PHILOSOPHY OF COSMOLOGY

UK/US CONFERENCE

12th – 16th SEPTEMBER 2014, TENERIFE, SPAIN

TOPICS

ORGANISERS

CONTACT

Cosmological Structure Formation

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Distinguished Professor of Physics,
University of California, Santa Cruz

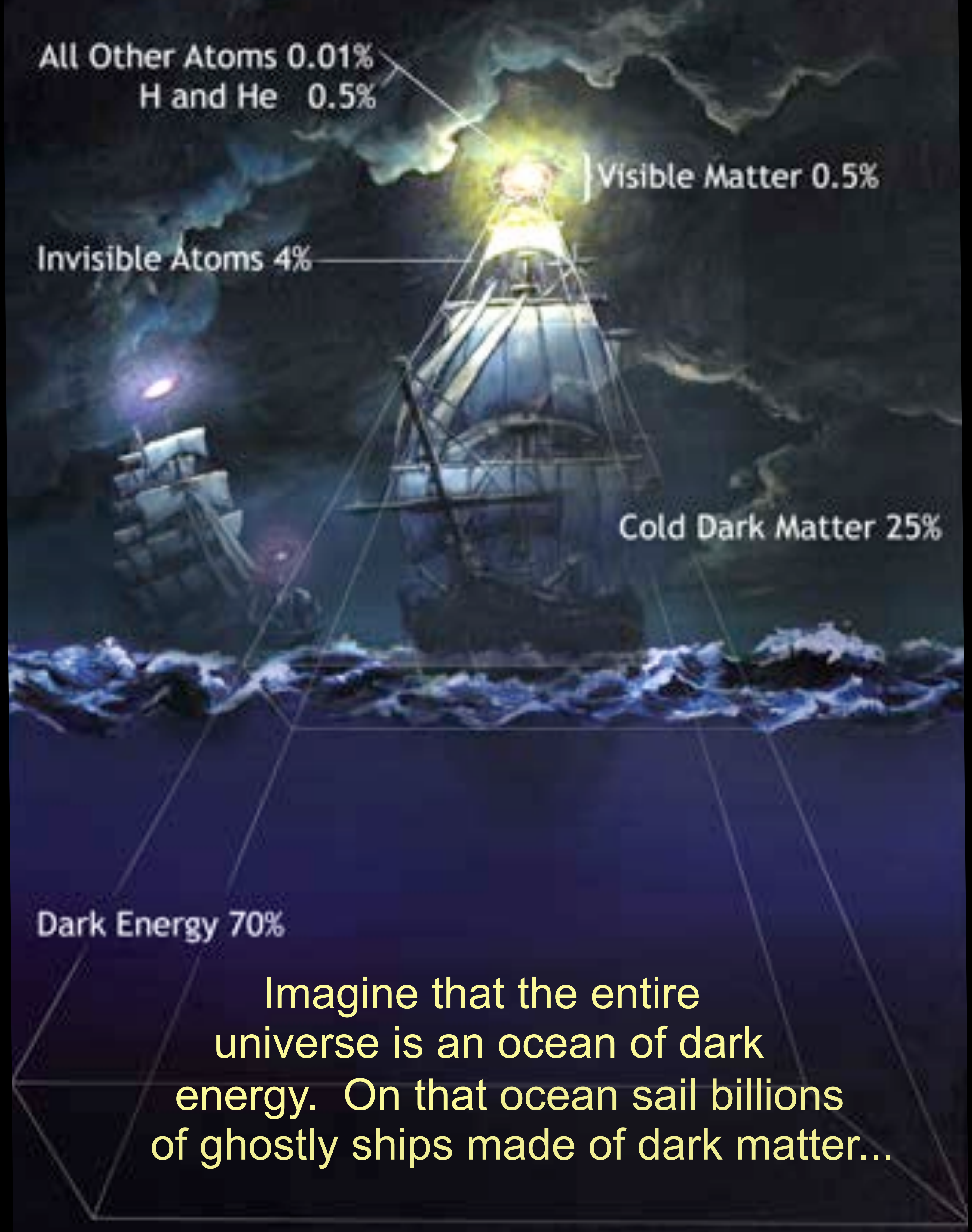
Director, University of California
High-Performance AstroComputing Center
(UC-HiPACC)

Hubble Space Telescope Ultra Deep Field - ACS

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

The other 99.5% of the universe is invisible.

Matter and Energy Content of the Universe

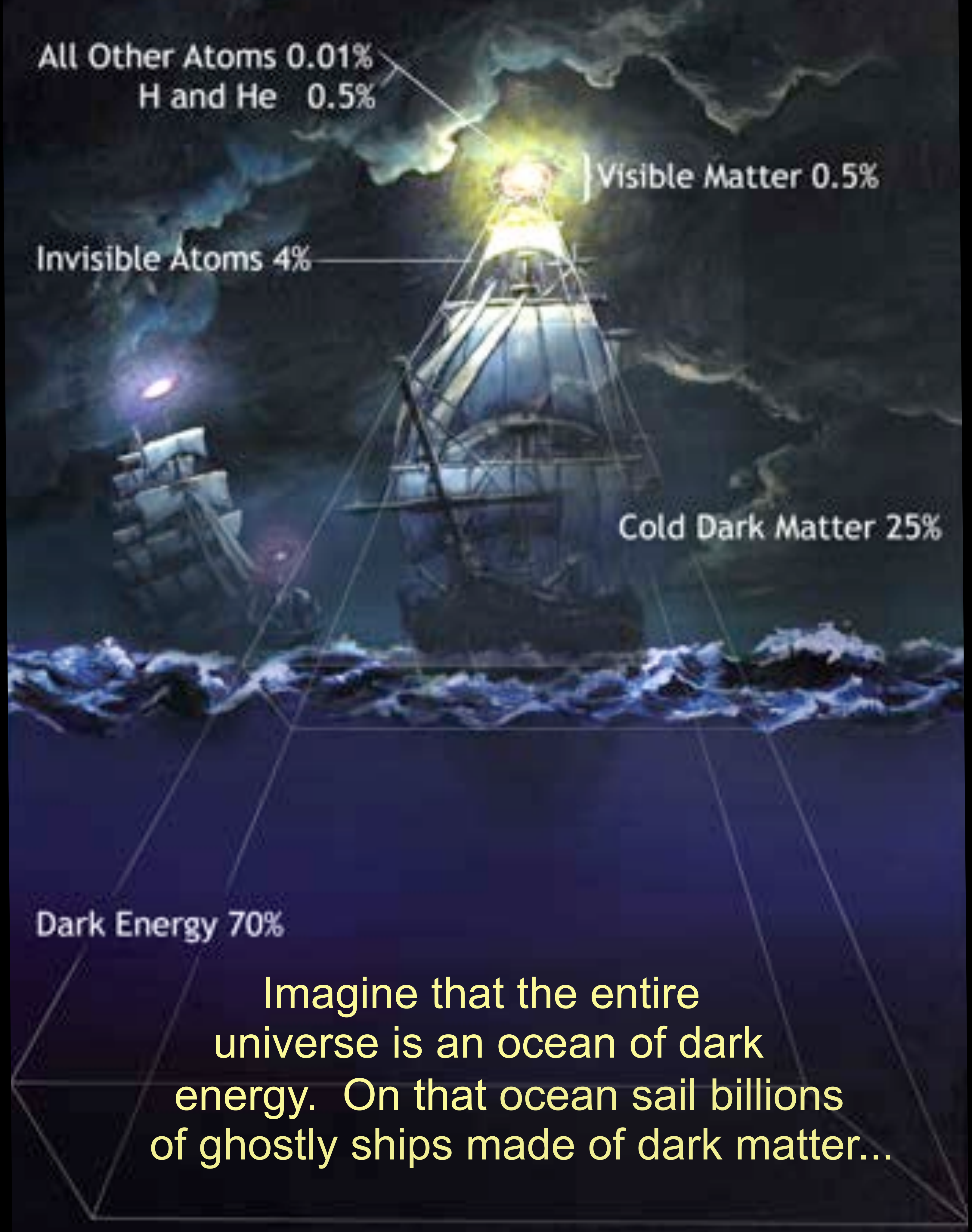


Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

Dark Matter Ships

on a

Dark Energy Ocean



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

ΛCDM

Double Dark Theory

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

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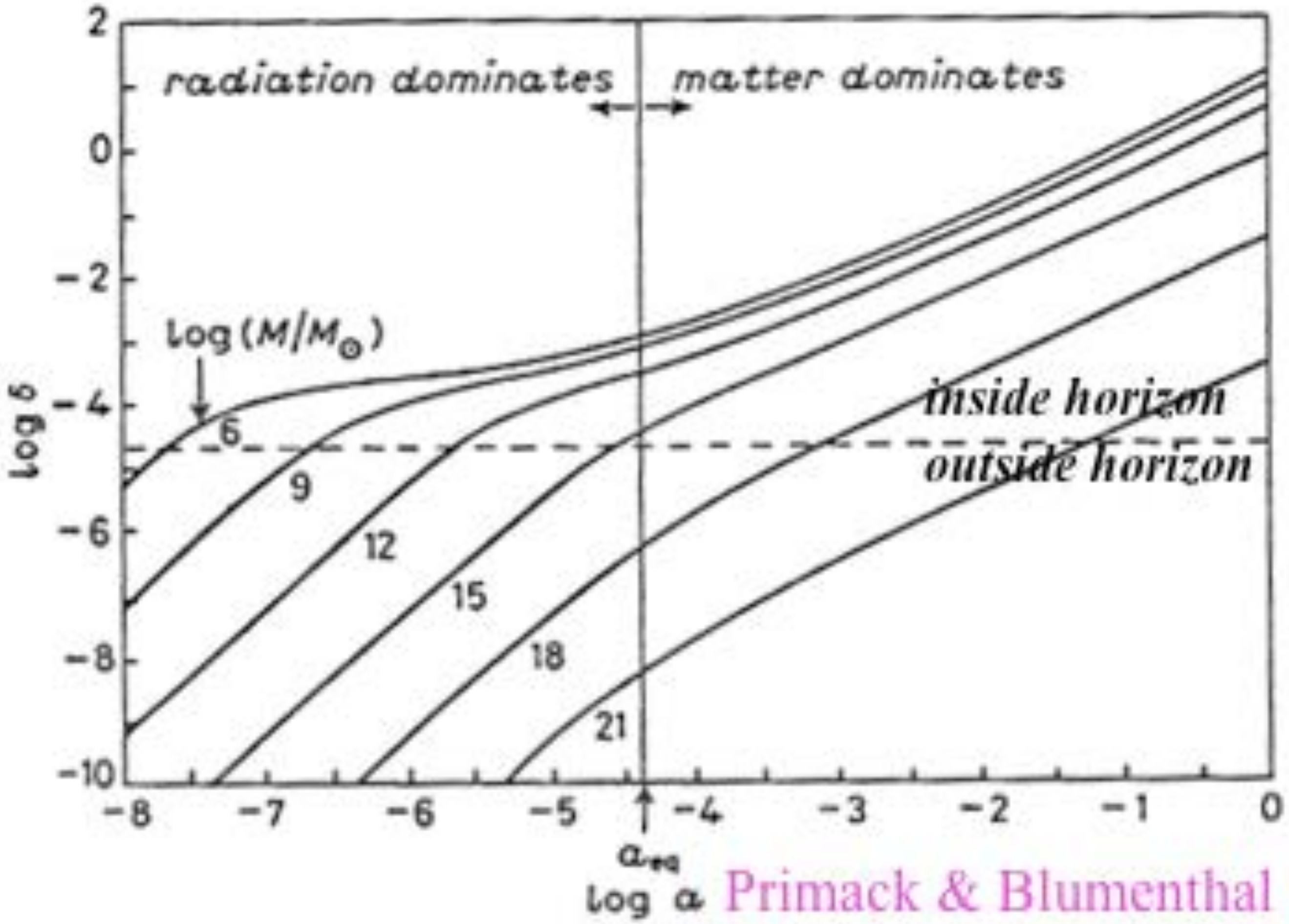
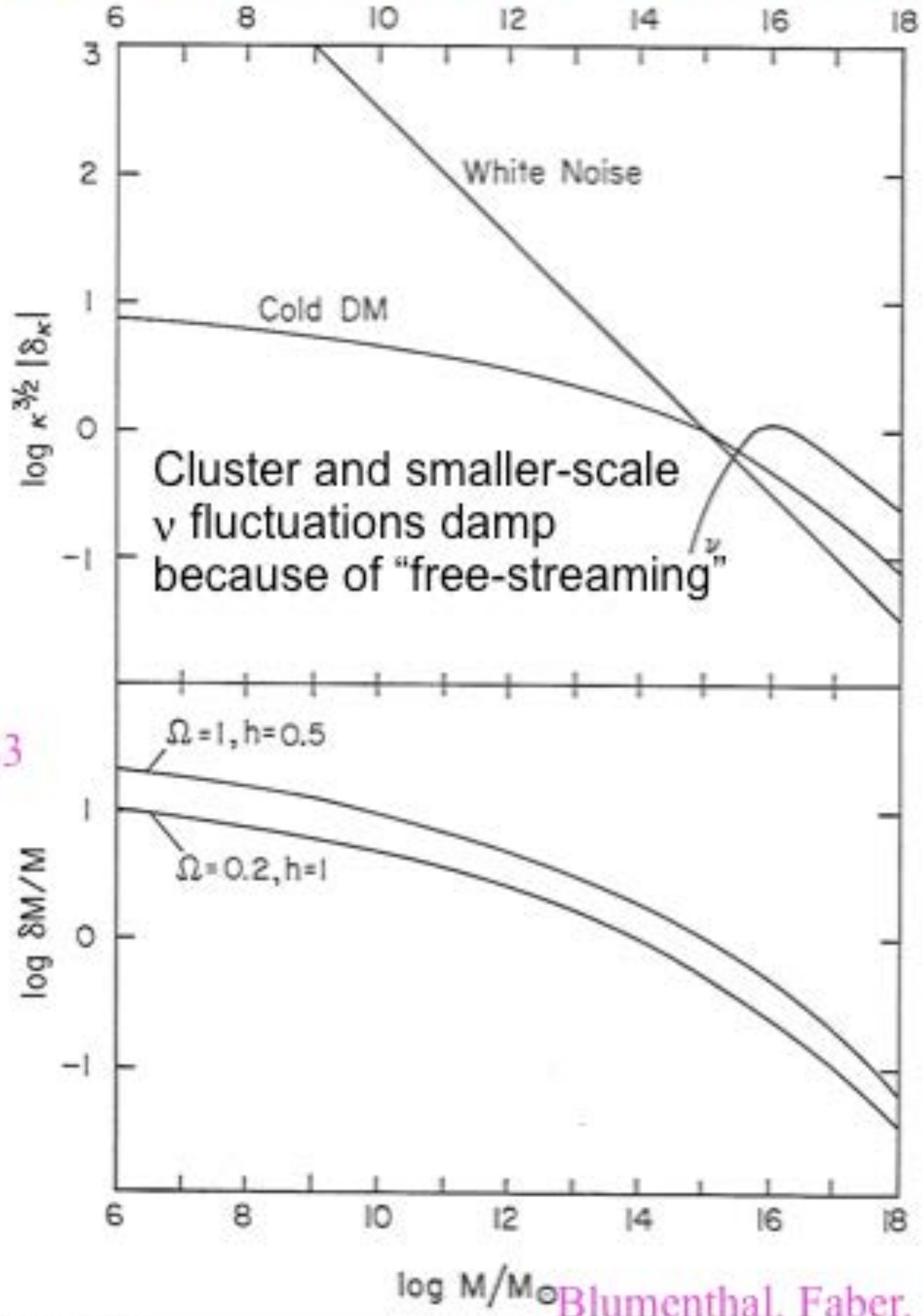
- On the large scale the simulations produce a universe just like the one we live in. We're always looking for new phenomena to predict — every one of which tests the whole theory!

