CosmoClub UC Santa Cruz 10 October 2016

Galaxy Formation: Simulations vs. Observations

Joel Primack

UCSC

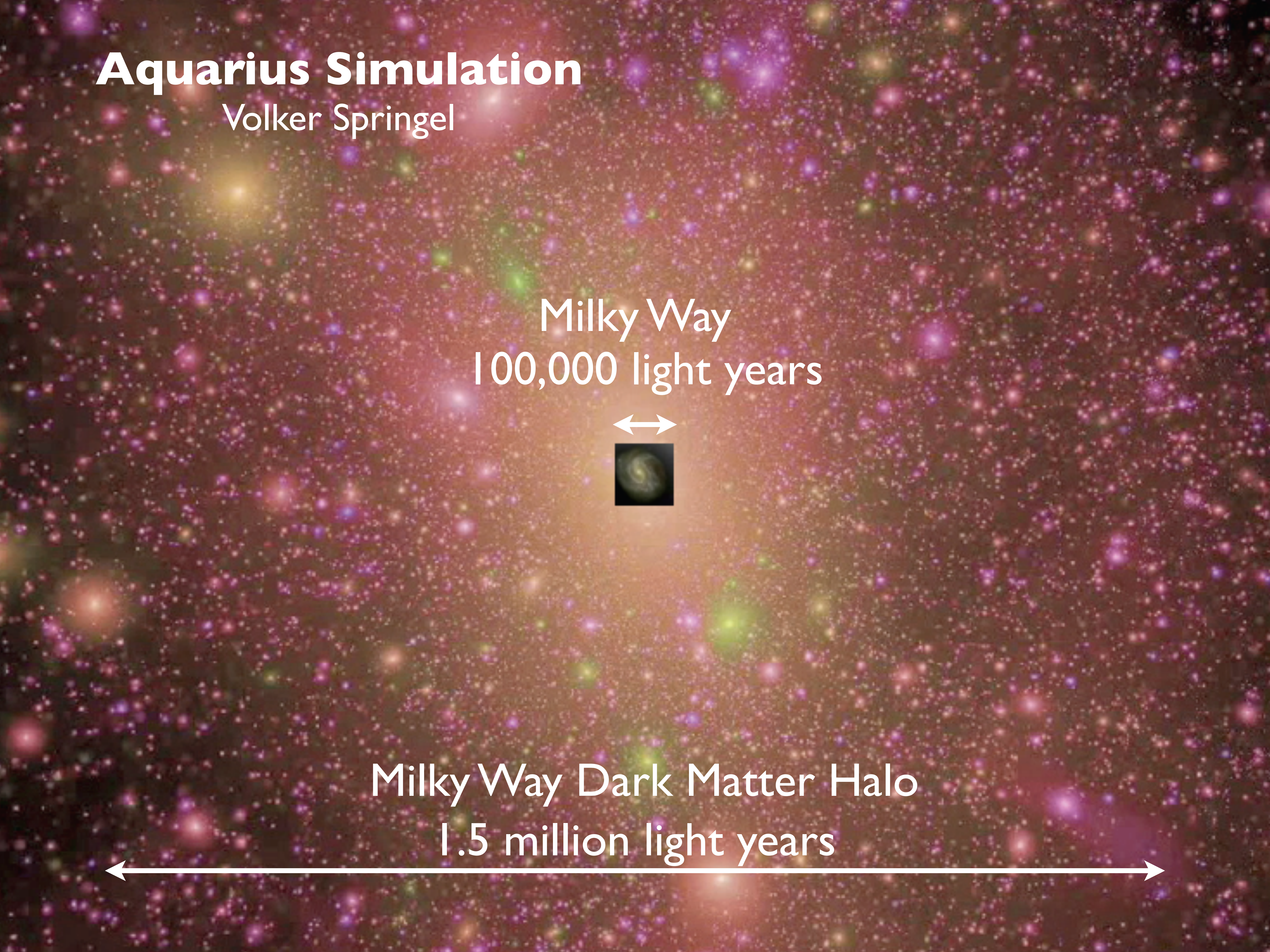
1. Dark Matter Still Matters
2. Stellar - Halo Accretion Rate Co-evolution (SHARC)
3. Galaxy Morphology Also Matters
4. Assembling Galaxies of Resolved Anatomy (AGORA)

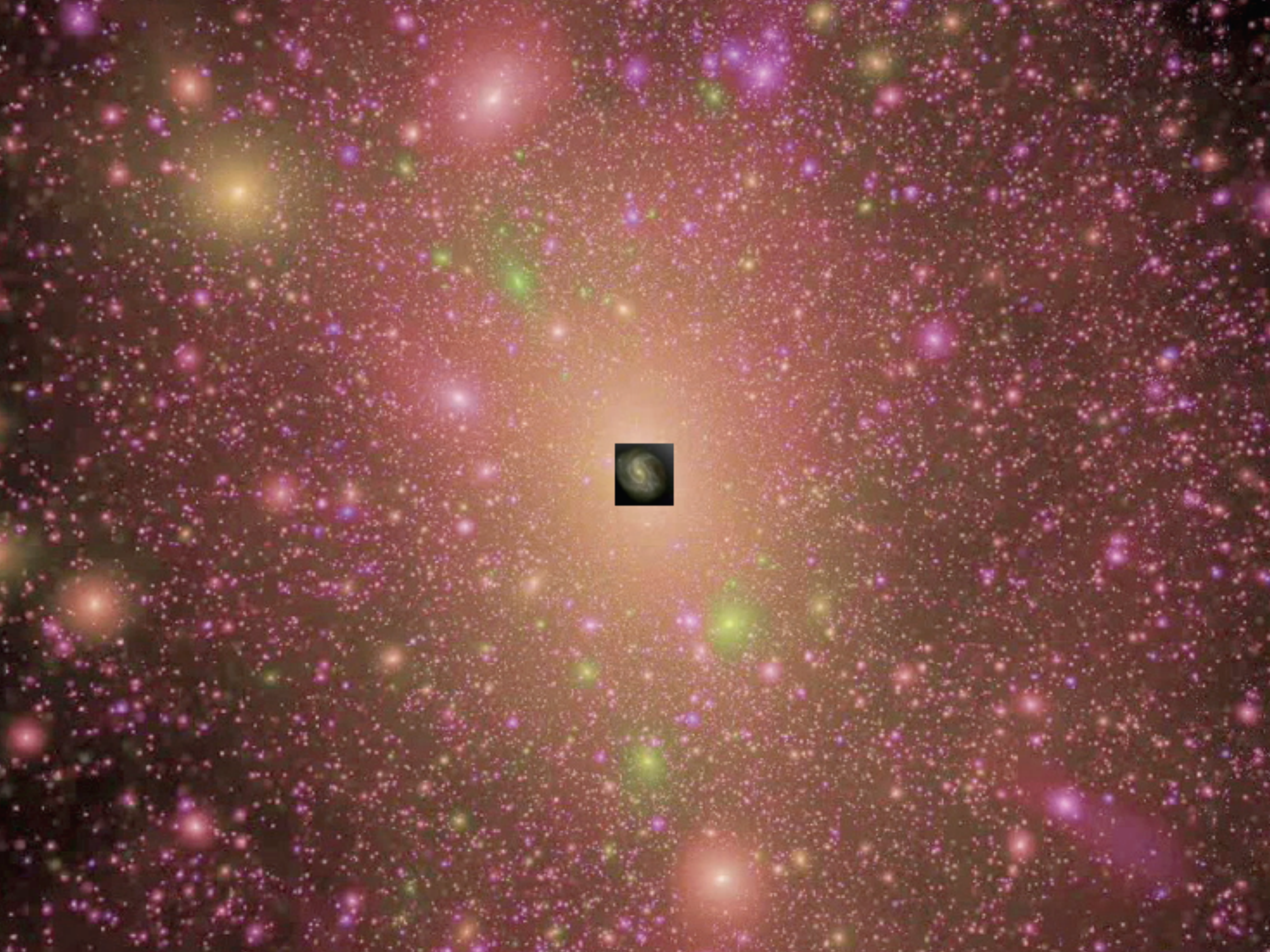
Cosmological Simulations

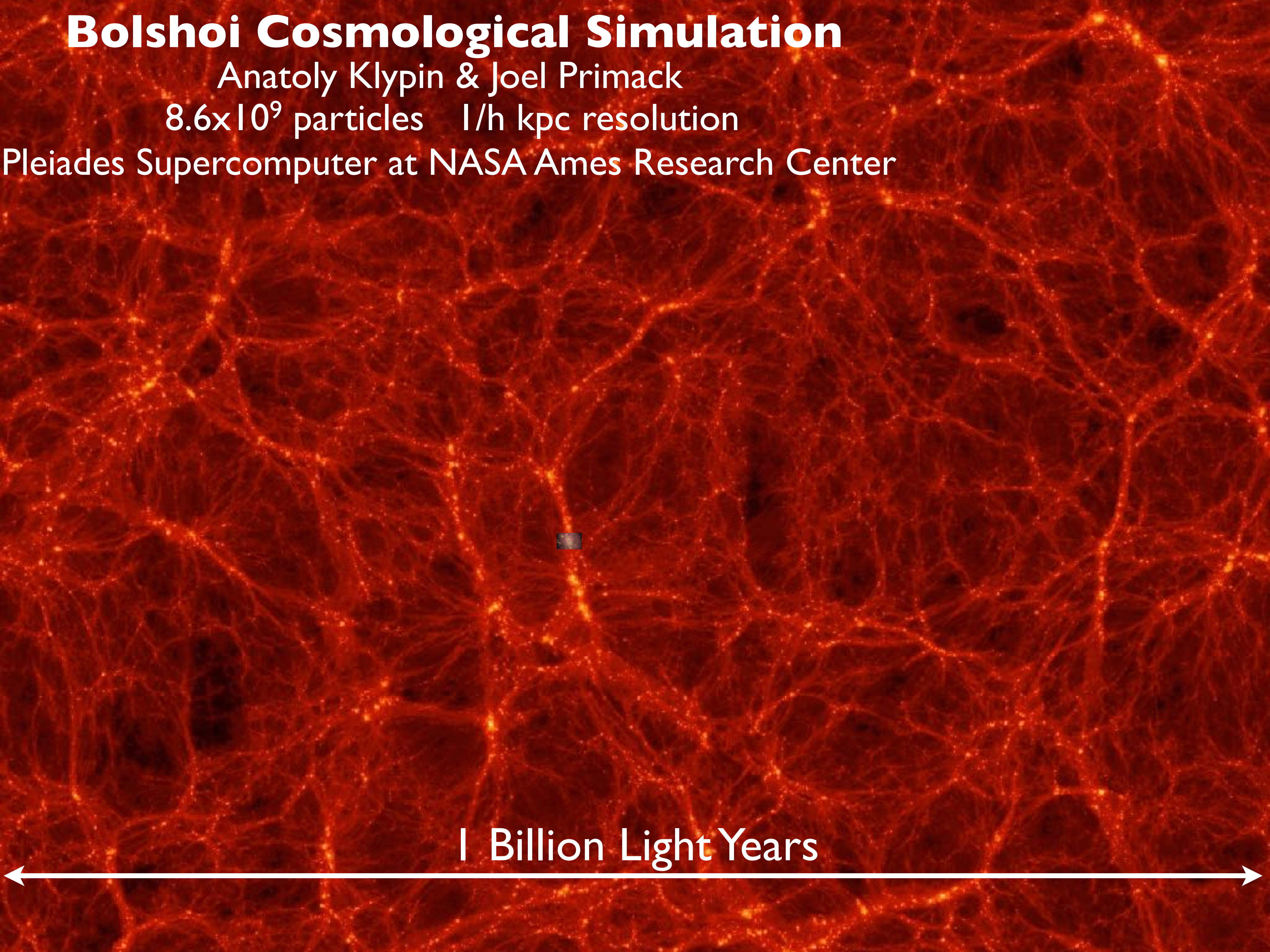
Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

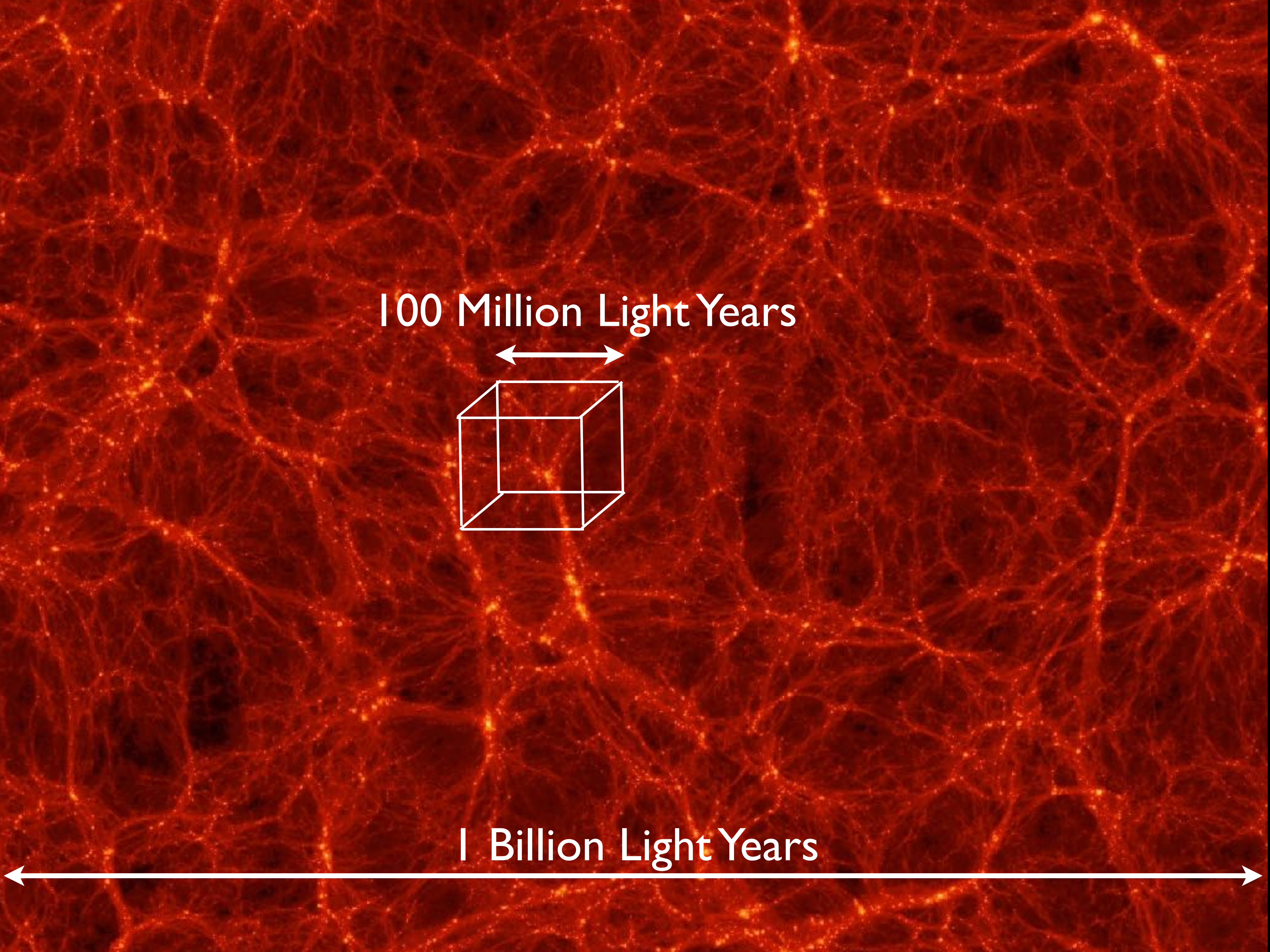
Cosmological dark matter simulations show large scale structure and dark matter halo properties, basis for semi-analytic models

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


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
1 Billion Light Years


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

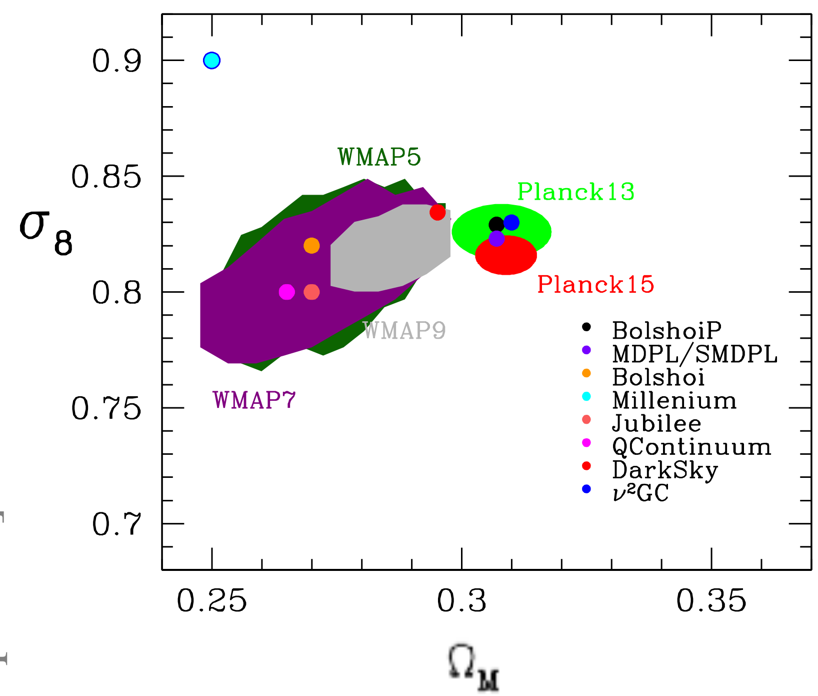
Peter Behroozi & Christoph Lee

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

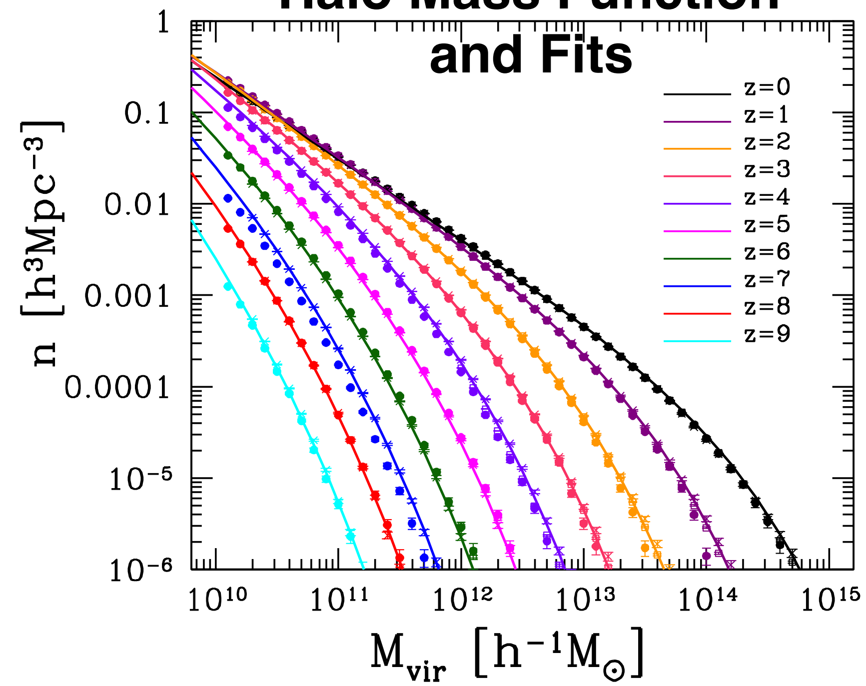
Aldo Rodrìguez-Puebla, Peter Behroozi, Joel Primack, Anatoly Klypin, Christoph Lee, Doug Hellinger

MNRAS 462, 893 (2016)

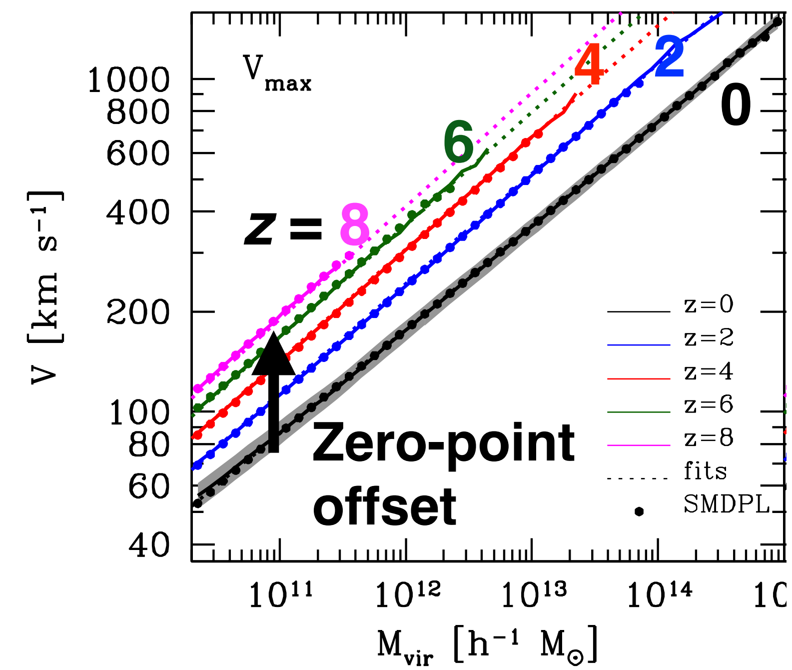
Cosmological Simulations



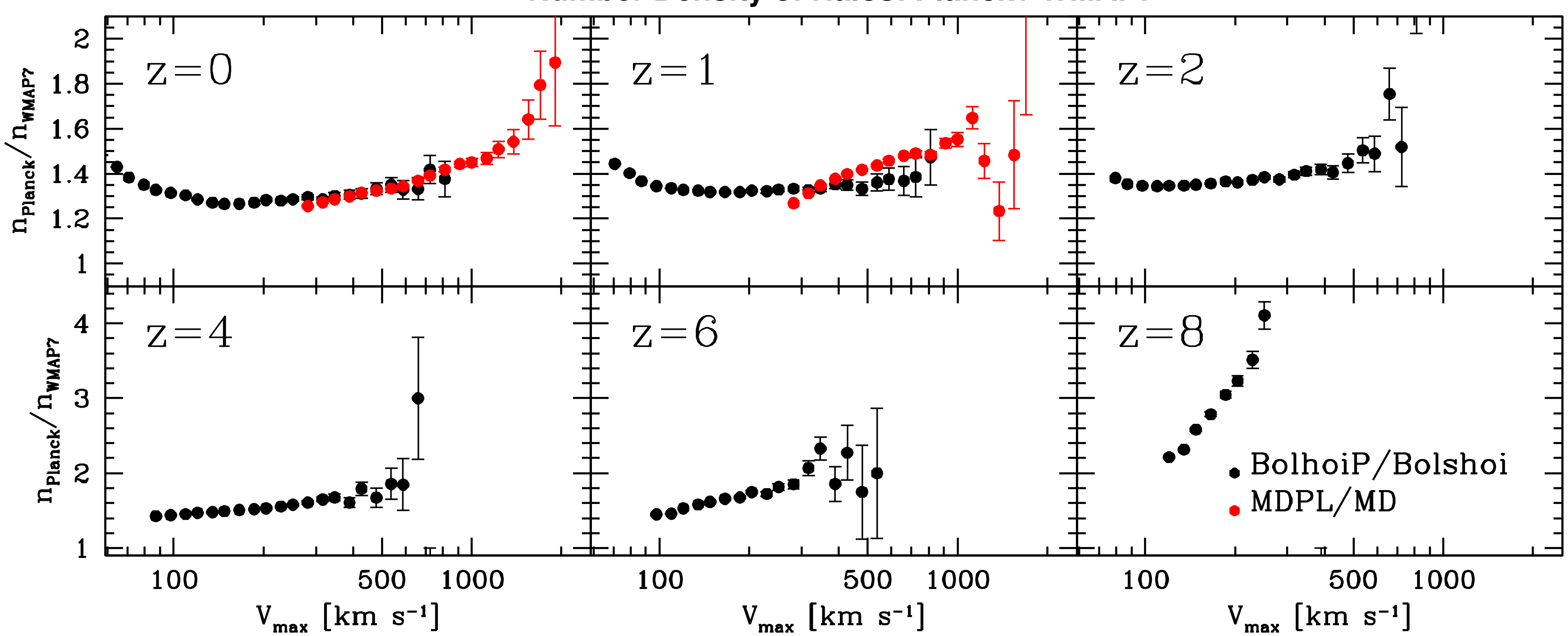
Halo Mass Function and Fits



$V_{max}(M_{vir}, z)$



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.

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

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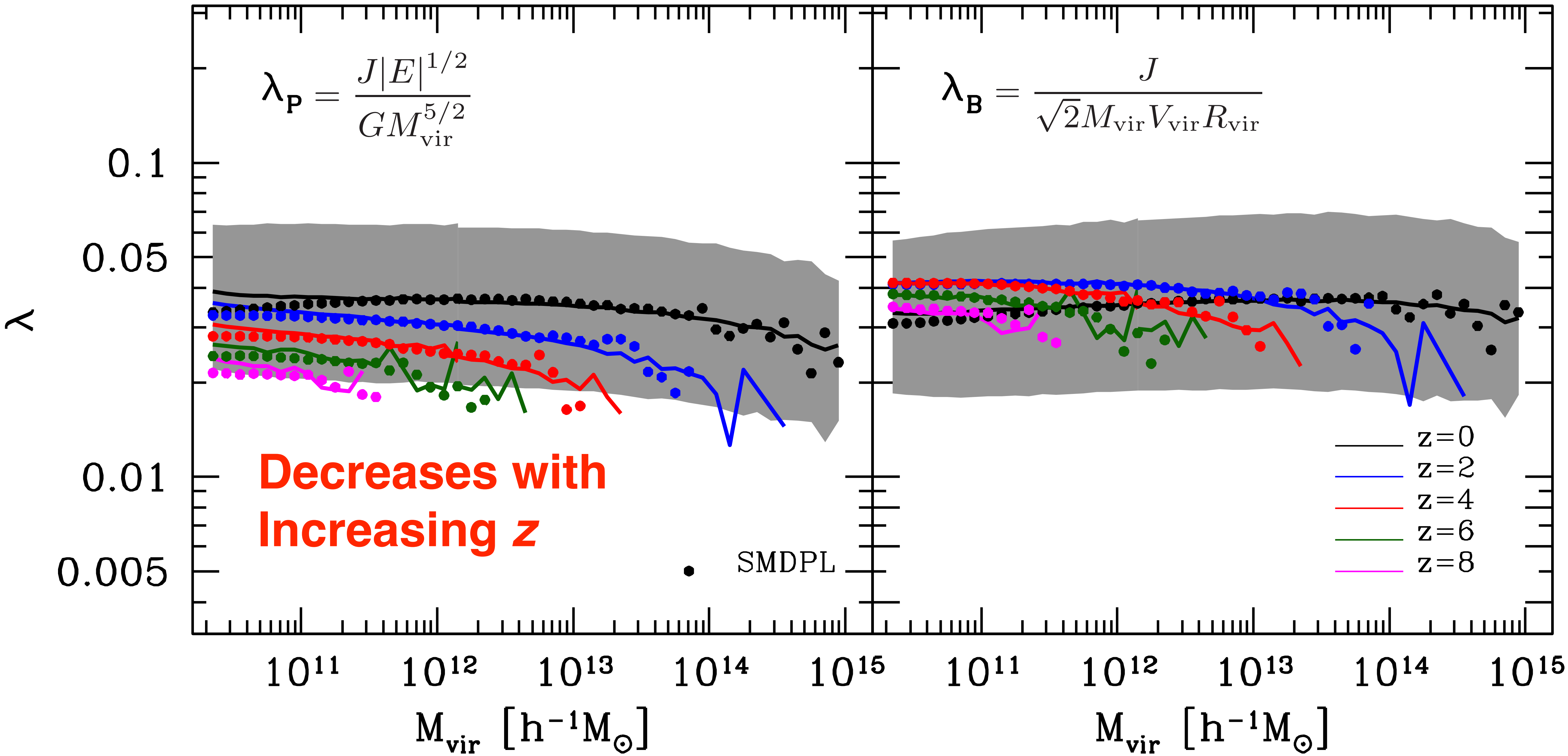
Dark Matter Halo Spin Parameter as a function of Mvir.



Medians are shown as the solid lines. At z = 0 the grey area is the 68% range of the distribution.

