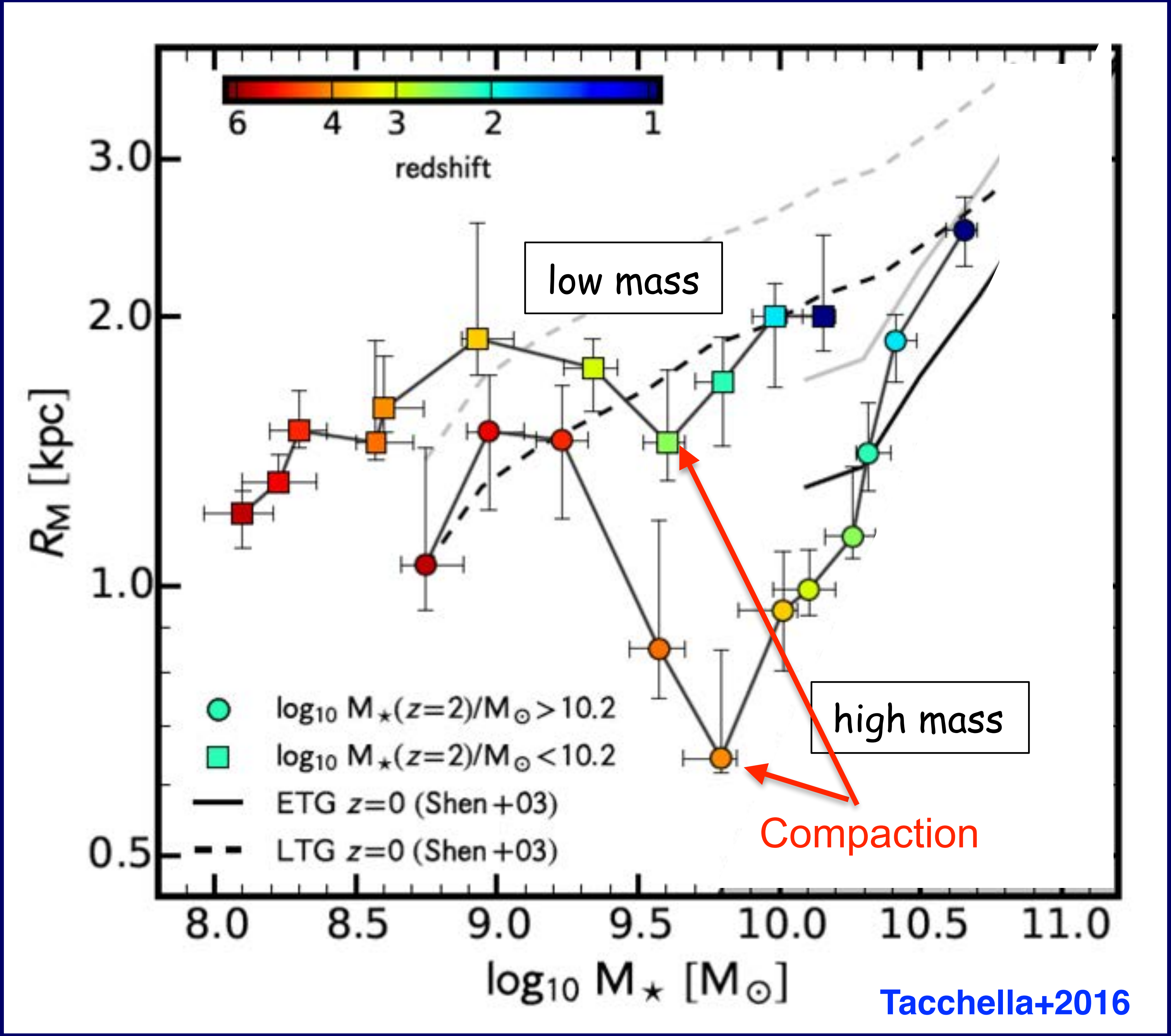


Face-on

Edge-on



Evolution in R_{eff}-M_*



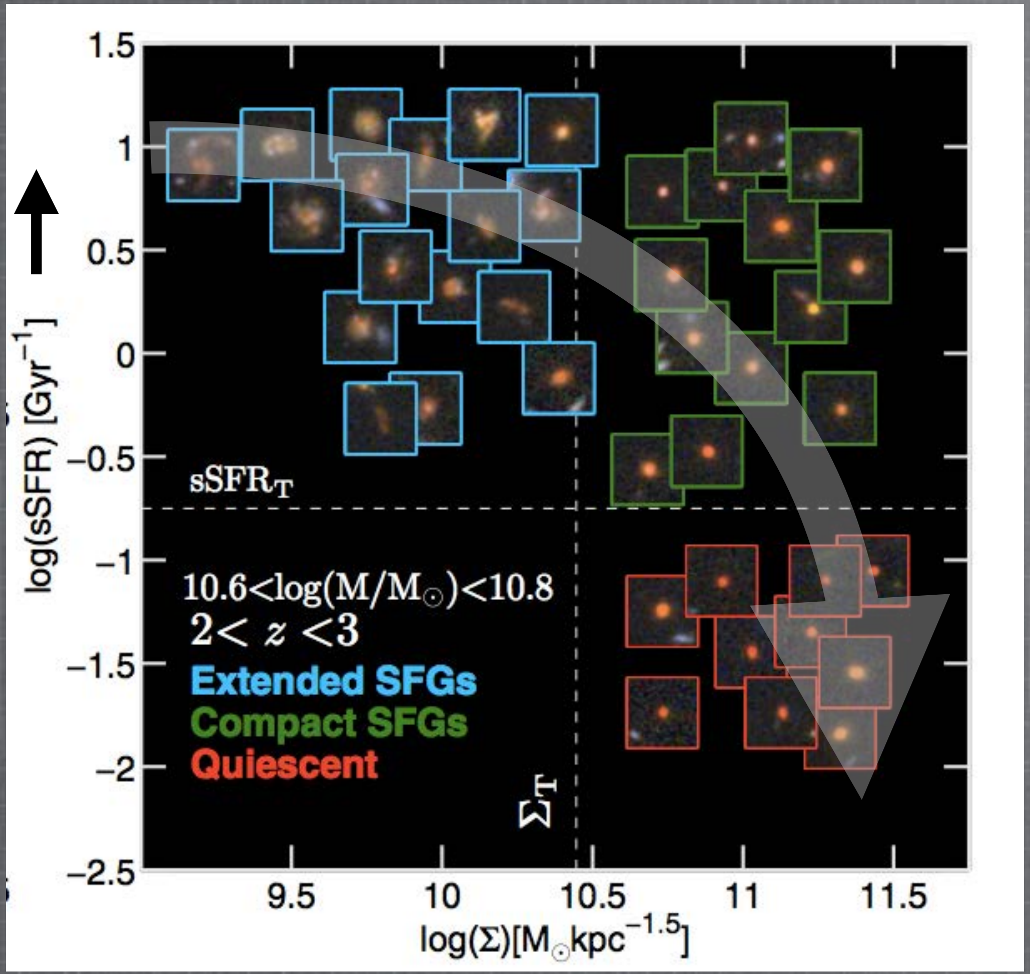
low mass

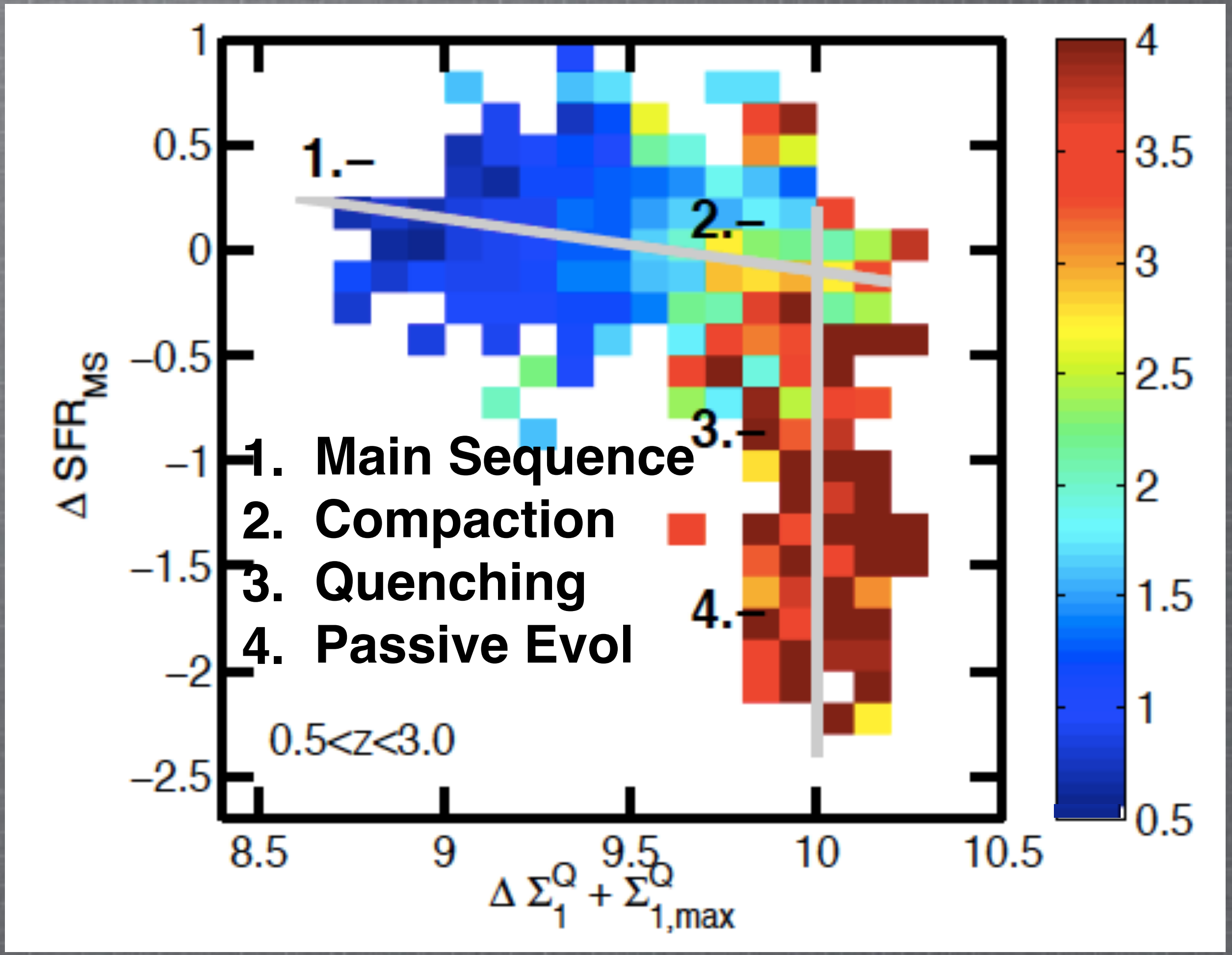
high mass

Compaction

Tacchella+2016

COMPACTION in CANDELS





Structural transformation (compaction) precedes quenching of star-formation

- “Normal” SFGs follow a SFR and structural Main-sequence
- Compaction triggered dissipational processes: strong core growth
- Relative distance from the SFR and MS universal relation to select progenitors of quiescent galaxies

G. Barro+ arXiv:1509.00469

Most $M_* < 10^{9.5}$ $M_\odot$ Star Forming Galaxies at $z > 1$ Are Elongated

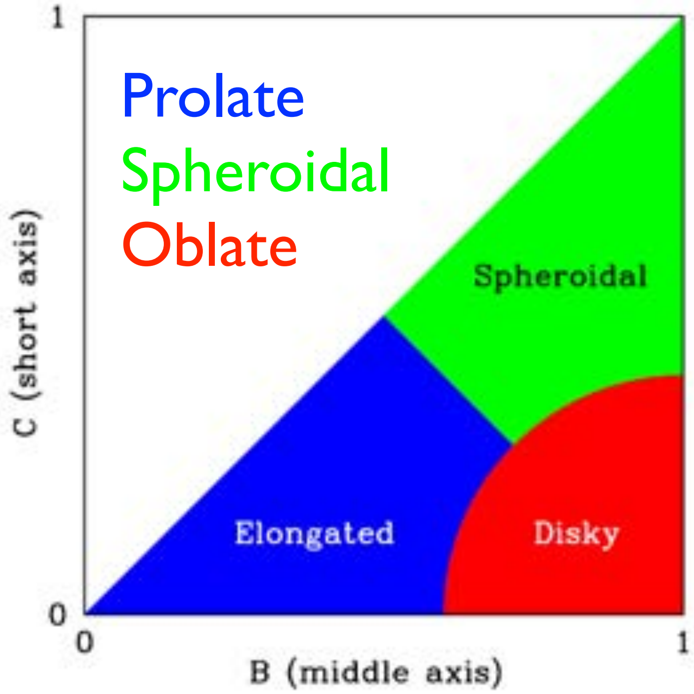
GEOMETRY OF STAR-FORMING GALAXIES FROM SDSS, 3D-HST AND CANDELS

A. van der Wel[1], Yu-Yen Chang[1], E. F. Bell[2], B. P. Holden[3], H. C. Ferguson[4], M. Giavalisco[5], H.-W. Rix[1], R. Skelton[6], K. Whitaker[7], I. Momcheva[8], G. Brammer[4], S. A. Kassin[4], A. Dekel[9], D. Ceverino[10], D. C. Koo[3], M. Mozena[3], P. G. van Dokkum[8], M. Franx[11], S. M. Faber[3], and J. Primack[12]

ApJL 2014

ABSTRACT

We determine the intrinsic, 3-dimensional shape distribution of star-forming galaxies at $0 < z < 2.5$, as inferred from their observed projected axis ratios. In the present-day universe star-forming galaxies of all masses $10^9 - 10^{11}$ $M_\odot$ are predominantly thin, nearly oblate disks, in line with previous studies. We now extend this to higher redshifts, and find that among massive galaxies ($M_* > 10^{10}$ $M_\odot$) disks are the most common geometric shape at all $z \lesssim 2$. Lower-mass galaxies at $z > 1$ possess a broad range of geometric shapes: the fraction of elongated (prolate) galaxies increases toward higher redshifts and lower masses. Galaxies with stellar mass 10^9 $M_\odot$ (10^{10} $M_\odot$) are a mix of roughly equal numbers of elongated and disk galaxies at $z \sim 1$ ($z \sim 2$). This suggests that galaxies in this mass range do not yet have disks that are sustained over many orbital periods, implying that galaxies with present-day stellar mass comparable to that of the Milky Way typically first formed such sustained stellar disks at redshift $z \sim 1.5 - 2$. Combined with constraints on the evolution of the star formation rate density and the distribution of star formation over galaxies with different masses, our findings imply that the majority of all stars across cosmic epochs formed in disks.