CDM Structure Formation: Linear Theory



Primack & Blumenthal 1983

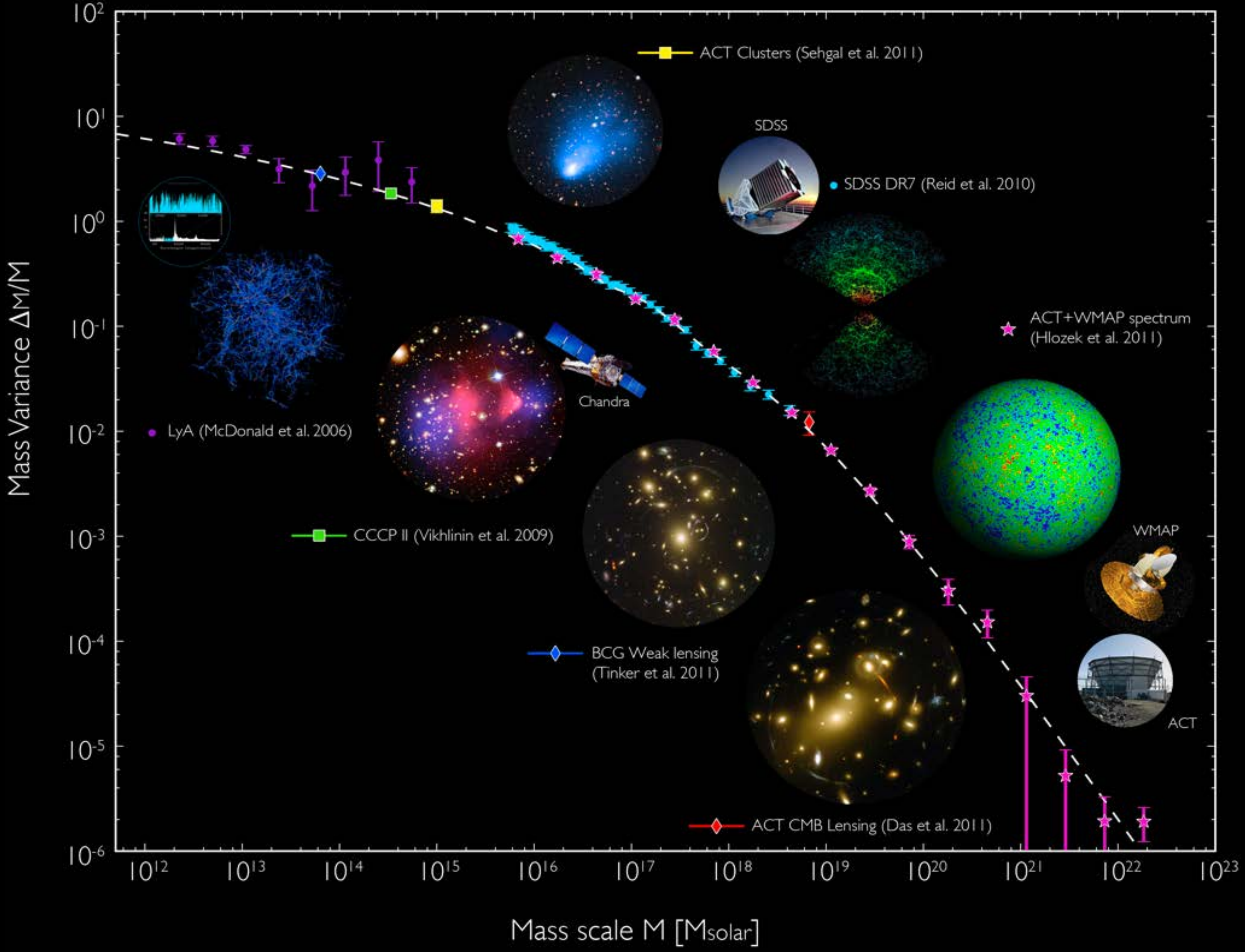
Matter fluctuations that enter the horizon during the radiation dominated era, with masses less than about $10^{15} M_{\odot}$, grow only $\propto \log a$, because they are not in the gravitationally dominant component. But matter fluctuations that enter the horizon in the matter-dominated era grow $\propto a$. This explains the characteristic shape of the CDM fluctuation spectrum, with $\delta(k) \propto k^{-n/2-2} \log k$ for $k \gg k_{eq}$.



Cluster and smaller-scale ν fluctuations damp because of "free-streaming"

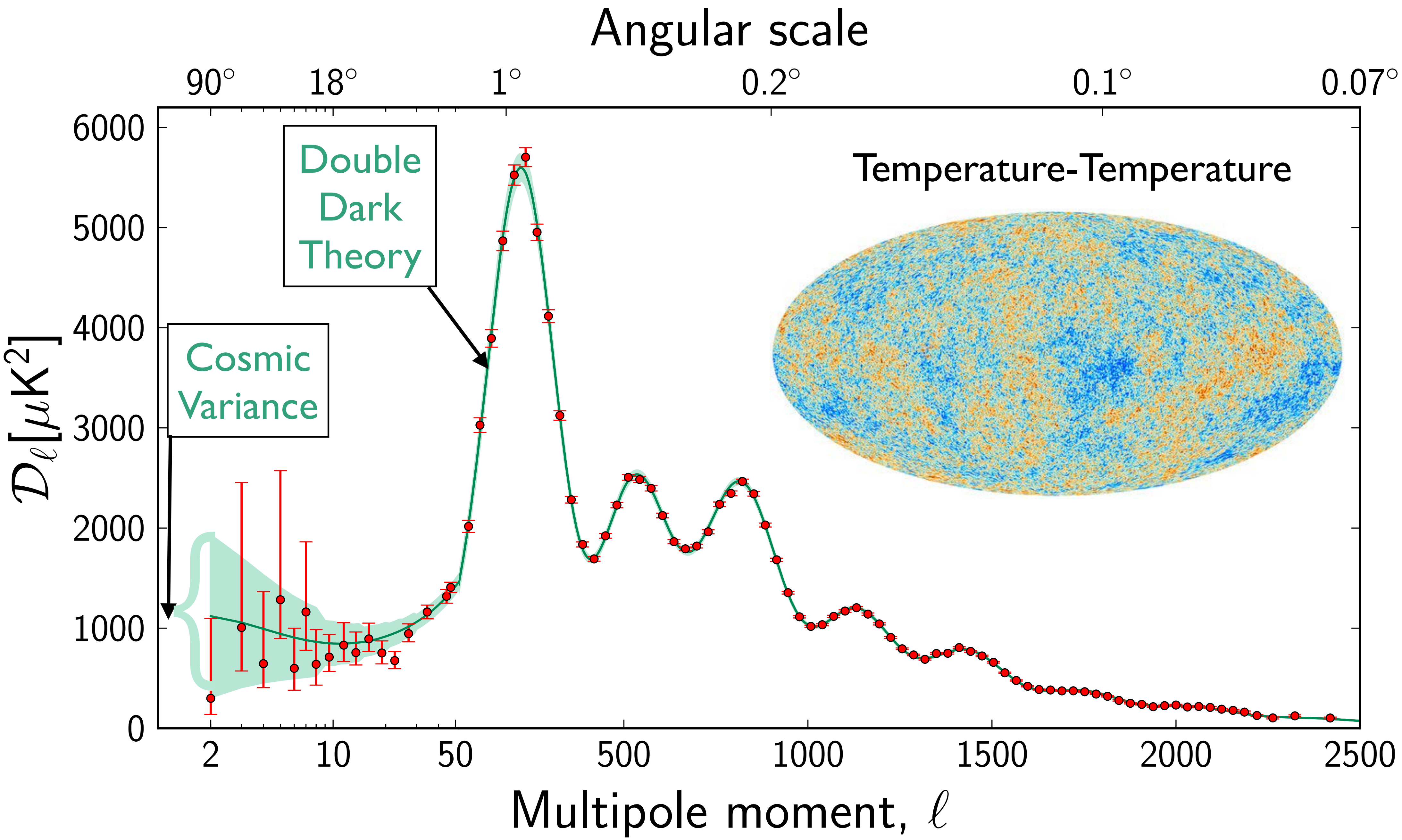
Blumenthal, Faber, Primack, & Rees 1984

Matter Distribution Agrees with Double Dark Theory!