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

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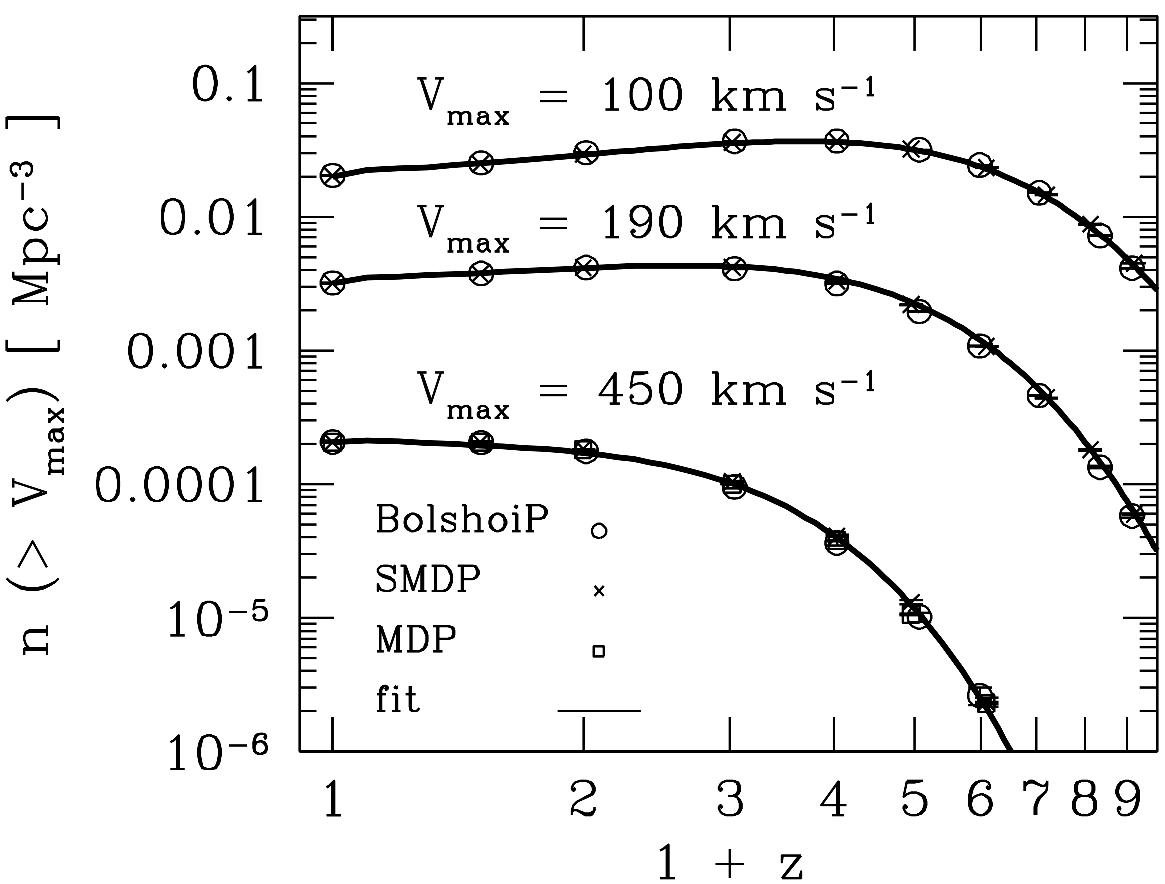
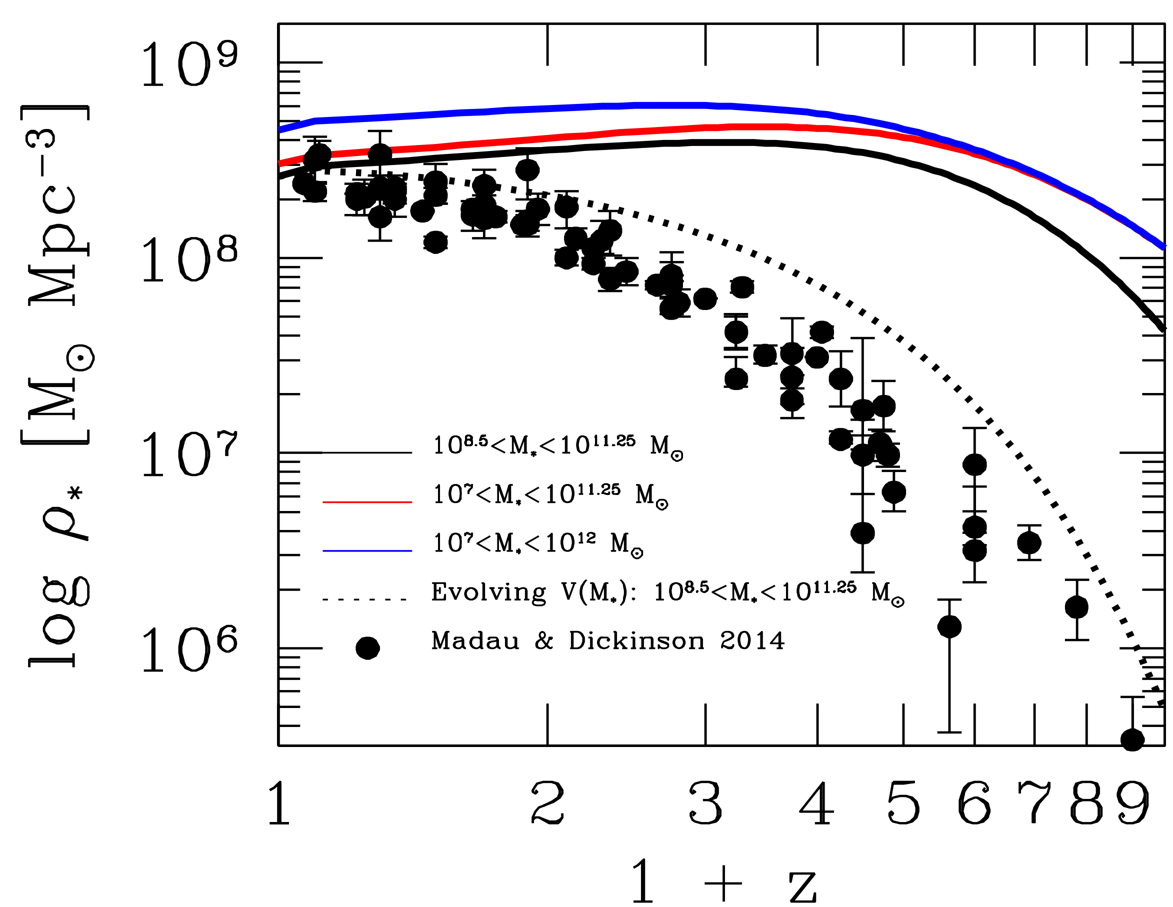
Halo Number Density





The cumulative number of halos > V_{max} is pretty constant out to redshift z ~ 4 for galaxy-mass halos. But these halos are smaller and denser, so they cannot host high-M* galaxies at high redshifts.

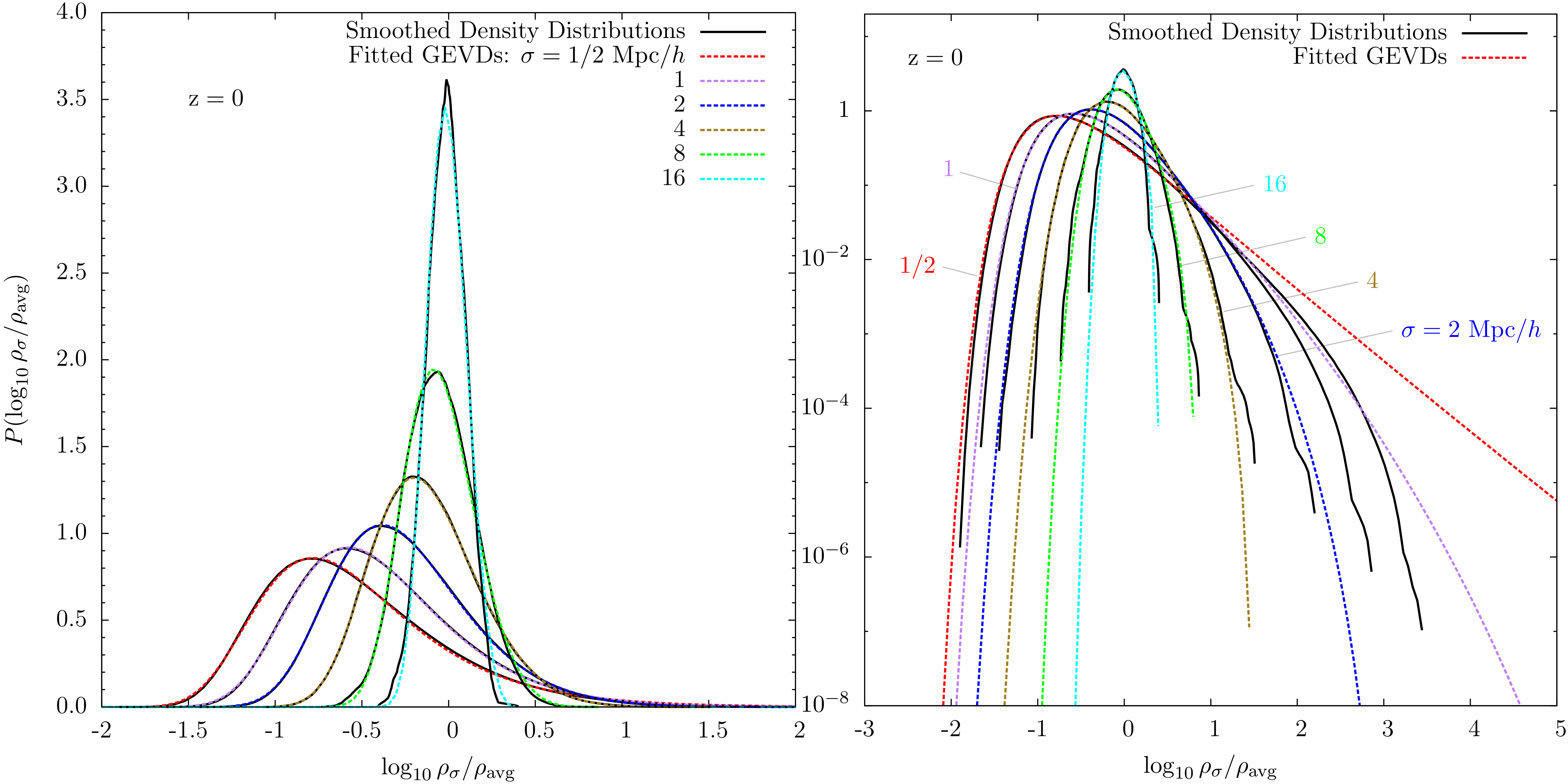
Tully-Fisher and Faber-Jackson M* ~ V^4 scaling relations for spiral and elliptical galaxies must raise their zero point by z ~ 1, or they would predict far too high stellar mass density at z > 1.

Properties of Dark Matter Haloes: Local Environment Density

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

submitted to MNRAS

Density Distributions



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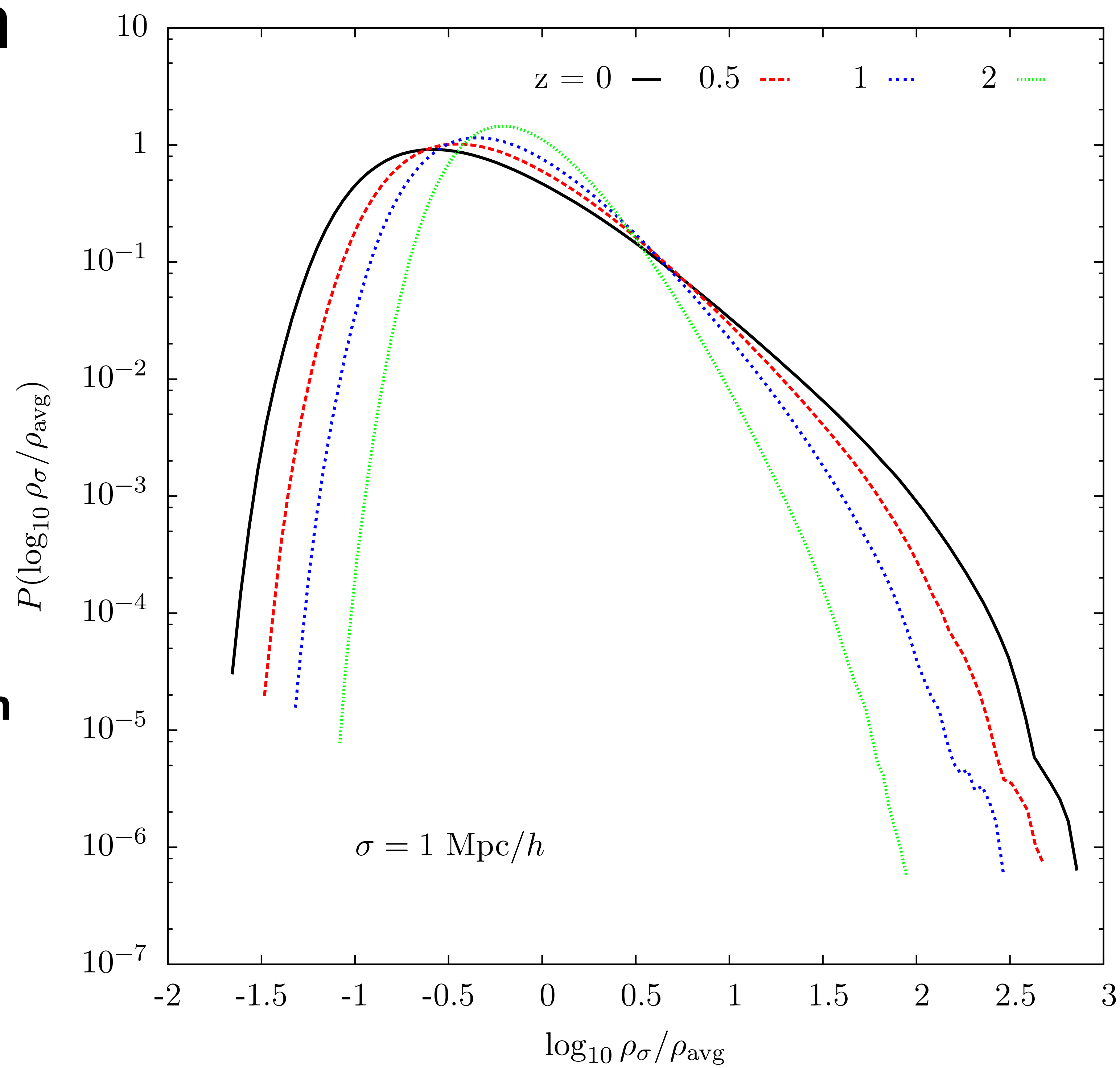
Density Distribution at $z = 0, 0.5, 1, 2$

- Range of densities increases with time
- Voids become emptier, clusters become denser



Generalized Extreme Value Distribution

$$f(x) = \frac{1}{\beta}\exp\left[-(1+kz)^{-1/k}\right](1+kz)^{-1-1/k},$$

$$z = \frac{x-\mu.}{\beta}$$

Properties of Dark Matter Haloes: Local Environment Density

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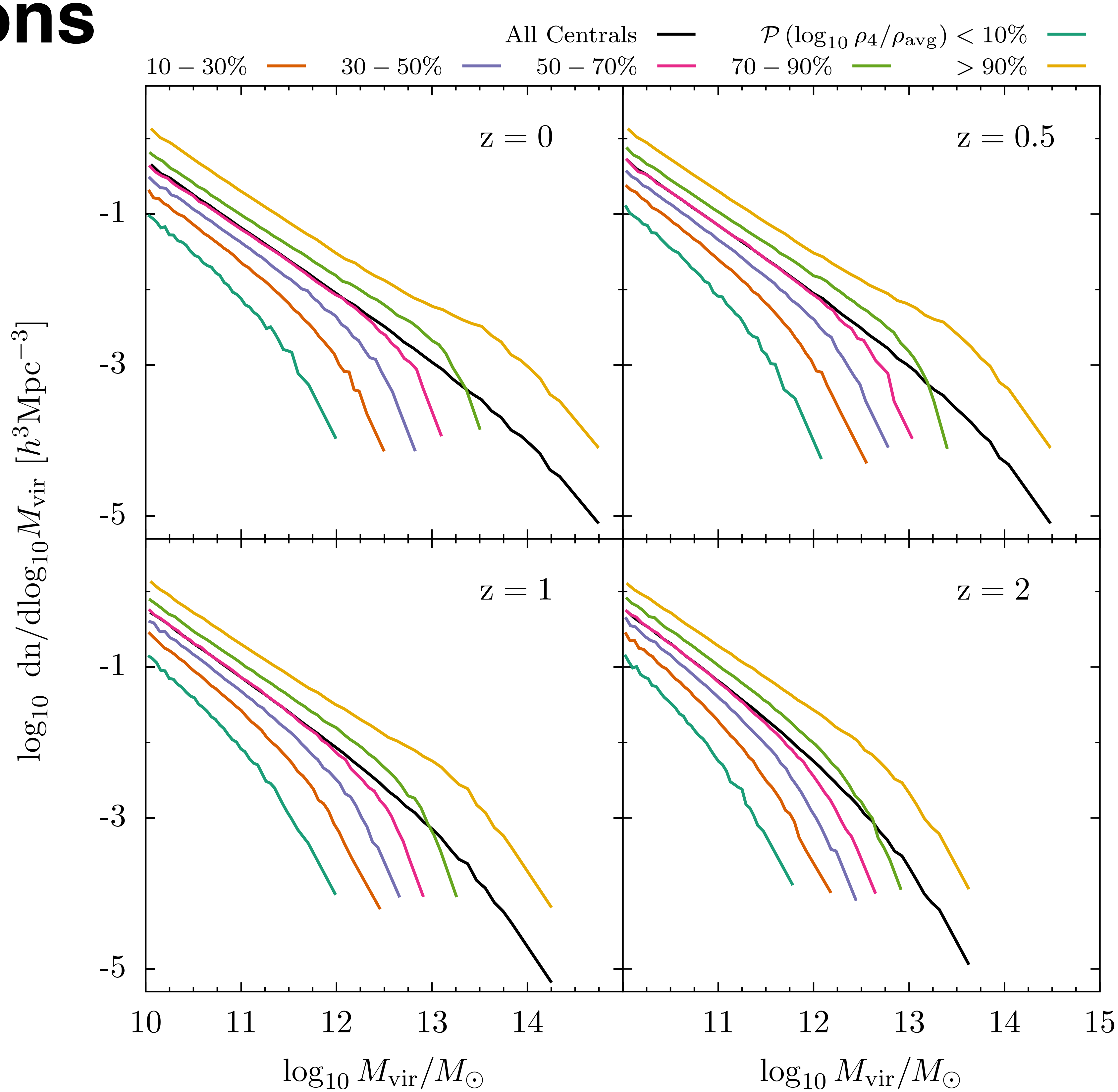
Halo Mass Functions

- Density percentiles of full simulation volume used to select consistent density ranges at different redshifts
- Characteristic mass lower in low density regions than high density regions
- More well defined characteristic mass at low redshift than high redshift (abrupt vs gradual change in slope)
- Abundance matching is ~ independent of density (Radu Dragomir, Aldo Rodriguez-Puebla, et al.)



Properties of Dark Matter Haloes: Local Environment Density

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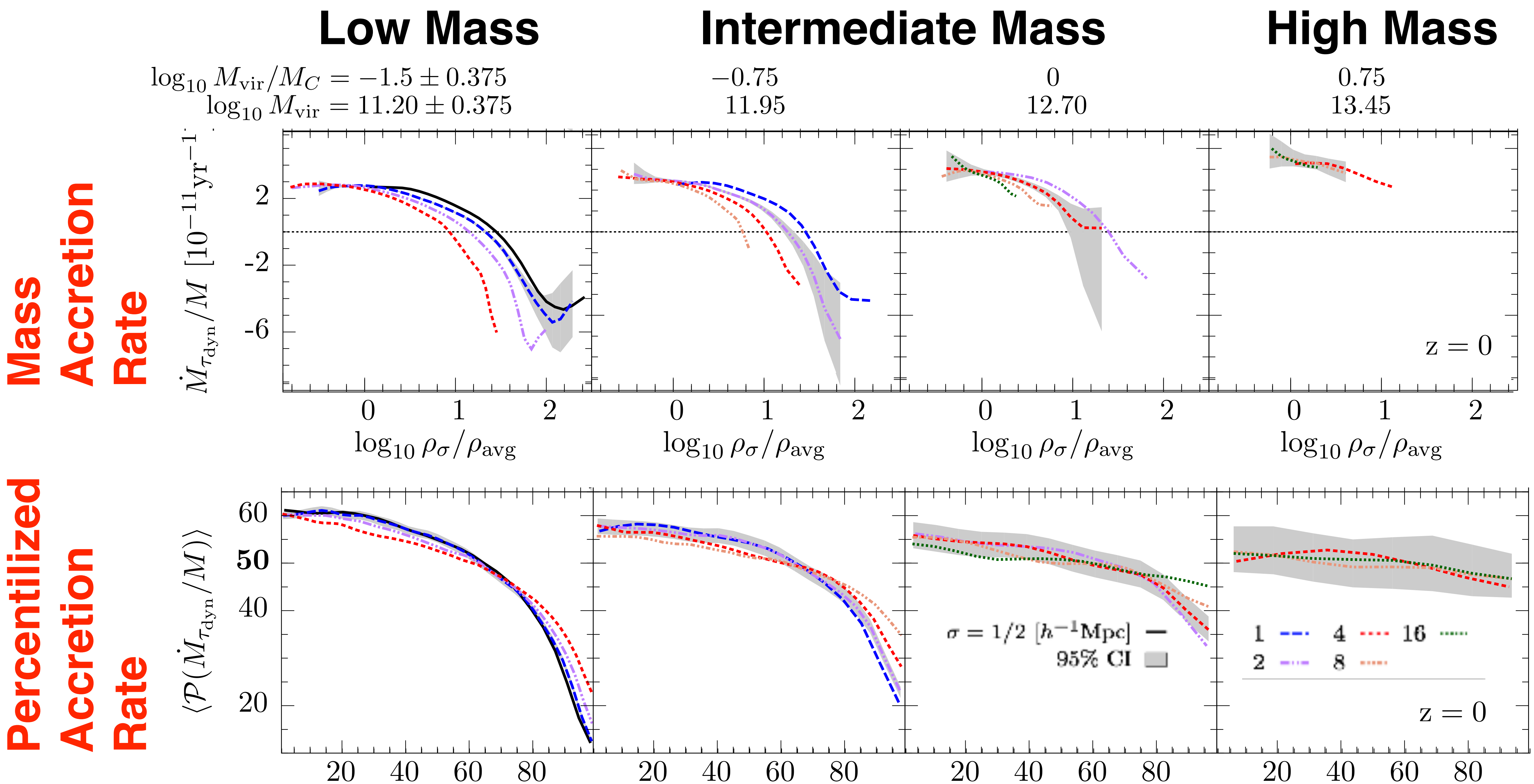
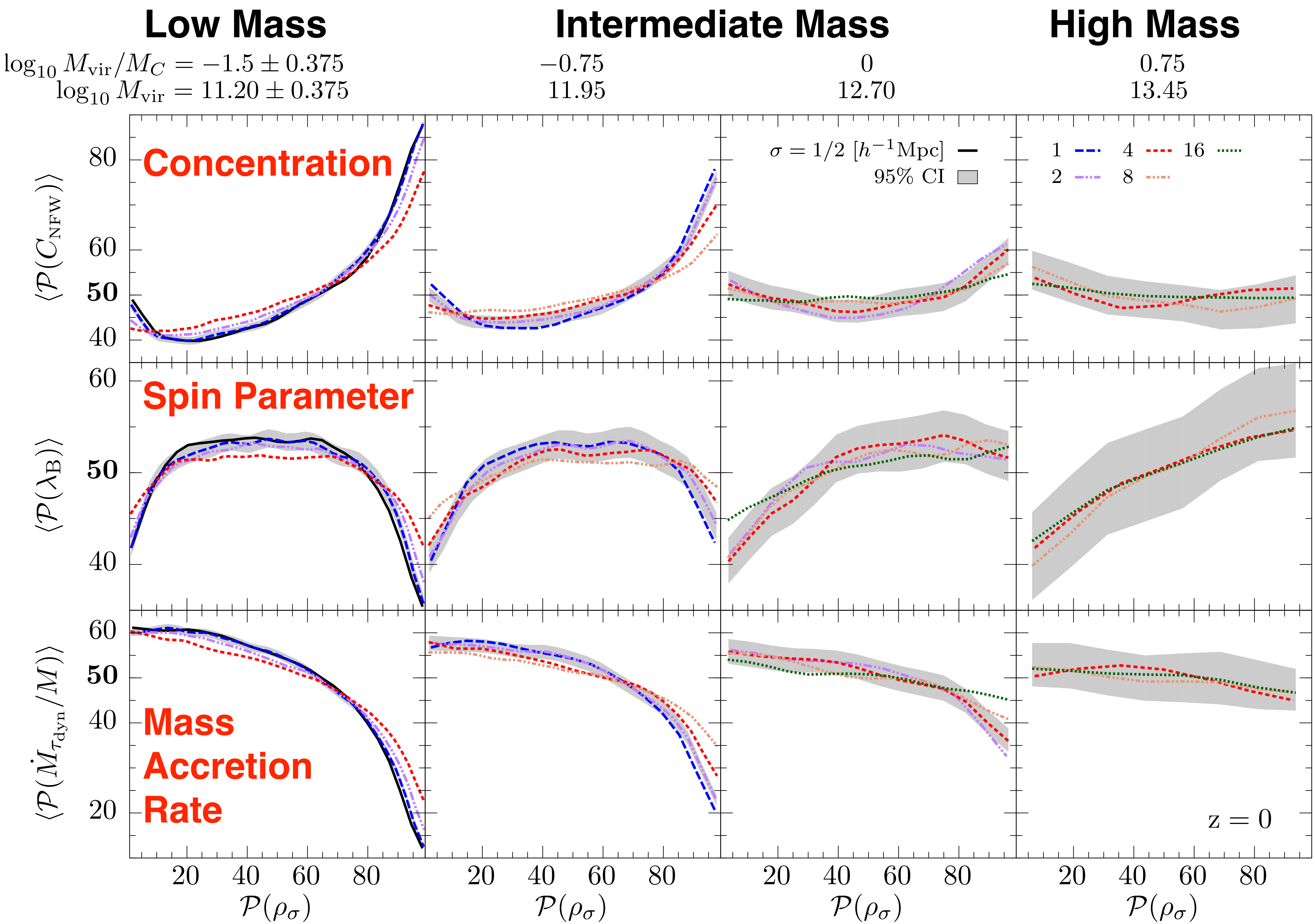


BOTTOM:

- Halos rank ordered by local density. Medians represented by rank in halo property
- Each mass bin adjusted such that density percentile bins contain consistent mass distributions
- Large smoothing scales reflect averaging of behavior seen at small smoothing scales
- Relevant ‘local’ scale changes with mass — environment of low mass halos well described with 1 Mpc/h scale, high mass with 4 Mpc/h scale

Properties of Dark Matter Haloes: Local Environment Density

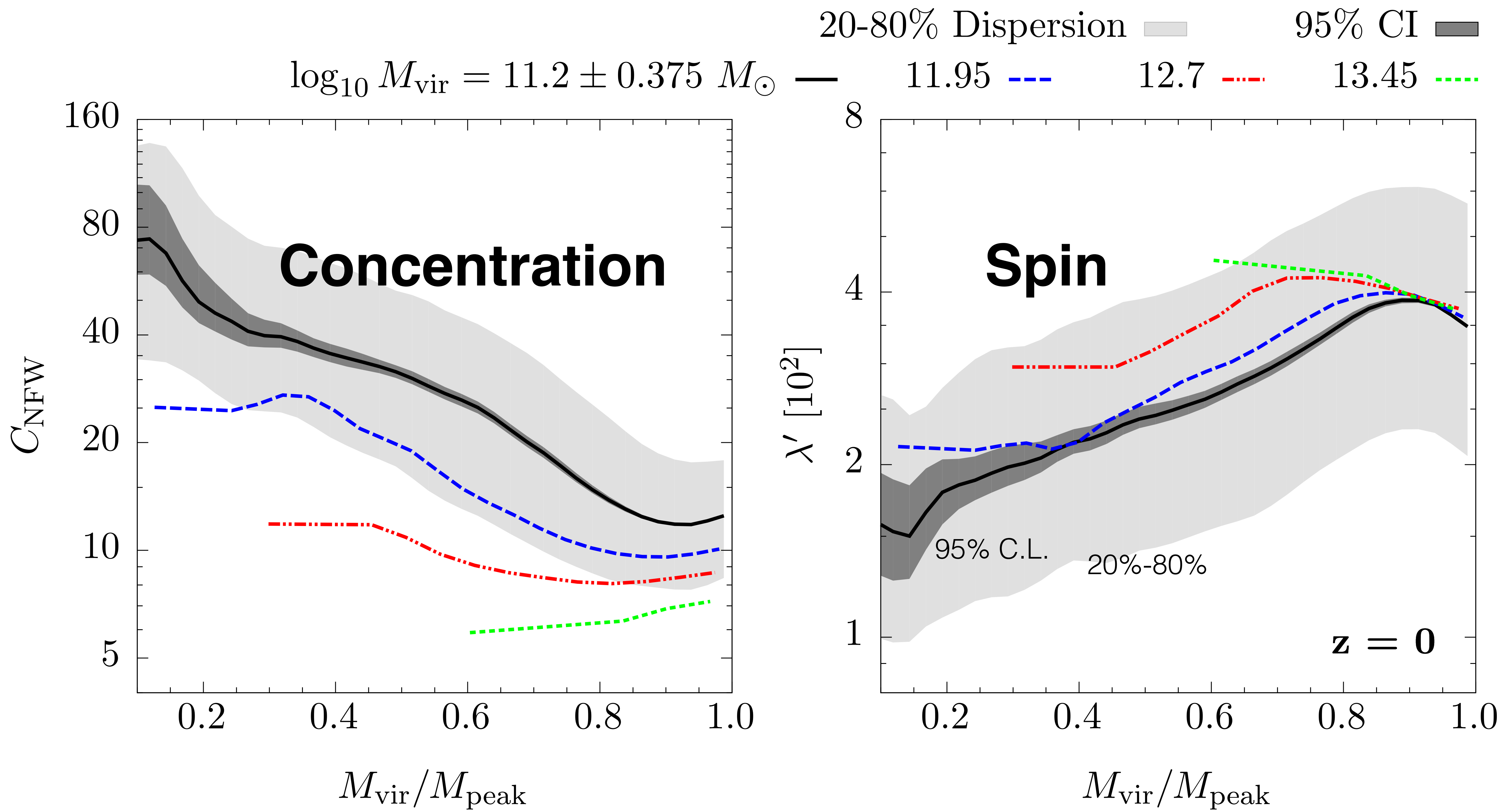
Christoph T. Lee, Joel R. Primack, Peter Behroozi, Aldo Rodríguez-Puebla, Doug Hellinger, Avishai Dekel



Properties of Dark Matter Haloes: Effects of Mass Stripping

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

Christoph Lee, USCC

We theorists make very complicated models of the star formation rate (SFR) in galaxies — but

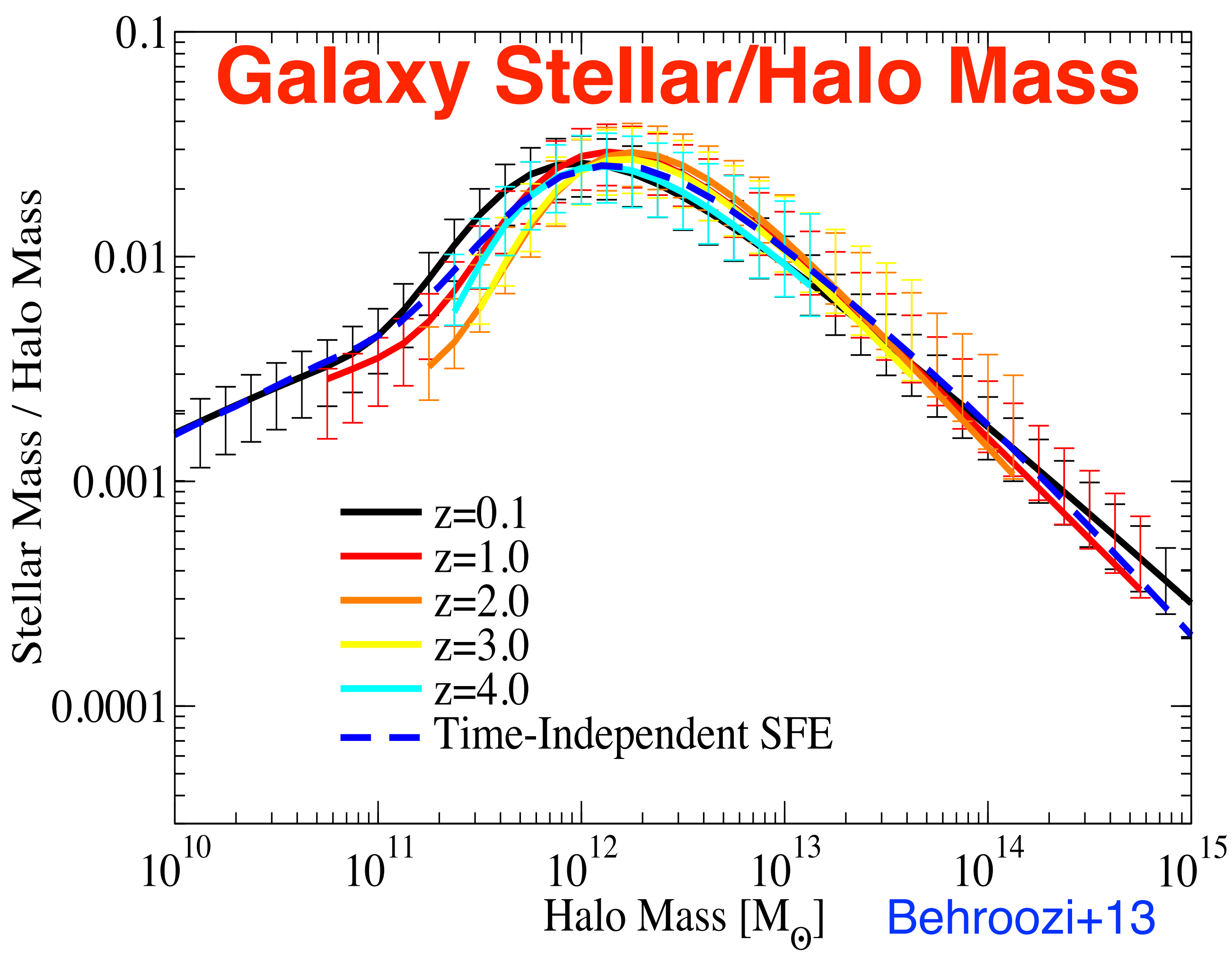
Is Main Sequence SFR Controlled by Halo Mass Accretion?