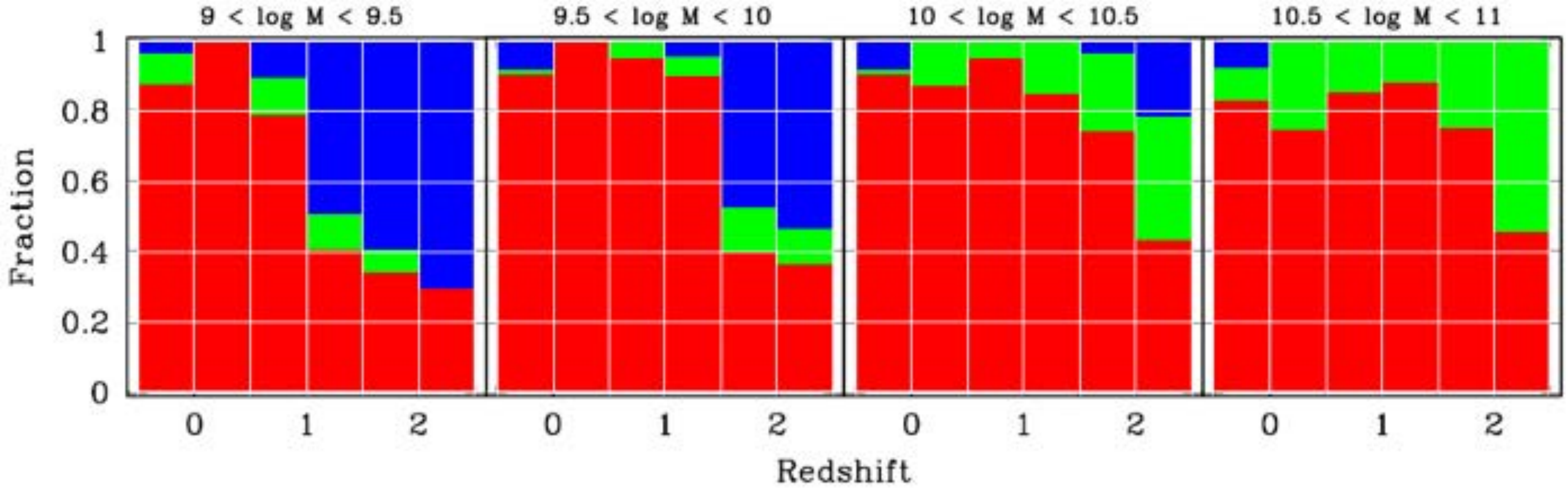
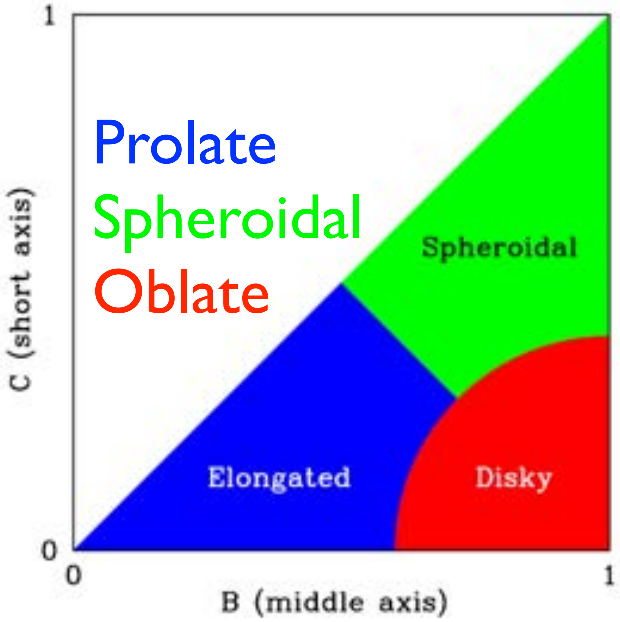


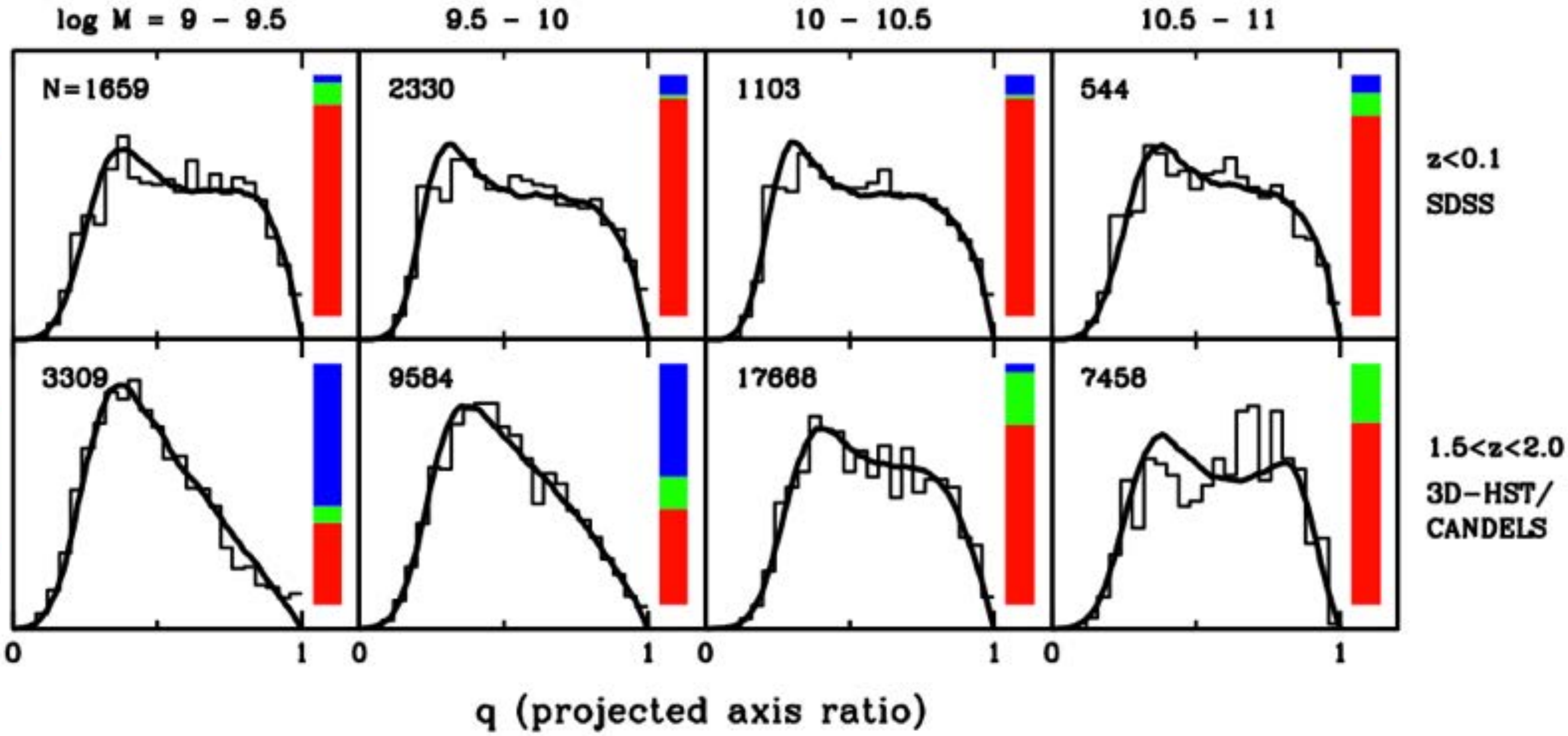
Figure 4. Color bars indicate the fraction of the different types of shape defined in Figure 2 as a function of redshift and stellar mass. The negative redshift bins represent the SDSS results for $z < 0.1$; the other bins are from 3D-HST/CANDELS.

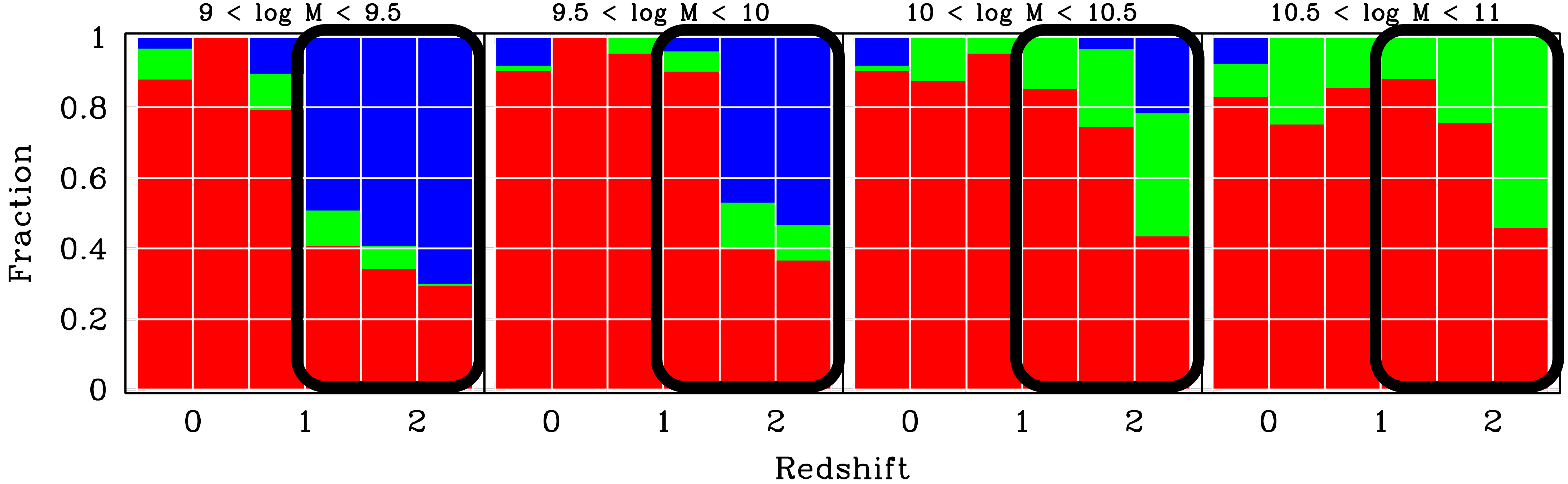
See also WHEN DID ROUND DISK GALAXIES FORM? T. M. Takeuchi et. al ApJ 2015