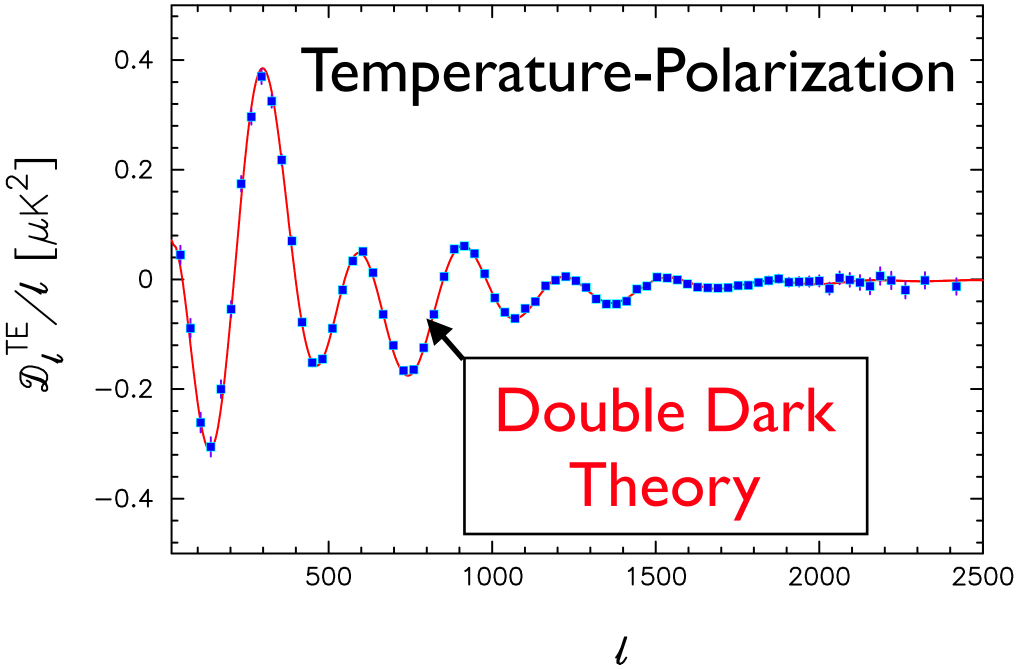
European Space Agency PLANCK Satellite Data

Released March 21, 2013

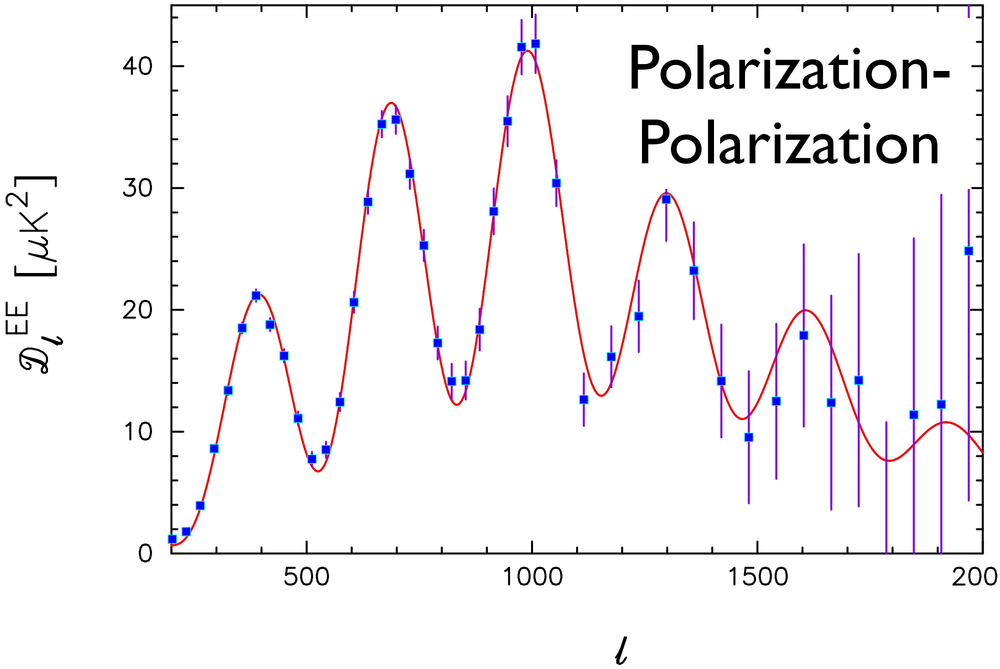


Double Dark Theory

Cosmic Variance



Double Dark Theory



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.

Cosmological Simulations

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

Cosmological dark matter simulations show large scale structure, growth of structure, dark matter halo properties, halo - galaxy connections

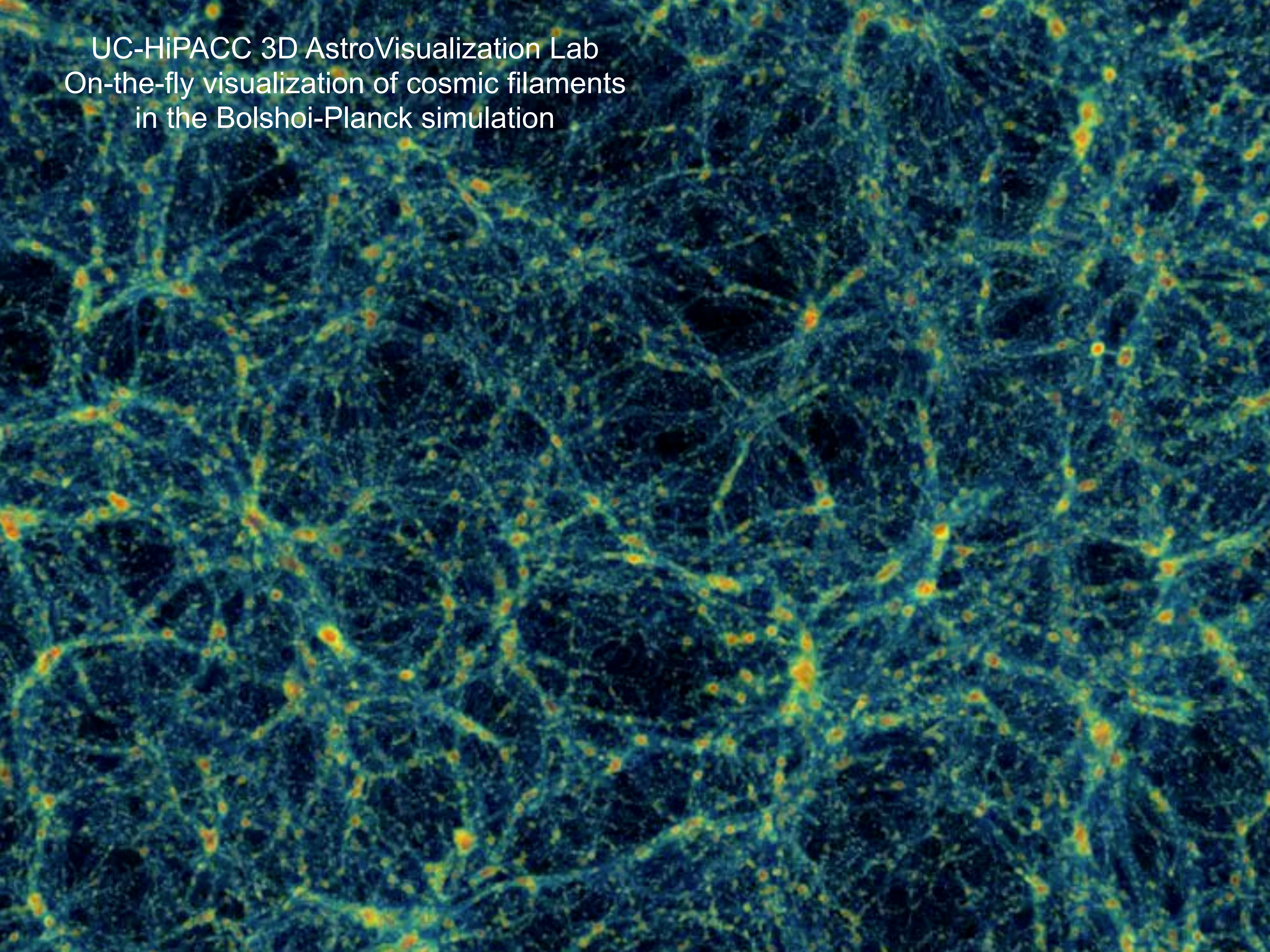
Hydrodynamic galaxy formation simulations: formation and evolution of galaxies, galaxy images in all wavebands and galaxy spectra including stellar evolution and dust effects

"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

CONSTRAINED LOCAL UNIVERSE SIMULATION

Stefan Gottloeber, Anatoly Klypin, Joel Primack

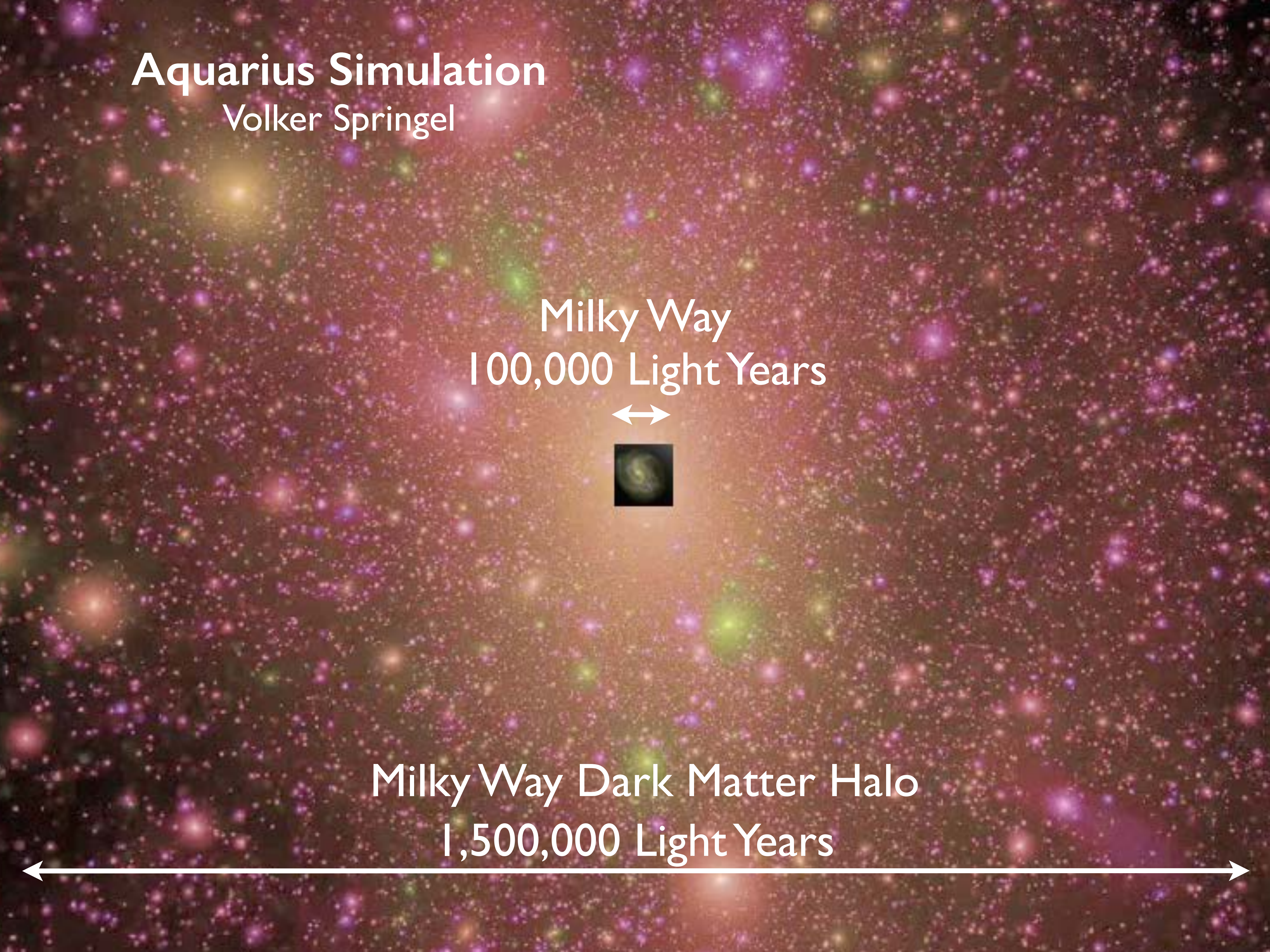
Visualization: Chris Henze (NASA Ames)



UC-HiPACC 3D AstroVisualization Lab
On-the-fly visualization of cosmic filaments
in the Bolshoi-Planck simulation