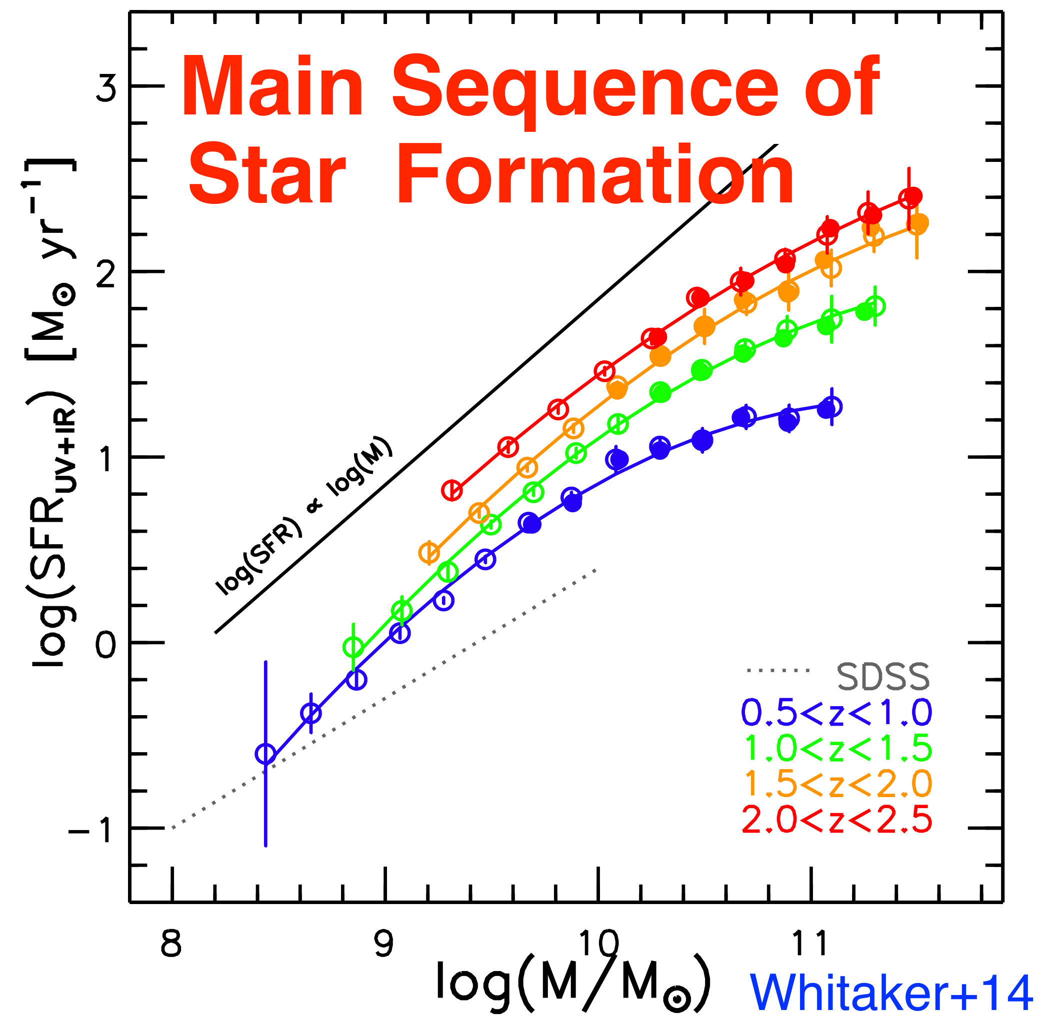
by Aldo Rodríguez-Puebla, Joel Primack, Peter Behroozi, Sandra Faber   MNRAS 2016

One can show that this must be true on average

Our radical SHARC (stellar halo accretion rate co-evolution) hypothesis is that this may be true halo-by-halo for dark matter halos hosting star-forming galaxies

Key Background Information

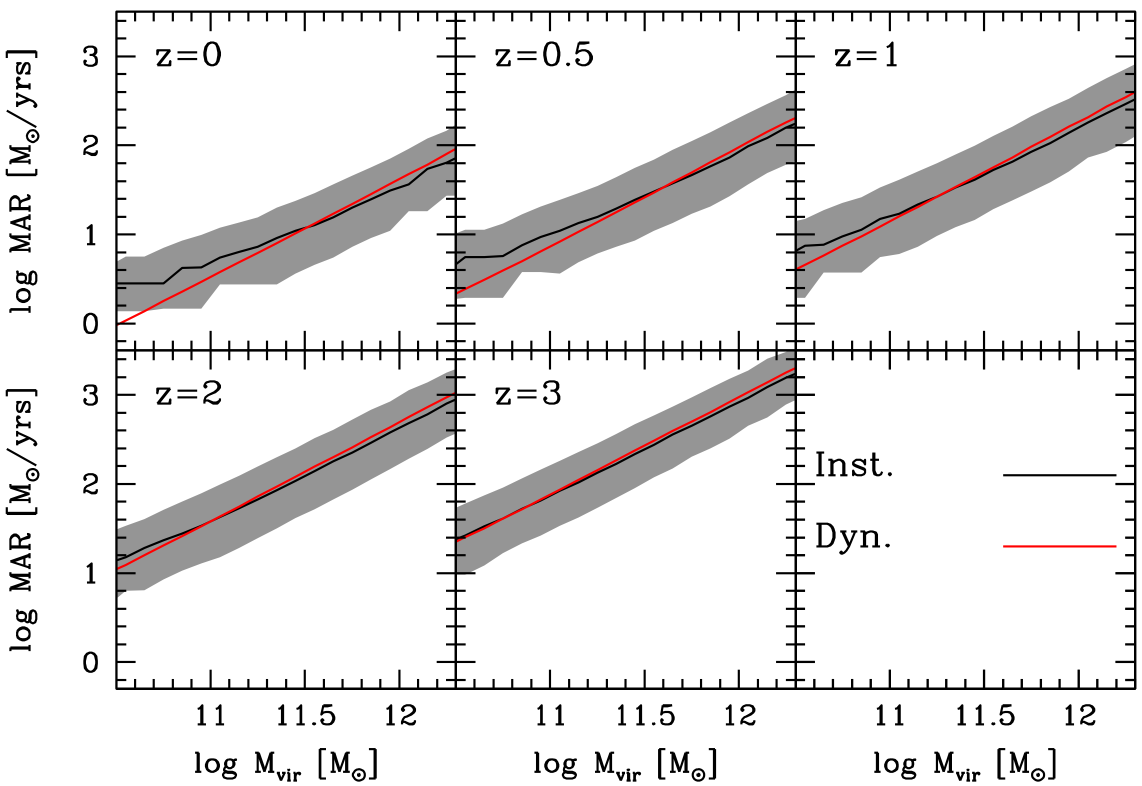




Is Main Sequence SFR Controlled by Halo Mass Accretion?

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

Halo mass accretion rates z=0 to 3



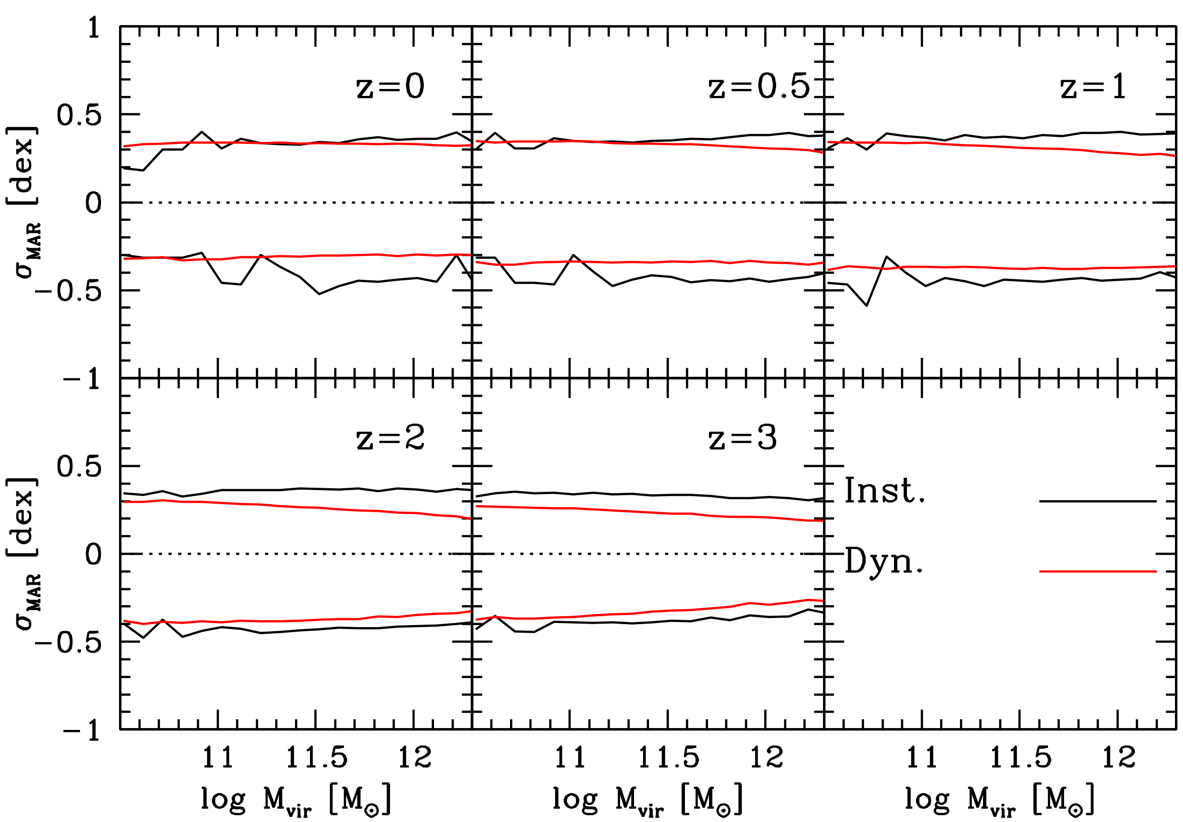
$$\frac{dM_*}{dt} = \frac{\partial M_*(M_{\rm vir}(t), z)}{\partial M_{\rm vir}} \frac{dM_{\rm vir}}{dt} + \frac{\partial M_*(M_{\rm vir}(t), z)}{\partial z} \frac{dz}{dt}$$

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

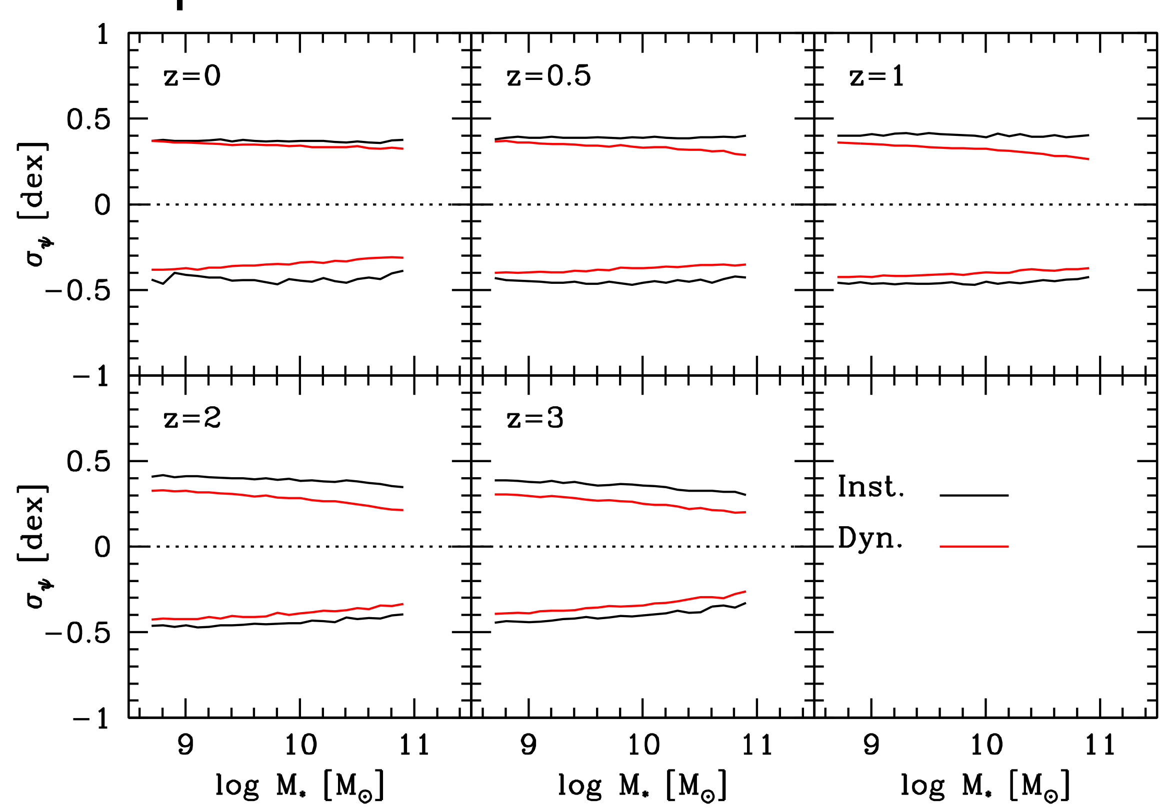
$$\frac{dM_*}{dt} = f_* \frac{d\log M_*}{d\log M_{\rm vir}} \frac{dM_{\rm vir}}{dt},$$

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

Scatter of halo mass accretion rates



Implied scatter of star formation rates

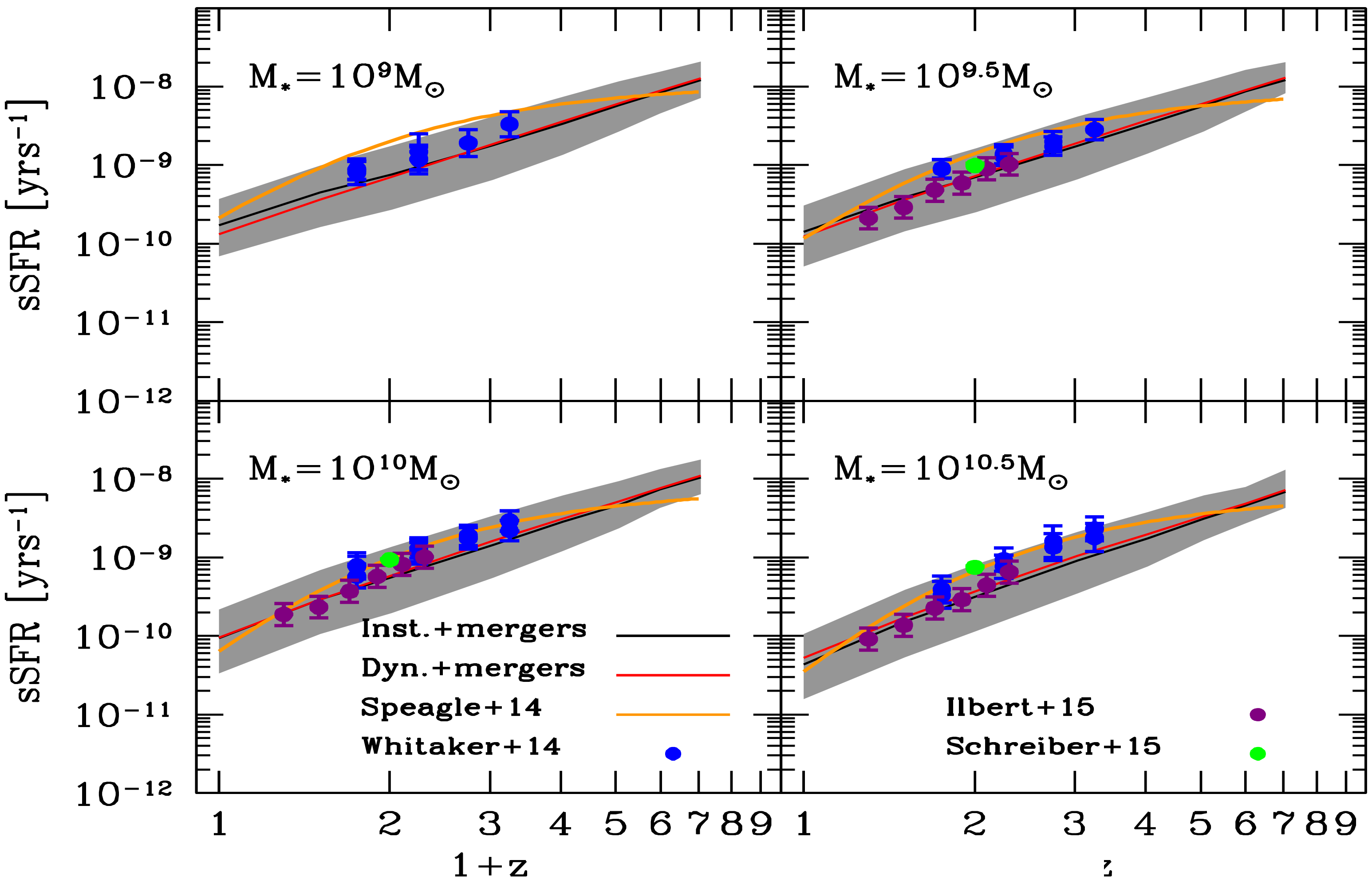


Consistent with observations!

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 ✓

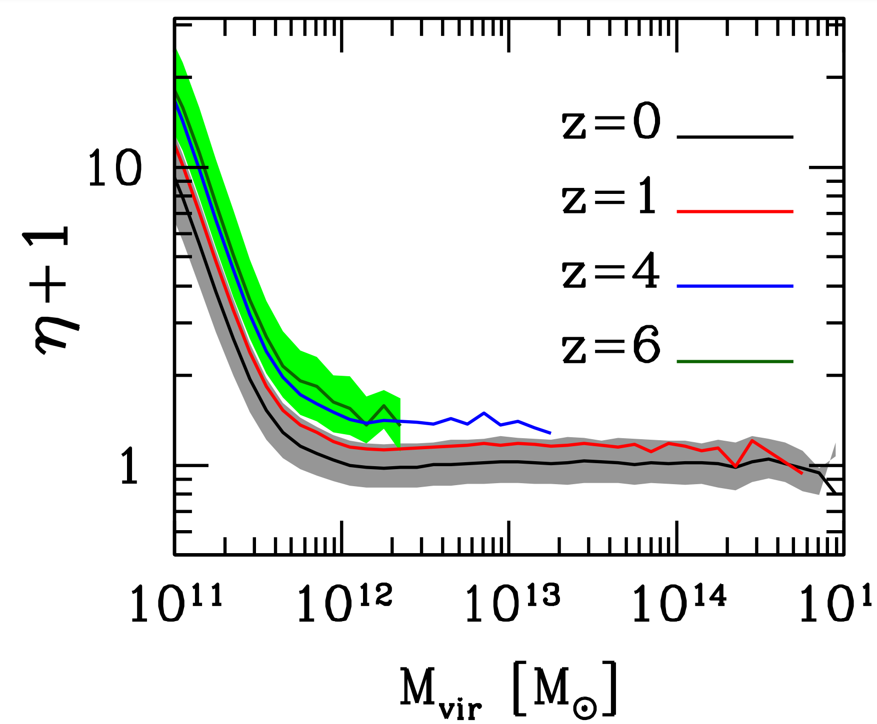
Open Questions:

Extend SHARC to higher-mass galaxies

Also take quenching into account

Does SHARC correctly predict the growth rate of central galaxy stellar mass from the accretion rate of their halos? Test this in simulations!

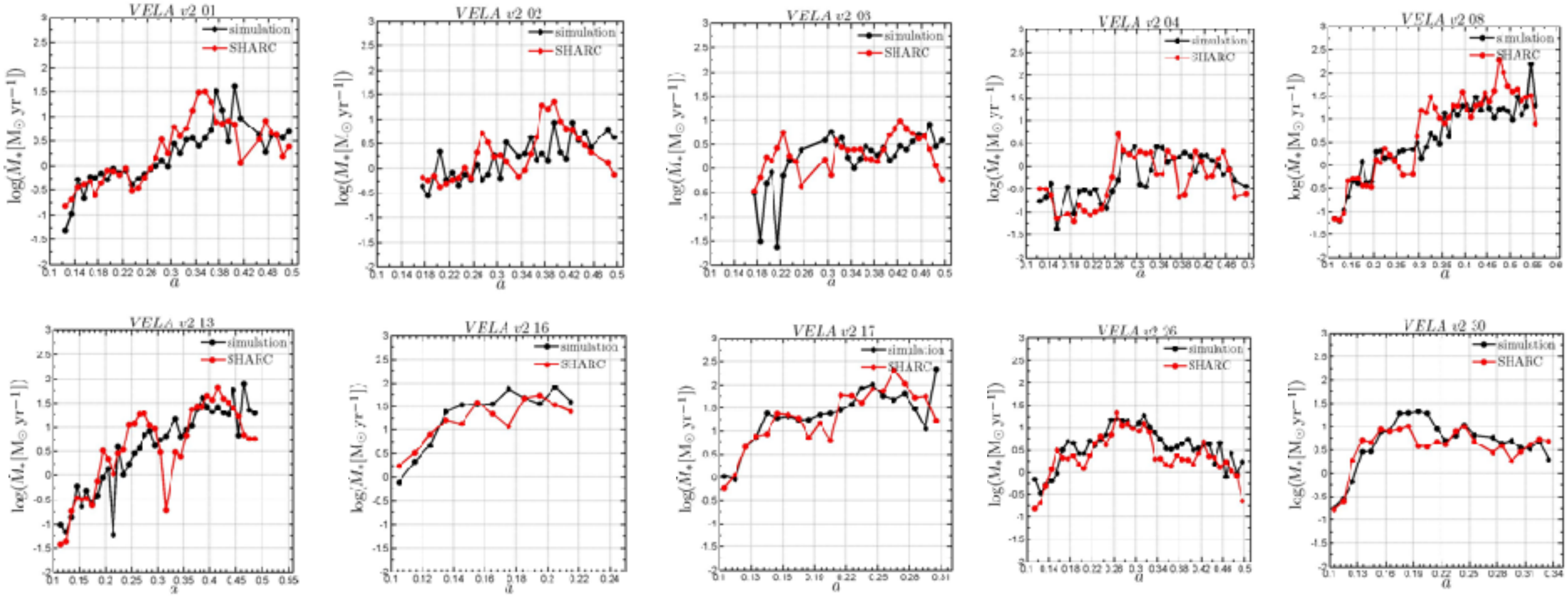
We put SHARC in "bathtub" equilibrium models of galaxy formation & predict mass loading and metallicity evolution



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

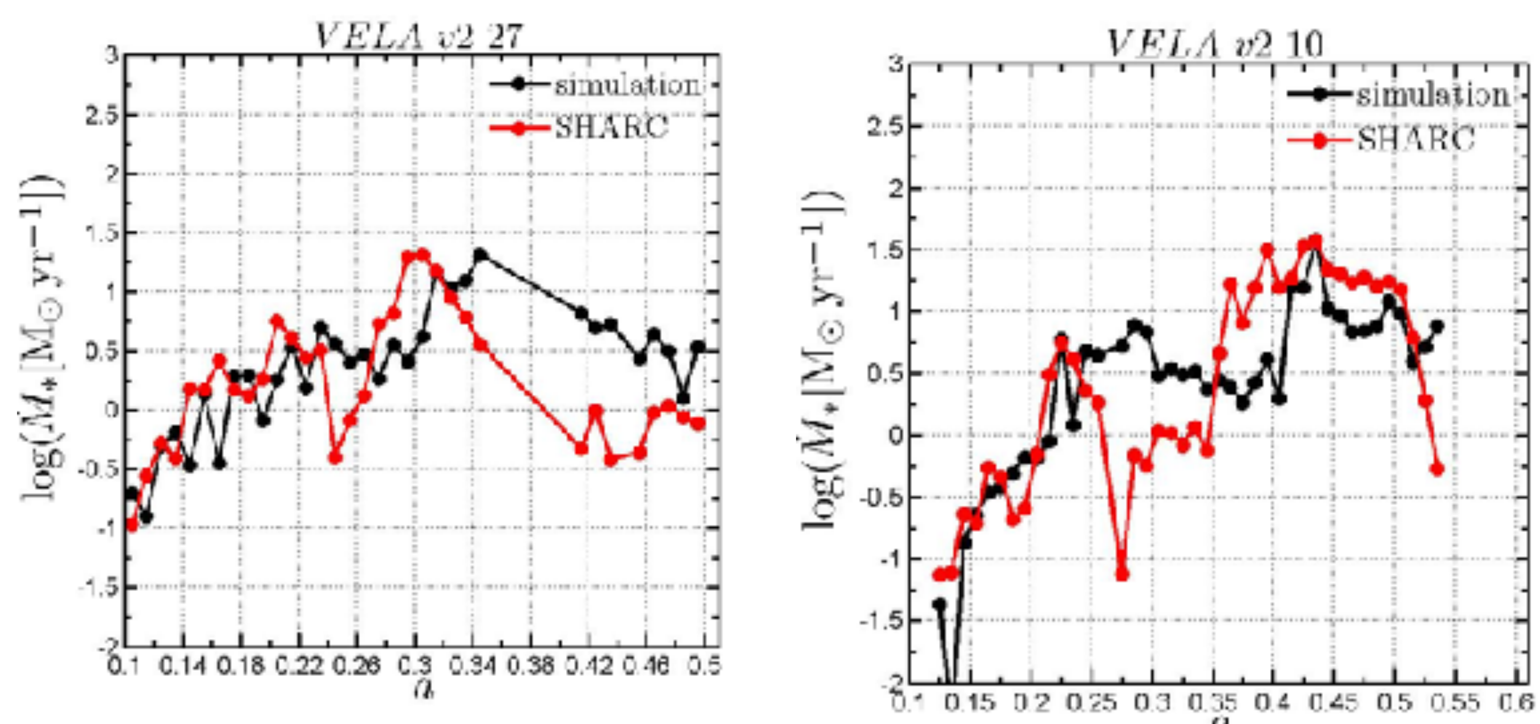
Does SHARC correctly predict the growth rate of central galaxy stellar mass from the accretion rate of their halos? Test this in simulations!

Many pretty successful SHARC predictions for our gen3 simulations:



Examples of SHARC prediction failures:

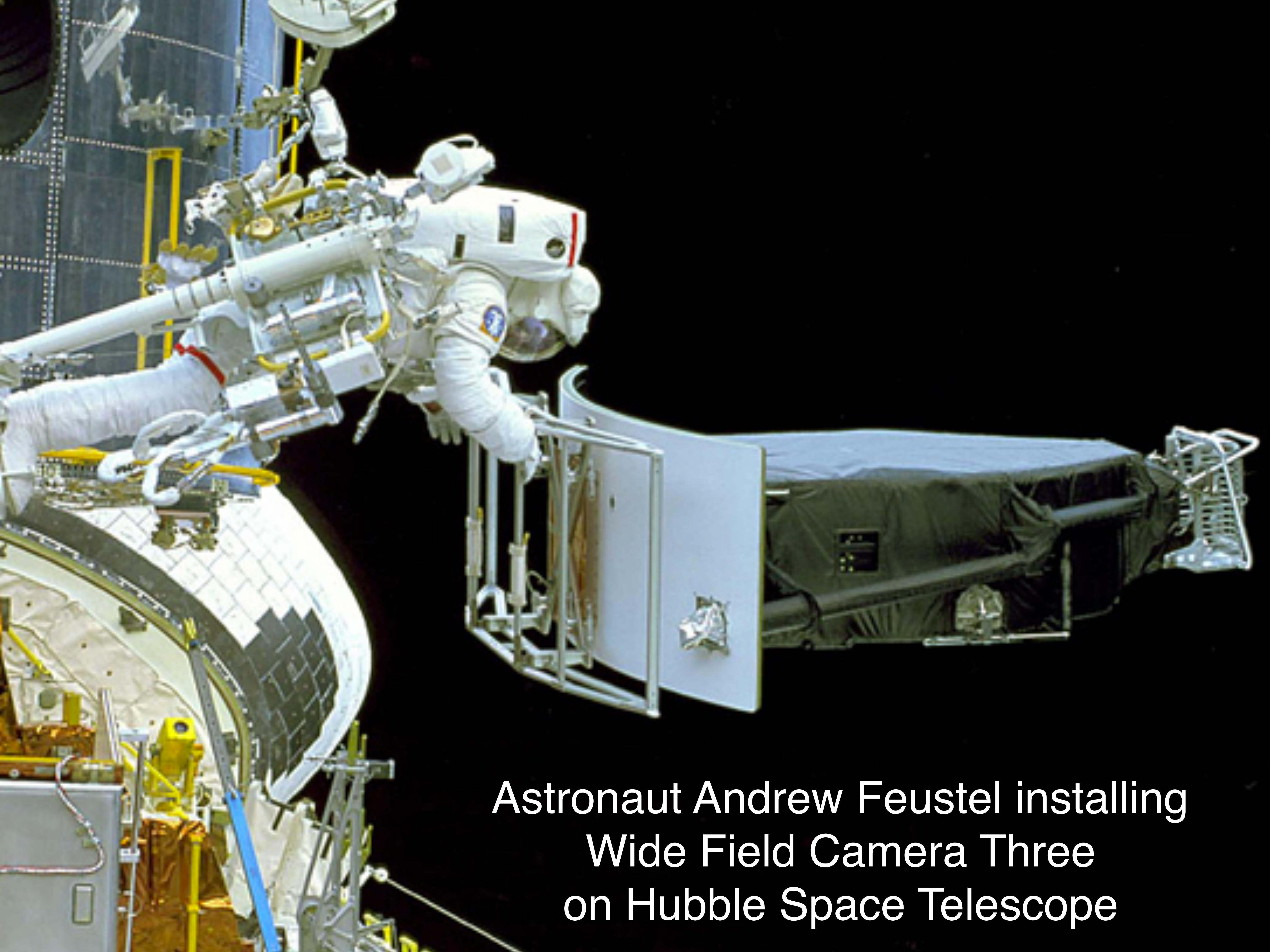
Smooth vs. Lumpy mass accretion?