Prolate objects dominate at high redshift/low masses

Prolate
Spheroidal
Oblate



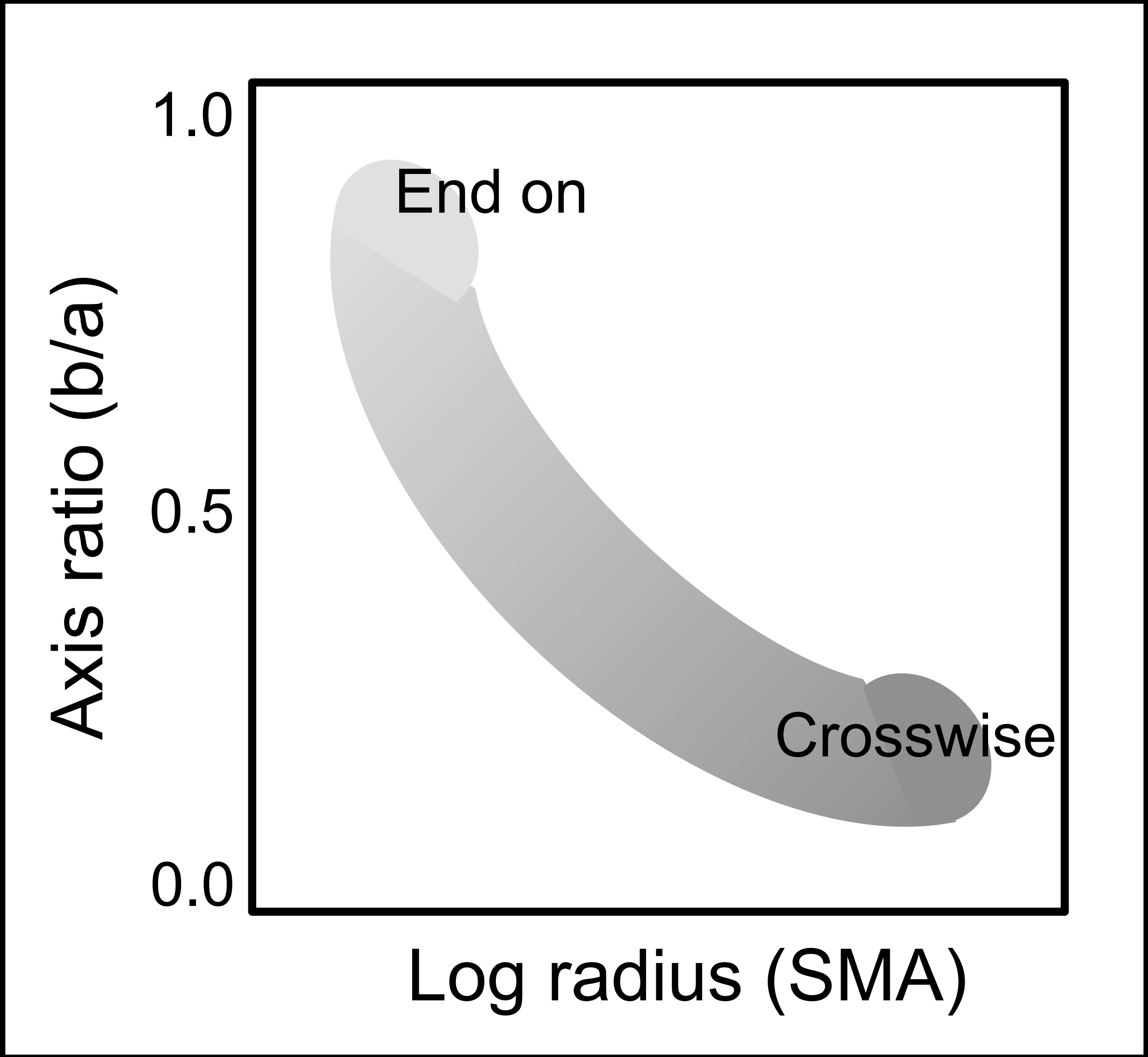




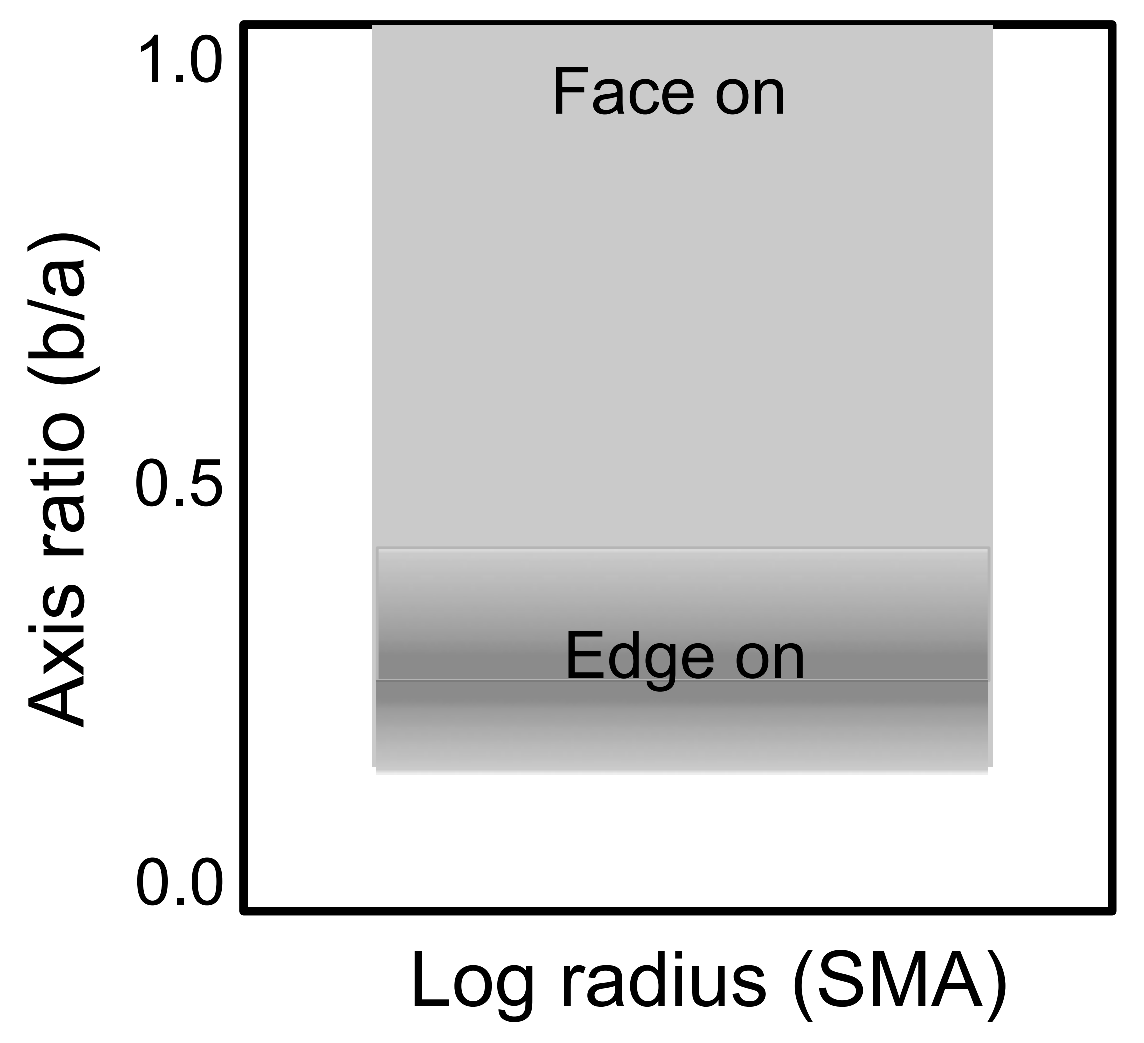
van der Wel+2014

Axis ratio vs. size for prolate galaxies vs. disky galaxies

Prolate spheroids with c/a ~0.25



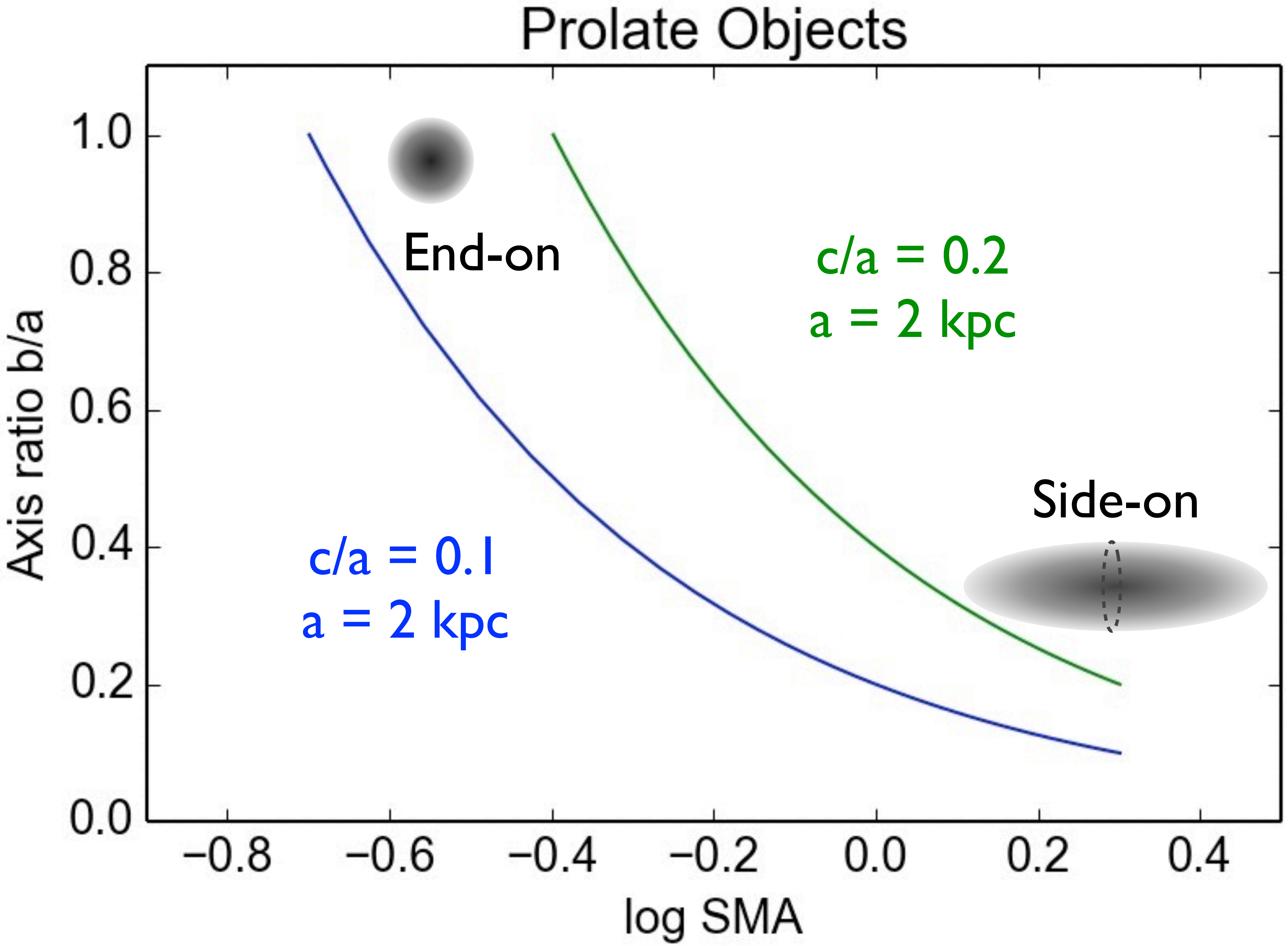
Real disks with axis ratio ~0.25



Sandy Faber

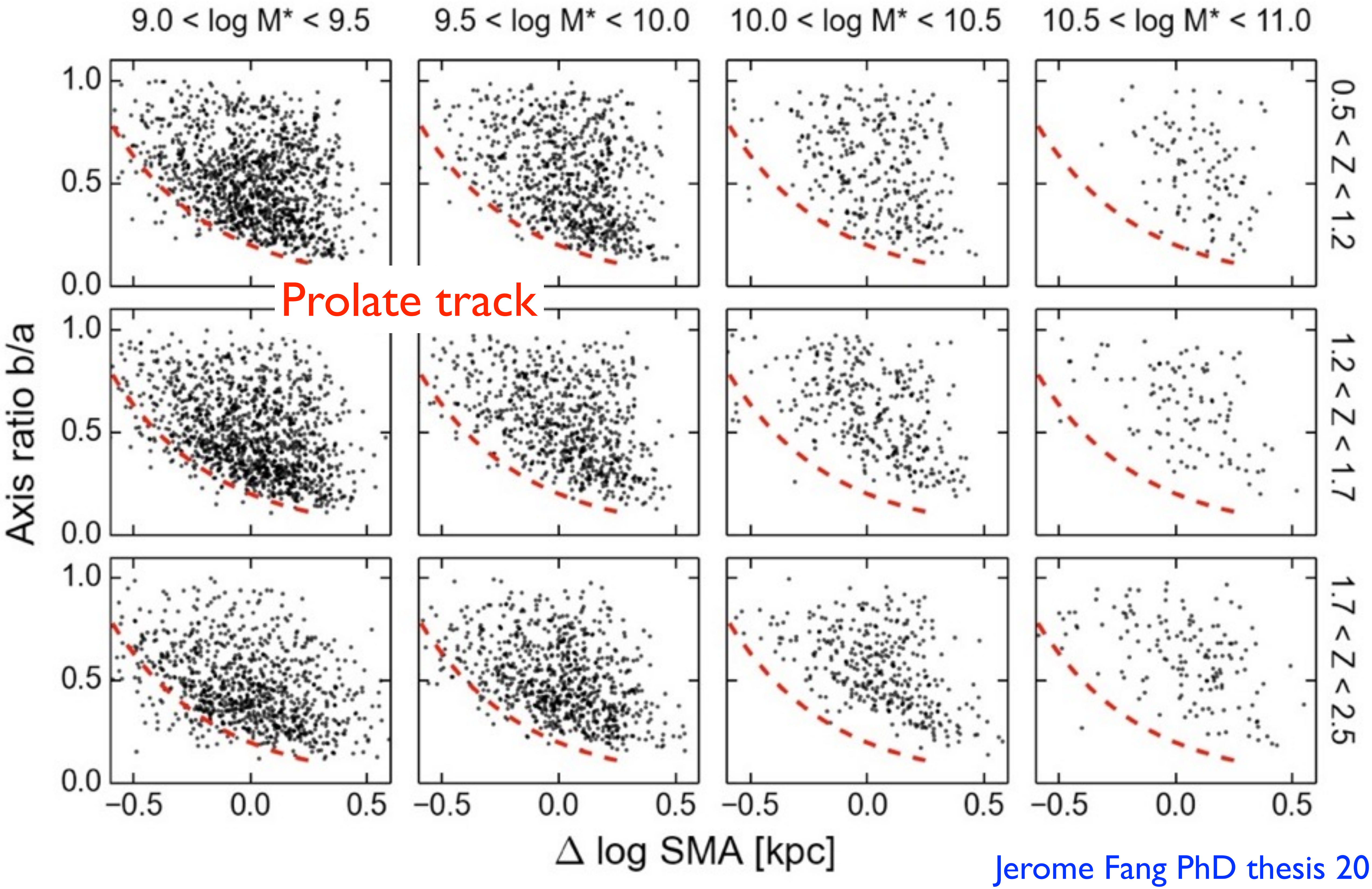
Further confirmation: axis ratio b/a vs. semi-major axis a

Prolate objects trace out curved tracks.