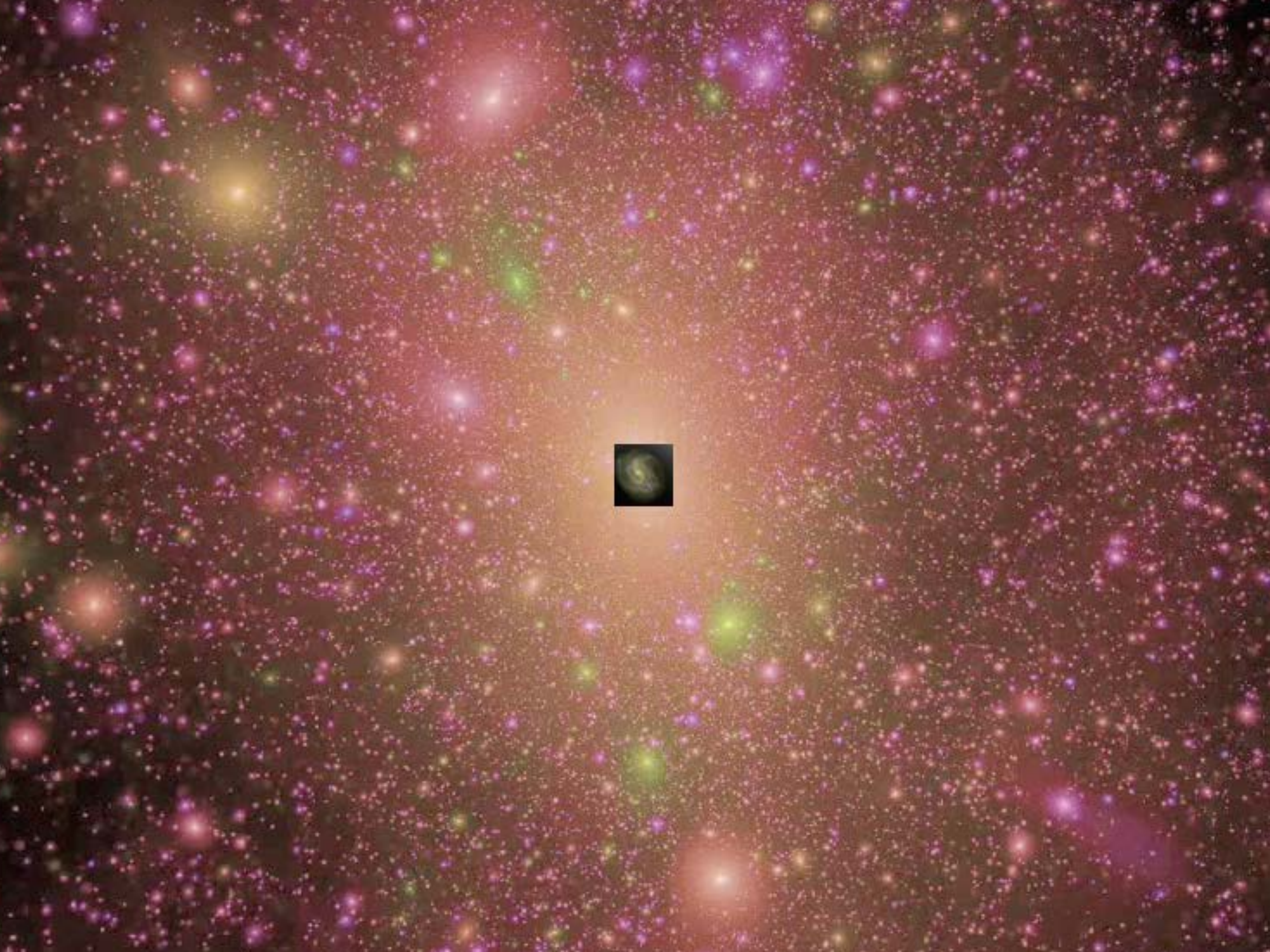
Aquarius Simulation

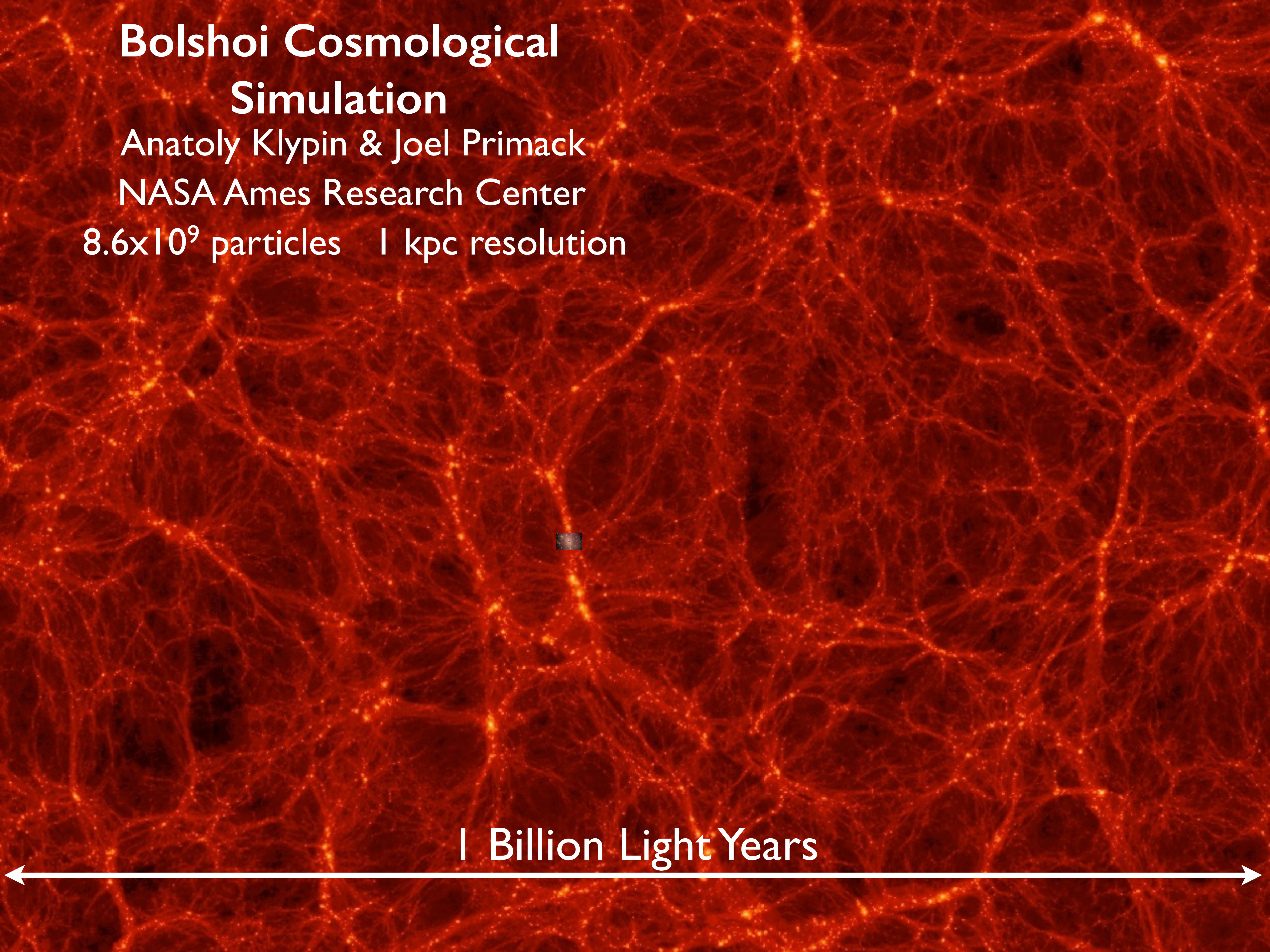
Volker Springel



Milky Way
100,000 Light Years

Milky Way Dark Matter Halo
1,500,000 Light Years





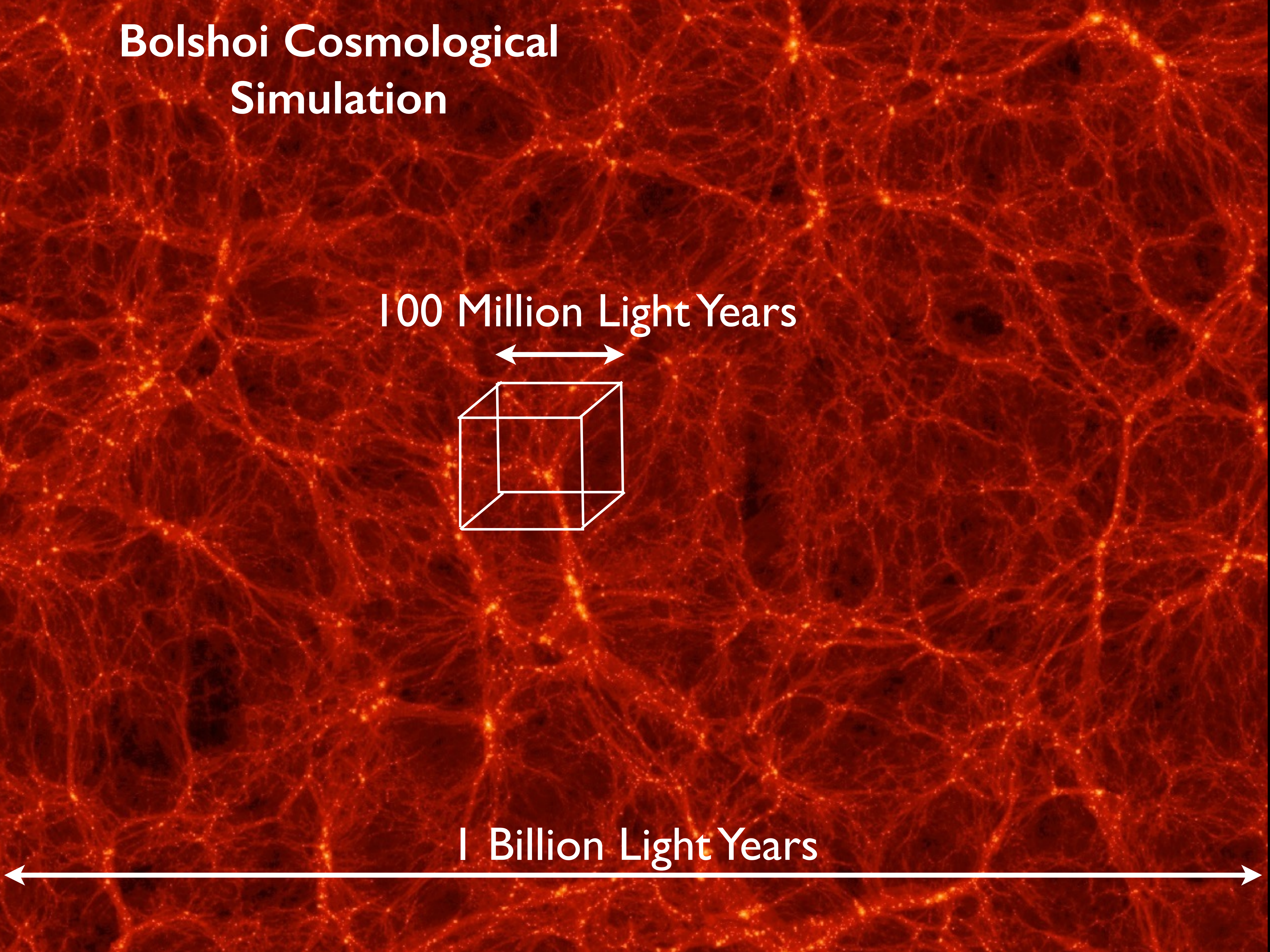
Bolshoi Cosmological Simulation

Anatoly Klypin & Joel Primack

NASA Ames Research Center

8.6×10^9 particles   1 kpc resolution

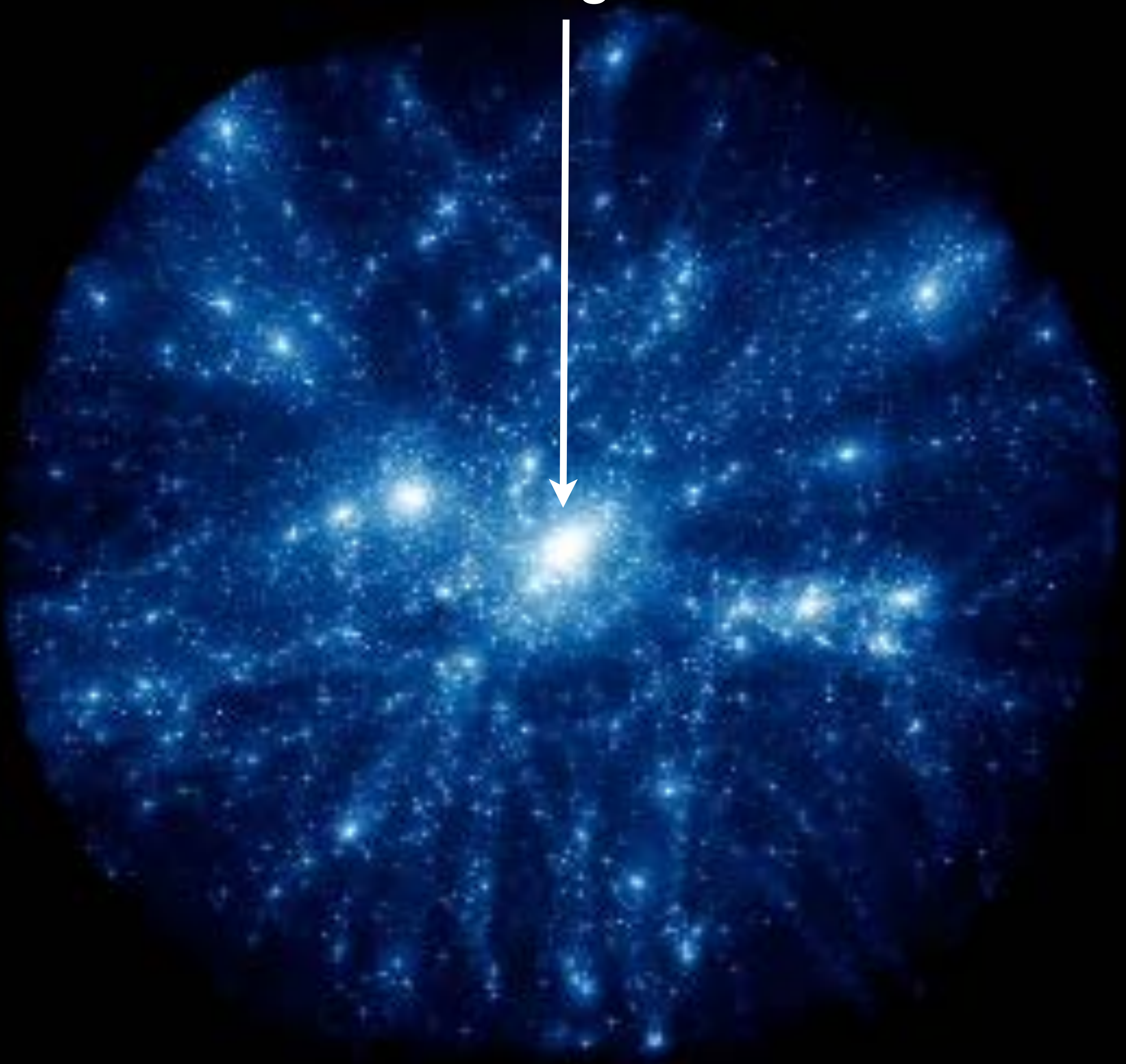
Bolshoi Cosmological Simulation



Bolshoi Cosmological Simulation

100 Million Light Years

How the Halo of the Big Cluster Formed