Daniel Ceverino, Nir Mandelker

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

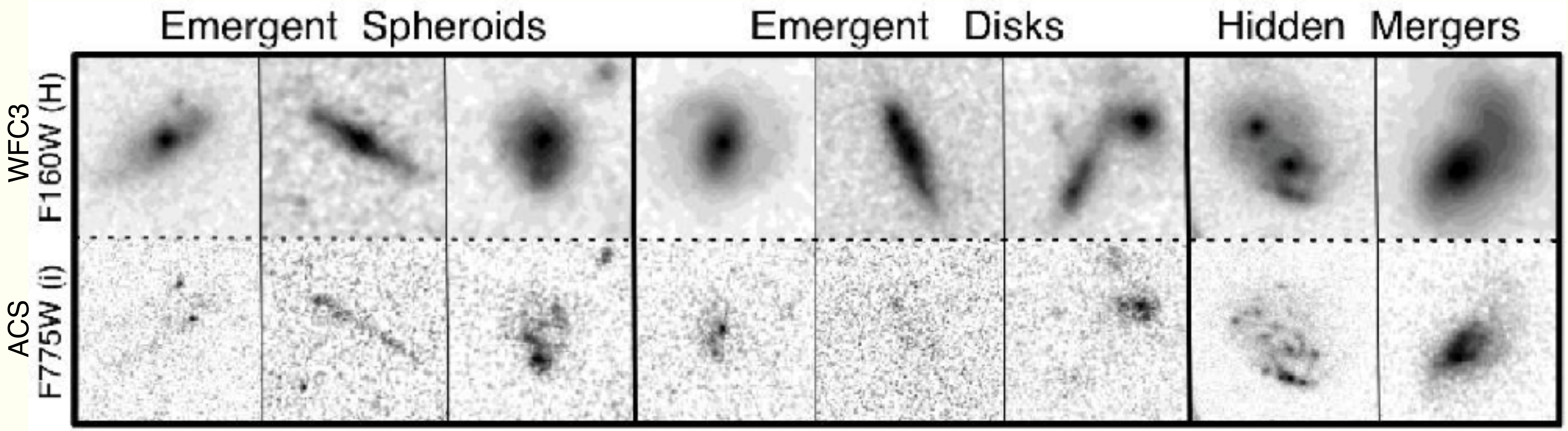
} Challenge for Observers & Simulators!



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

The CANDELS Survey

candels.ucolick.org



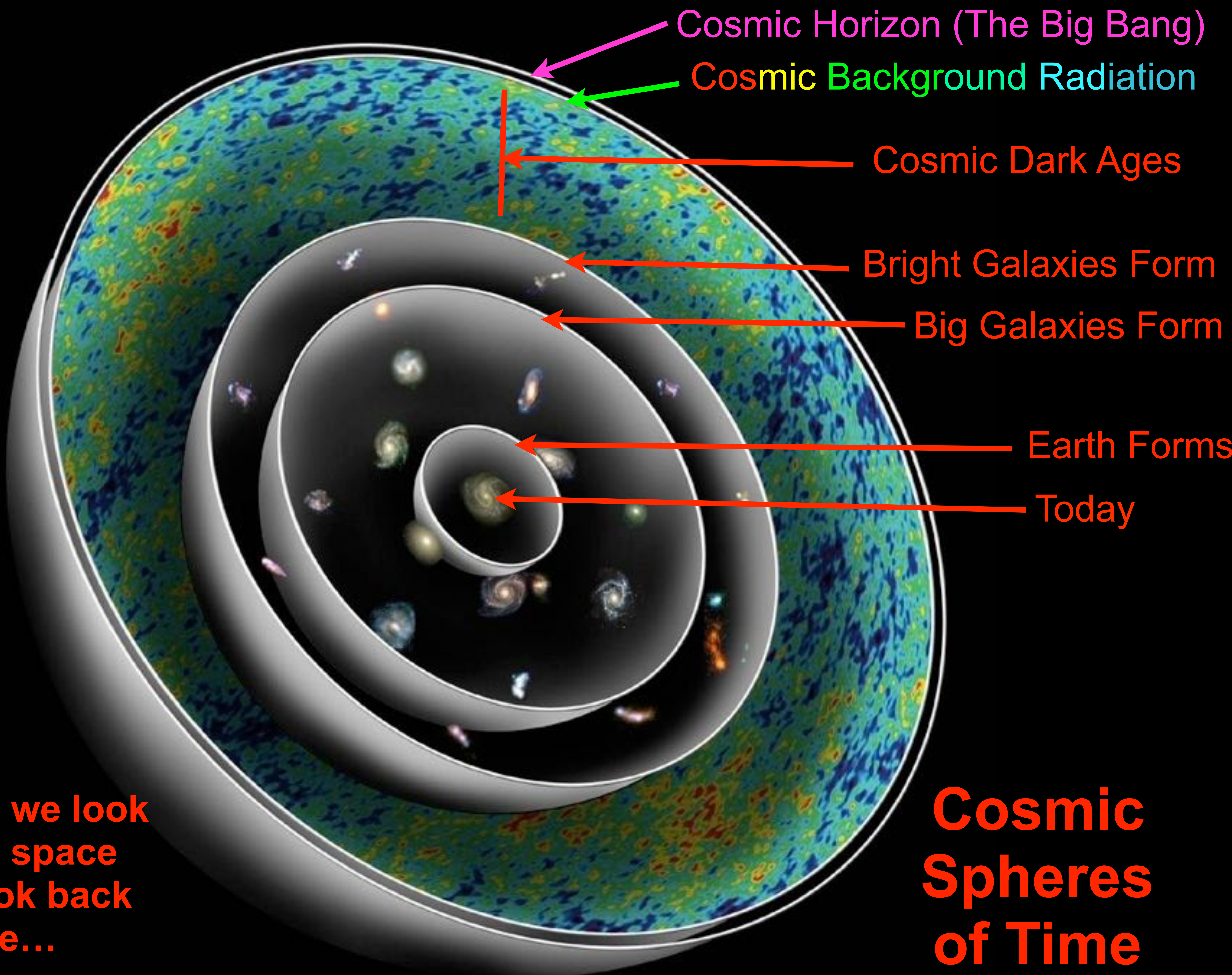
CANDELS: A Cosmic Odyssey

(blue 0.4 μm)(1+z) = 1.6 μm @ z = 3

(red 0.7 μm)(1+z) = 1.6 μm @ z = 2.3

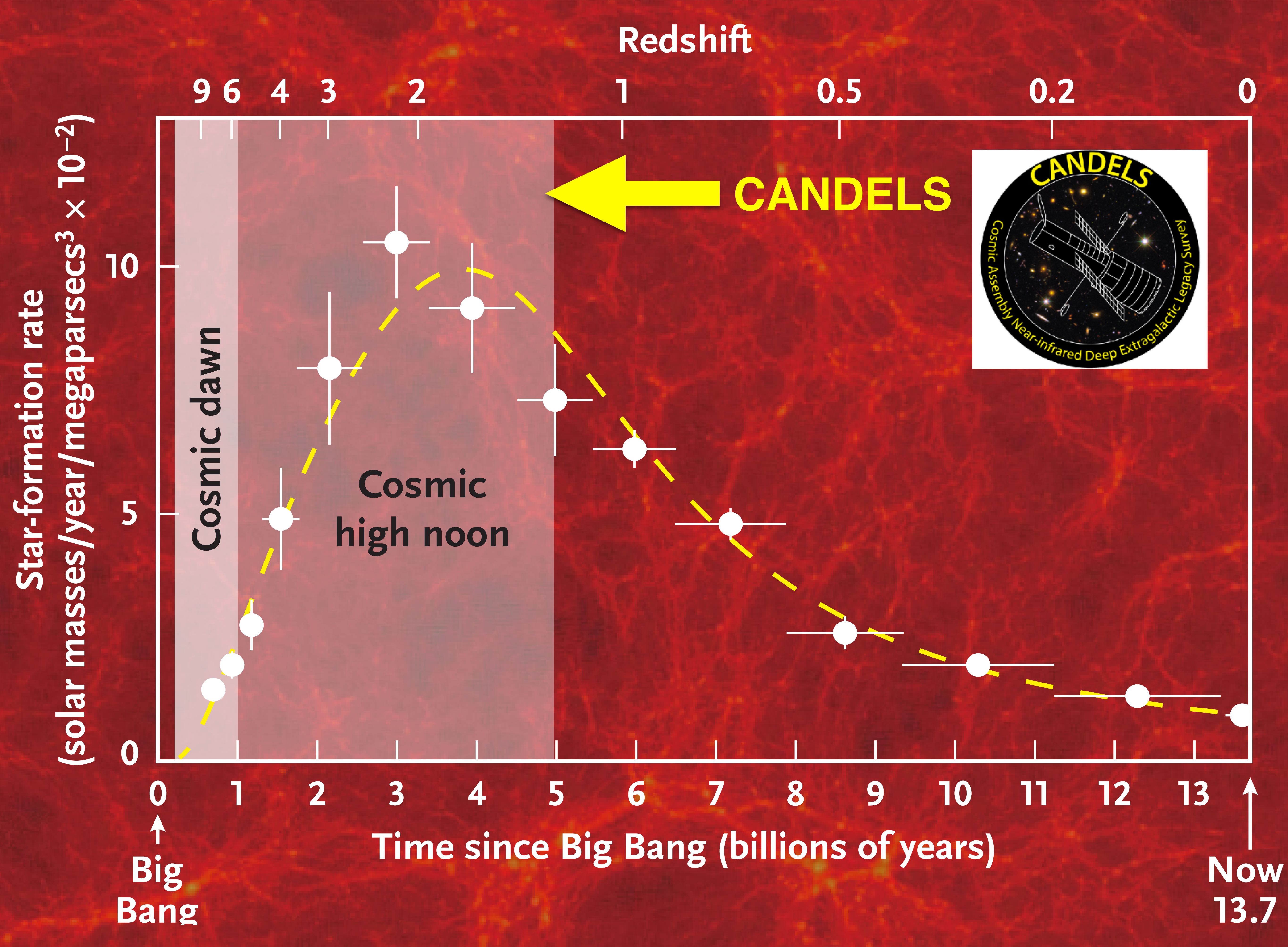
CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

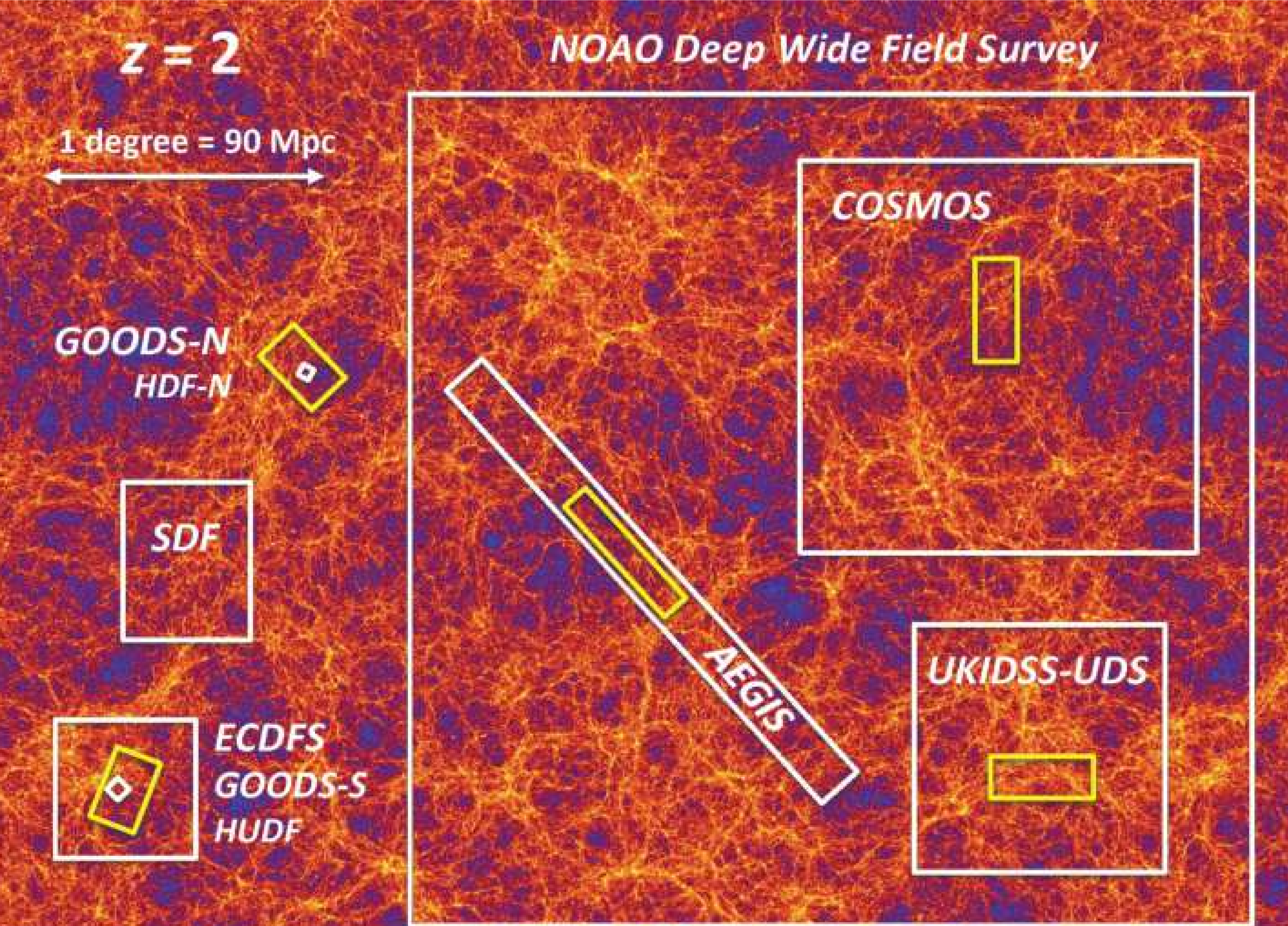
- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared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

Cosmological Simulations

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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).

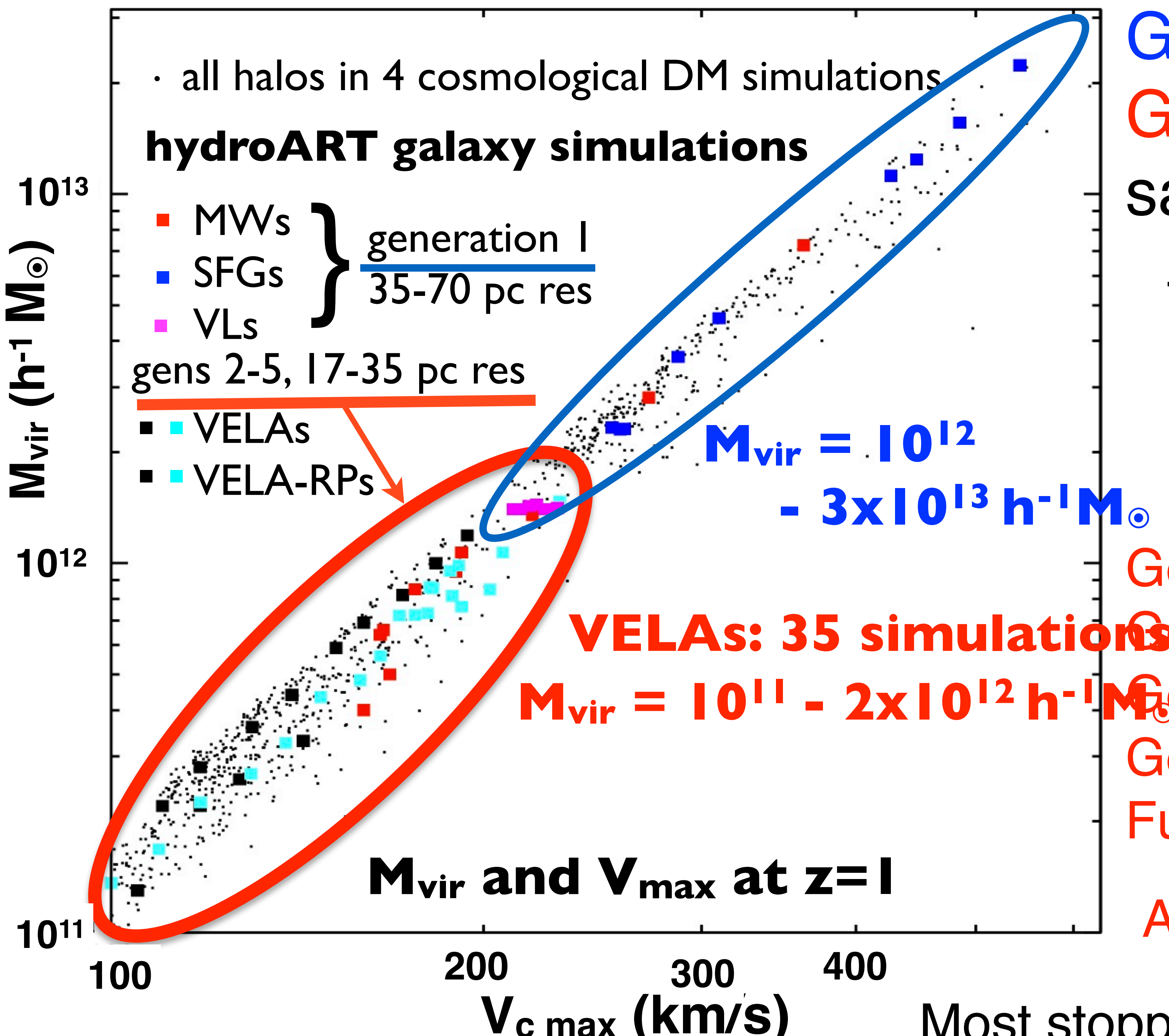
2. High resolution (~10s of pc) ← THIS TALK

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: 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.

5 Generations of hydroART simulations

ART code: Andrey Kravtsov, Anatoly Klypin, Daniel Ceverino

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



Gen 1: higher masses

Gen 2,3,4,5: VELA

same 35 initial conditions

17-35 pc best resolution

$M_{DM} = 8x10^4\ M_\odot$

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

Gen 2: SN Thermal Feedback

Gen 3: SN+UV Rad Pressure

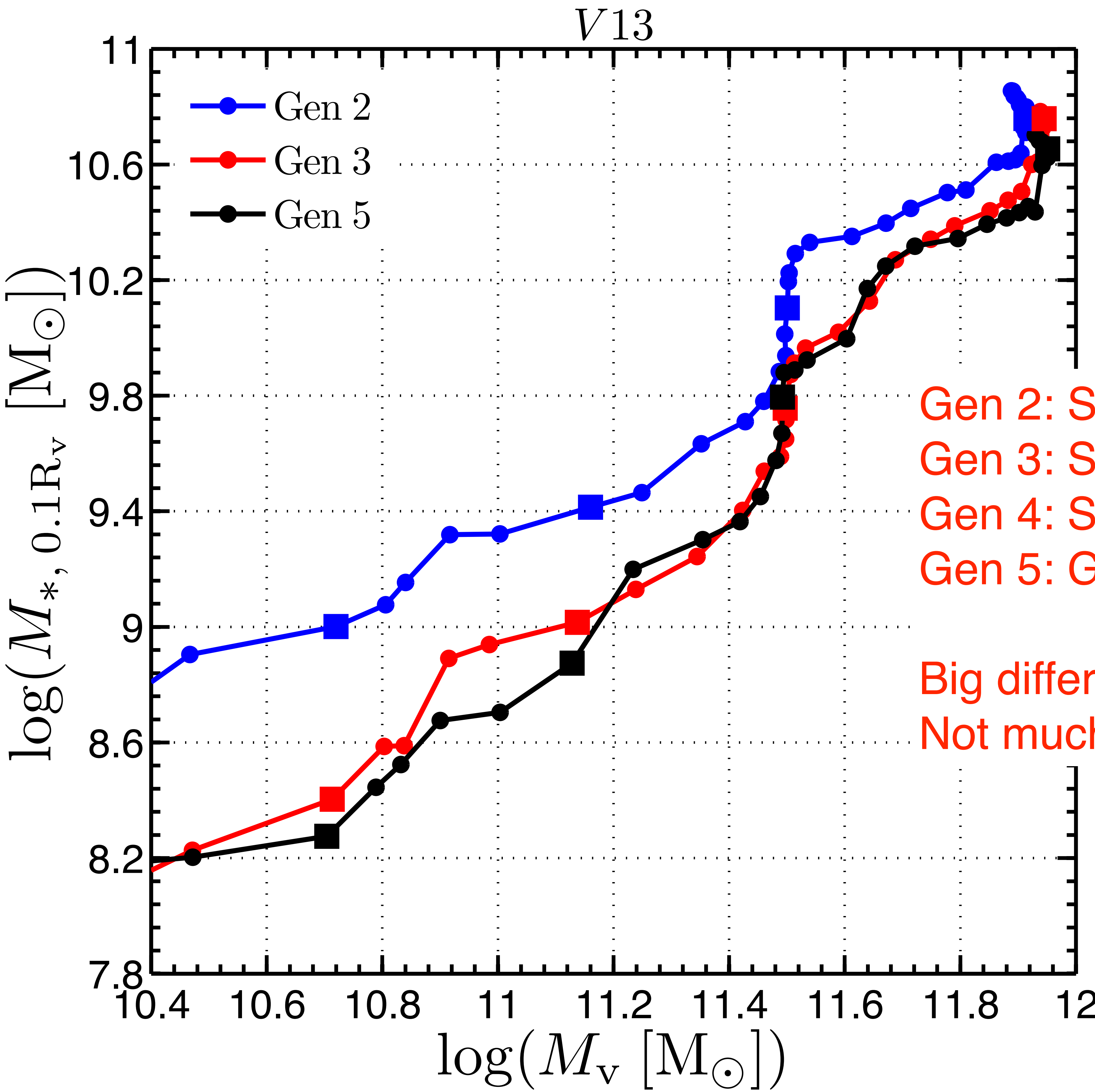
Gen 4: SN+UV/IR Rad Pressure

Gen 5: Gen4 + SN Pressure

Future: also include AGN

A feedback laboratory!

Most stopped at z ~ 1 to save cpu time.



Gen 2: SN Thermal Feedback

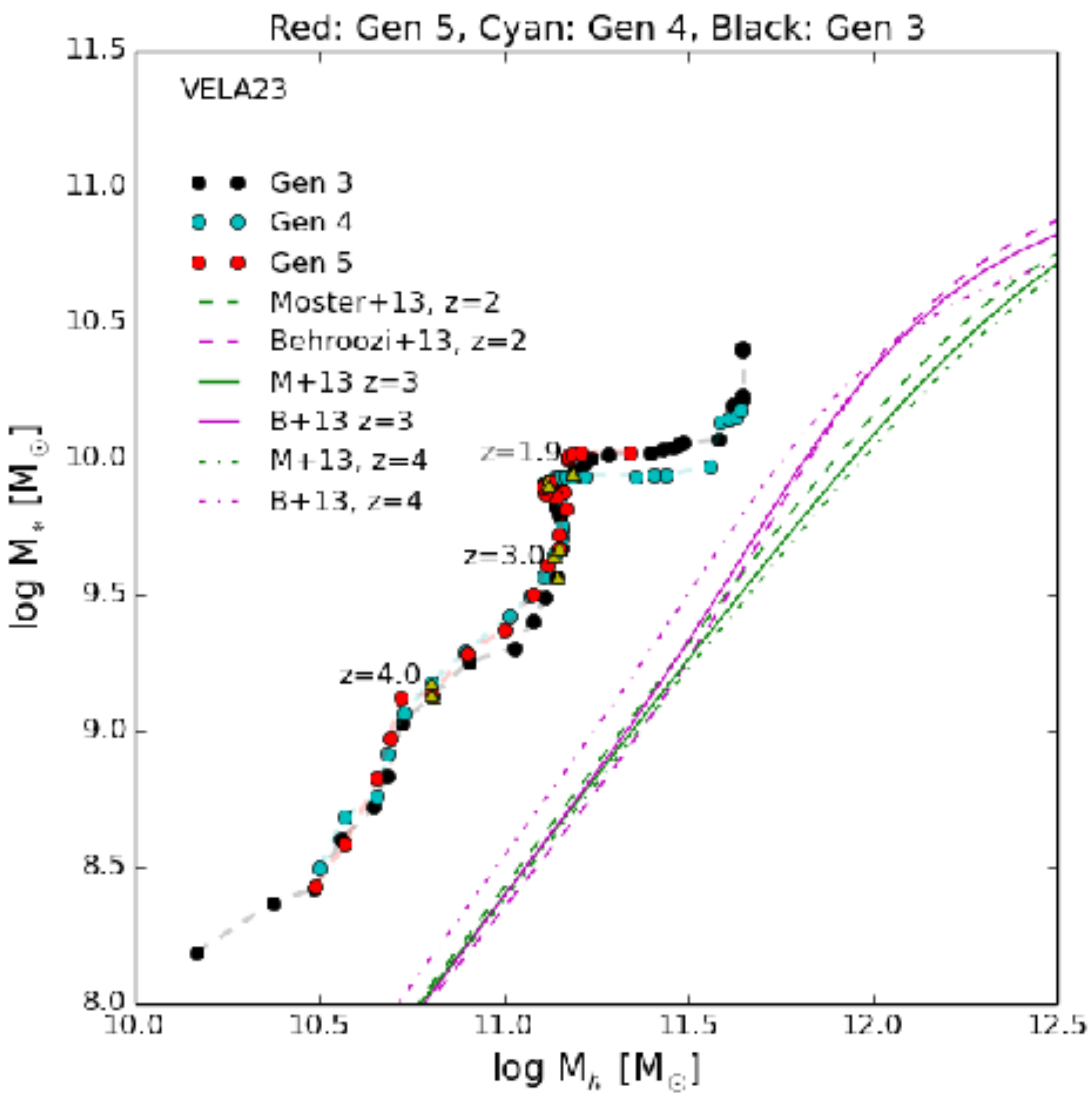
Gen 3: SN+UV Rad Pressure

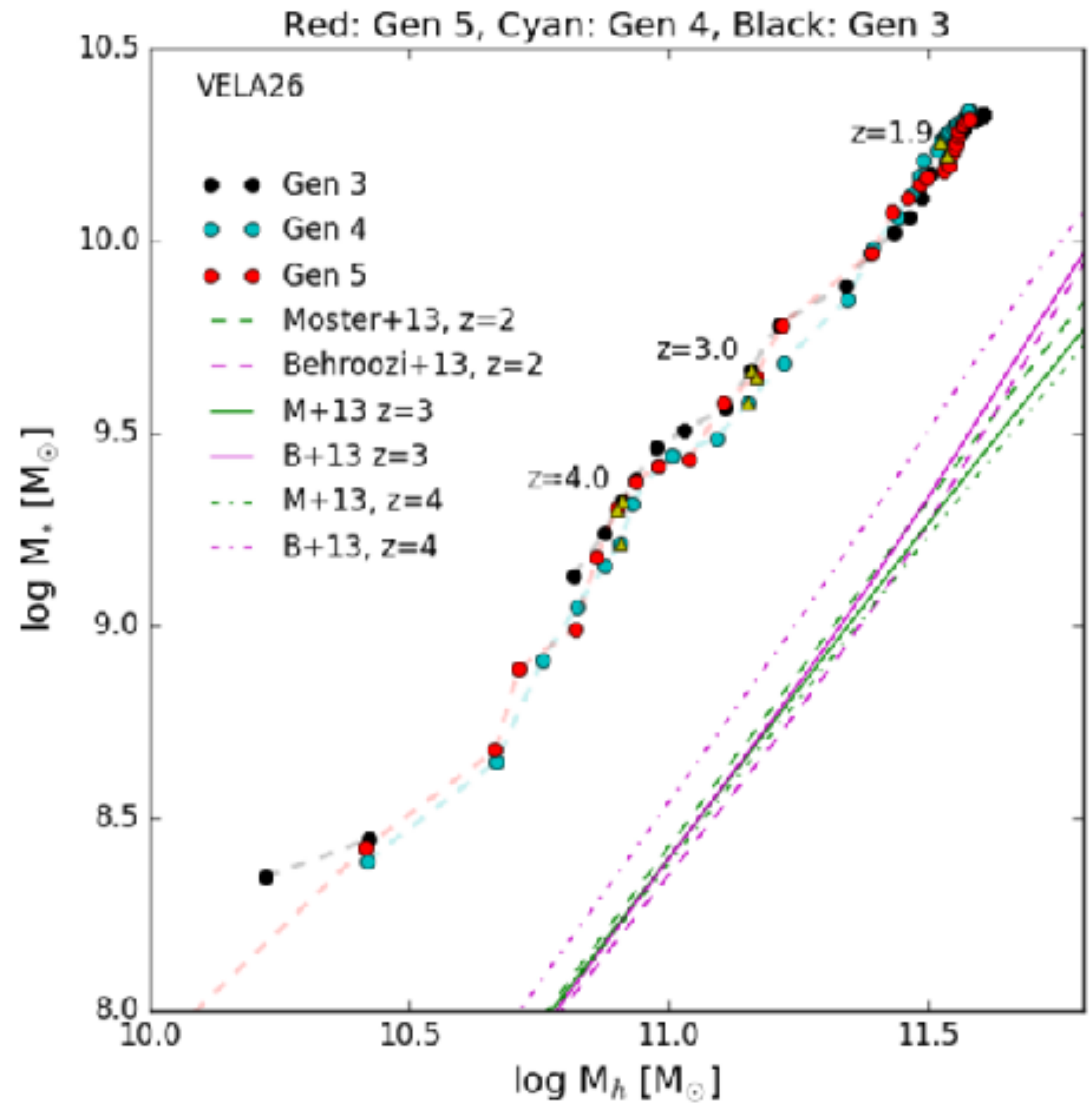
Gen 4: SN+UV/IR Rad Pressure

Gen 5: Gen4 + SN Pressure

Big difference between Gen 2 & 3

Not much between Gen 3 and 5



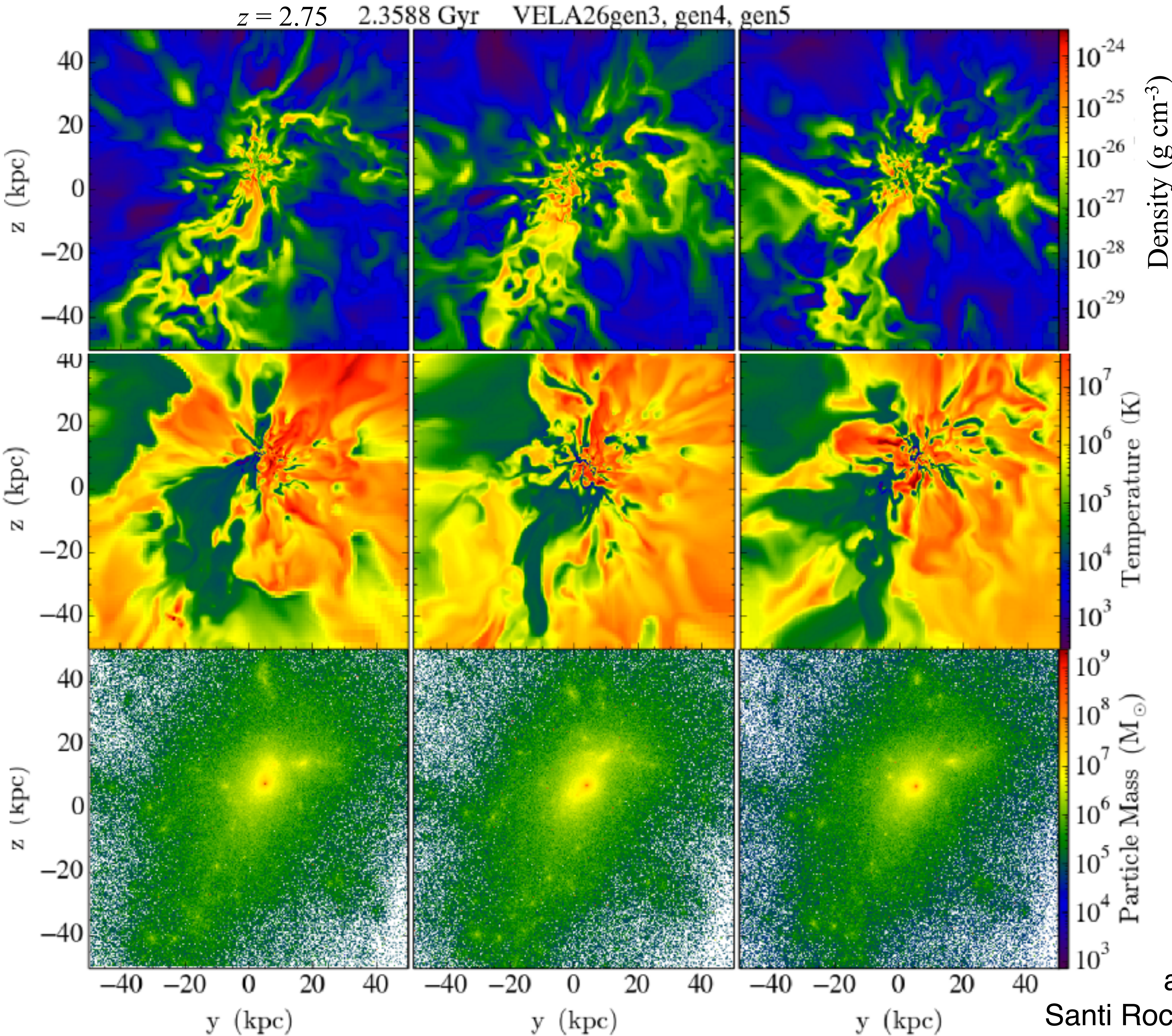


Gen 2: SN Thermal Feedback
Gen 3: SN+UV Rad Pressure
Gen 4: SN+UV/IR Rad Pressure
Gen 5: Gen4 + SN Pressure