Jerome Fang PhD thesis 2015

A curved boundary is seen in nearly all panels.

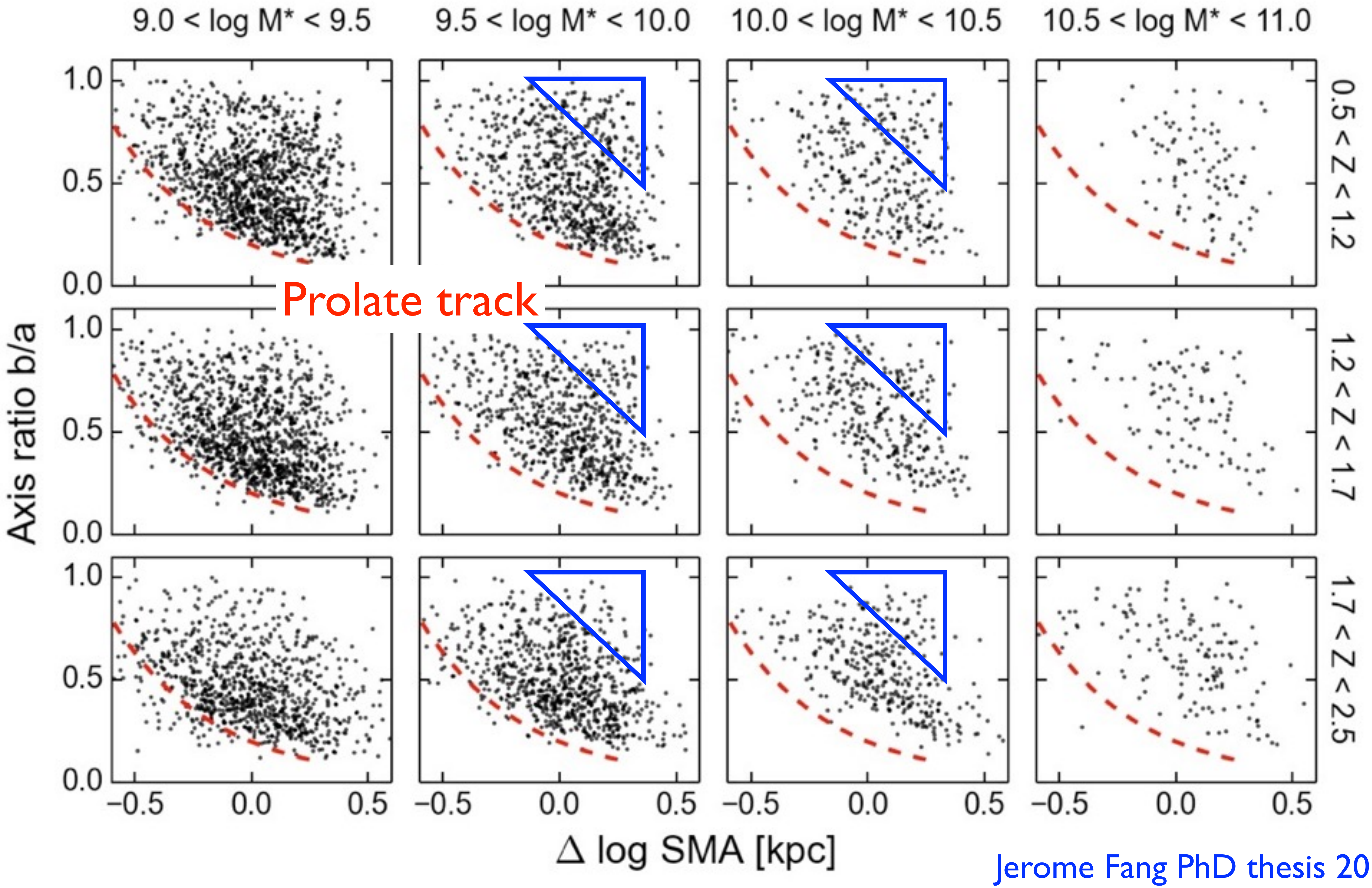


Prolate track

Jerome Fang PhD thesis 2015

A curved boundary is seen in nearly all panels.

Disks are seen to emerge after z ~ 1.5.