Bolshoi-Planck

Cosmological Simulation

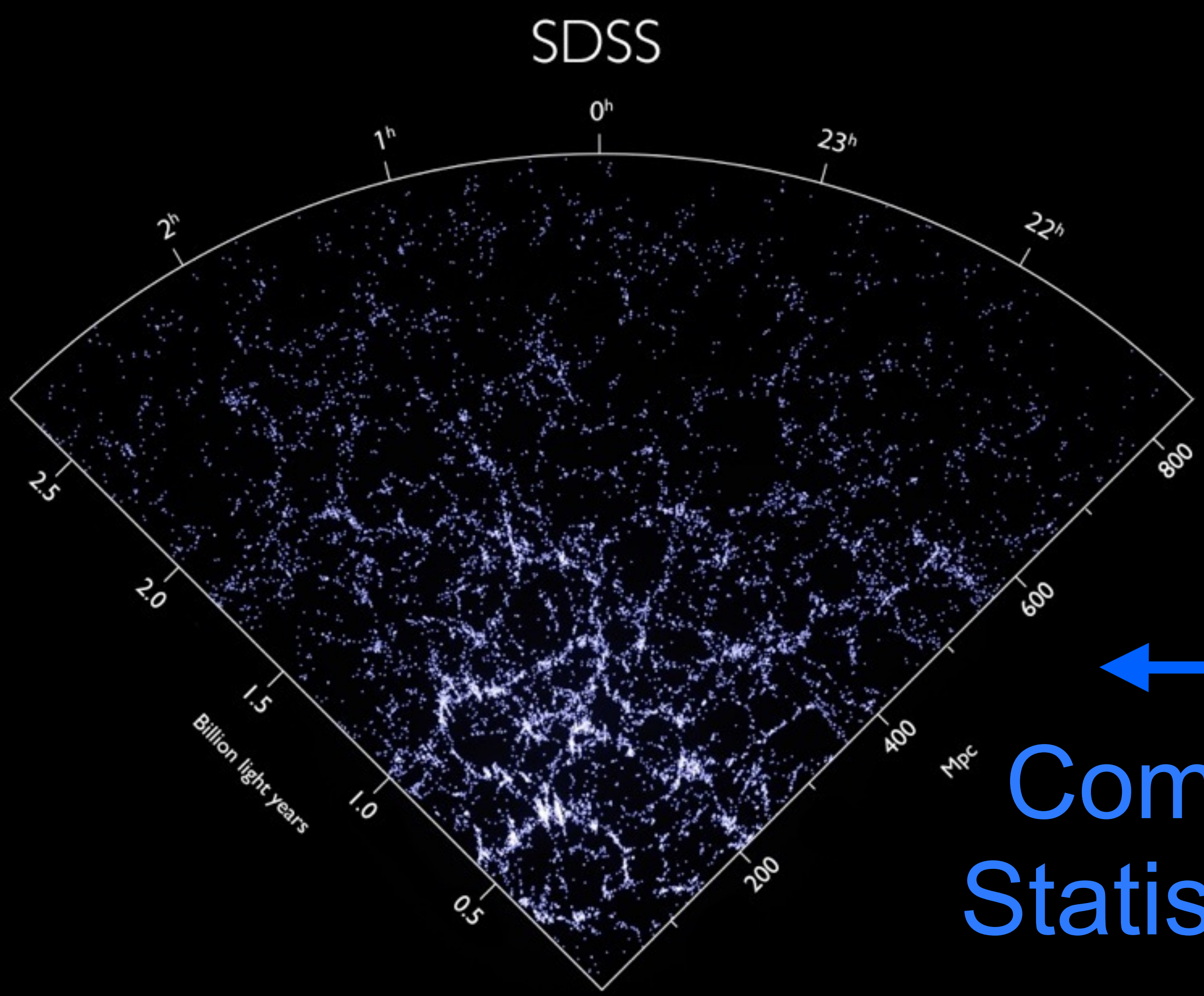
Merger Tree of a Large Halo

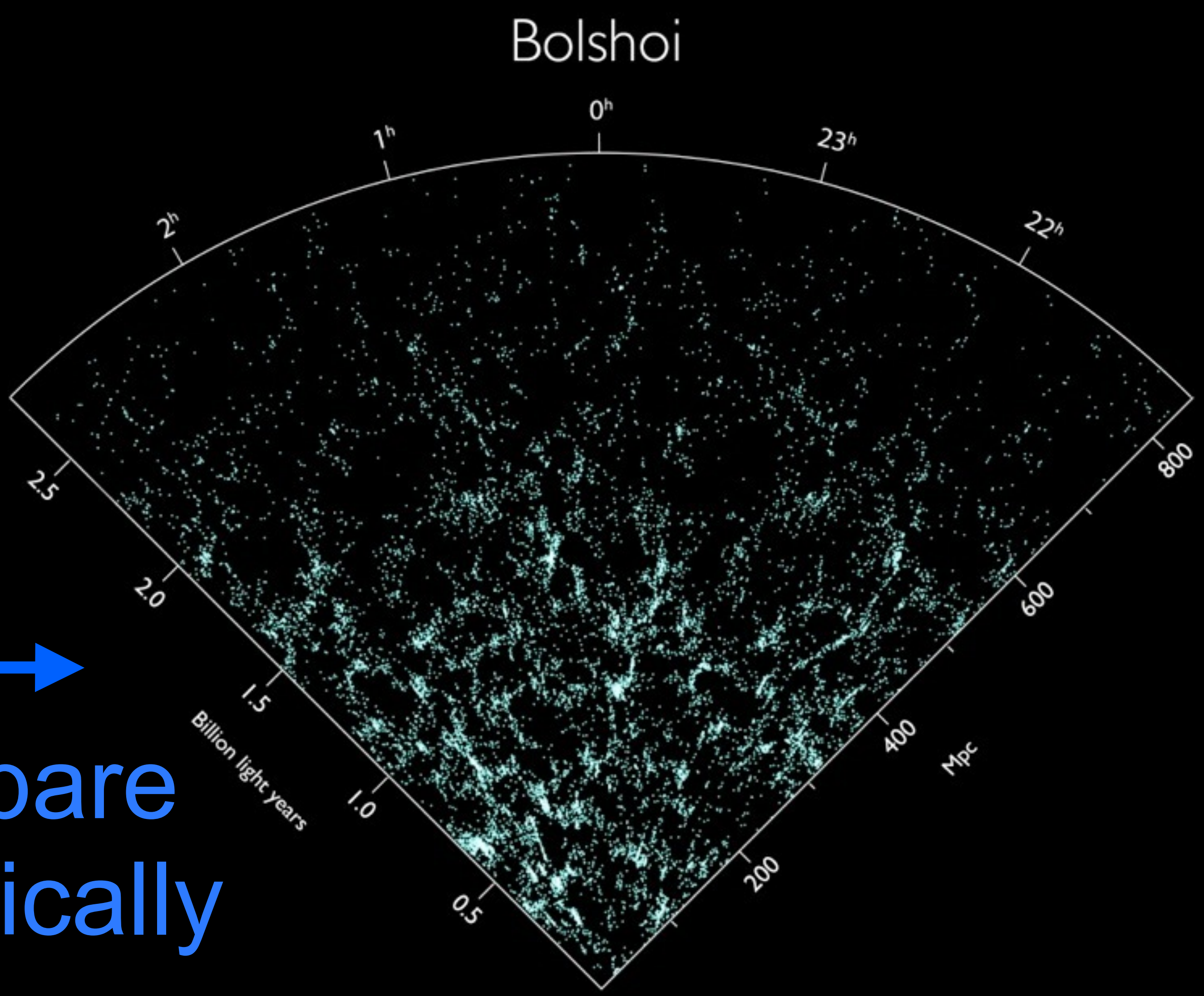
Observational Data

Sloan Digital Sky Survey

Bolshoi Simulation

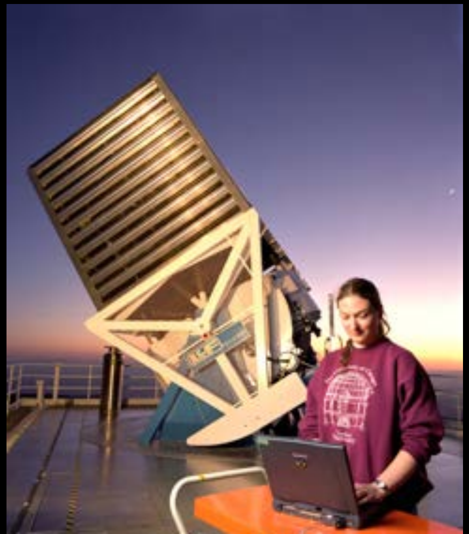
Anatoly Klypin, Joel Primack, Peter Behroozi
Risa Wechsler, Ralf Kahler, Nina McCurdy

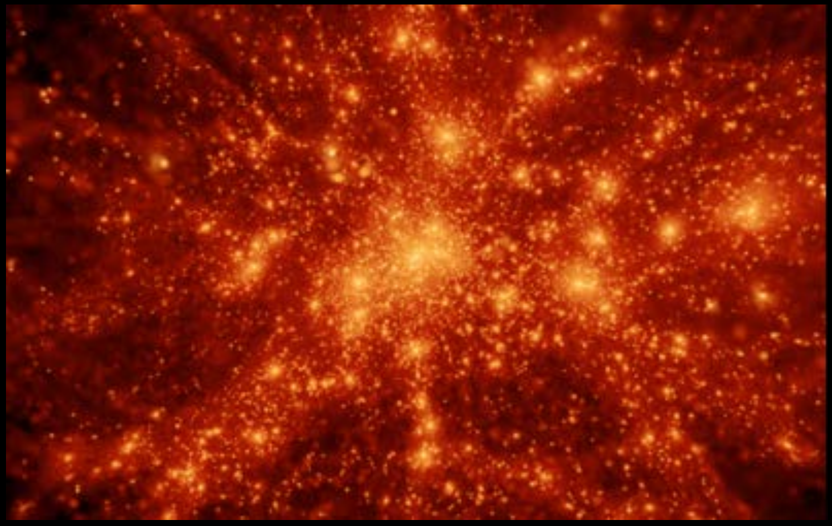




↔

Compare Statistically





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

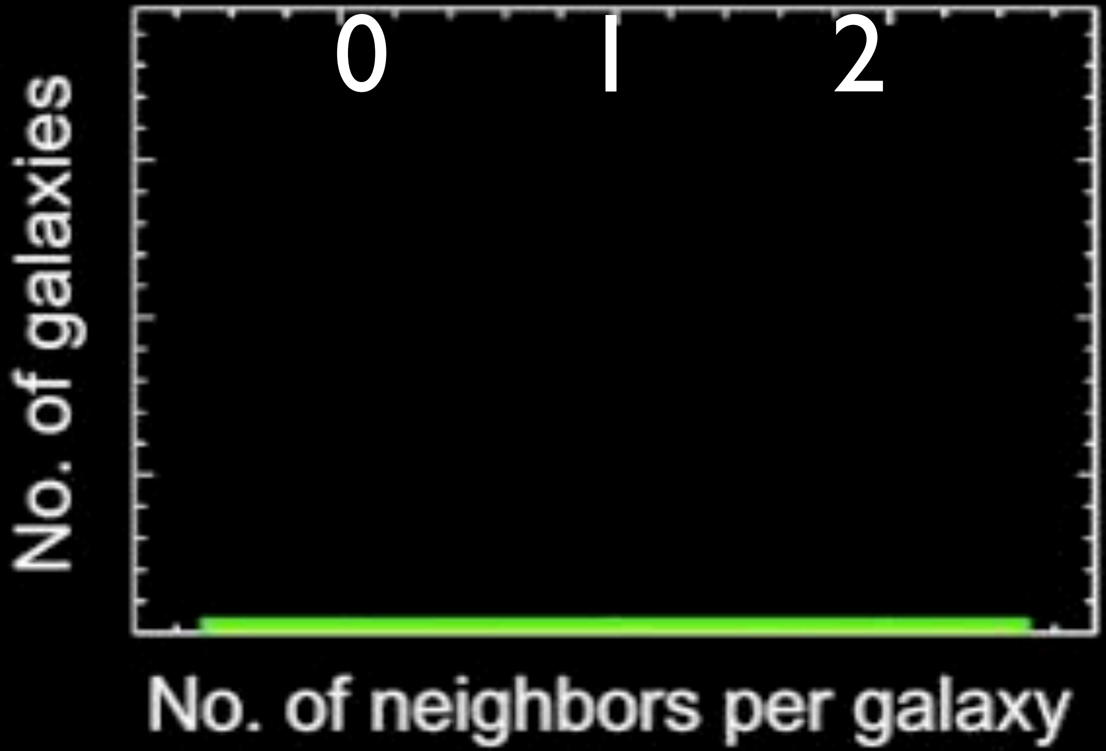
How common is this?