Not much difference in M*/Mhalo between Gen 3, 4, and 5

But gas density & temperature and stellar mass distributions are subtly different (next slide)

analysis by Santi Roca-Fabrega



analysis by
Santi Roca-Fabrega

CANDELS

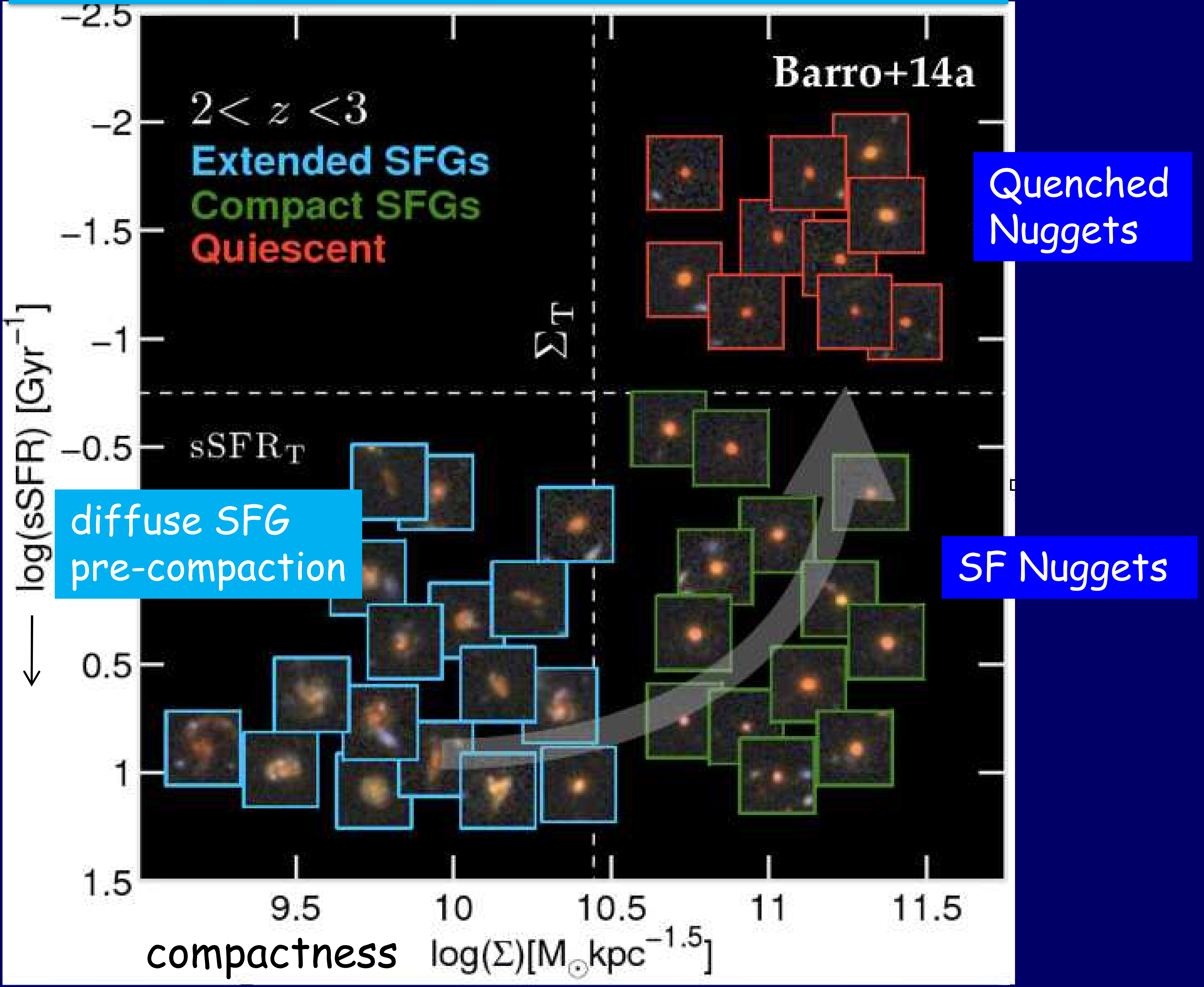
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

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

} Challenge for Observers & Simulators!

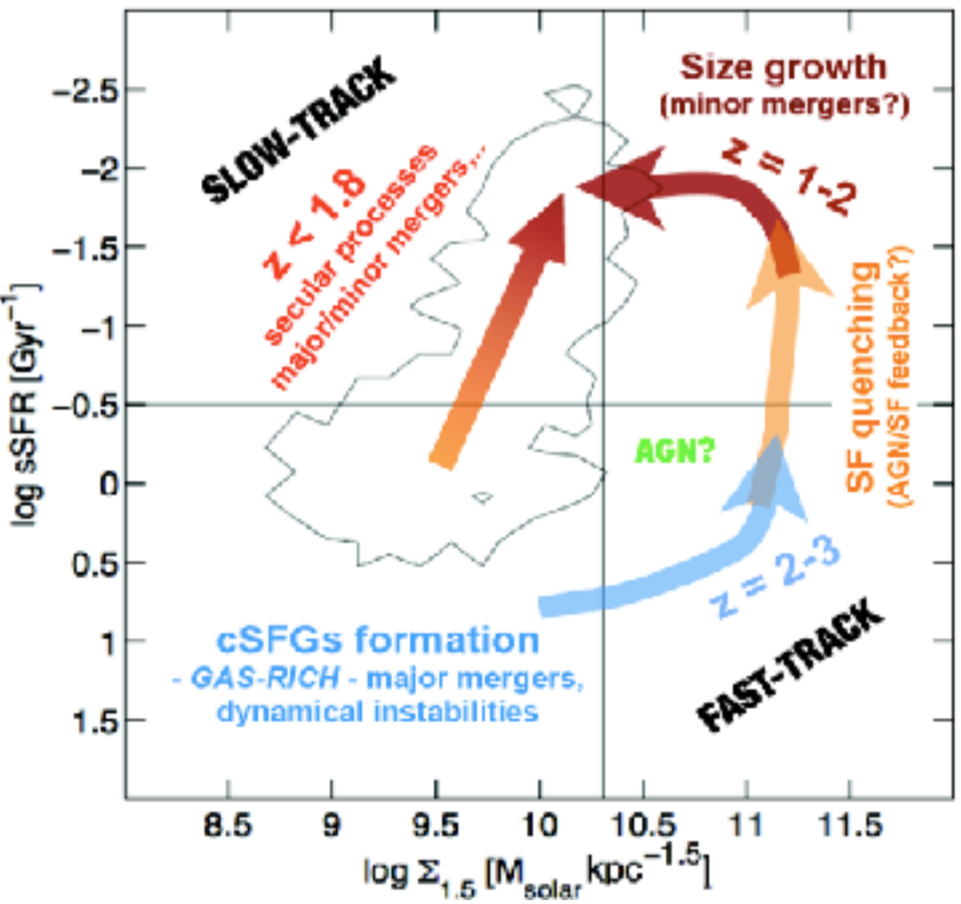
The hydroART cosmological zoom-in simulations produce all of these phenomena!

The Fast Track of Galaxy Evolution



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

Barro+ (CANDELS) 2013

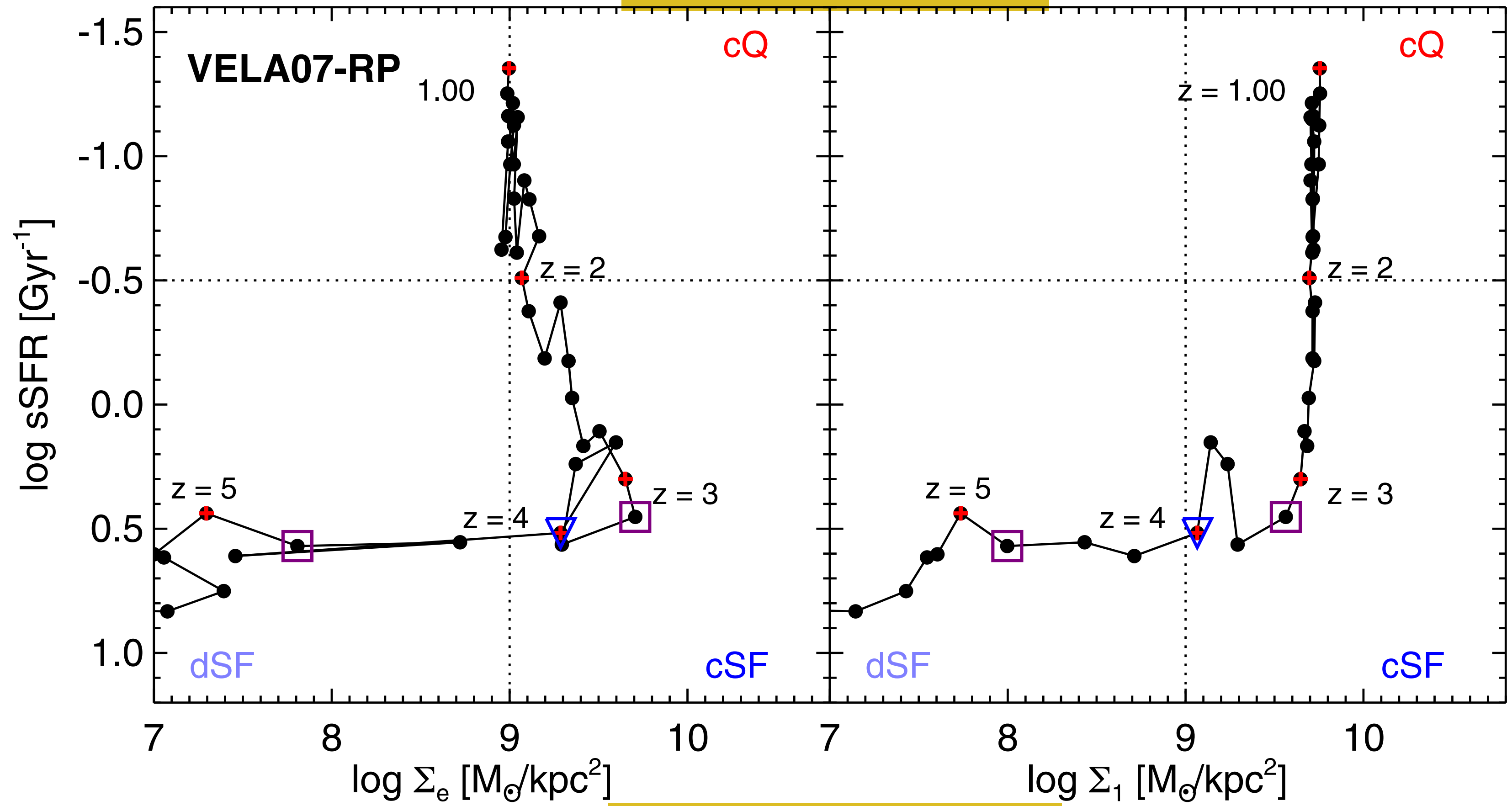


COMPACTION —>

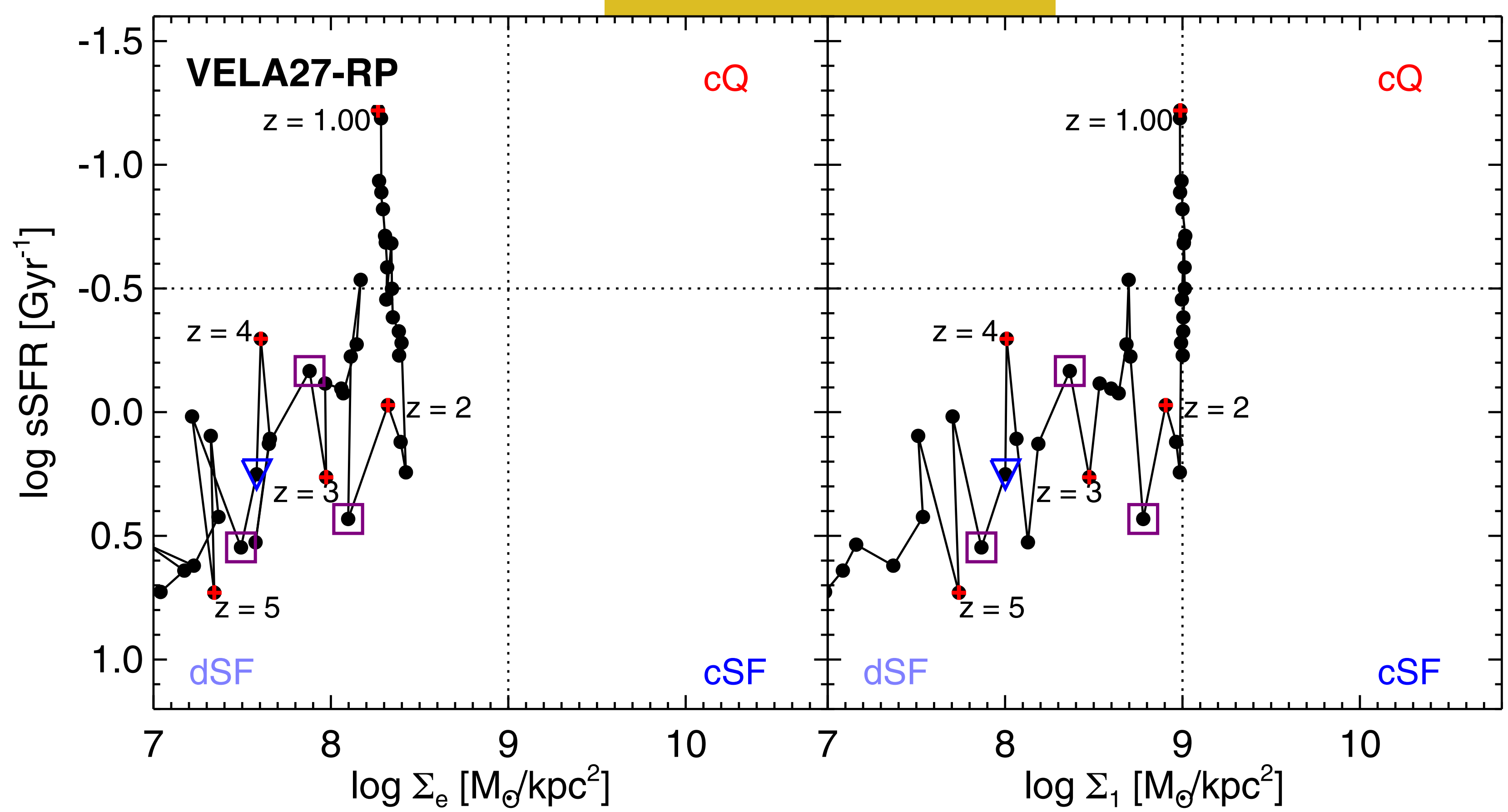
major merger

minor merger

FAST-TRACK

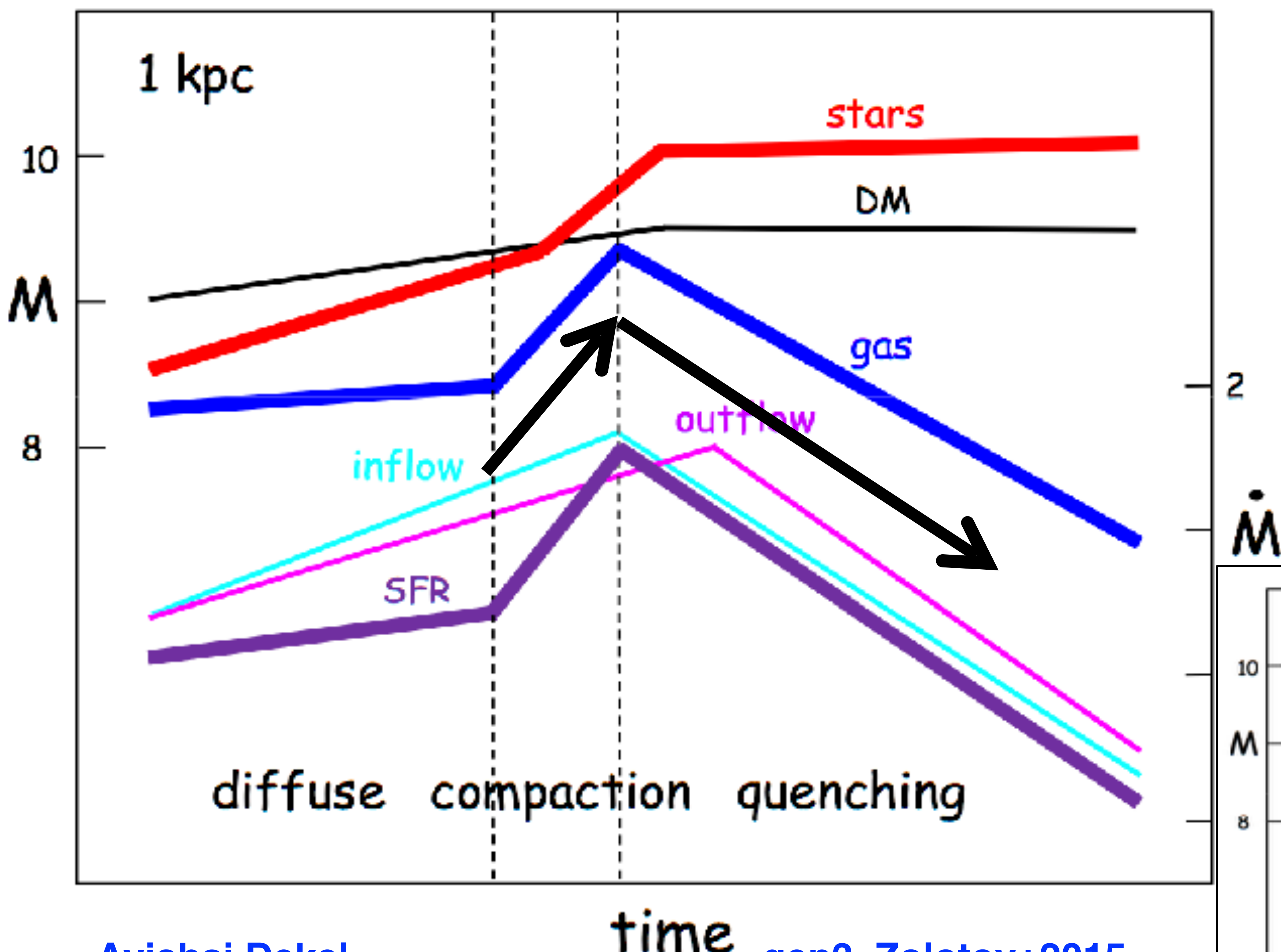


SLOW-TRACK



Zolotov+2015

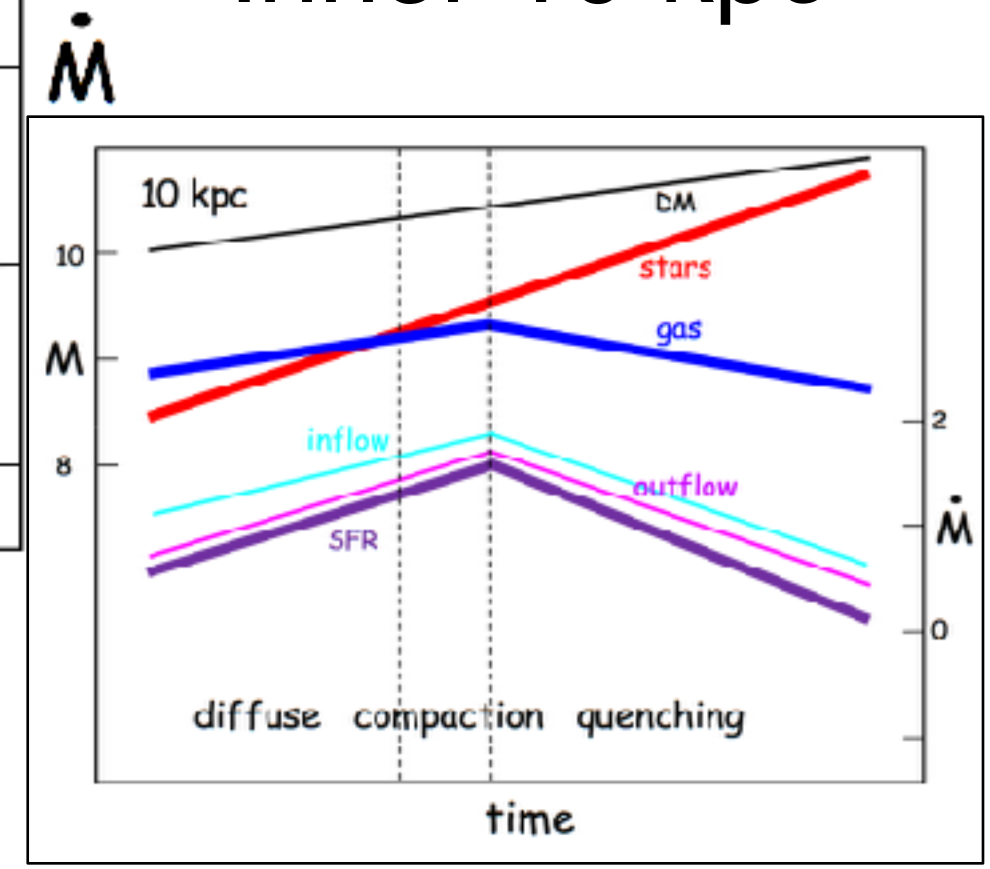
Compaction and Quenching in the Inner 1 kpc