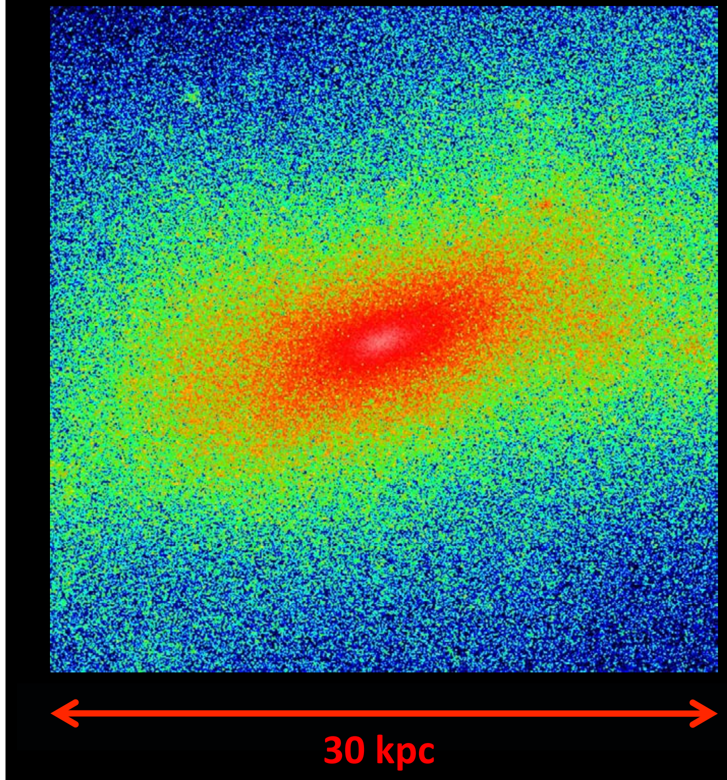


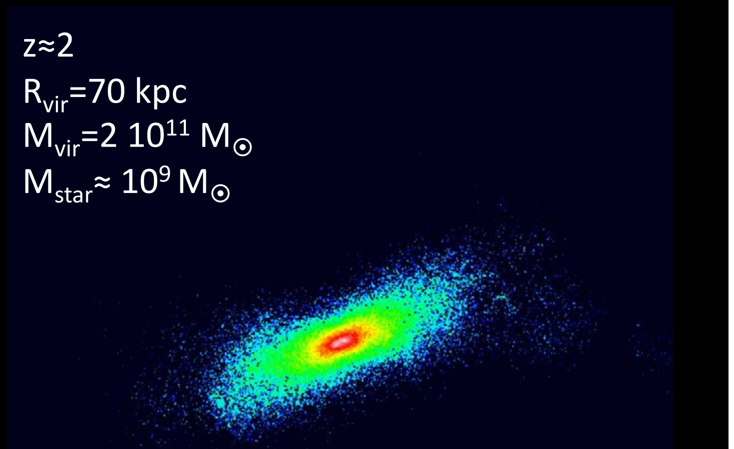
Jerome Fang PhD thesis 2015

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**





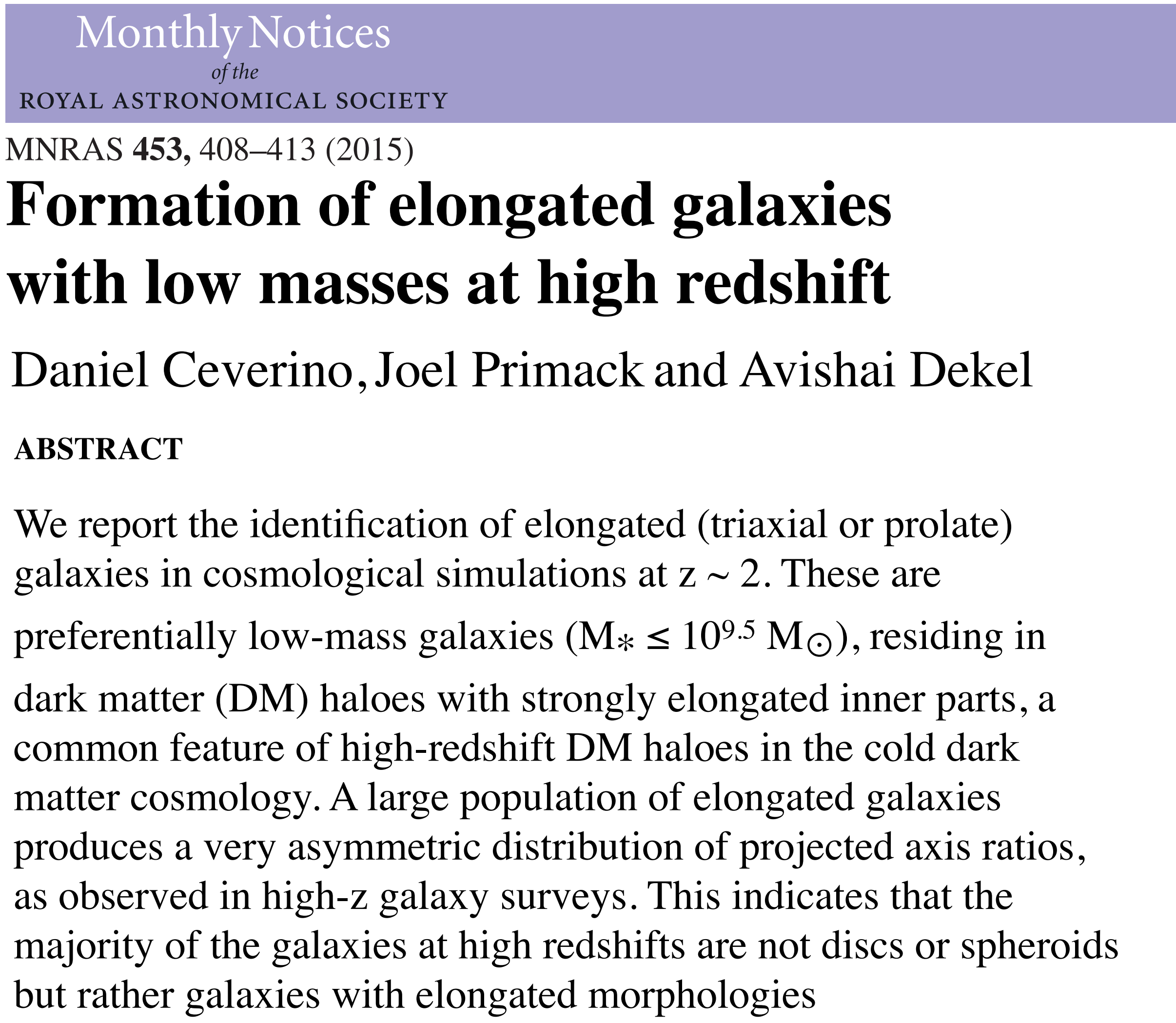
$z \approx 2$

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

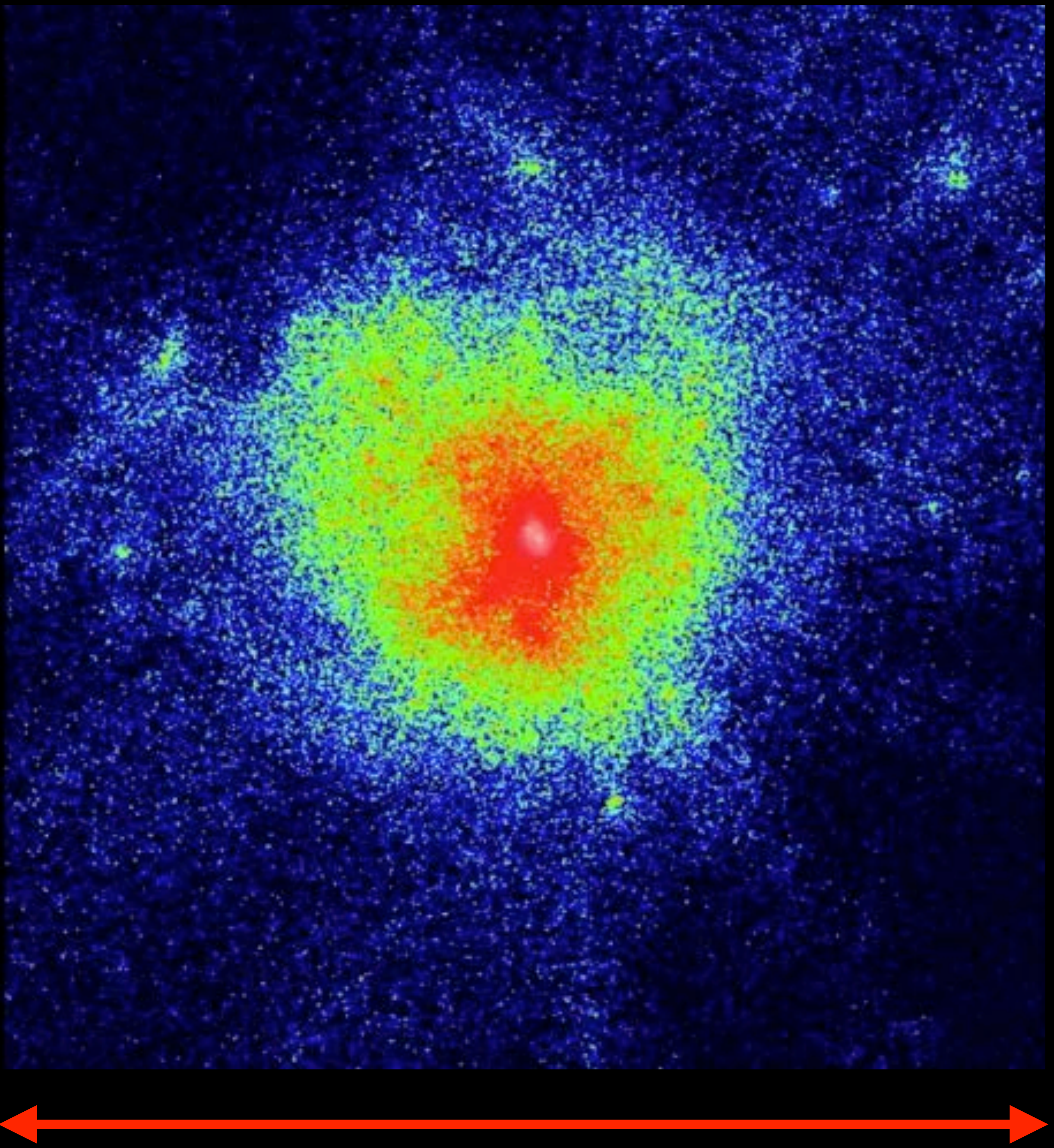
We report the identification of elongated (triaxial or prolate) galaxies in cosmological simulations at z ~ 2. These are preferentially low-mass galaxies ($M_* \leq 10^{9.5}$ $M_\odot$), residing in dark matter (DM) haloes with strongly elongated inner parts, a common feature of high-redshift DM haloes 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 zucchinis.

Our cosmological zoom-in simulations often produce elongated galaxies like observed ones. The elongated distribution of stars follows the elongated inner dark matter halo. Here we show the evolution of the dark matter and stellar mass distributions in our zoom-in galaxy simulation VELA28, viewed from the same fixed vantage point.