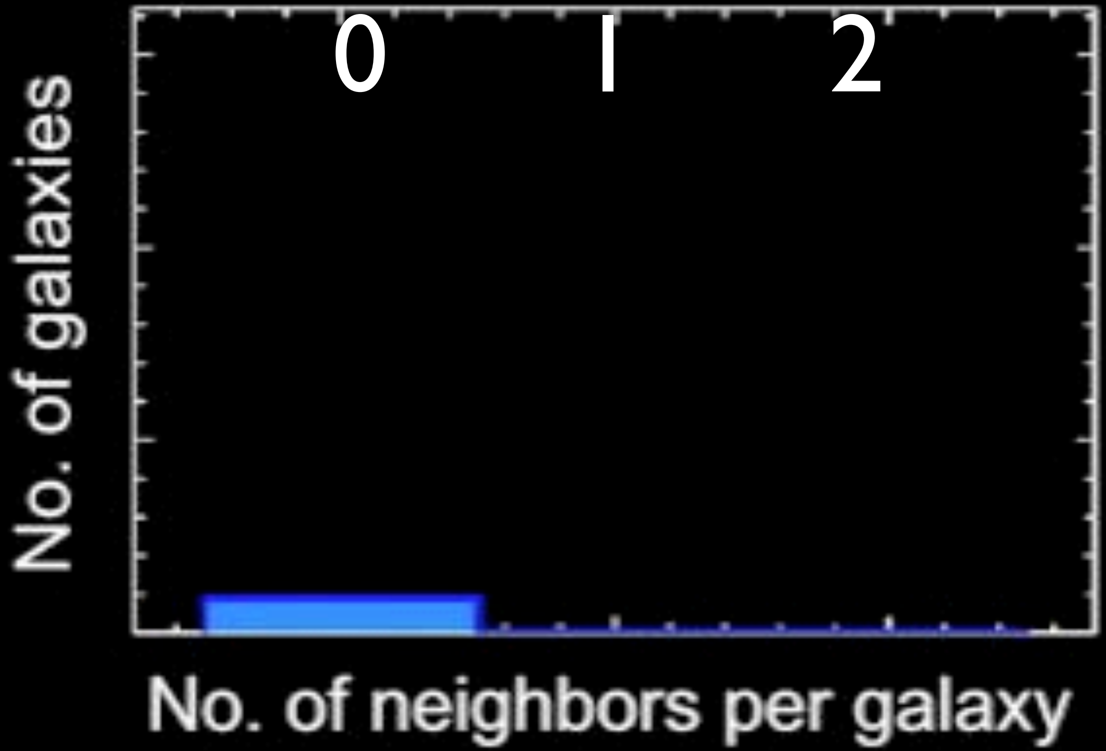
The Bolshoi simulation predicts the likelihood that a galaxy as bright as ours will have 0, 1, 2, 3, ... large satellite galaxies.

If the answer matches observations, that increases our confidence in this theory.

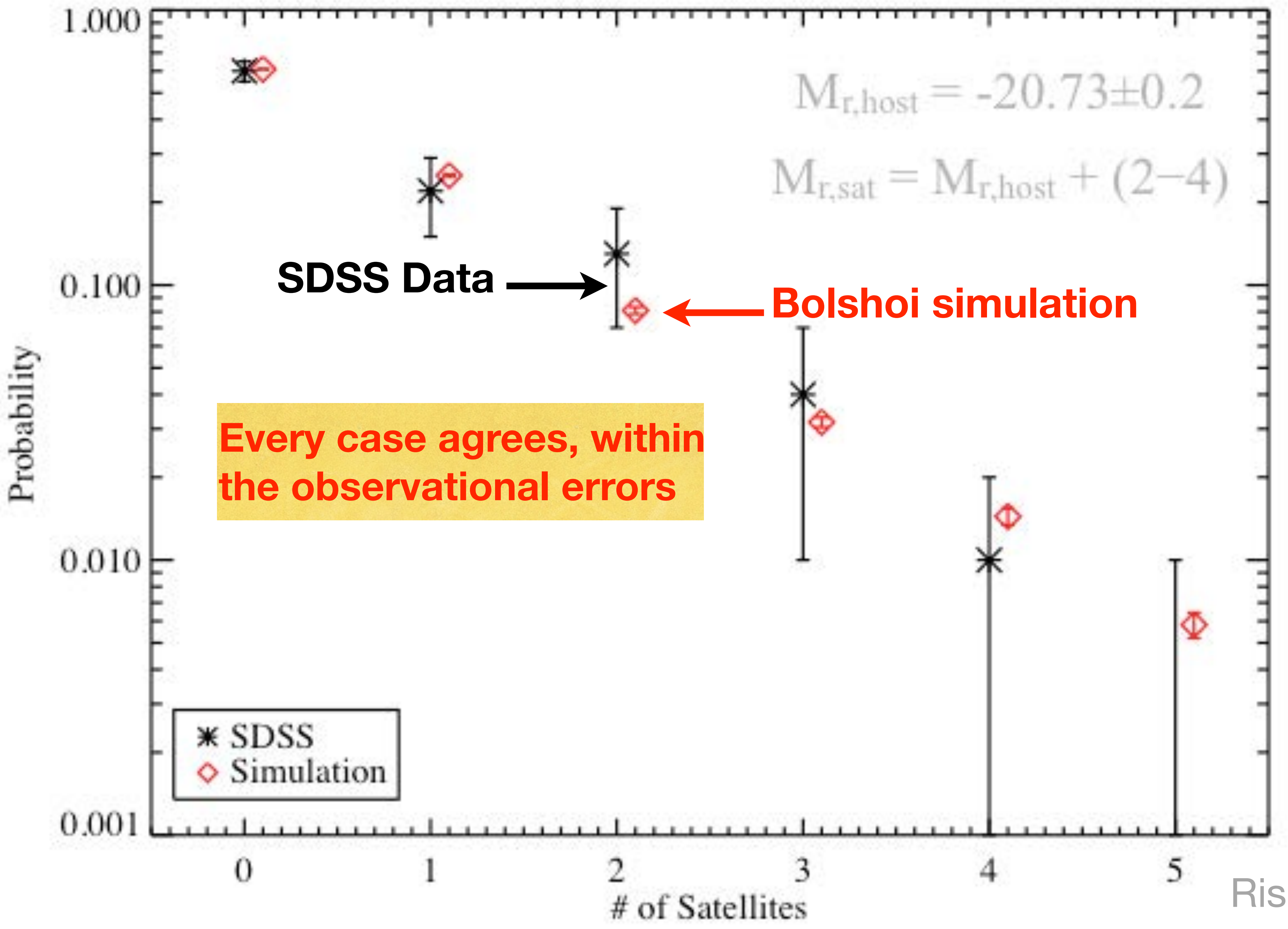

SDSS sky


Bolshoi simulation





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



SDSS Data →

← **Bolshoi simulation**

Every case agrees, within the observational errors

Risa Wechsler

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

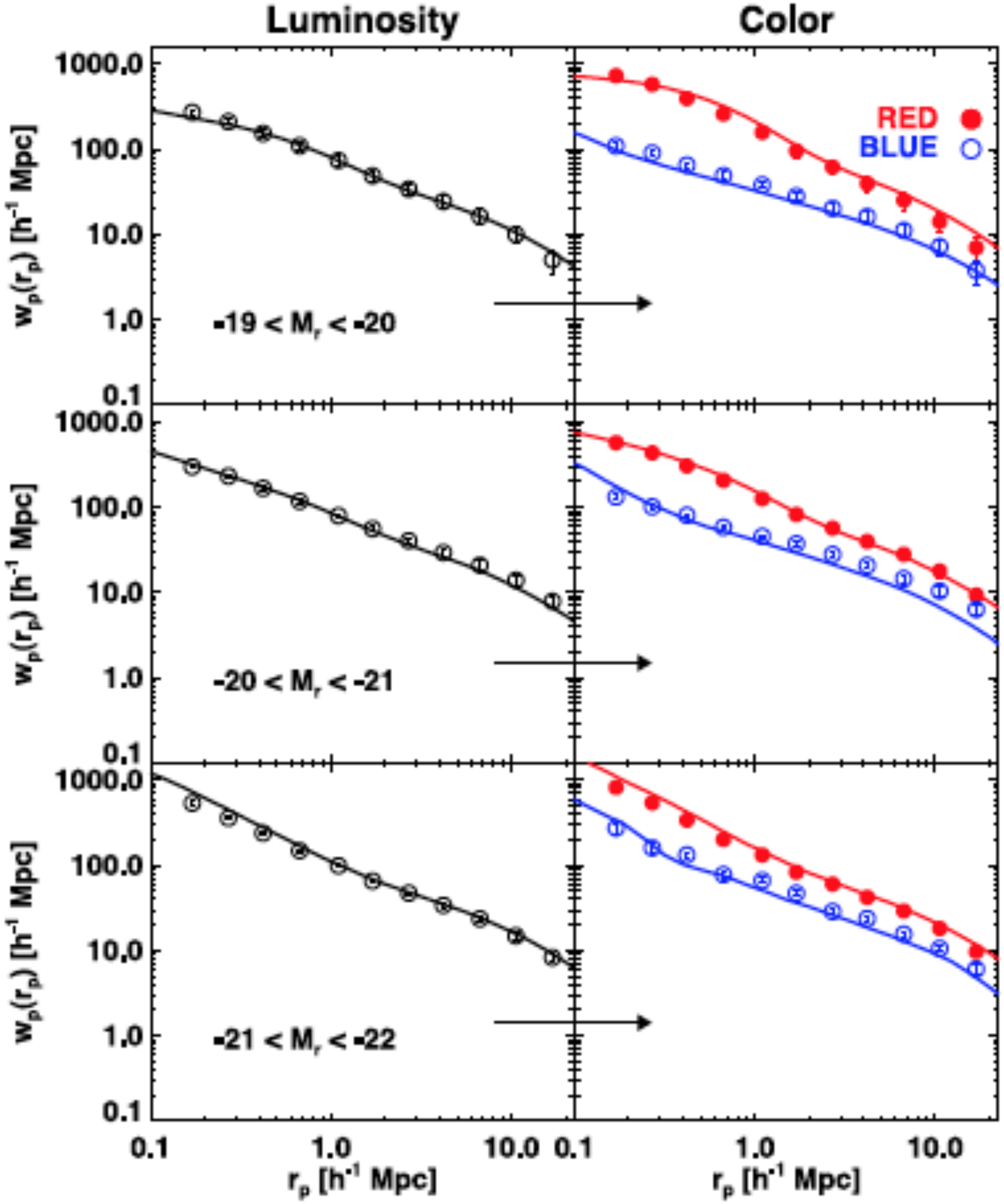
The dark side of galaxy colour

Andrew P. Hearin & Douglas F. Watson MNRAS 435, 1313 (2013)