Avishai Dekel

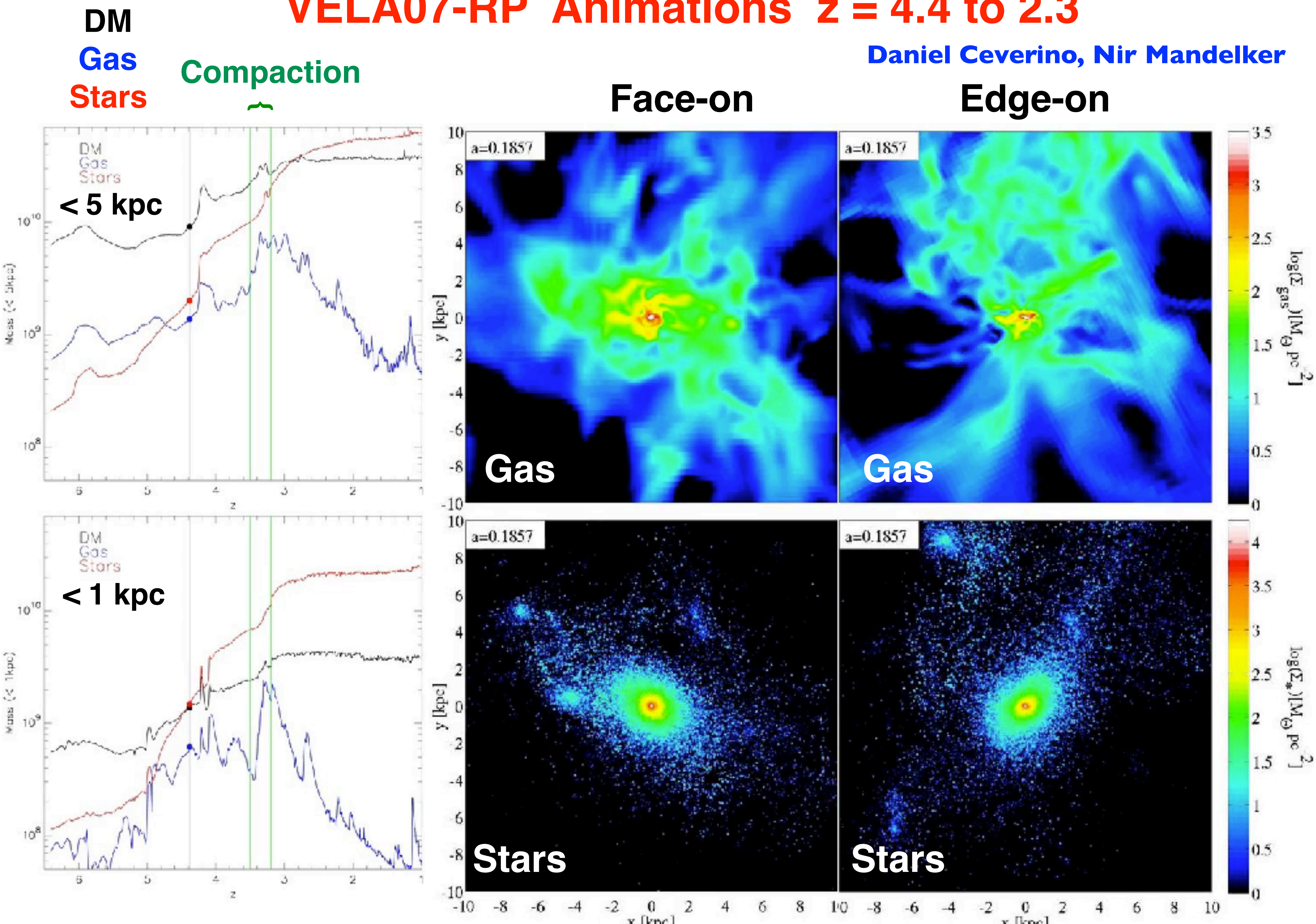
gen3 Zolotov+2015

Inner 10 kpc

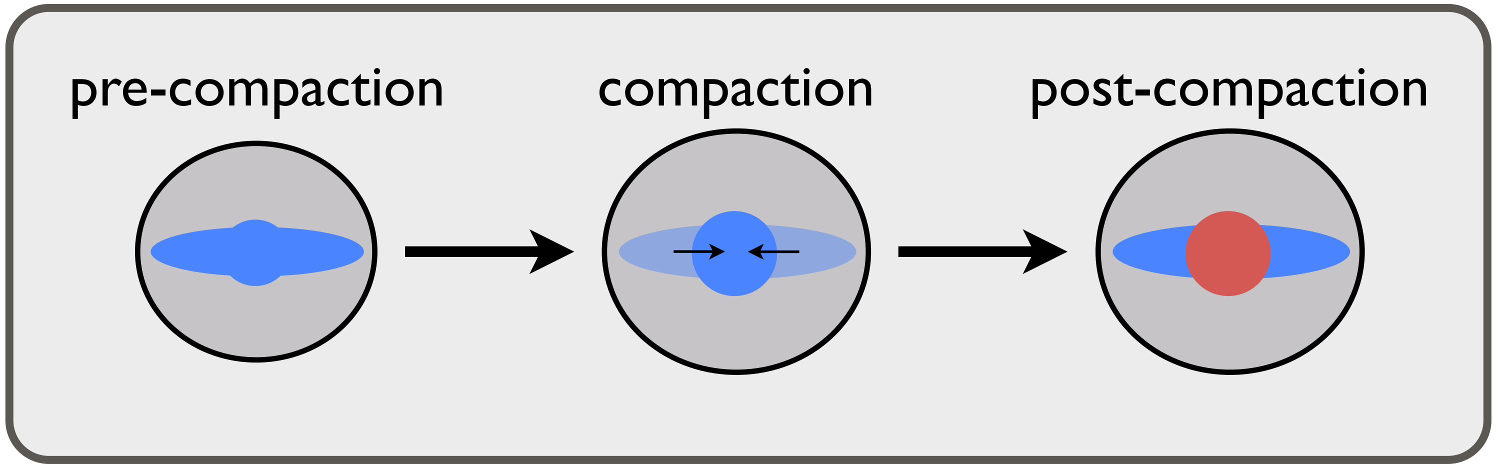


VELA07-RP Animations z = 4.4 to 2.3

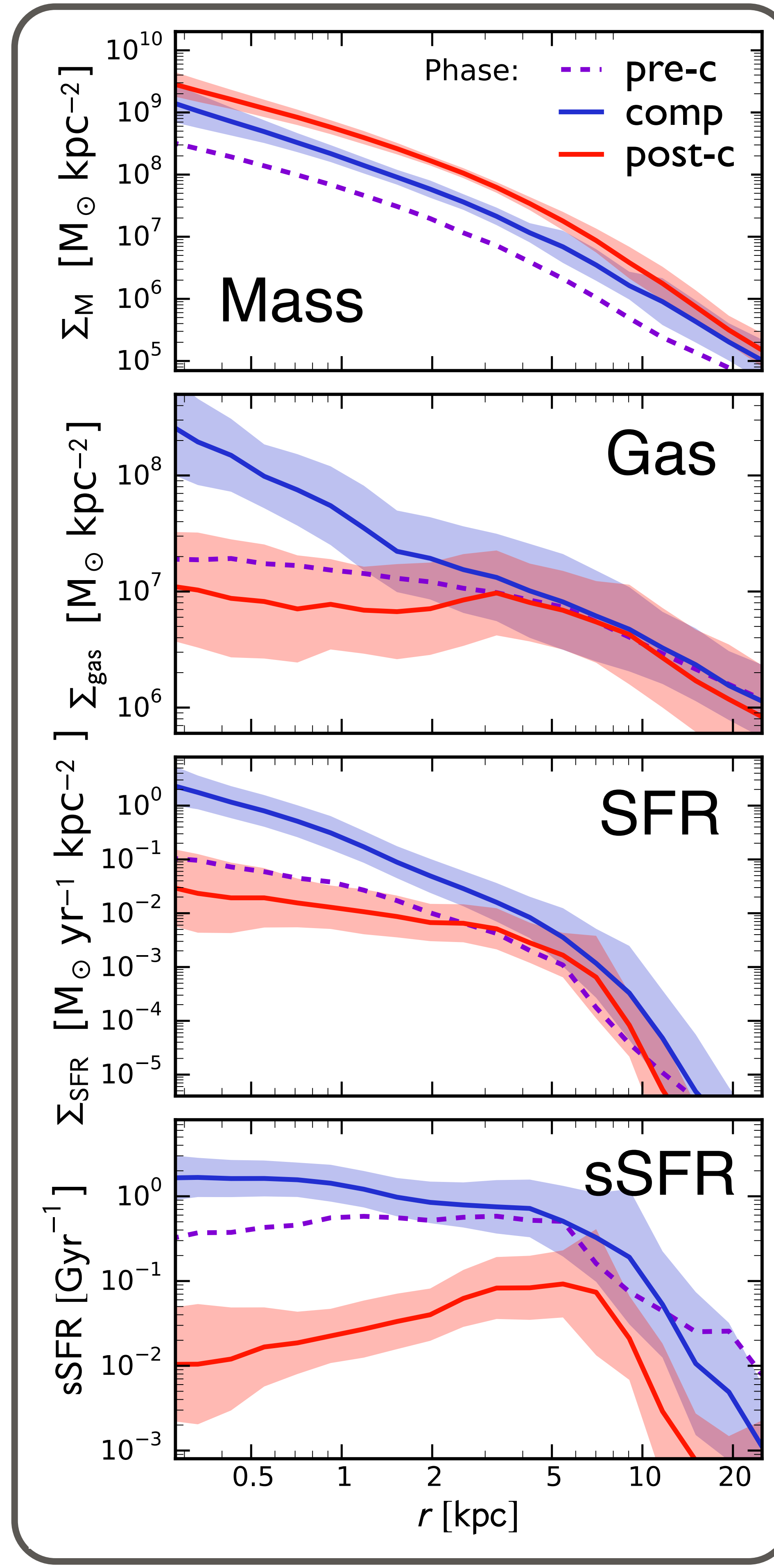
Daniel Ceverino, Nir Mandelker



Phase of Compaction



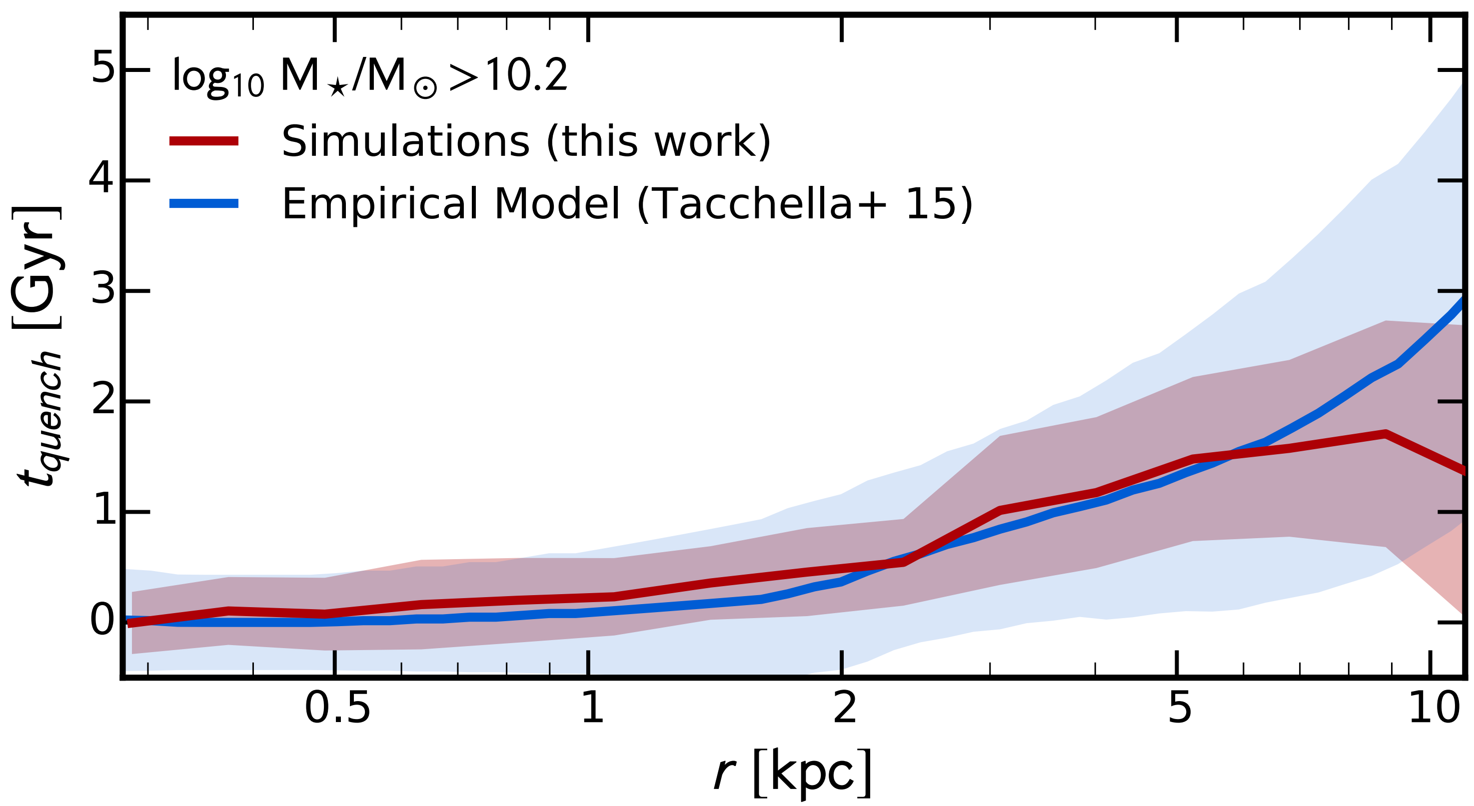
- stellar mass profiles:
  - growth self-similar
  - convergence in the center
- gas mass and SFR profiles:
  - cusp in the compaction phase
  - ring thereafter
- sSFR profiles:
  - inside-out quenching

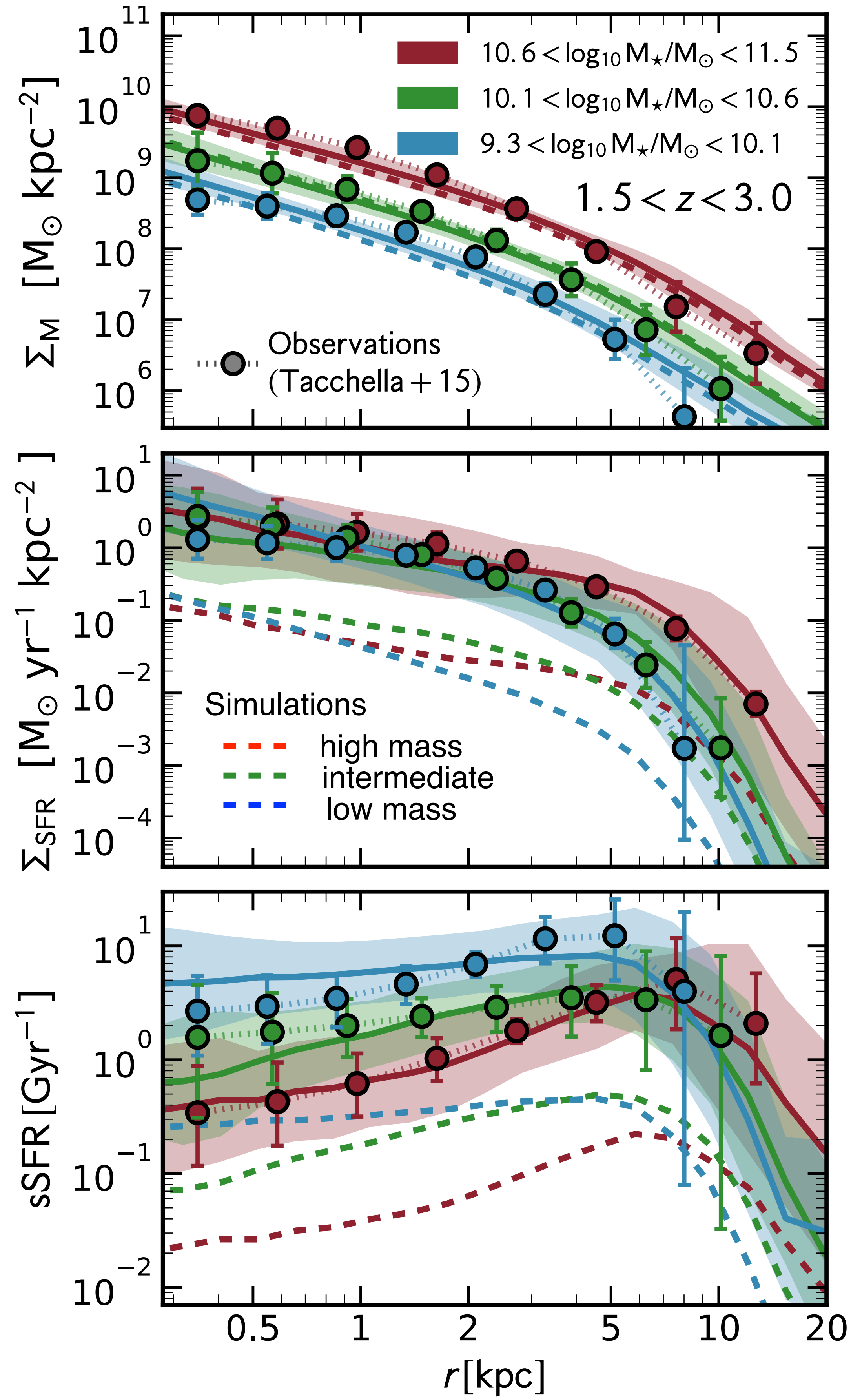


Tacchella+2016 Evolution of Density Profiles in High-z Galaxies: Compaction and Quenching Inside-Out

Comparison: Simulations — Observations

Stellar profiles agree over 4 orders of magnitude in surface density ➜

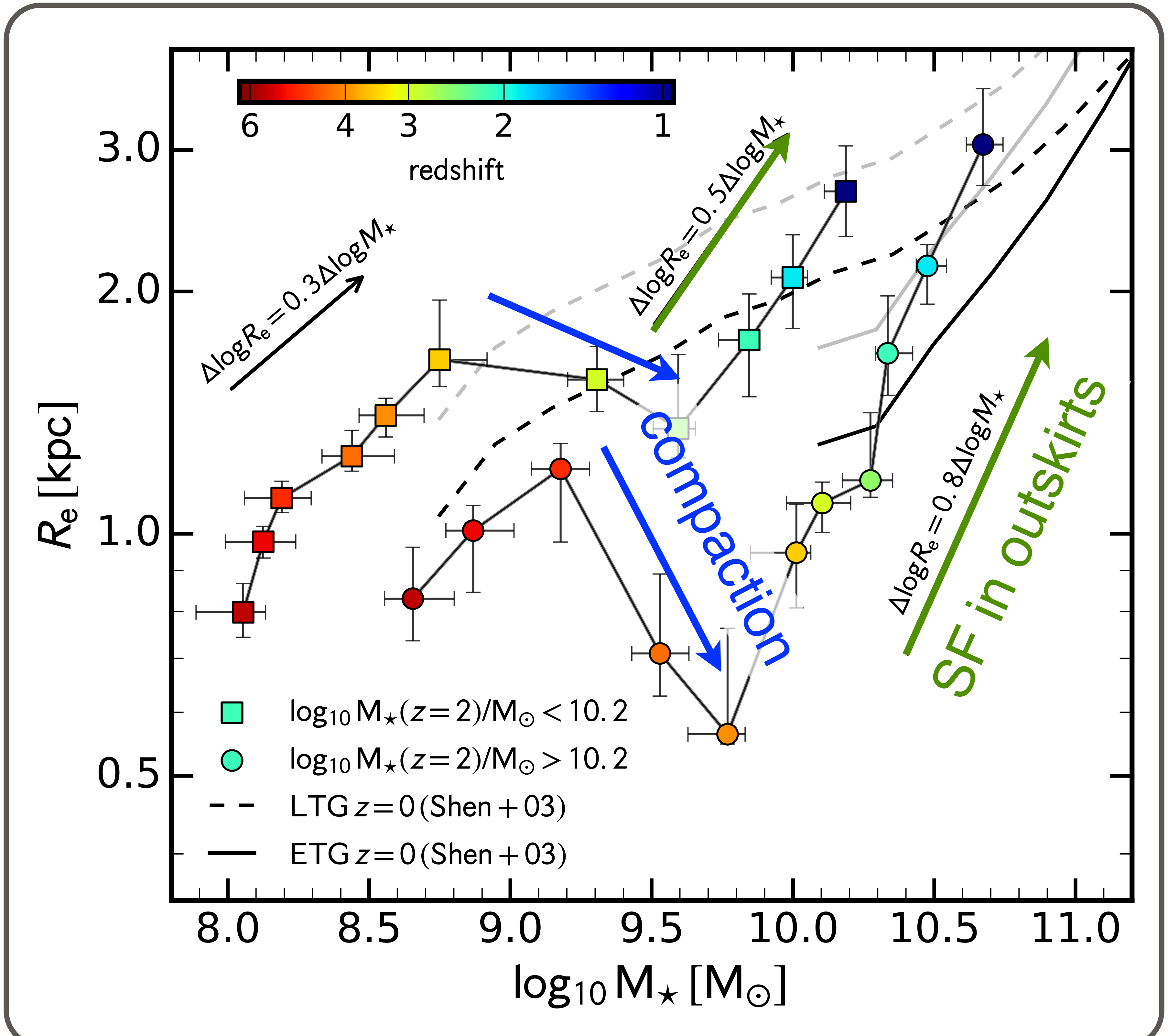




qualitative similar quenching progression in empirical model and simulations

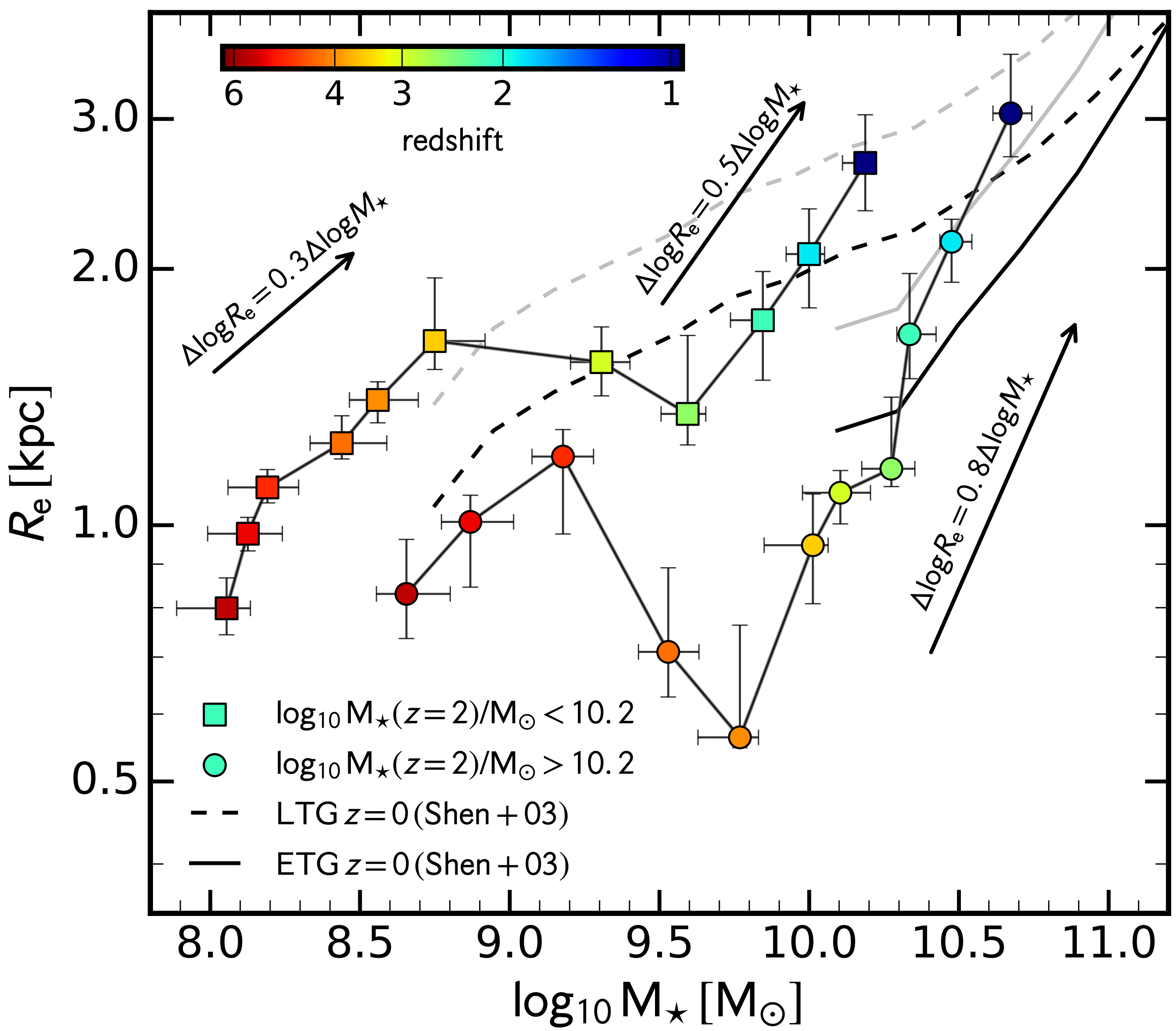
Tacchella+2016 Evolution of Density Profiles in High-z Galaxies: Compaction and Quenching Inside-Out

Evolution of the Average Size

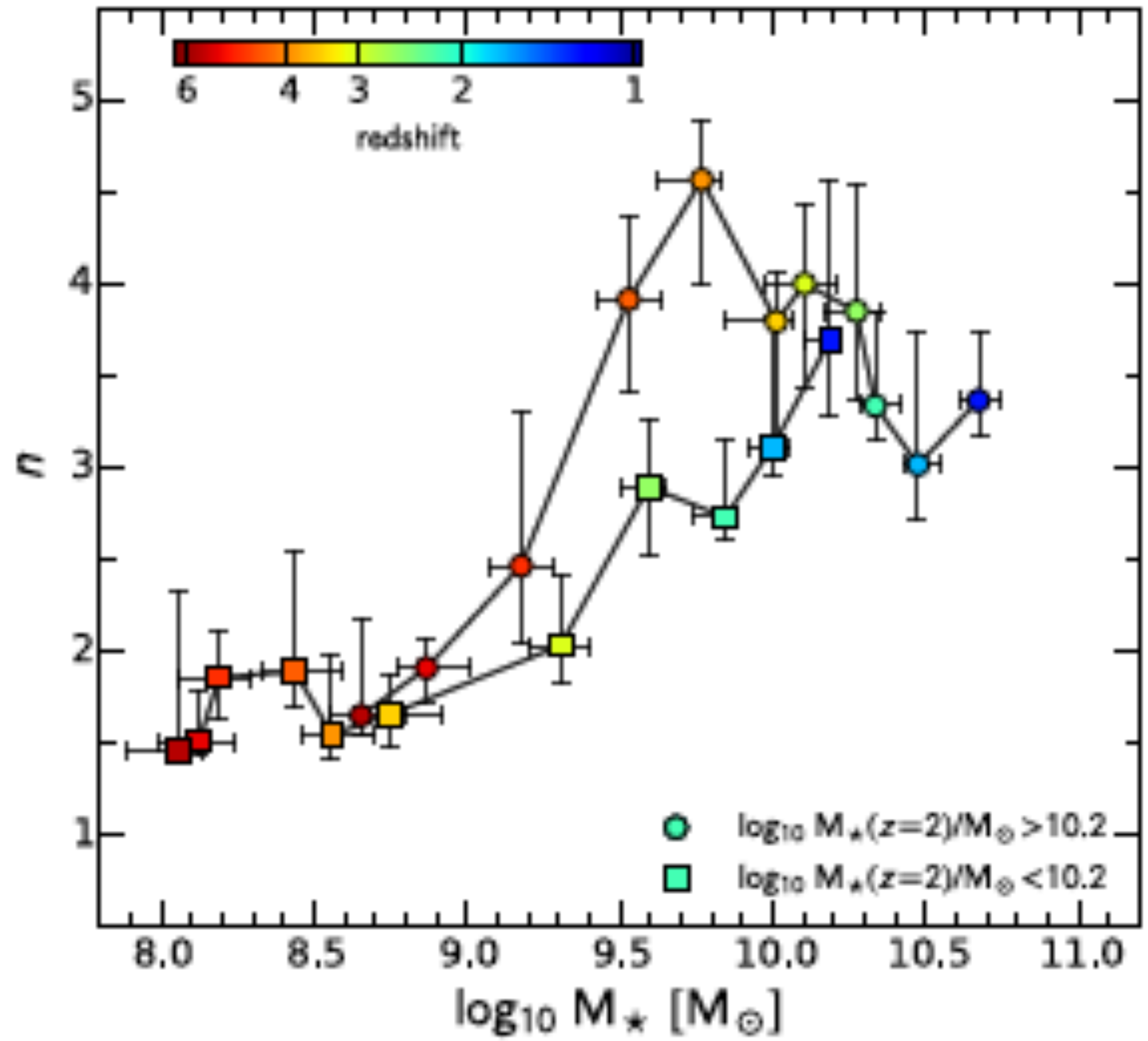


Tacchella+2016 Evolution of Density Profiles in High-z Galaxies:
Compaction and Quenching Inside-Out

Size vs. Stellar Mass

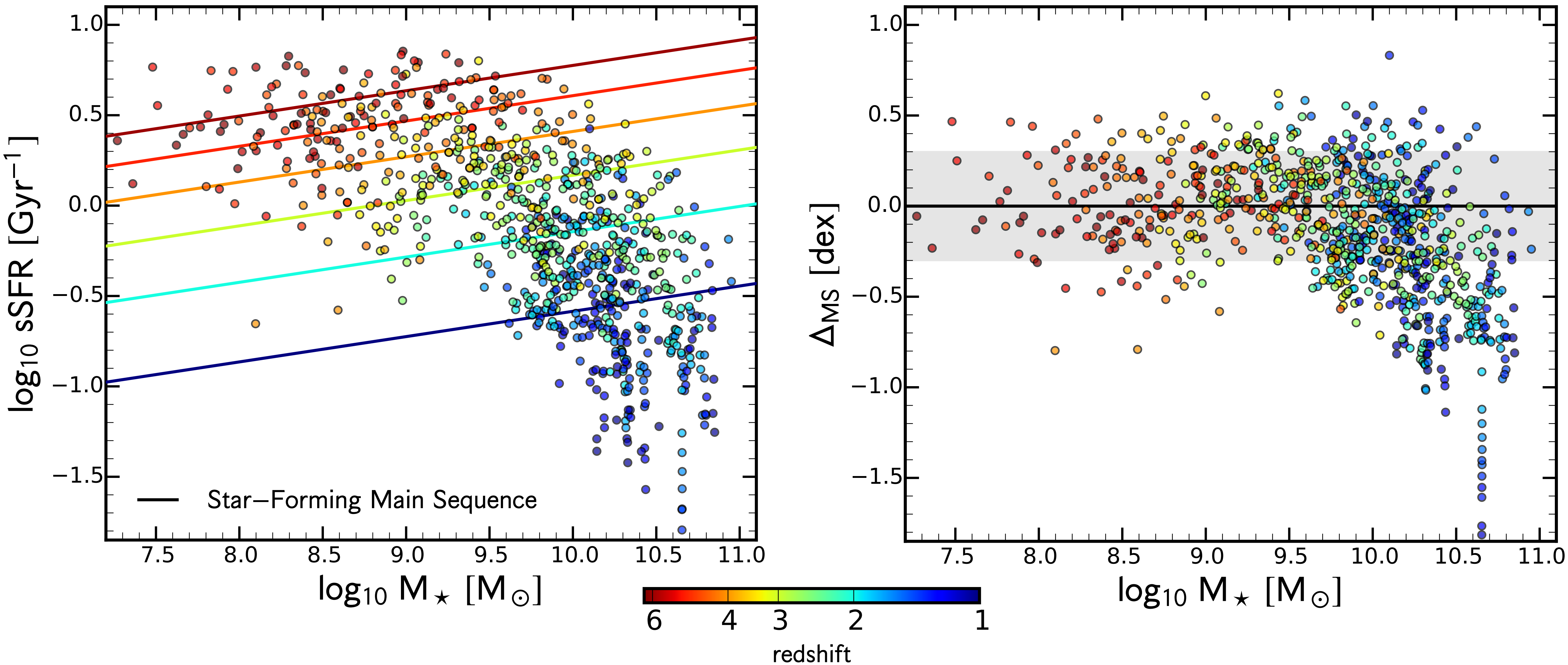


Sersic Index vs. Stellar Mass



Tacchella+2016 Evolution of Density Profiles in High-z Galaxies:
Compaction and Quenching Inside-Out

Star-Forming Main Sequence in the Simulations



- distance from the MS:

$$\Delta_{\rm MS} = \log_{10}\left(\frac{\rm sSFR}{\rm sSFR_{MS}}\right) \qquad {\rm sSFR_{MS}}(M_\star, z) = s \cdot \left(\frac{M_\star}{10^{10}\ M_\odot}\right)^{\beta} \cdot (1+z)^{\mu}\ \ {\rm Gyr}^{-1}$$

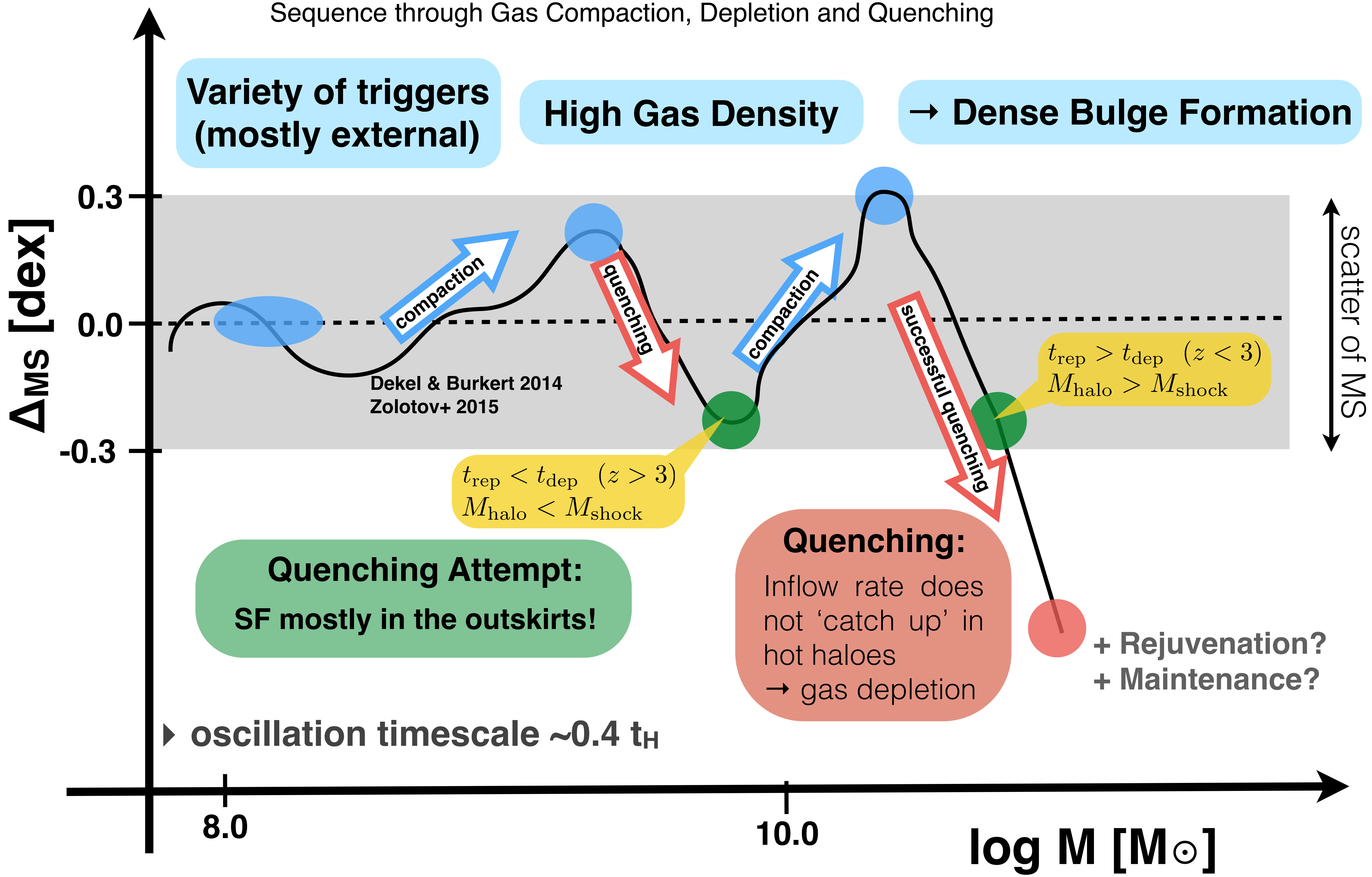
- scatter in the simulations:

$$\sigma_{\rm MS} = 0.24\ {\rm dex}\ (z=5) \rightarrow 0.31\ {\rm dex}\ (z=3)$$

Tacchella+2016 The Confinement of Star-Forming Galaxies into a Main Sequence through Gas Compaction, Depletion and Quenching