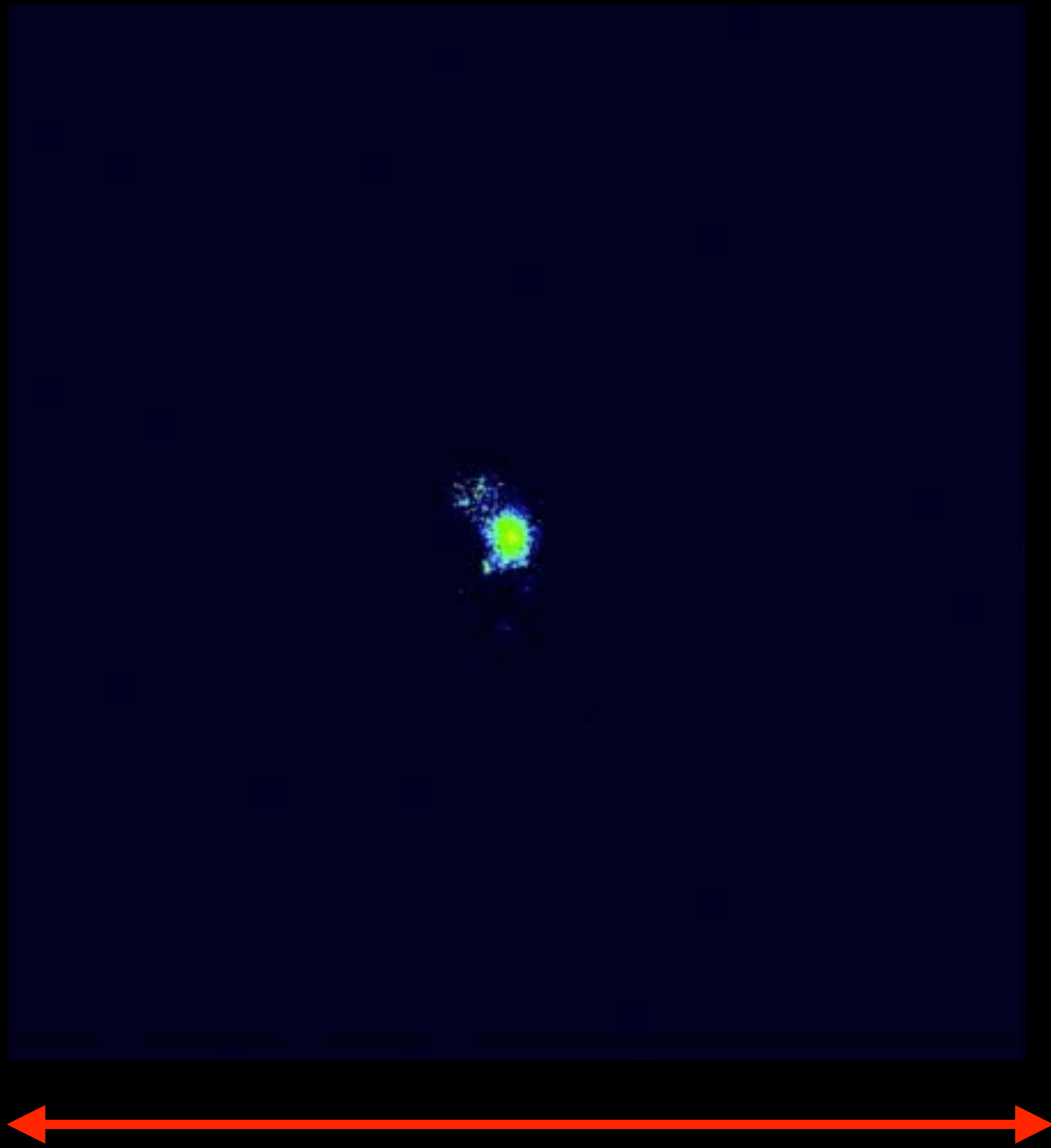
VELA28RP

DM



30 kpc

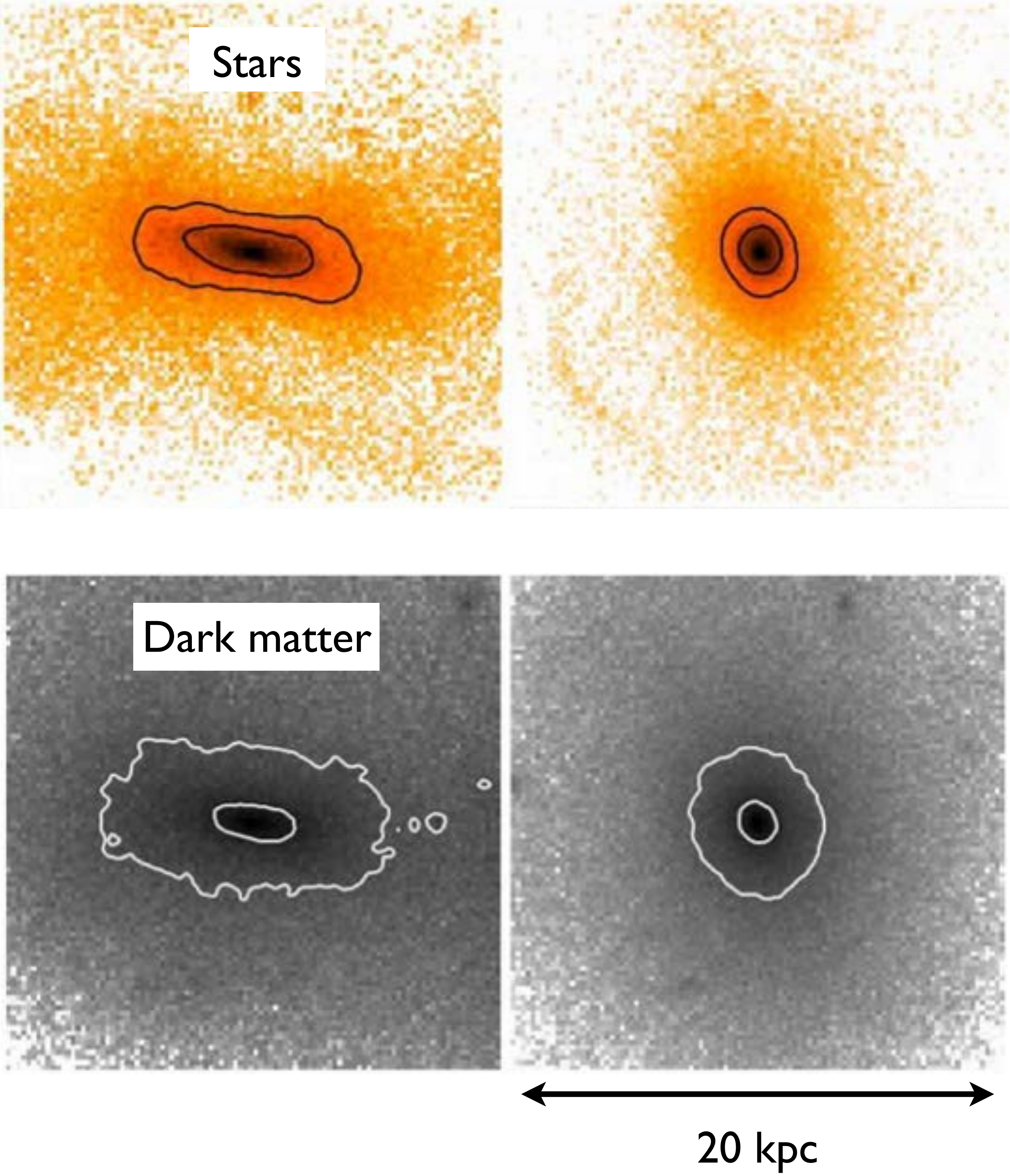
stars



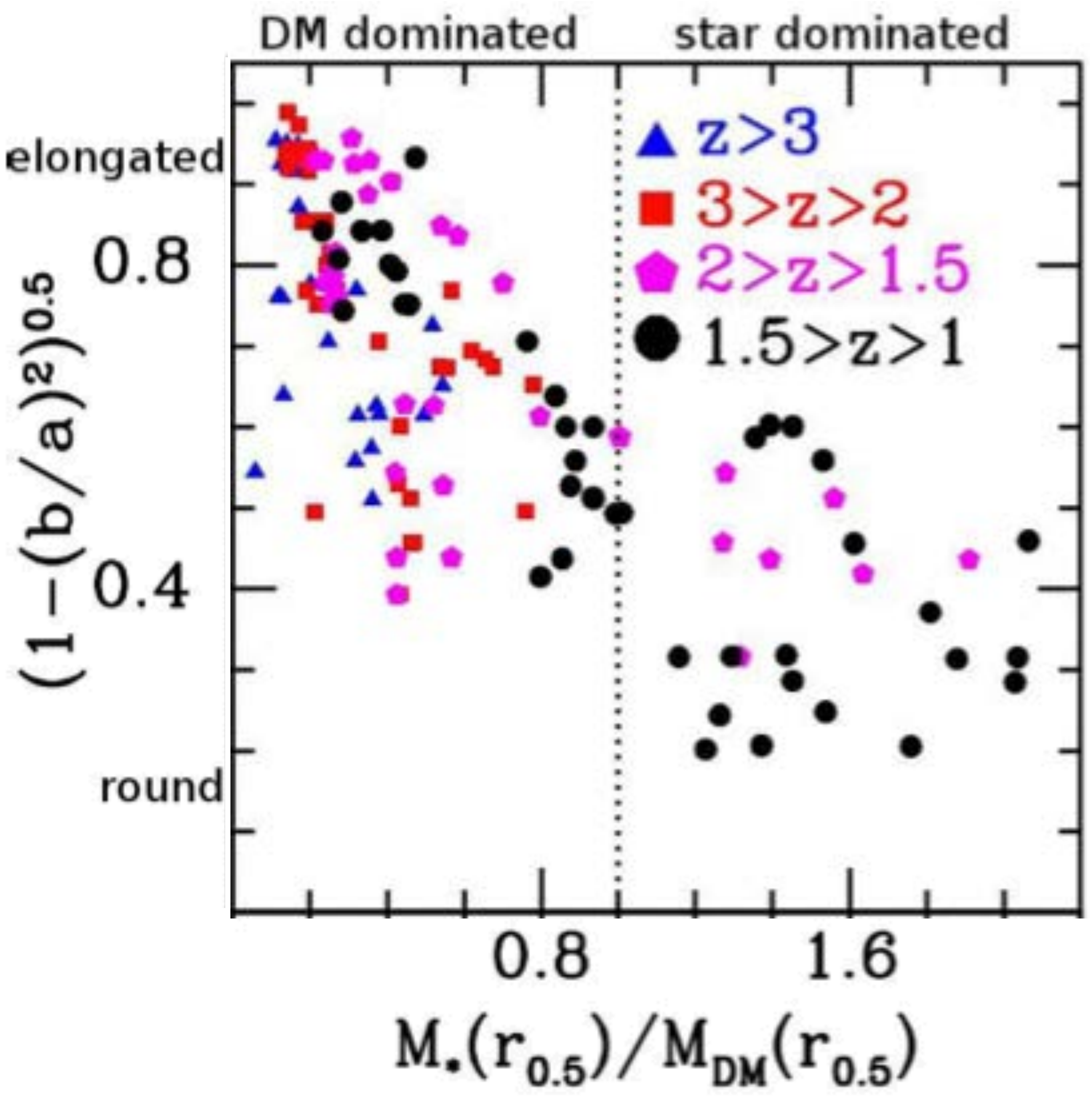
30 kpc

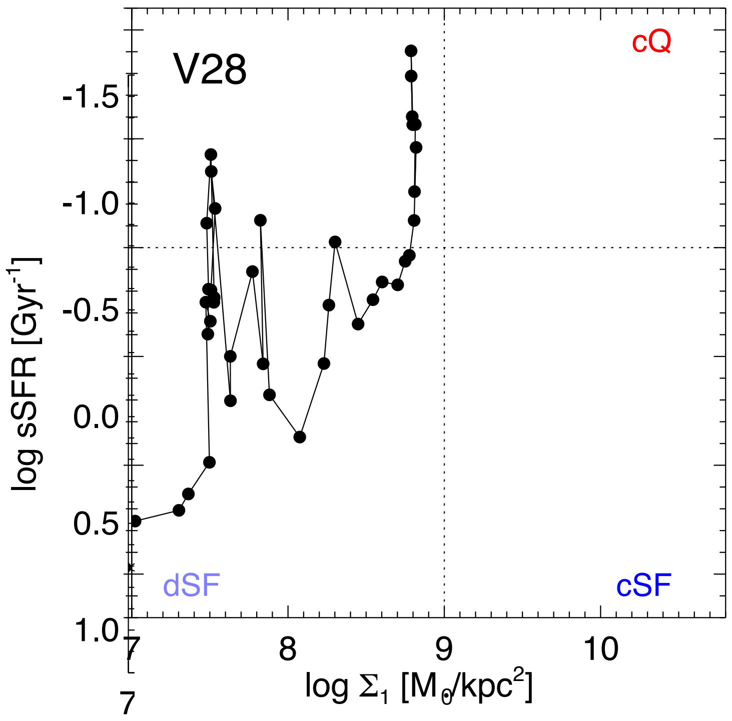
Formation of elongated galaxies with low masses at high redshift

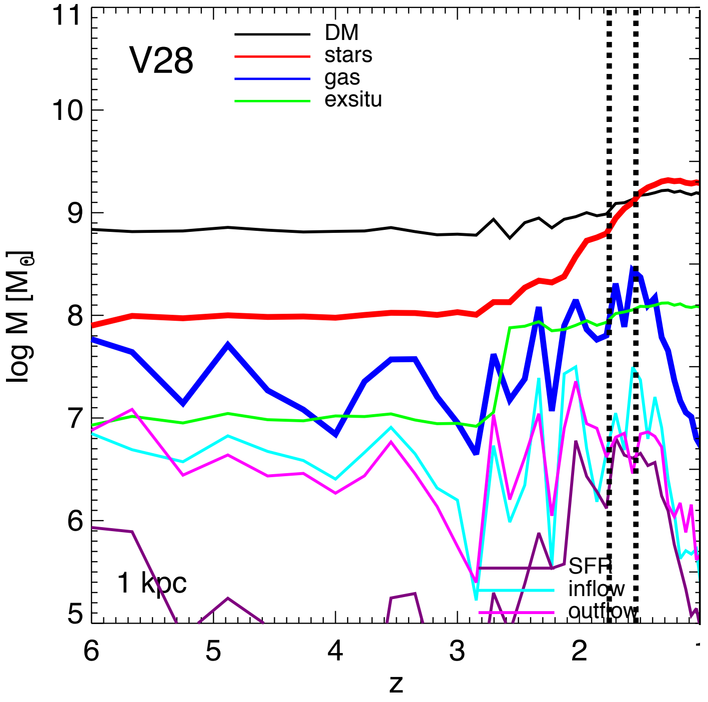
Ceverino, Primack, Dekel **MNRAS 453, 408 (2015)**

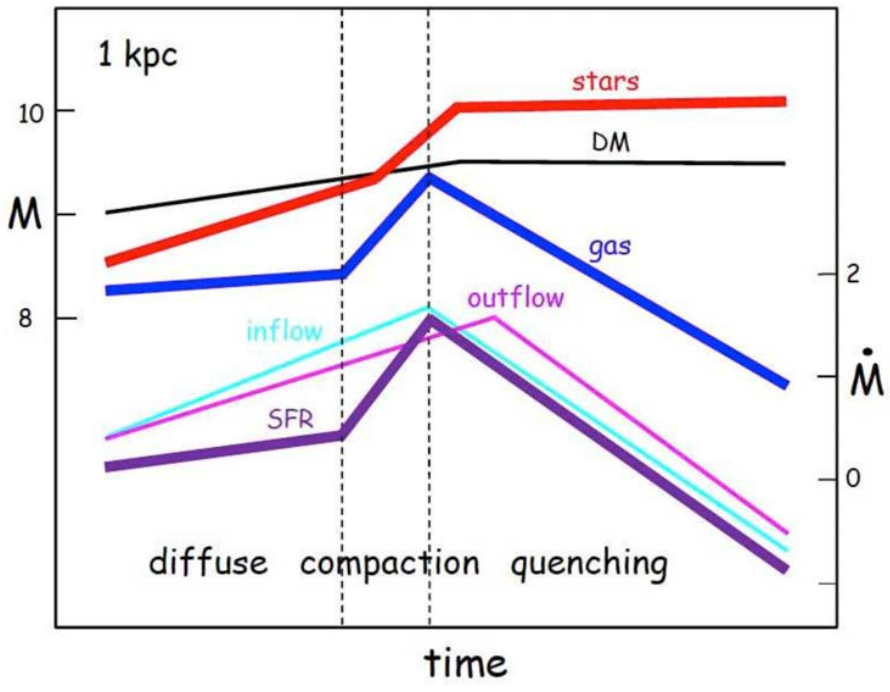


$M_* < 10^{10} M_\odot$ at z=2







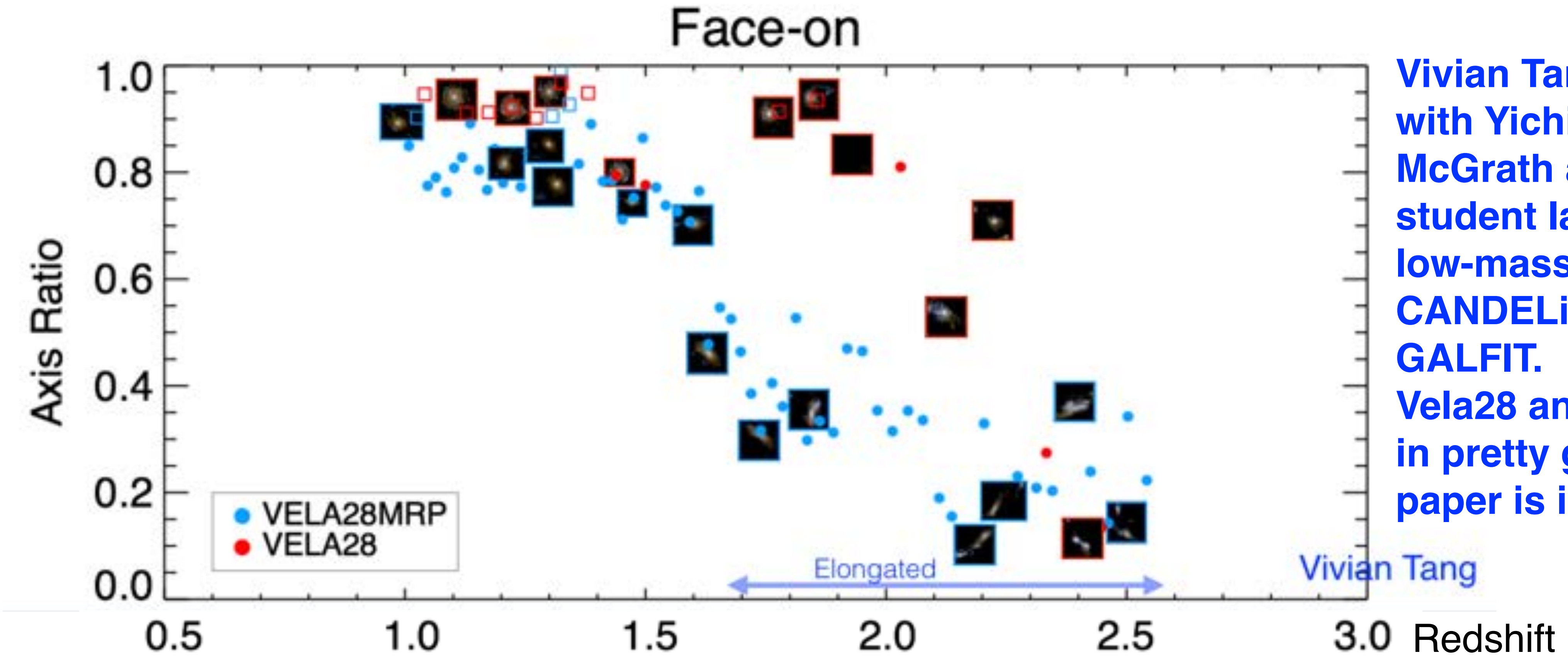


High-z / DM-dominated regime

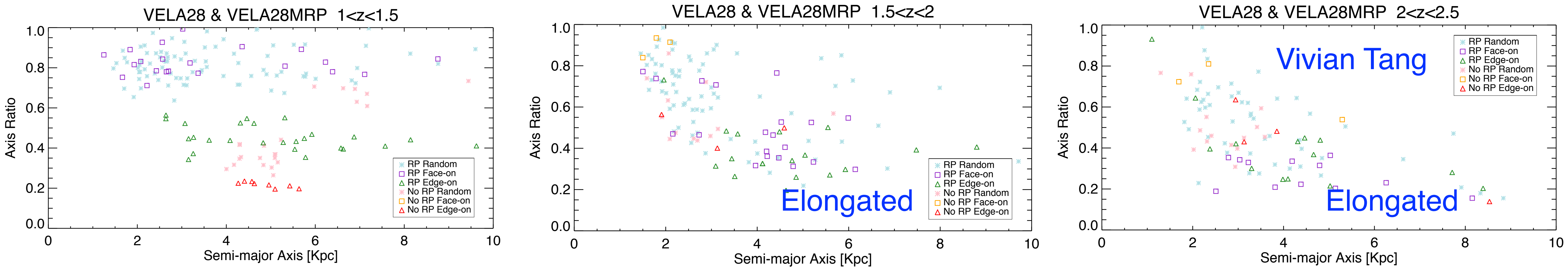
- Stars and DM systems are **prolate** and **mutually aligned**
- The elongation is supported by an **anisotropic velocity dispersion** that results from the assembly of the galaxy via mergers and cold streams along a **dominant filament** of the cosmic web
- Torques exerted by the DM halo are capable of inducing the elongation of the stellar system and its alignment with the halo.