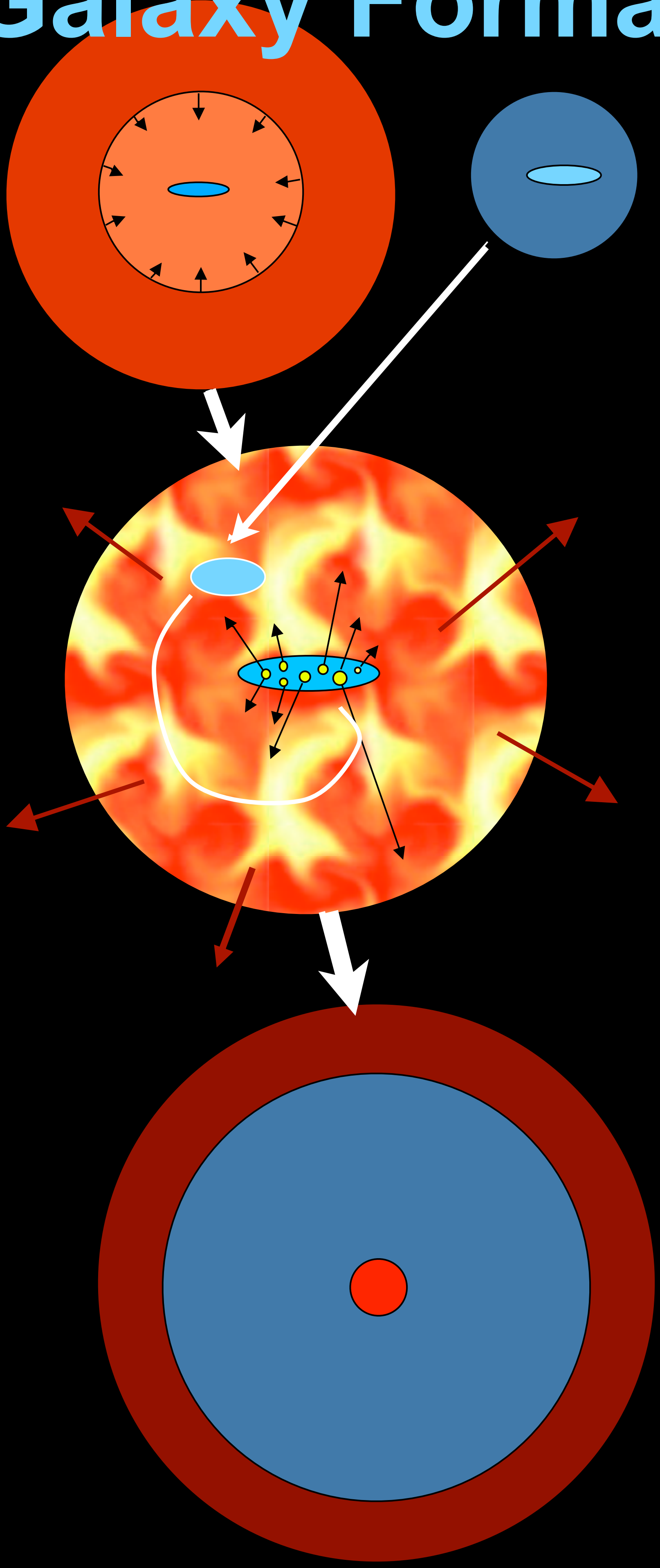
Hearin and Watson 2013 showed that by extending the traditional abundance matching formalism to consider an additional halo property beyond V_{max}, the observed spatial distribution of galaxies as a function of luminosity and color could be accurately reproduced. Specifically, the authors considered the redshift, dubbed z_{starve}, that correlates with the epoch at which the star formation in the galaxy is likely stifled, ultimately leading to the quenching of the galaxy.

By using Bolshoi merger trees to map the full mass assembly history (MAH) of halos, a halo's z_{starve} value is determined by whichever of the following three events happens first in its MAH: (1) the epoch a halo accretes onto a larger halo, thus becoming a subhalo, (2) the epoch a halo reaches a characteristic mass, and (3) the epoch a halo transitioned from the fast- to slow-accretion regime. Under the simple assumption that z_{starve} correlates with g – r color at fixed luminosity, the age matching technique was able to accurately predict color-dependent clustering in the Sloan Digital Sky Survey (SDSS) and a variety of galaxy group statistics. **The success of the model supports the idea that the assembly history of ΛCDM halos and their central galaxies are correlated.**

Galaxy Angular Correlations



Galaxy Formation via SemiAnalytic Models



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

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

10^{8-9} $M_\odot$ Clumps in Simulated Galaxies

gen 1 simulations

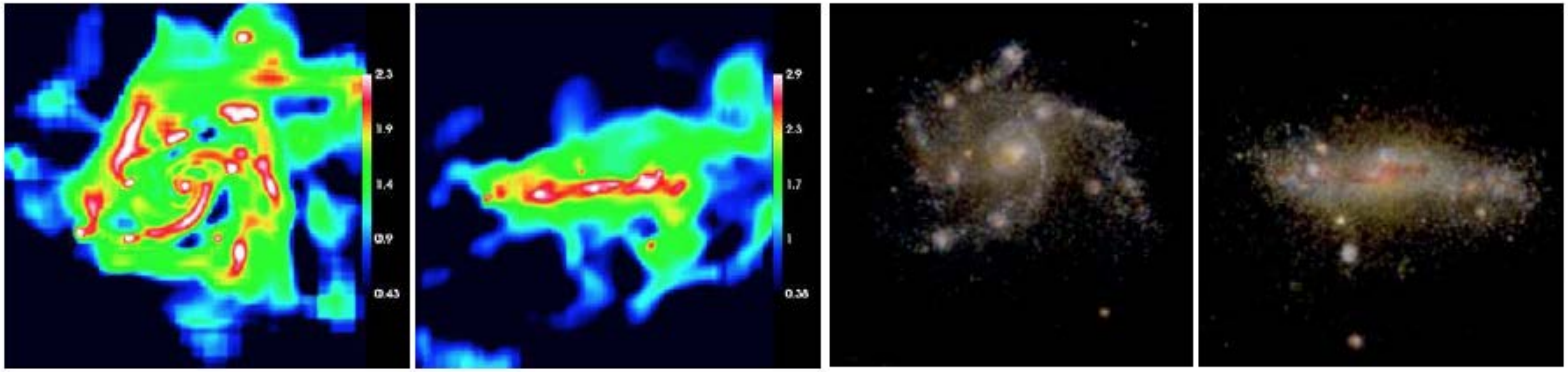
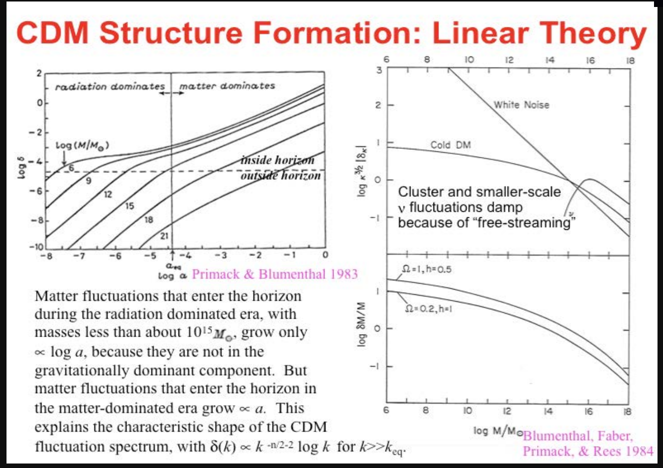


Figure 1: Violently unstable disks in $\sim 10^{11} M_\odot$ halos with $\sim 10^{9} M_\odot$ clumps at $z = 2.3$: (a) face-on, (b) edge-on (Ceverino et al. 2009, resolution 70 pc, images 10 kpc across). RGB color images of the same simulated galaxy through dust using *Sunrise*: (c) face-on, (d) edge-on,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

Semi-Analytic Models find that a majority of galactic spheroids form by violently unstable disks forming clumps and bars that drive stars and gas to the galactic center, rather than by galaxy mergers: Porter, Somerville, Primack, Johansson MNRAS 2014.

- Elliptical galaxies follow a size-mass relation. Our semi-analytic model correctly predicts this and the other scaling relations of elliptical galaxies.

- Disk galaxies follow a relation between their rotation velocity and their luminosity. The model also correctly predicts this.



CDM Structure Formation: Linear Theory

Primack & Blumenthal 1983

Matter fluctuations that enter the horizon during the radiation dominated era, with masses less than about $10^{15} M_\odot$, grow only $\propto \log a$, because they are not in the gravitationally dominant component. But matter fluctuations that enter the horizon in the matter-dominated era grow $\propto a$. This explains the characteristic shape of the CDM fluctuation spectrum, with $\delta(k) \propto k^{-n/2-2} \log k$ for $k >> k_{eq}$.

Cluster and smaller-scale ν fluctuations damp because of “free-streaming”

Blumenthal, Faber, Primack, & Rees 1984

- The theory also correctly predicts the numbers of large Disk galaxies and Elliptical galaxies.

SAM Predictions vs. SDSS Observations

Age and Metallicity depend mainly on velocity dispersion σ, not R

Galaxy Age

Galaxy Metallicity

SAM

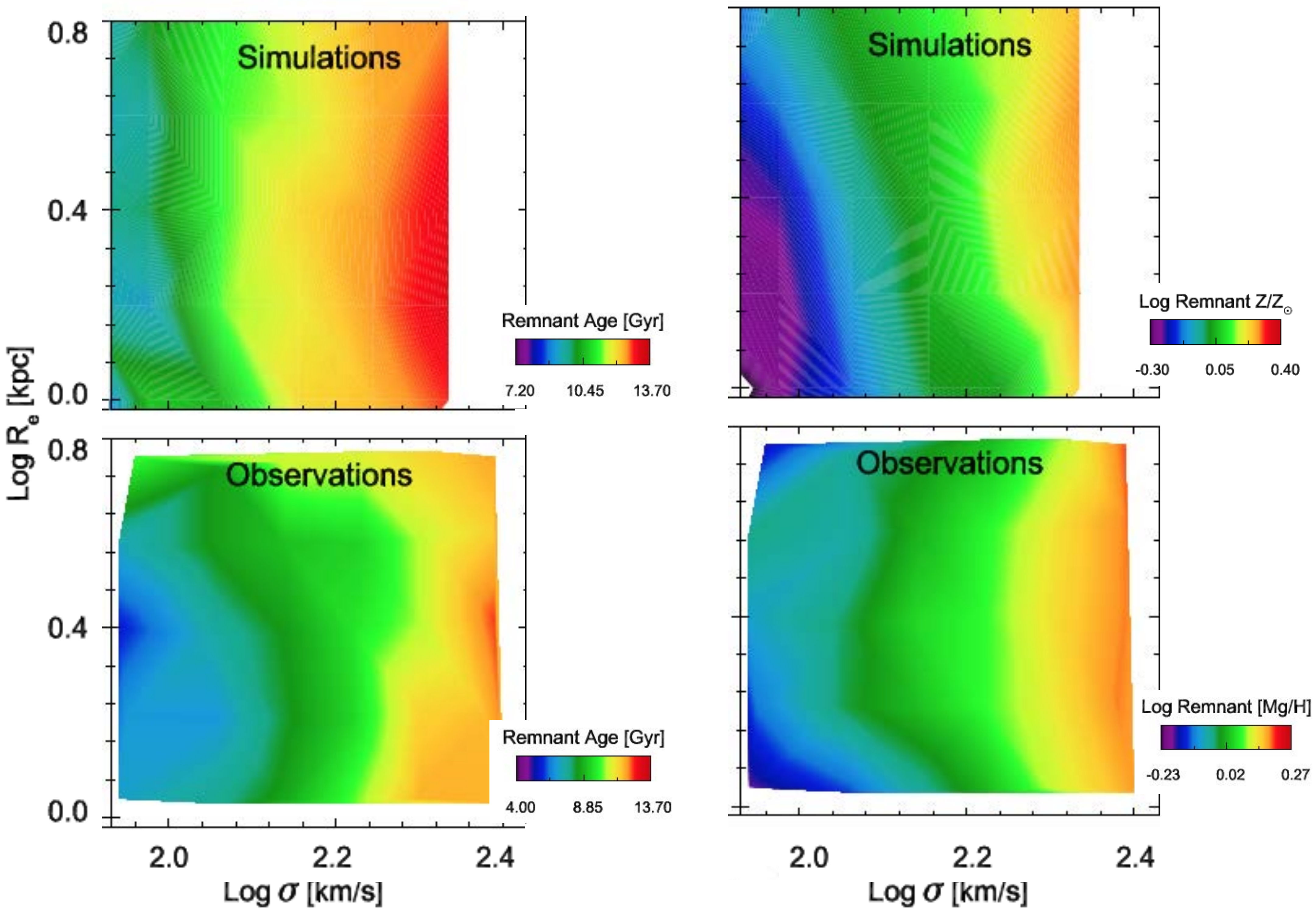
Predictions

Lauren Porter et al. 2013b

SDSS

Observations

Jenny Graves et al. 2009



Lauren Porter, Rachel Somerville, Joel Primack, et al. 2014b

Galaxy 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.