Evolution of Galaxies about the Star-Forming Main Sequence

Tacchella+2016 The Confinement of Star-Forming Galaxies into a Main Sequence through Gas Compaction, Depletion and Quenching



Gradient across the Main Sequence

- galaxies at the upper envelope of the MS have …
  - … high central gas densities
  - … high total gas masses
  - … high gas to stellar mass ratios
  - … depletion time - MS correlation

agree with Genzel+2015 observations

- central gas mass density:

$$\log_{10} \rho_{\rm gas,1kpc} \propto 0.8 \times \Delta_{\rm MS}$$

- total gas mass:

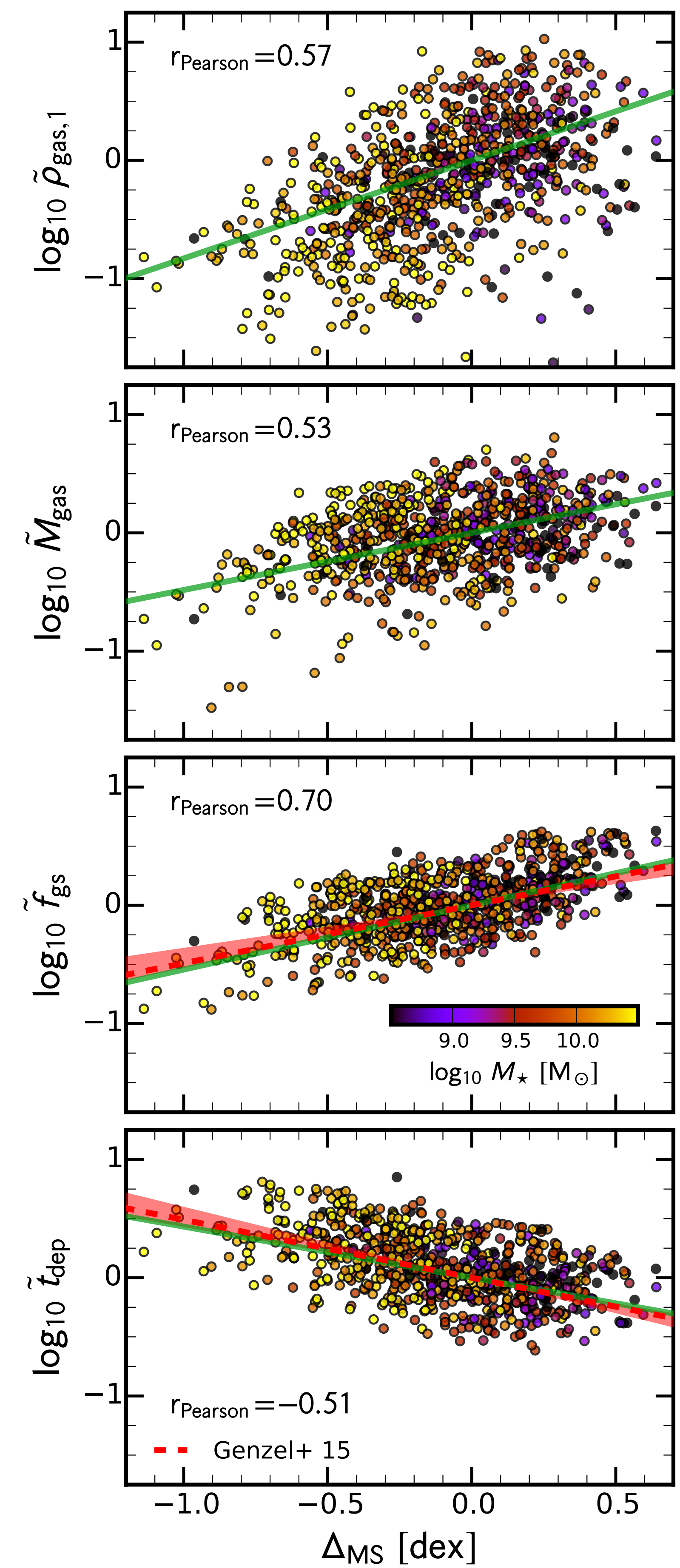
$$\log_{10} M_{\rm gas} \propto 0.5 \times \Delta_{\rm MS}$$

- gas to stellar mass ratio:

$$\log_{10} M_{\rm gas}/M_{\star} \propto 0.5 \times \Delta_{\rm MS}$$

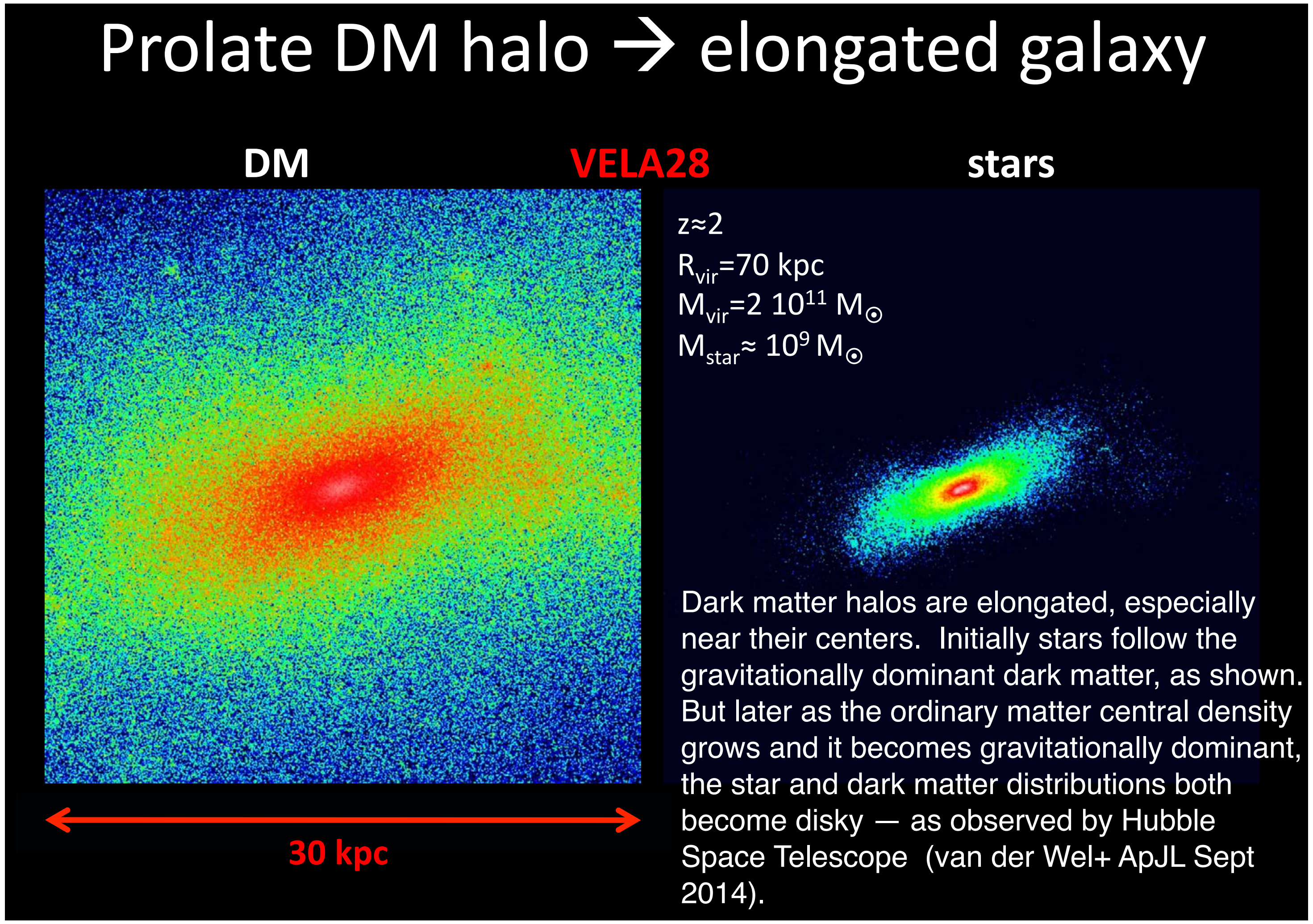
- depletion time:

$$\log_{10} t_{\rm dep} \propto 0.5 \times \Delta_{\rm MS}$$



Tacchella+2016 The Confinement of Star-Forming Galaxies into a Main Sequence through Gas Compaction, Depletion and Quenching

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

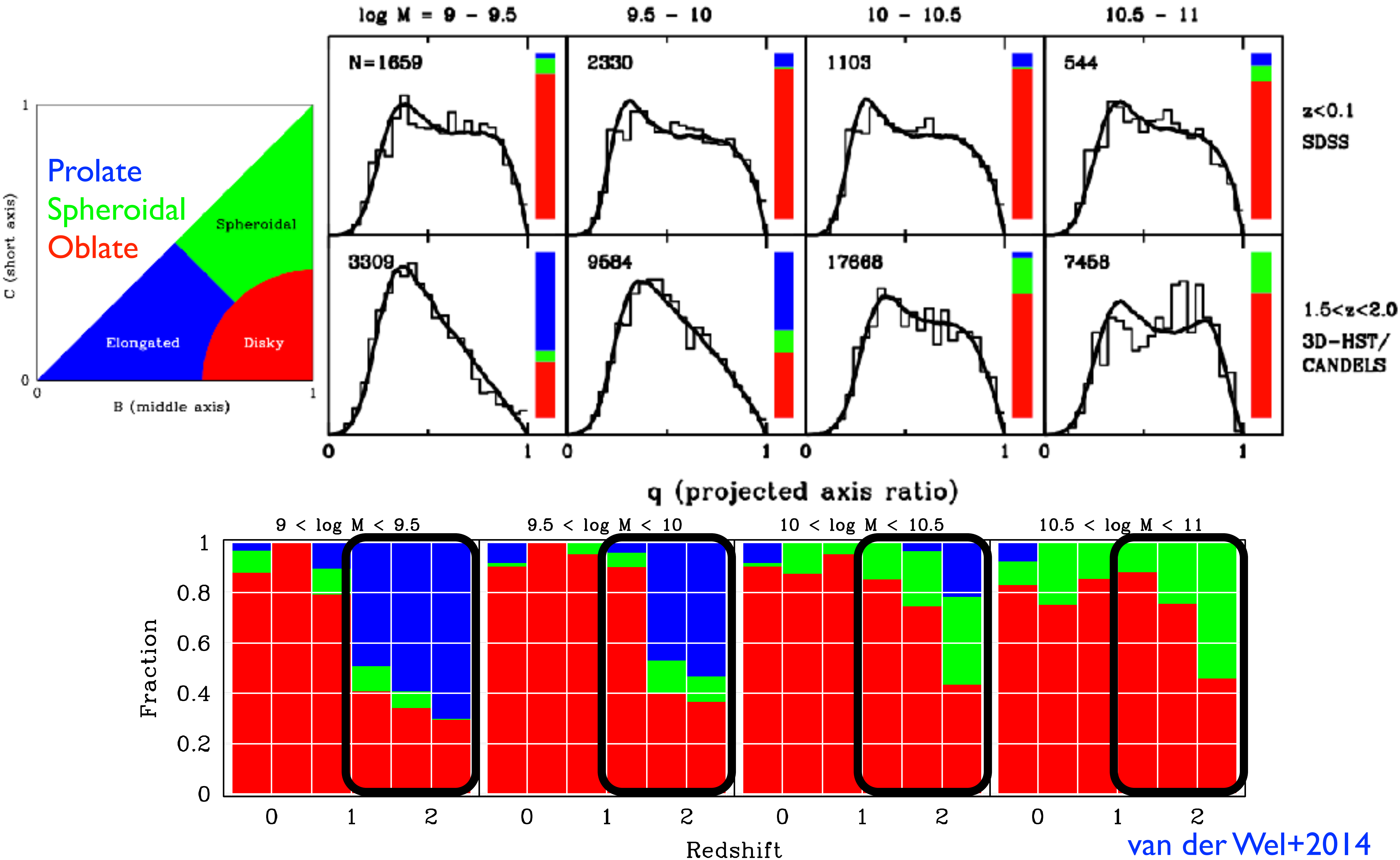
Daniel Ceverino, Joel Primack and Avishai Dekel

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

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

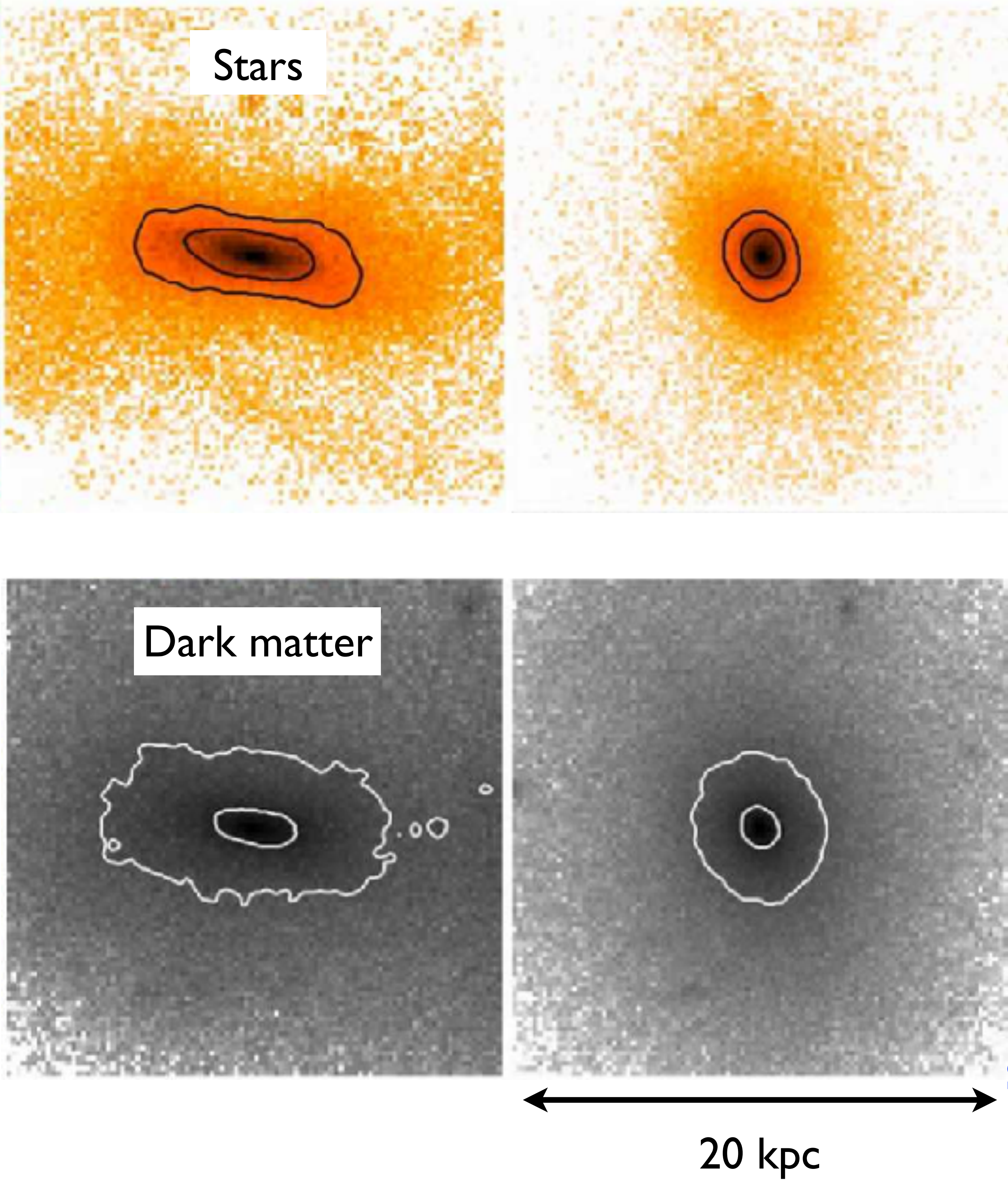
Prolate galaxies dominate at high redshift/low masses

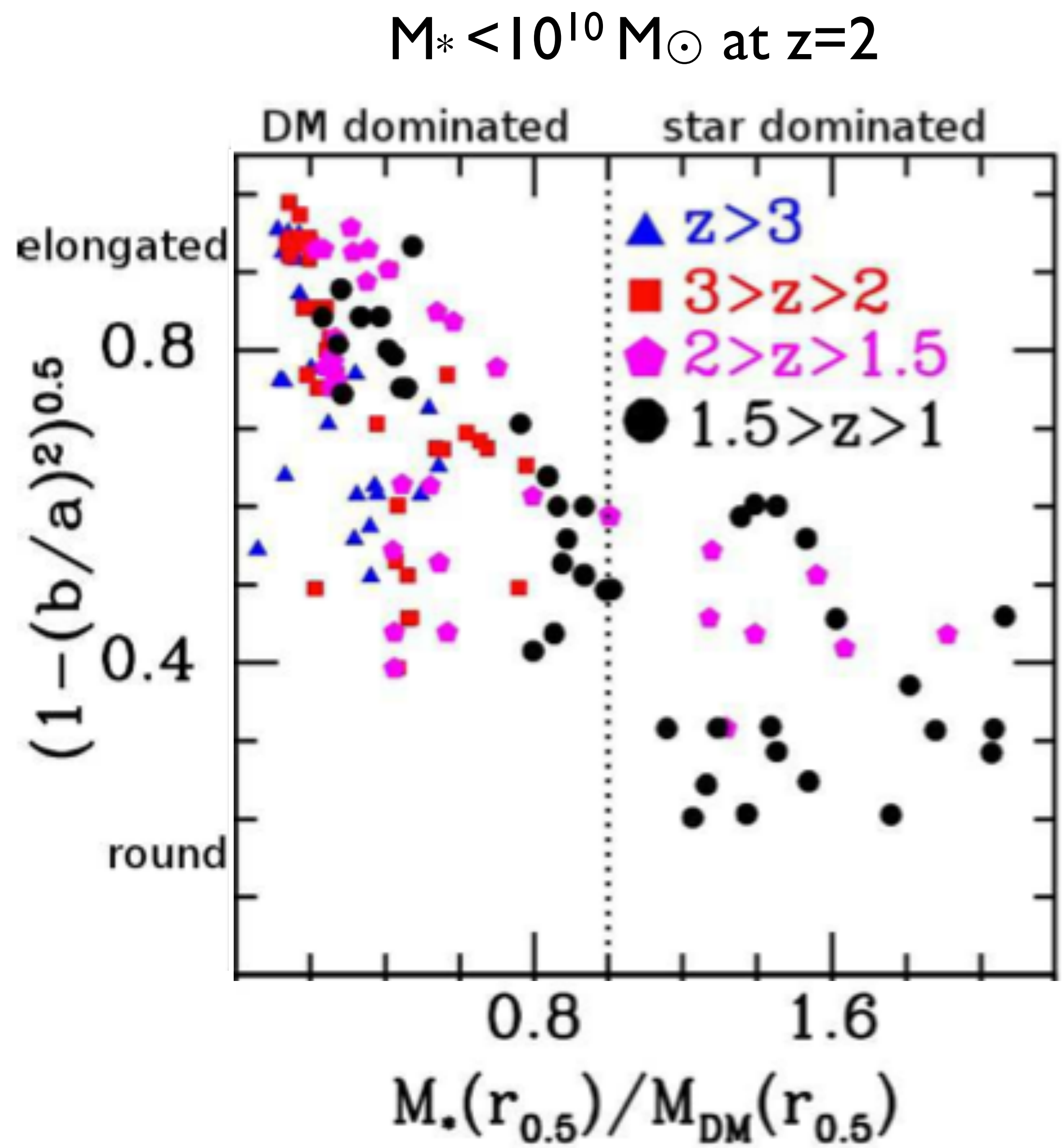


van der Wel+2014

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

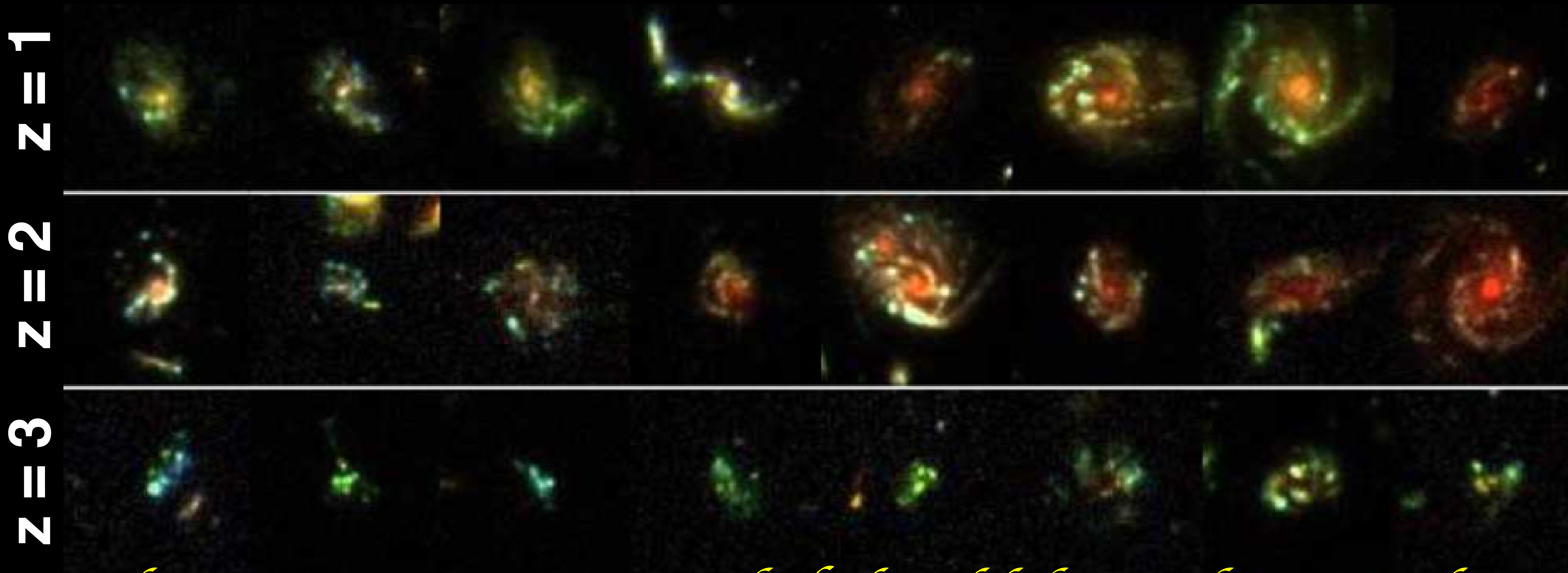
- 3 Aspects of Star-Forming Galaxies Seen in CANDELS
  - Compaction
  - Elongation
  - Clumps

} 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

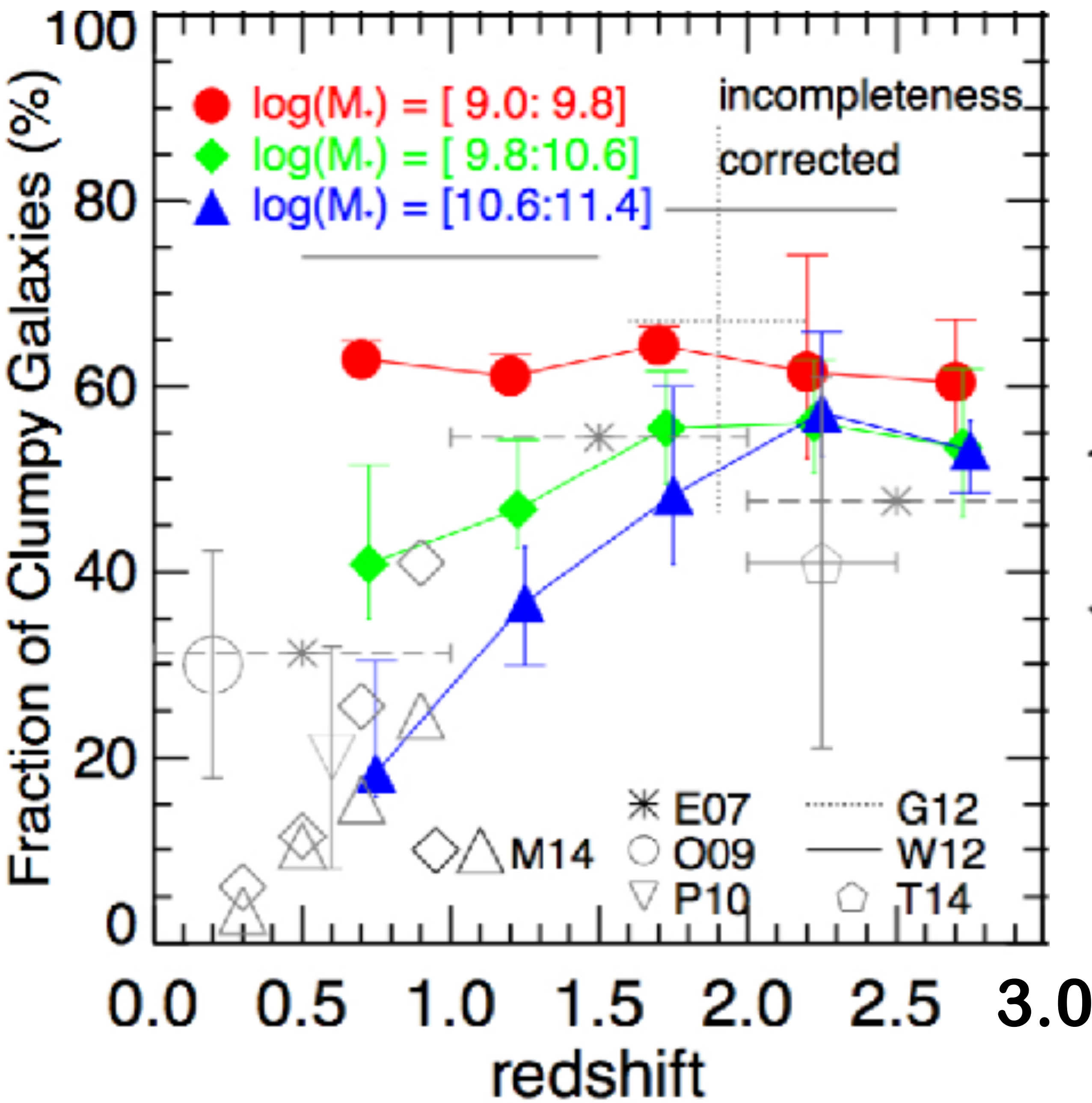
About 60% of star-forming galaxies are clumpy at z ~ 2.5.

The evolution of the clump fraction is mass-dependent.

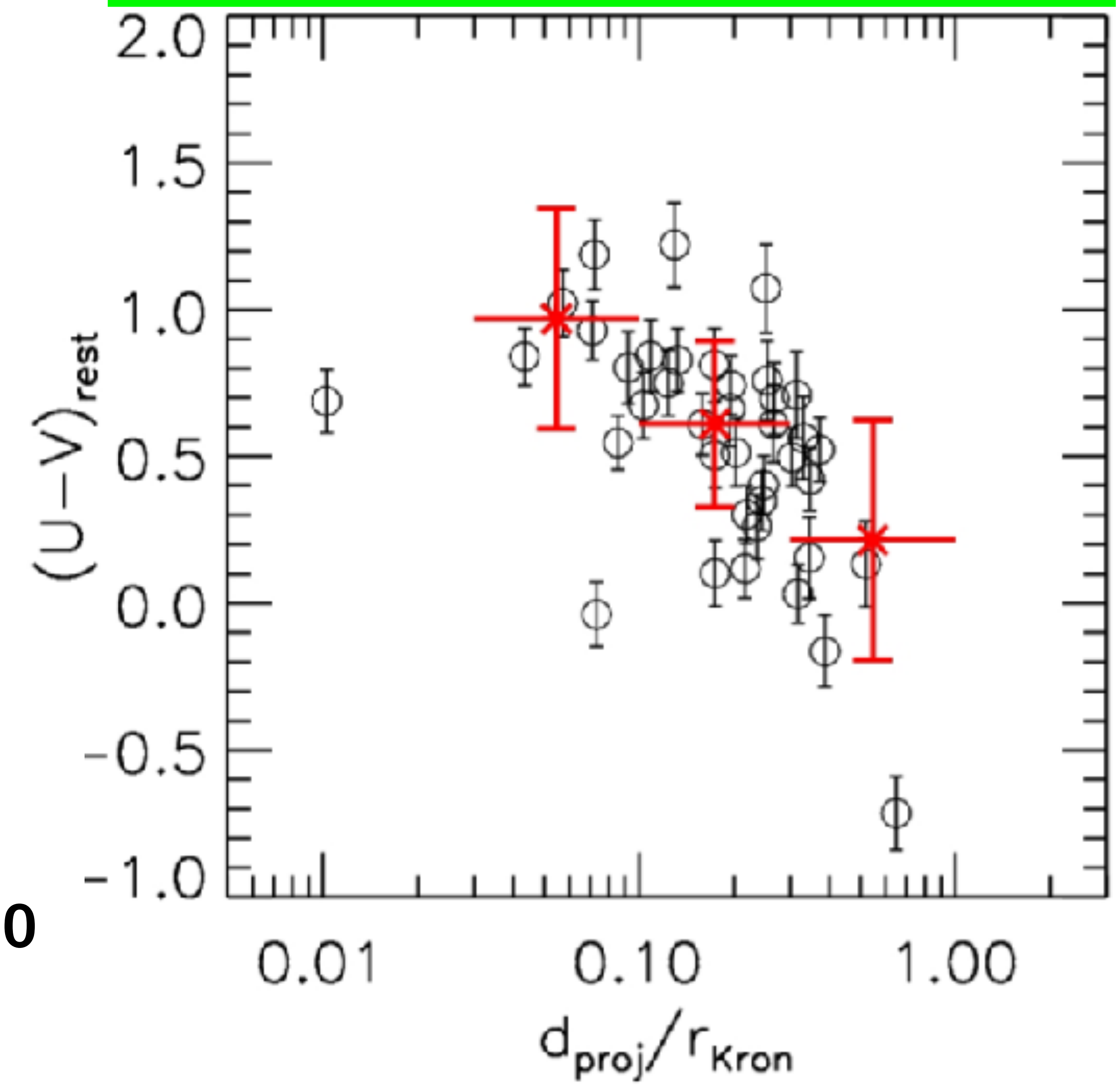
Clumps have radial variation of their UV-optical colors:

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

as clump radial migration predicts.