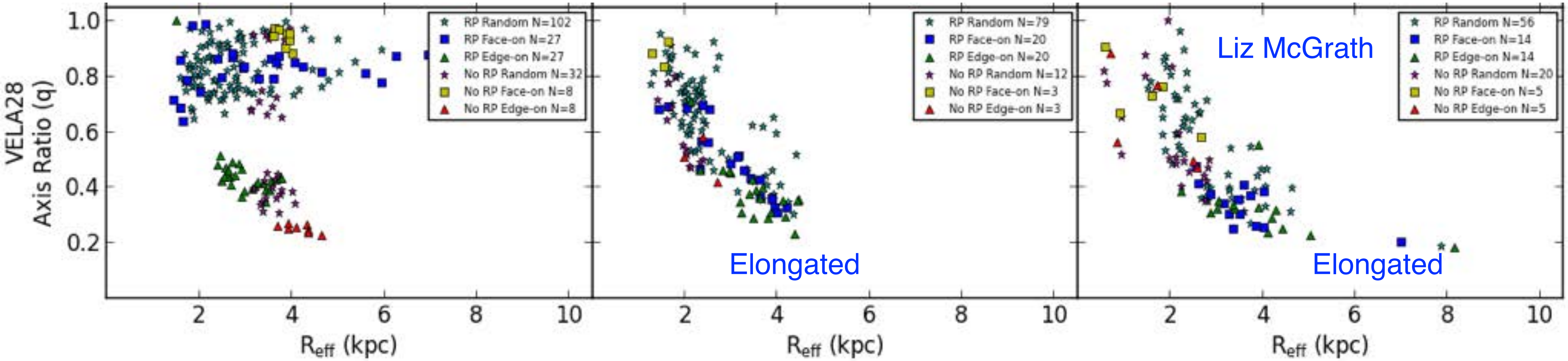
Low-z / Baryon-dominated regime

- Stars and DM systems evolve into a more **spherical / oblate** configuration and they're aligned with the gas disc
- The early elongated phase itself may be responsible for the compaction event by generating angular-momentum loss, and that the transition to the oblate phase may be instrumental in suppressing inflows in the galaxy and thus help driving the subsequent quenching in the core.



Vivian Tang's UCSC senior thesis with Yiching Guo and me, and Liz McGrath and her Colby College student Ian Tibbetts analyzed all the low-mass Vela and Vela-RP mock CANDELized images run through GALFIT. Below are comparisons for Vela28 and 28RP. All results are in pretty good agreement, and a paper is in preparation.

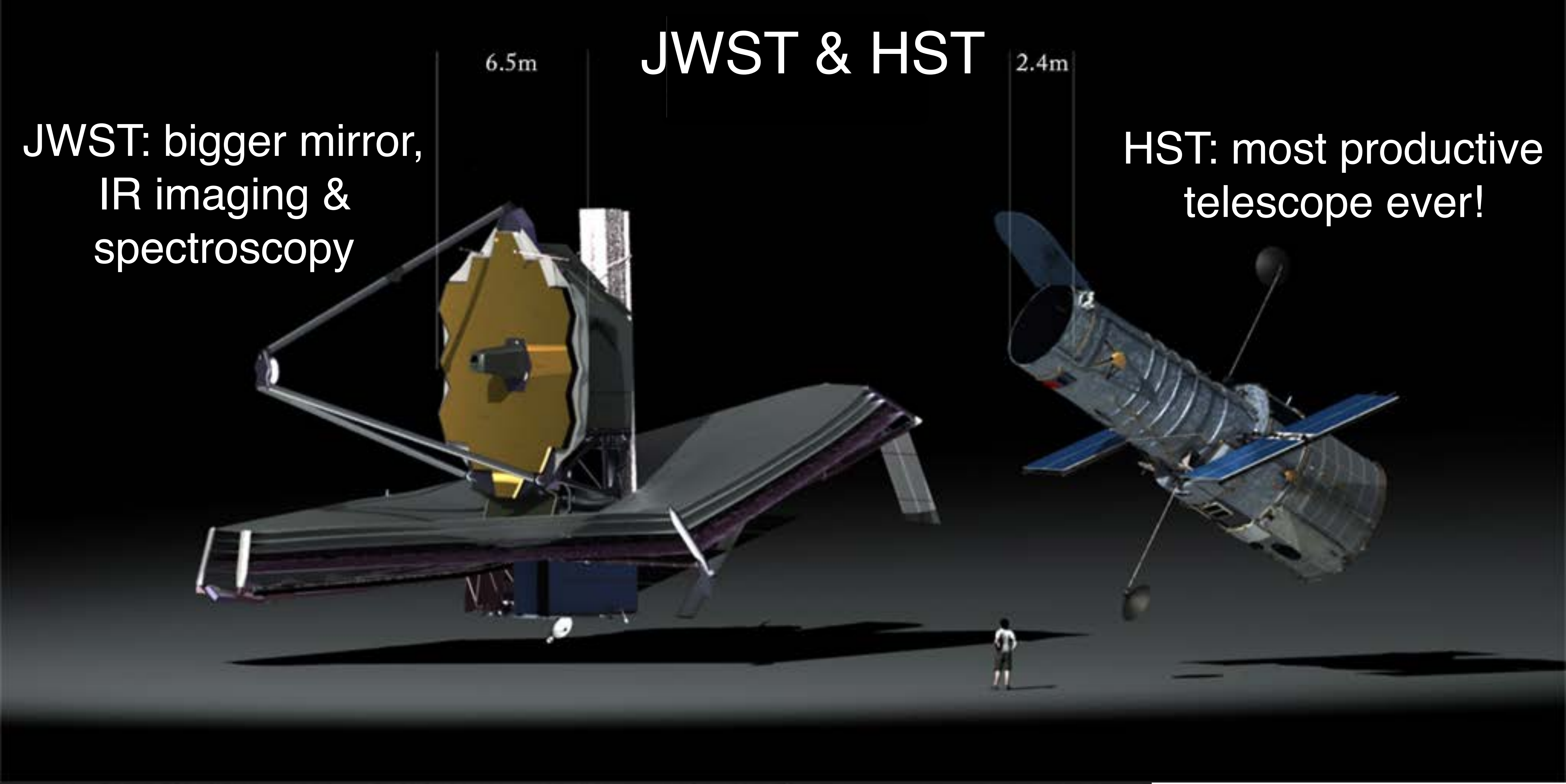


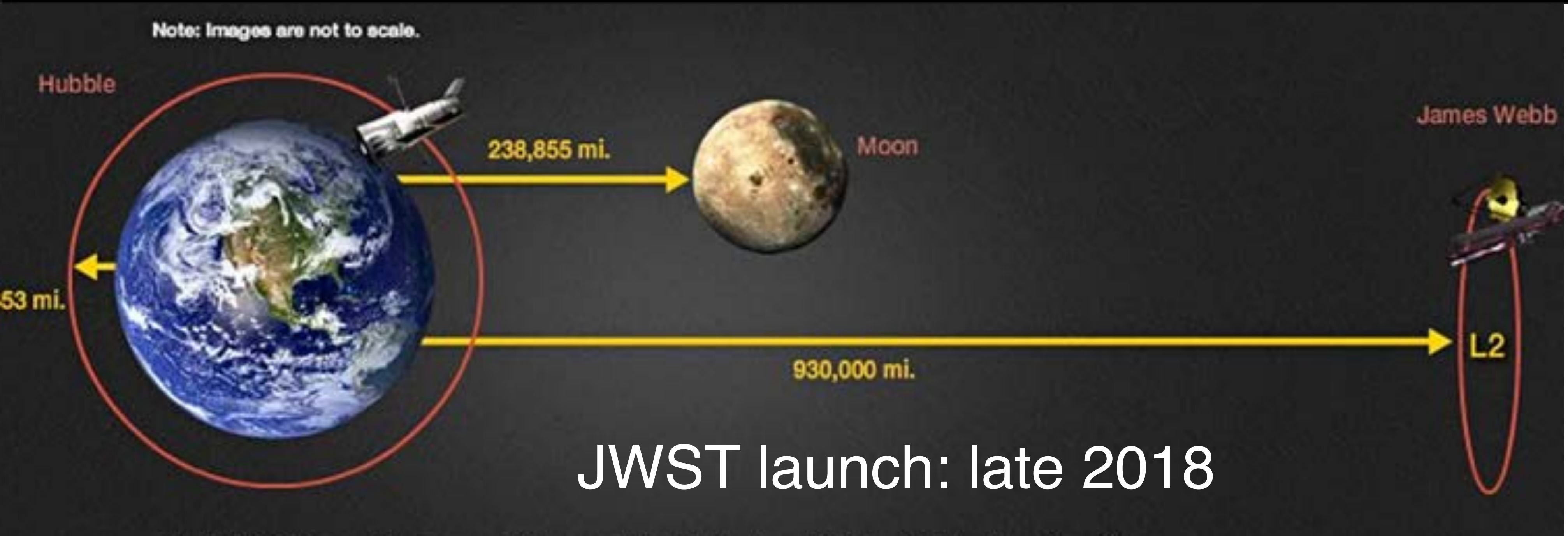


JWST & HST

JWST: bigger mirror, IR imaging & spectroscopy

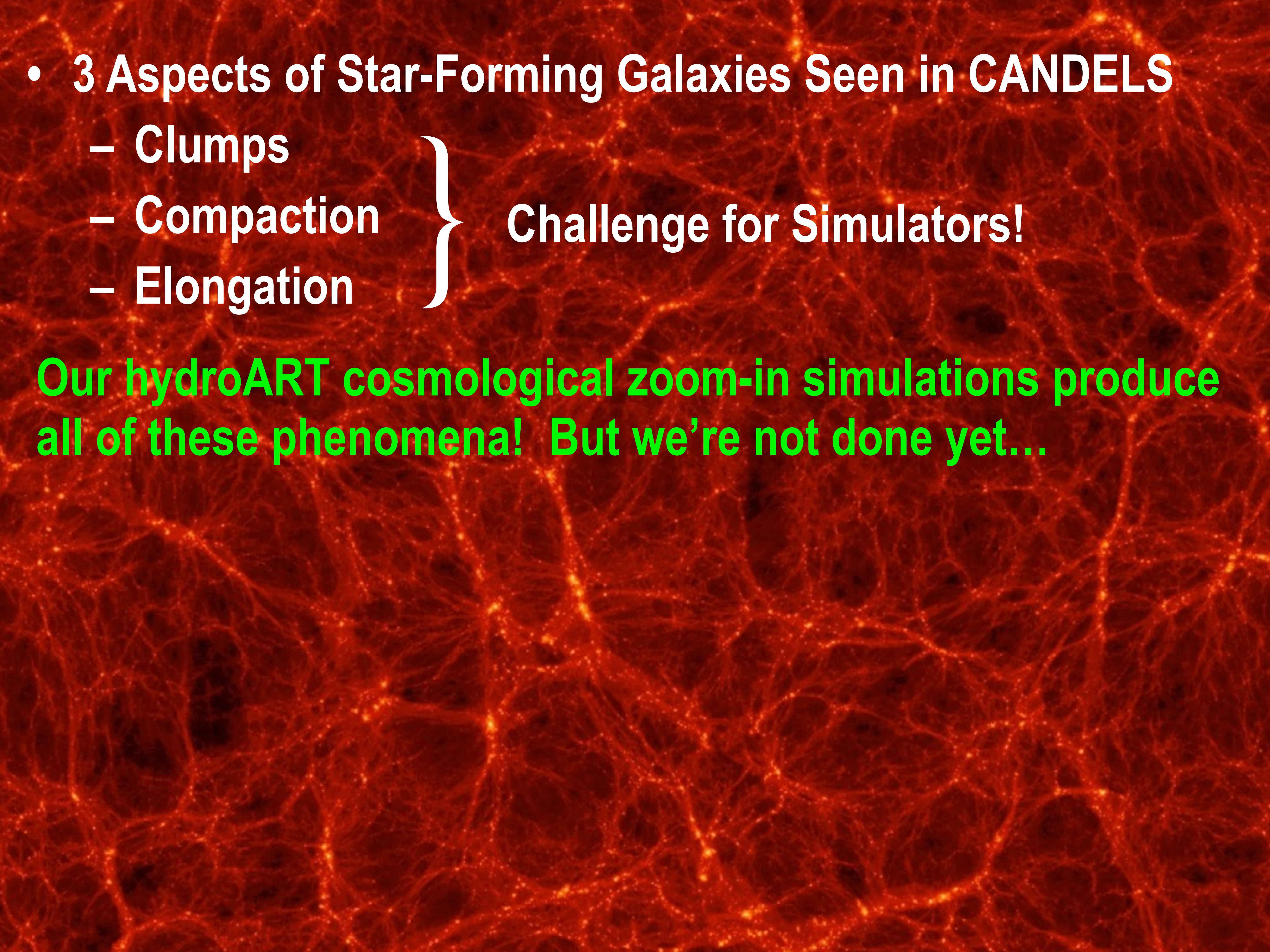
HST: most productive telescope ever!





JWST launch: late 2018

MIRI: Mid Infrared Instrument, 5-28 μm
NIRCam: Near Infrared Camera, 0.6 - 5 μm
NIRISS: Near-InfraRed Imager/SSpectrograph
NIRSpec: Near Infrared Spectrograph, 0.6-5 μm



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

} Challenge for Simulators!

Our hydroART cosmological zoom-in simulations produce all of these phenomena! But we're not done yet…

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

} Challenge for Simulators!

Our hydroART cosmological zoom-in simulations produce all of these phenomena! But we're not done yet…

  - Are the simulations reliable? Resolution? Feedback?
  - Do other simulations produce these phenomena?
  - What are the astrophysical explanations?
    - Clumps apparently *don't* arise from Toomre Q<1
    - What causes Compaction? Observational tests?
    - Elongation appears to reflect cosmic filaments

- AGORA Galaxy Simulation Comparison Project

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 Primack, UCSC, Co-Chairs
Tom Abel, Stanford
Nick Gnedin, Chicago/Fermilab
Lucio Mayer, University of Zurich
Romain Teyssier, Zurich
James Wadsley, McMaster

Ji-hoon Kim, Caltech/KIPAC (Coordinator)

~100 astrophysicists have joined AGORA from ~50 institutions in 8 countries using 10 simulation codes

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 $z\sim1$: $\sim10^{12}$ $M_\odot$

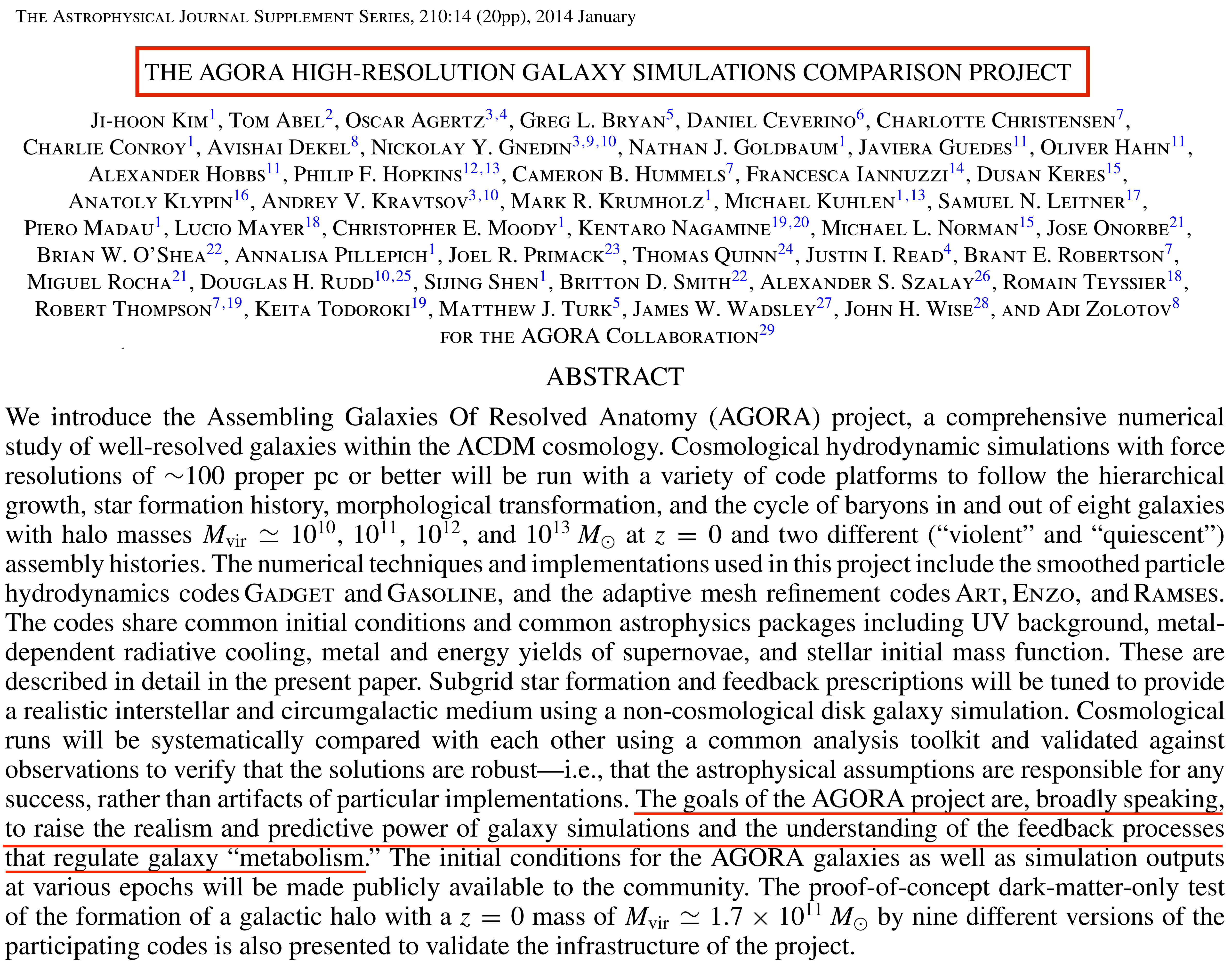
Astrophysics that all groups will include

UV background (Haardt-Madau 2012); 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



The Astrophysical Journal Supplement Series, 210:14 (20pp), 2014 January

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], Dusan Keres[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 Onorbe[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],
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ABSTRACT

We introduce the Assembling Galaxies Of Resolved Anatomy (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 eight 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 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 nine different versions of the participating codes is also presented to validate the infrastructure of the project.

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

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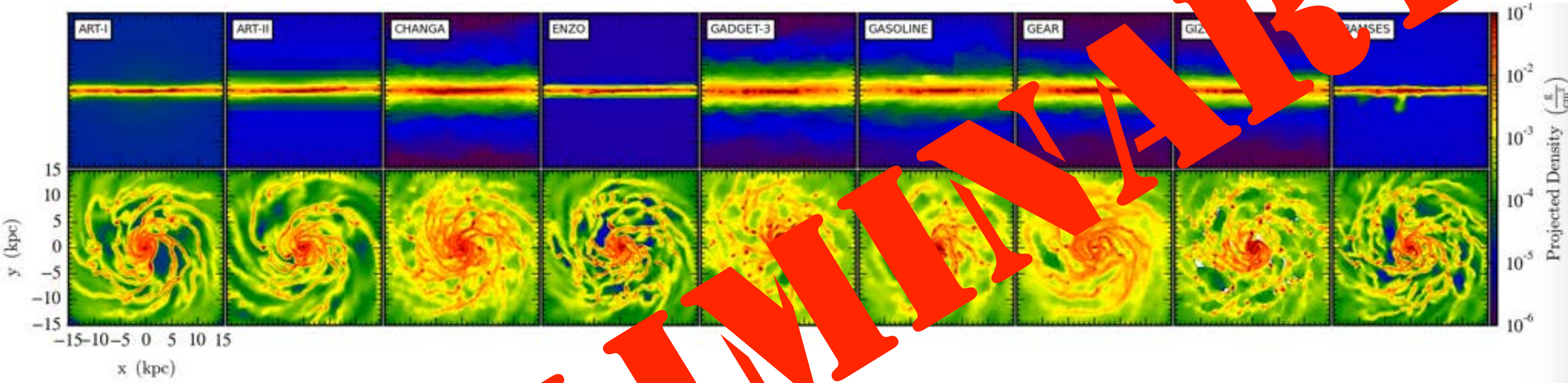
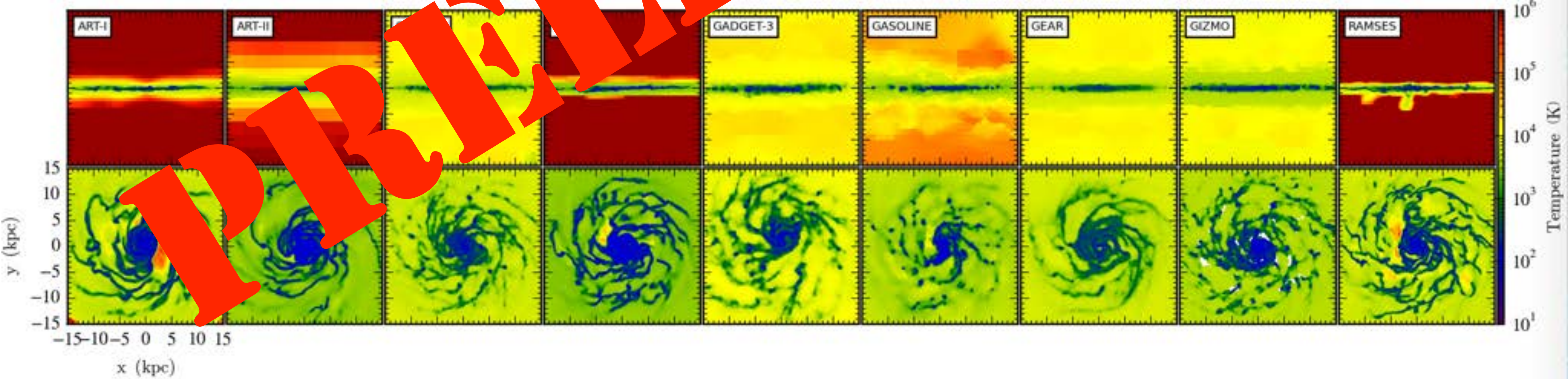
AGORA High-Resolution Simulation Comparison: Isolated Disk Simulations by Nine Code Groups

Work in progress...

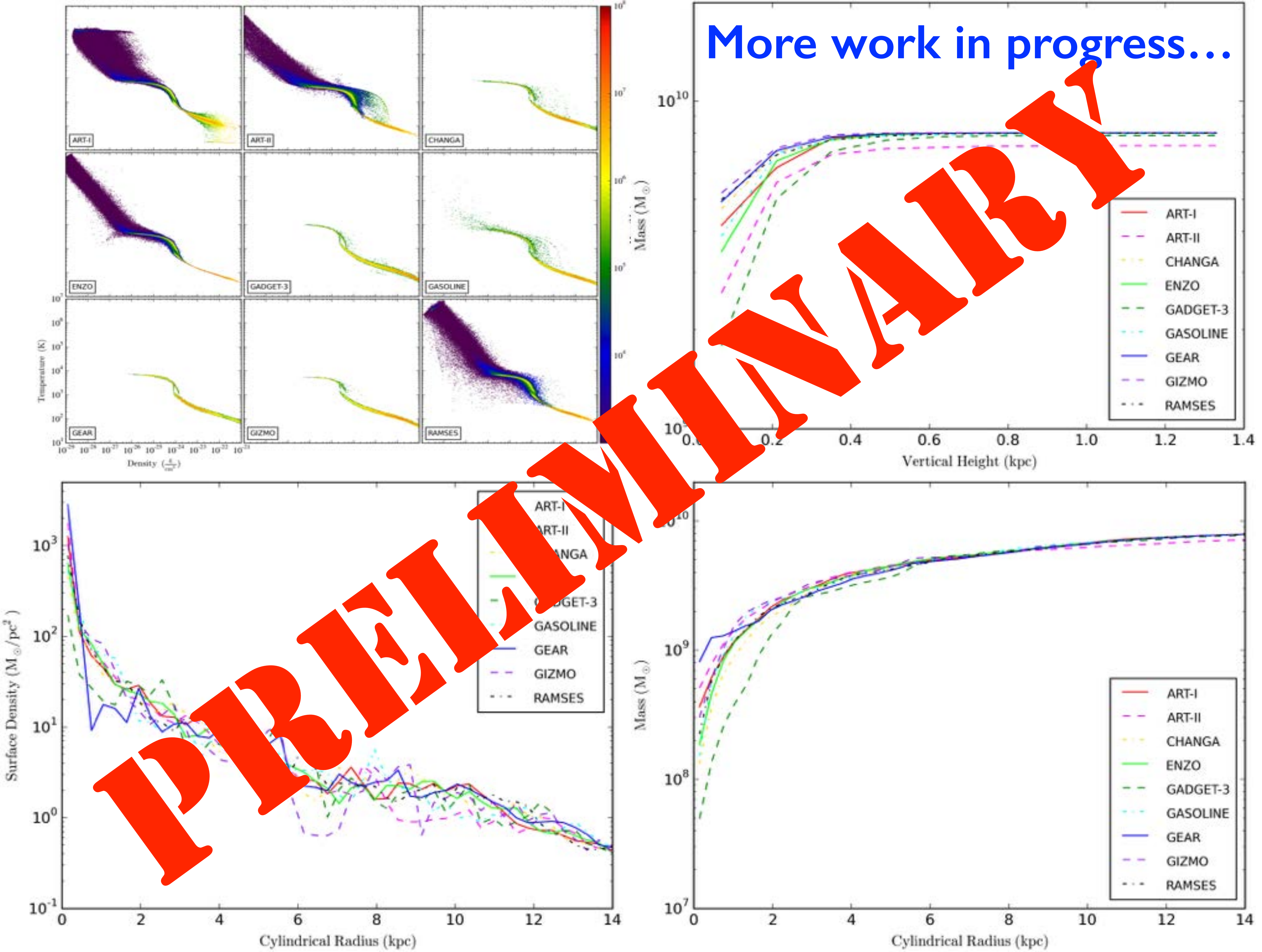
Gas Surface Density Ma[illegible]



Proj[illegible]ted [illegible]mperature Maps



More work in progress…



PRELIMINARY

Summary

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

All of these are seen in our simulations!

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!