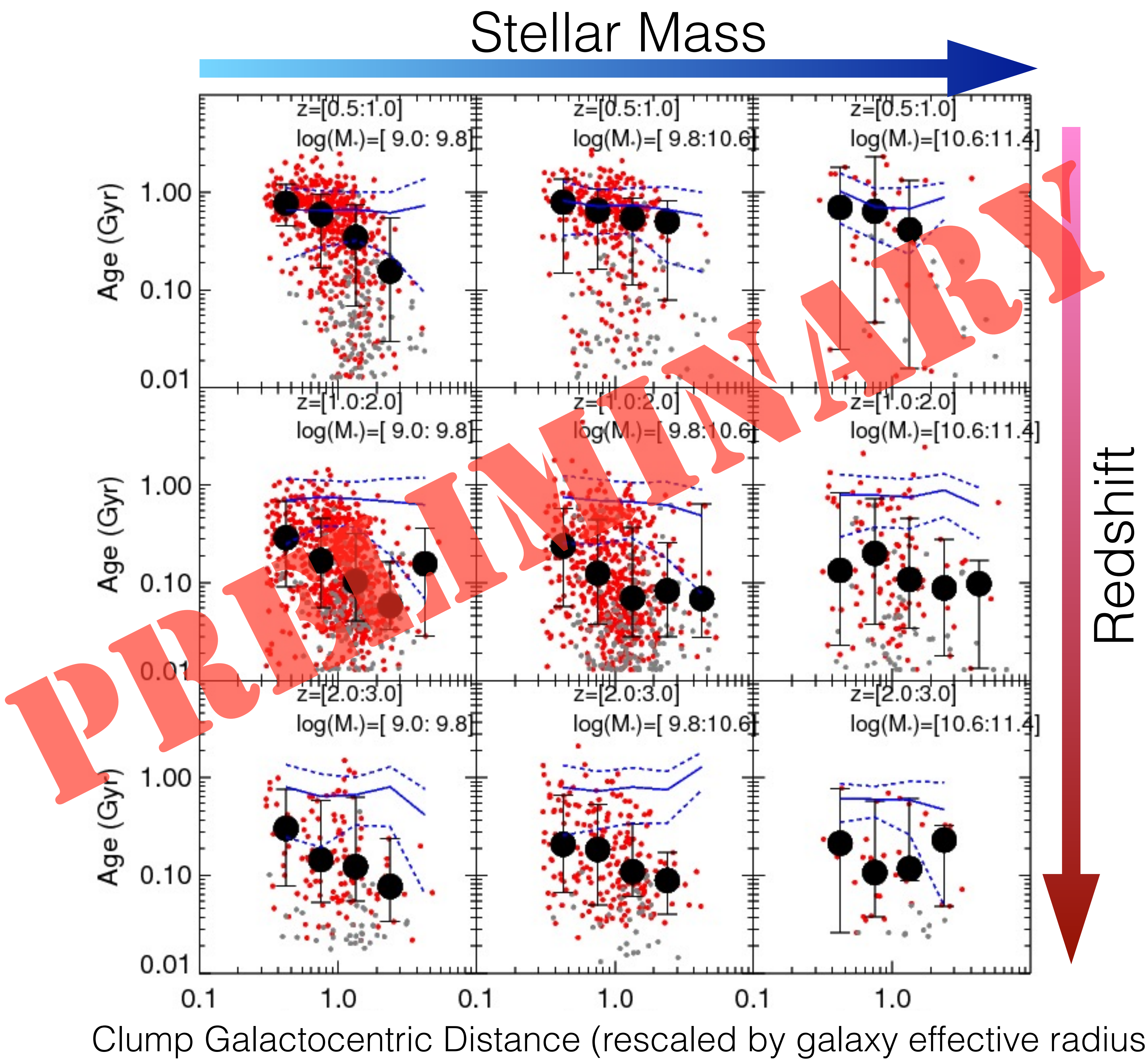


Yicheng Guo+2015



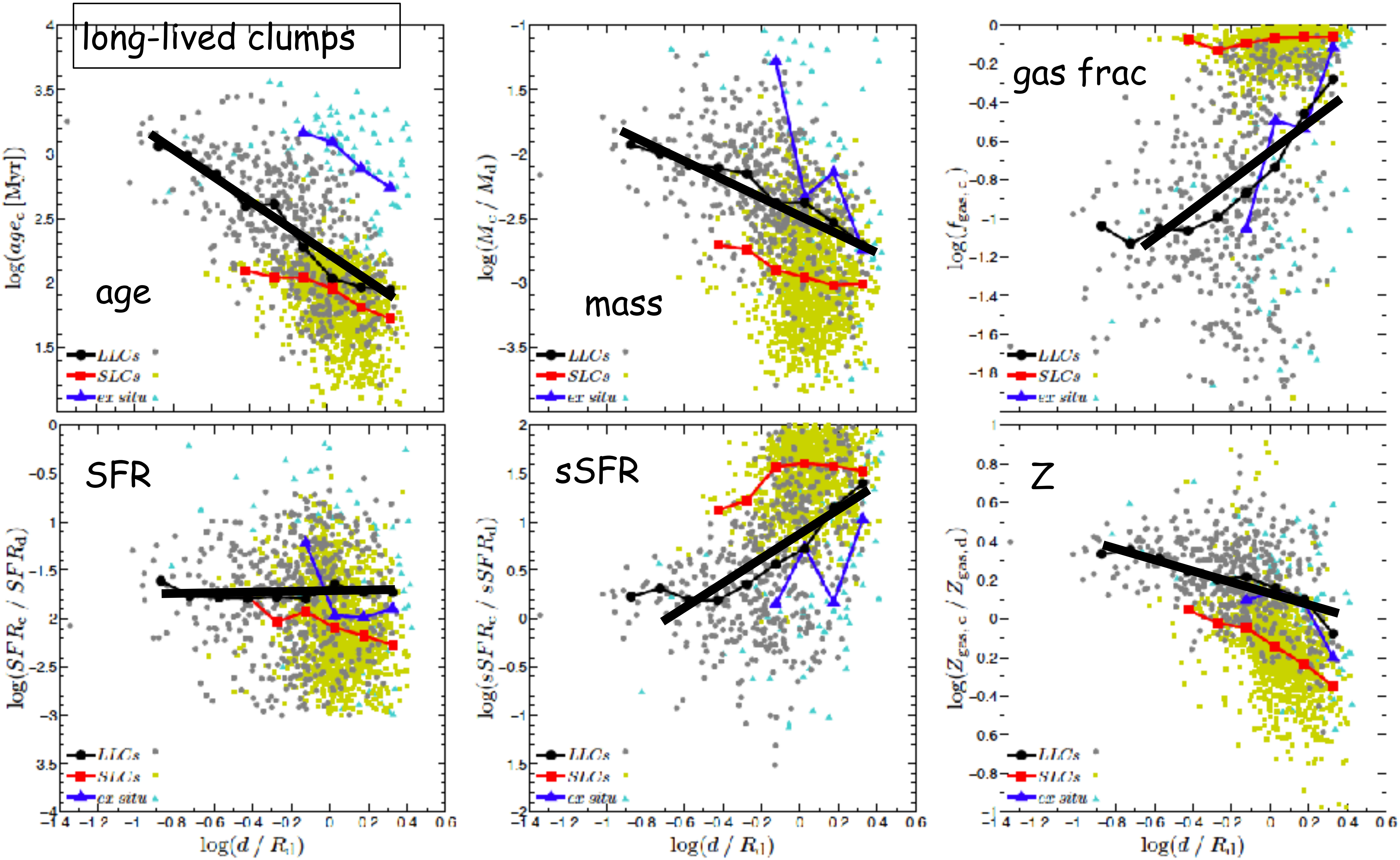
Yicheng Guo+2012

CLUMPS in CANDELS - Yicheng Guo



Predicted Gradients of Clump Properties

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



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

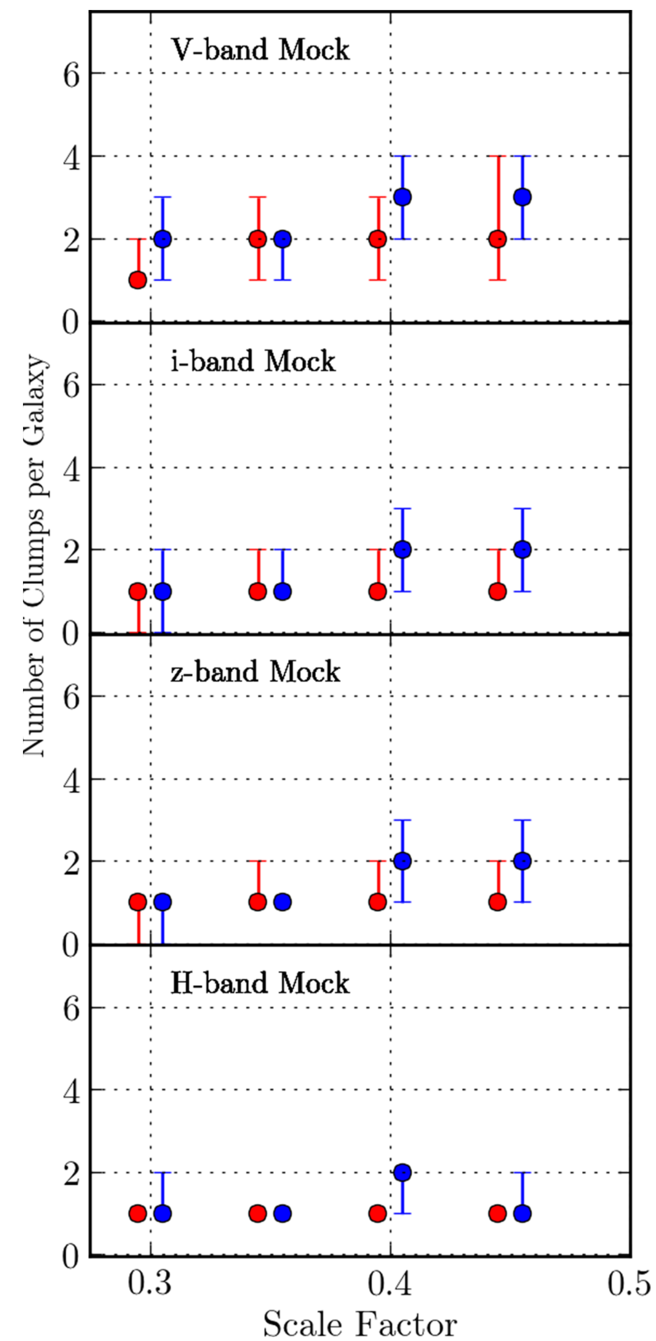
MNRAS **444,** 1389–1399 (2014) doi:10.1093/mnras/stu1534

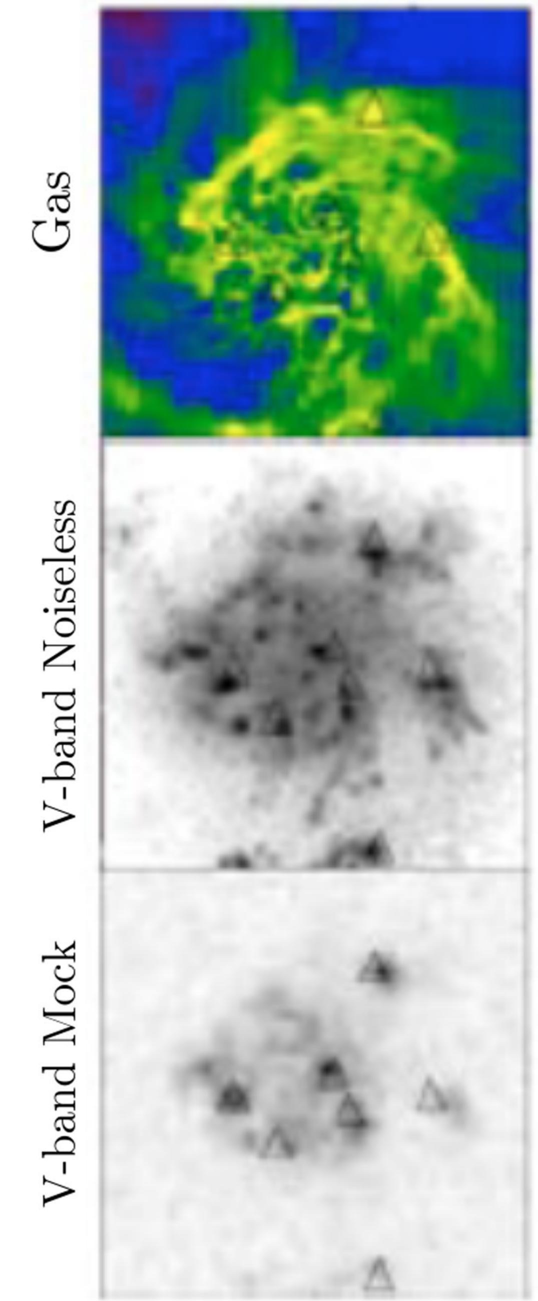
Star formation and clumps in cosmological galaxy simulations with radiation pressure feedback

Comparing gen2 & gen3

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 $M_{\mathrm{clump}}/M_{\mathrm{disc}} \leq 5$ 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.

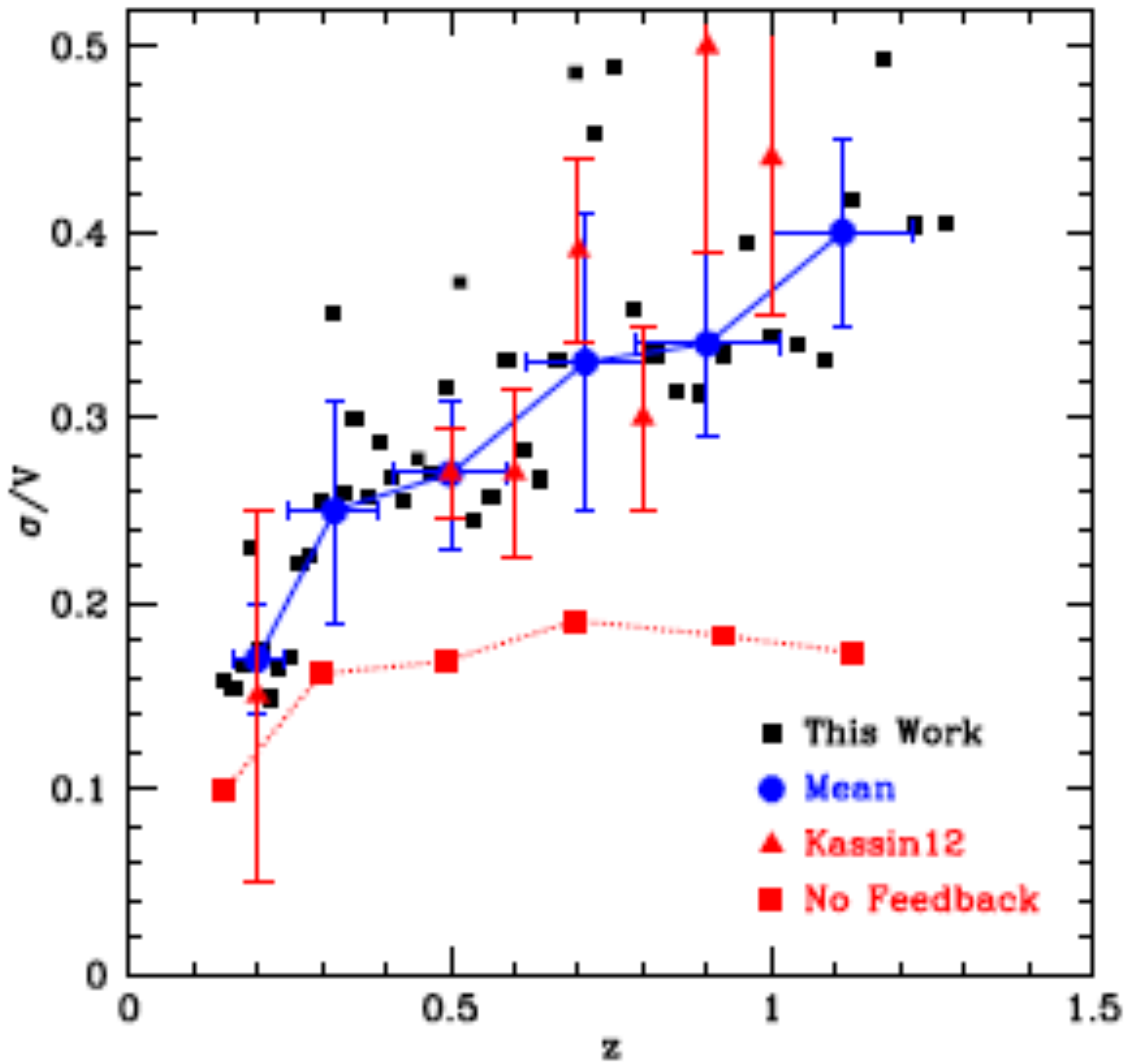




	f_{clumpy} $z = 3.0$–2.3	f_{clumpy} $z = 2.3$–1.9	f_{clumpy} $z = 1.9$–1.5
No-RP (blue)	0.32	0.53	0.64
RP (red)	0.24	0.48	0.54

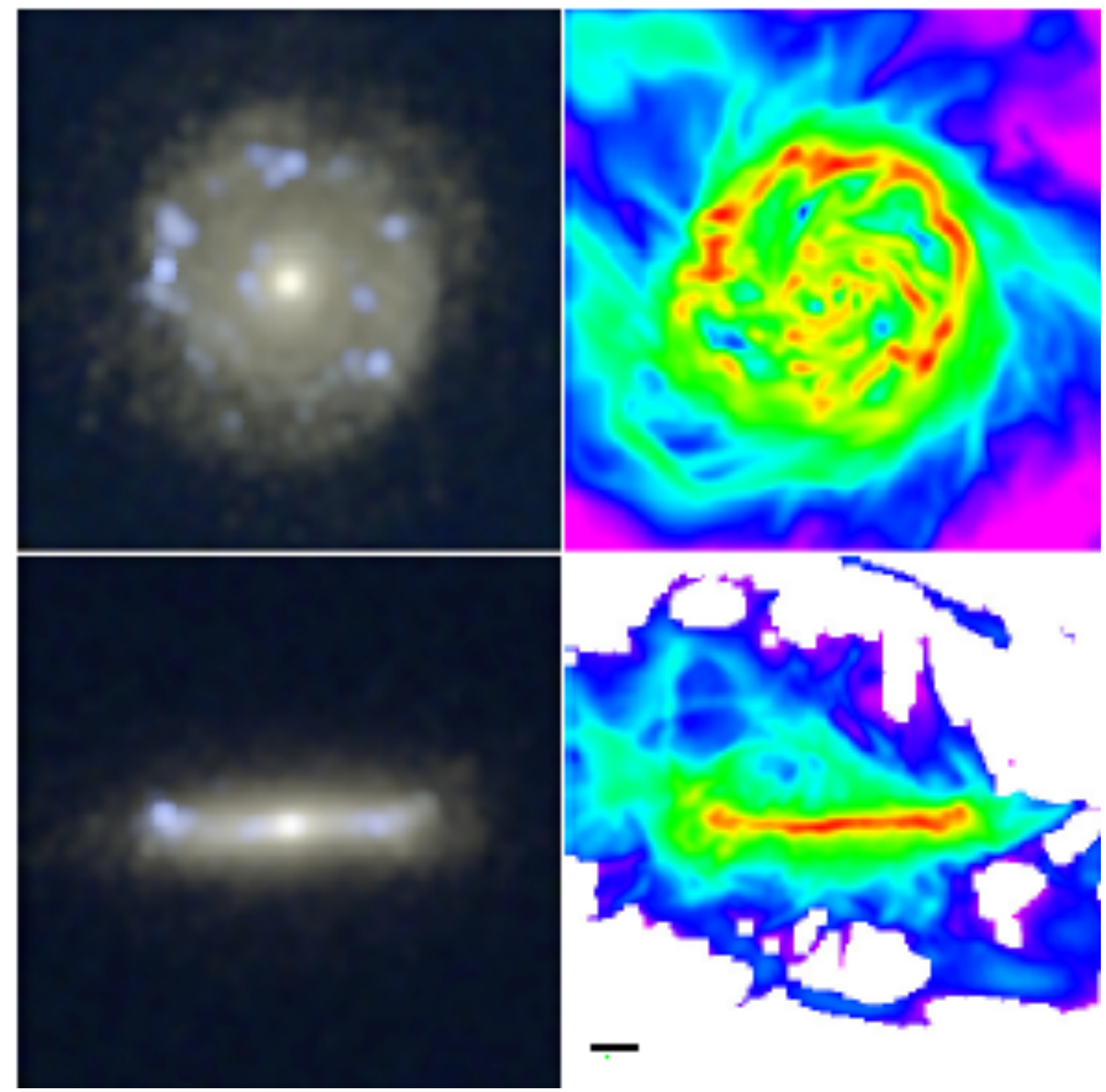
Formation and Settling of a Disc Galaxy During the Last 8 Billion Years in a Cosmological Simulation

Daniel Ceverino, Joel Primack, Avishai Dekel, Susan A. Kassin - MNRAS submitted



Disk Settling: σ/V declines as observed in similar-mass galaxies (M_{halo} = 1.7x10^{11})

This is one of the AGORA initial conditions.

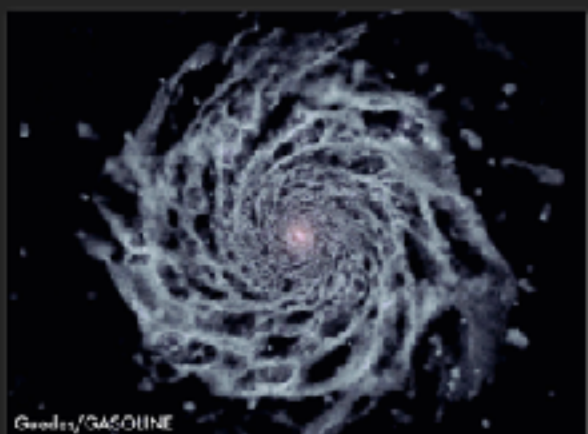


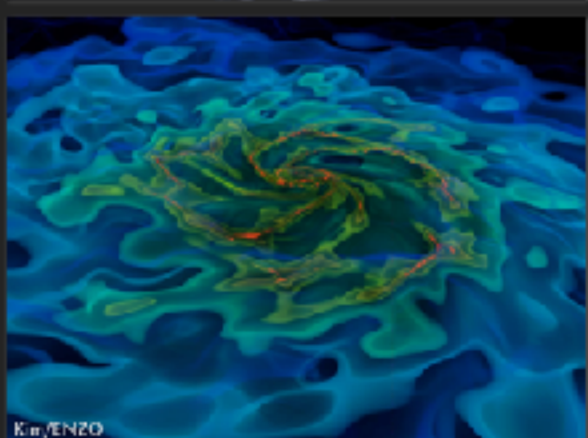
The simulation at $z = 0.1$ produces a thin disk, much like observed galaxies of this mass

AGORA

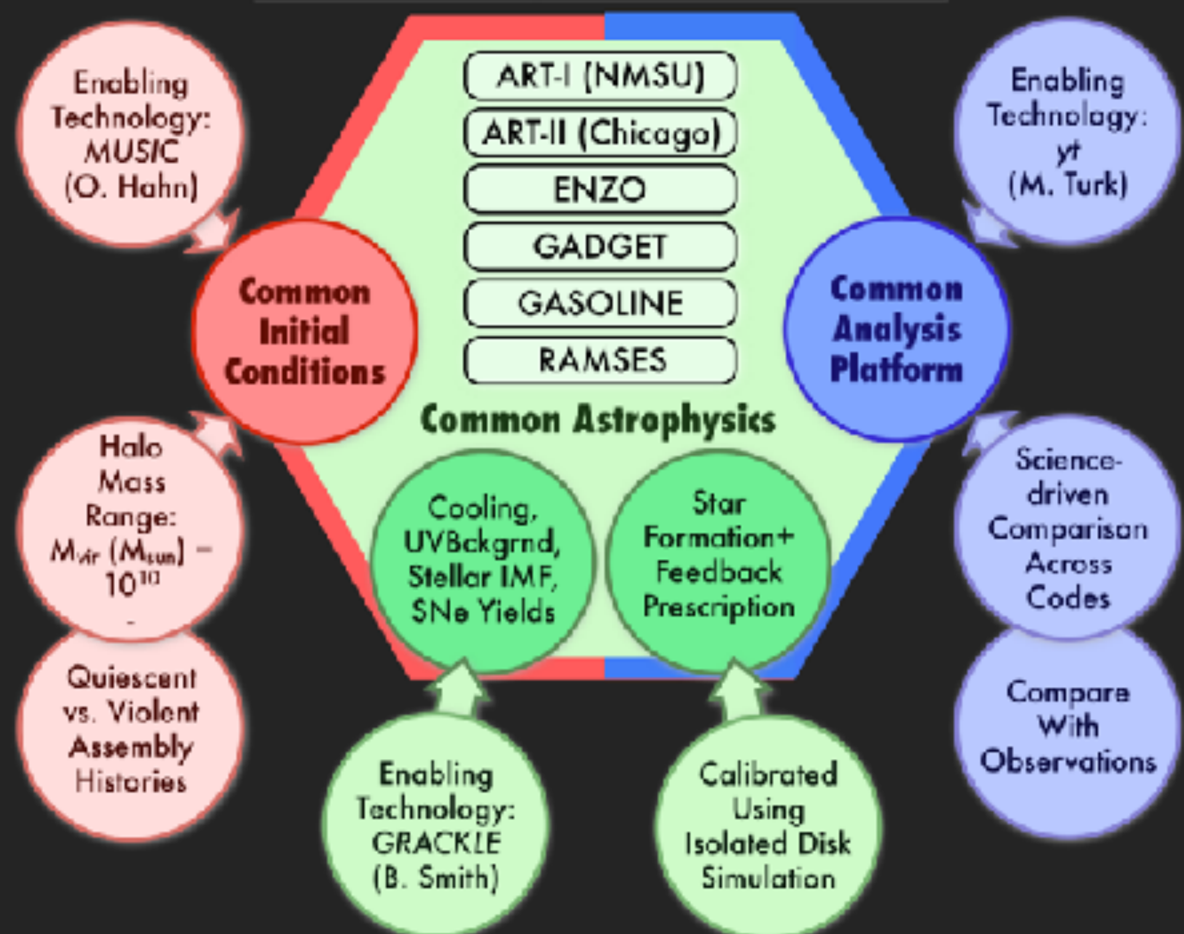
A High-resolution Galaxy Simulations Comparison Initiative: www.AGORAsimulations.org

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~0: ~10^{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~1: ~10^{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], Robert Thompson[7,19], Keita Todoroki[19], Matthew J. Turk[5], James W. Wadsley[27], John H. Wise[28], and Adi Zolotov[8]
for the AGORA Collaboration[29]

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

www.AGORAsimulations.org

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S9	Massive Black Holes	black hole growth and feedback in galactic context

AGORA Isolated Disk Comparison

submitted to ApJ

Milky Way-mass Disk Galaxy Formation with 80 pc Resolution

Summary of preliminary 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.

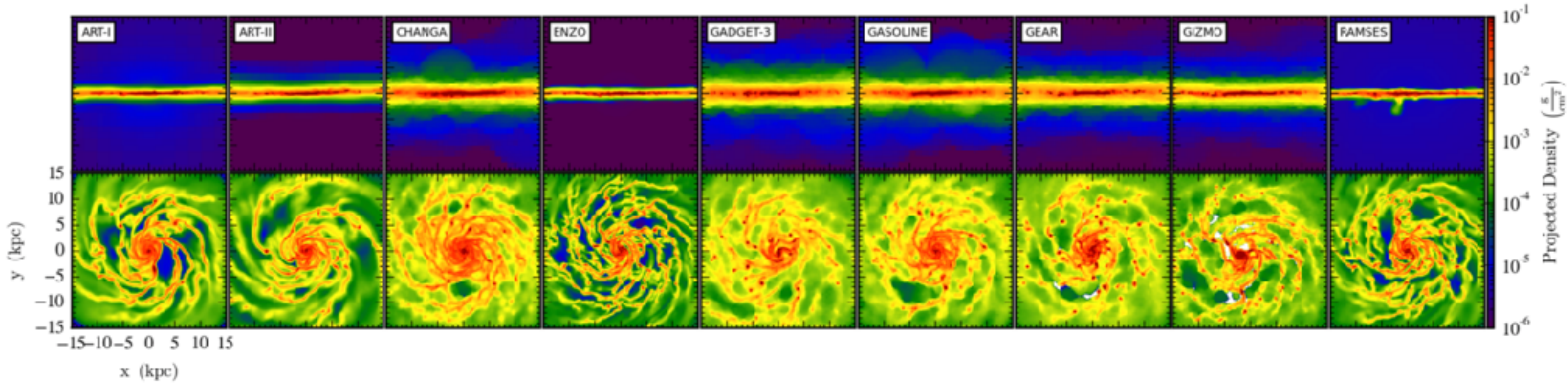

Figure 2. The 500 Myr composite snapshots of gas surface density from *Sim-1* with radiative gas cooling but without star formation or feedback. Each frame is centered on the location of maximum gas density within 1 kpc from the center of gas mass. Simulations performed by: Daniel Ceverino (ART-I), Robert 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

- 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!!