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Hydrodynamic galaxy formation simulations: formation and evolution of galaxies, galaxy images in all wavebands and galaxy spectra including stellar evolution and dust effects

Galaxy Hydro Simulations: 2 Approaches

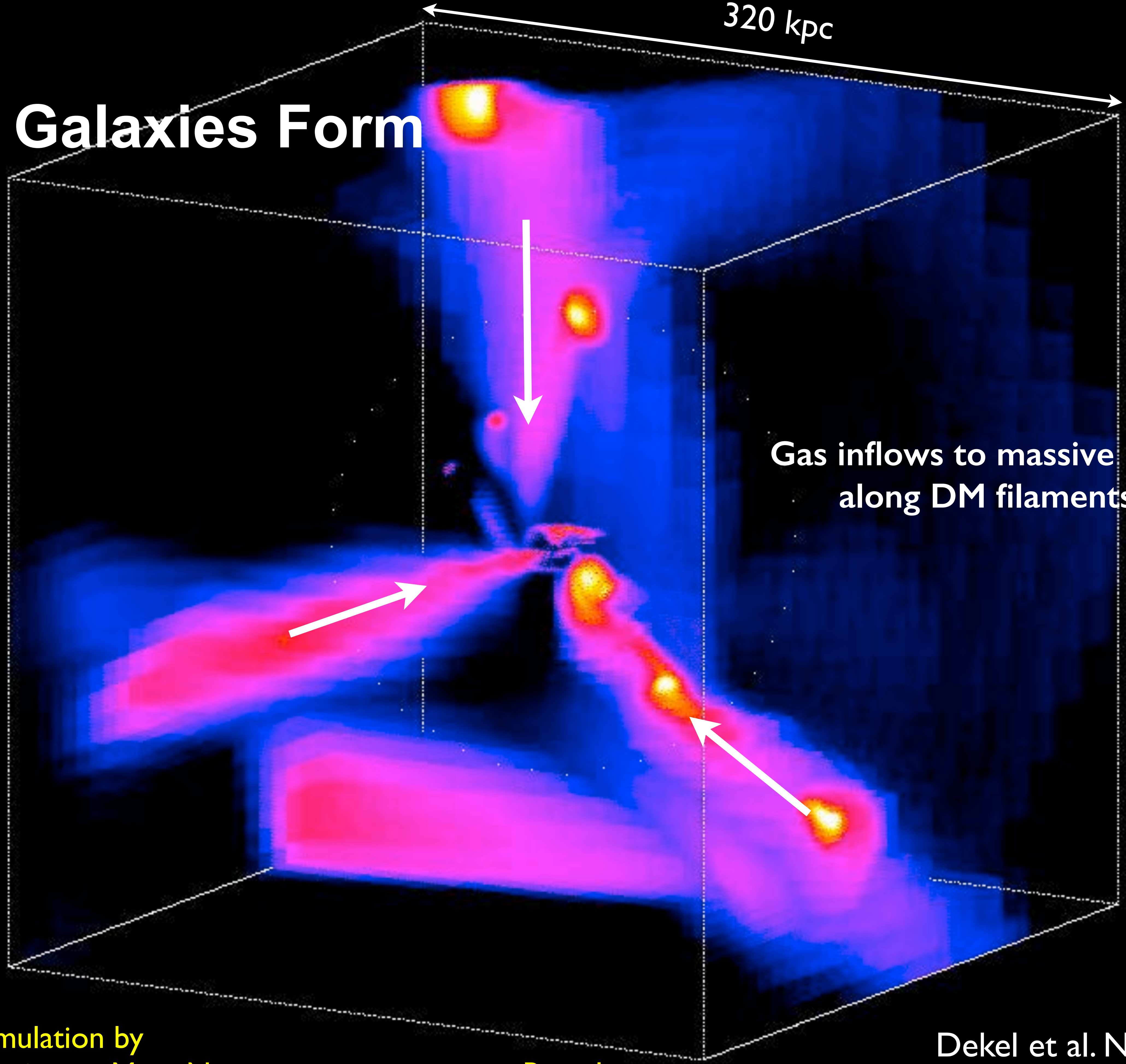
1. Low resolution (~ kpc)

Advantages: it's possible to simulate many galaxies and study galaxy populations and their interactions with CGM & IGM.
Disadvantages: we learn little about how galaxies themselves evolve, and cannot compare in detail with high-z galaxy images and spectra.
Examples: AREPO simulations in 100 Mpc box (Illustris), GADGET-3 simulations in 25-100 Mpc box (EAGLE), CHanGa

2. High resolution (~10s of pc)

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, origins of galactic spheroids, quenching). Radiative feedback essential?
Disadvantages: it's hard to run statistical galaxy samples, so the best approach puts simulation insights into SAMs.
Examples: ART simulation suite, AGORA simulation comparison project

How Galaxies Form

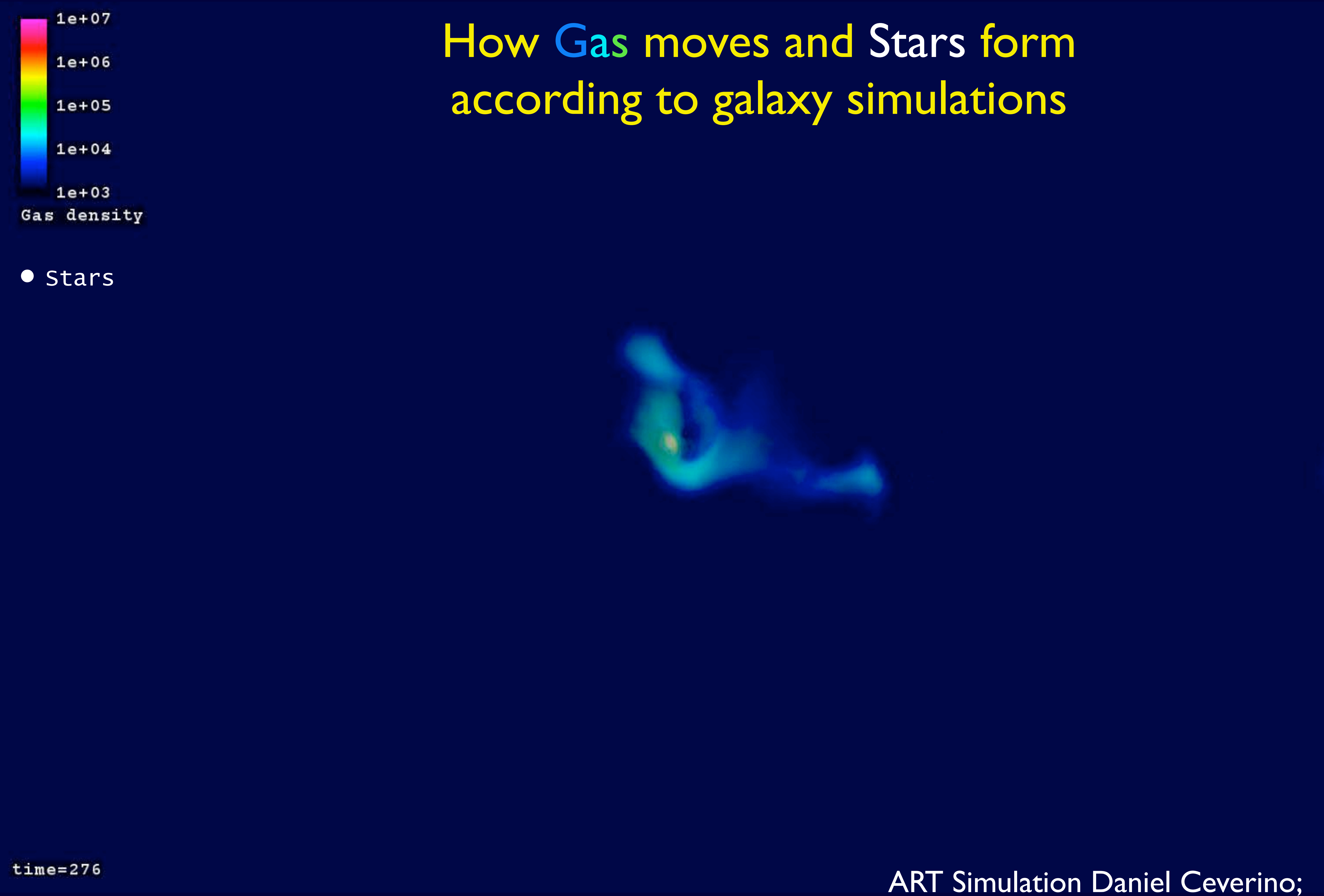


Gas inflows to massive halos along DM filaments

RAMSES simulation by
Romain Teyssier on Mare Nostrum supercomputer, Barcelona

Dekel et al. Nature 2009

How Gas moves and Stars form according to galaxy simulations



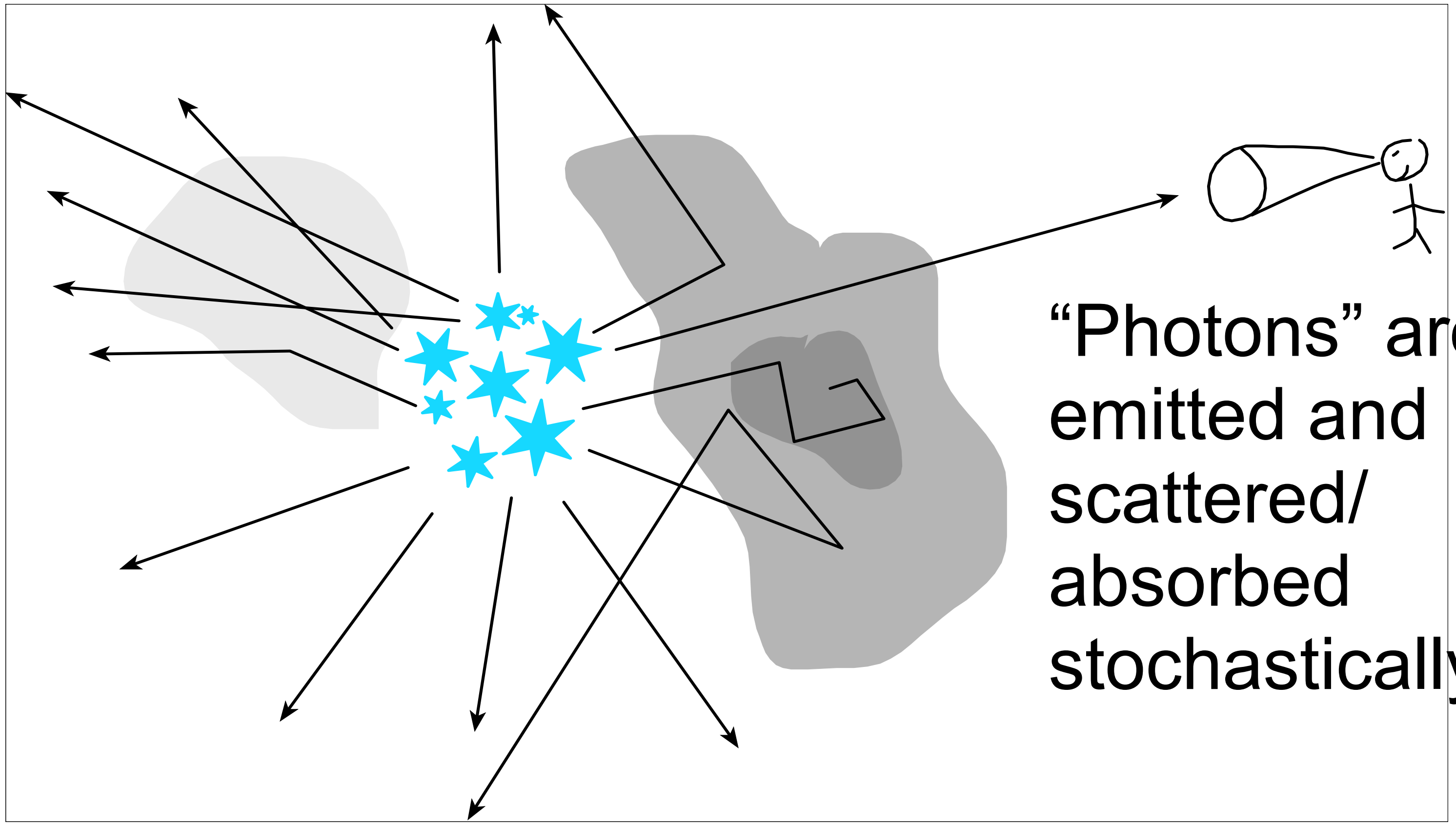
ART Simulation Daniel Ceverino;
Visualization: David Ellsworth

Sunrise Radiative Transfer Code

Patrik Jonsson
& Joel Primack

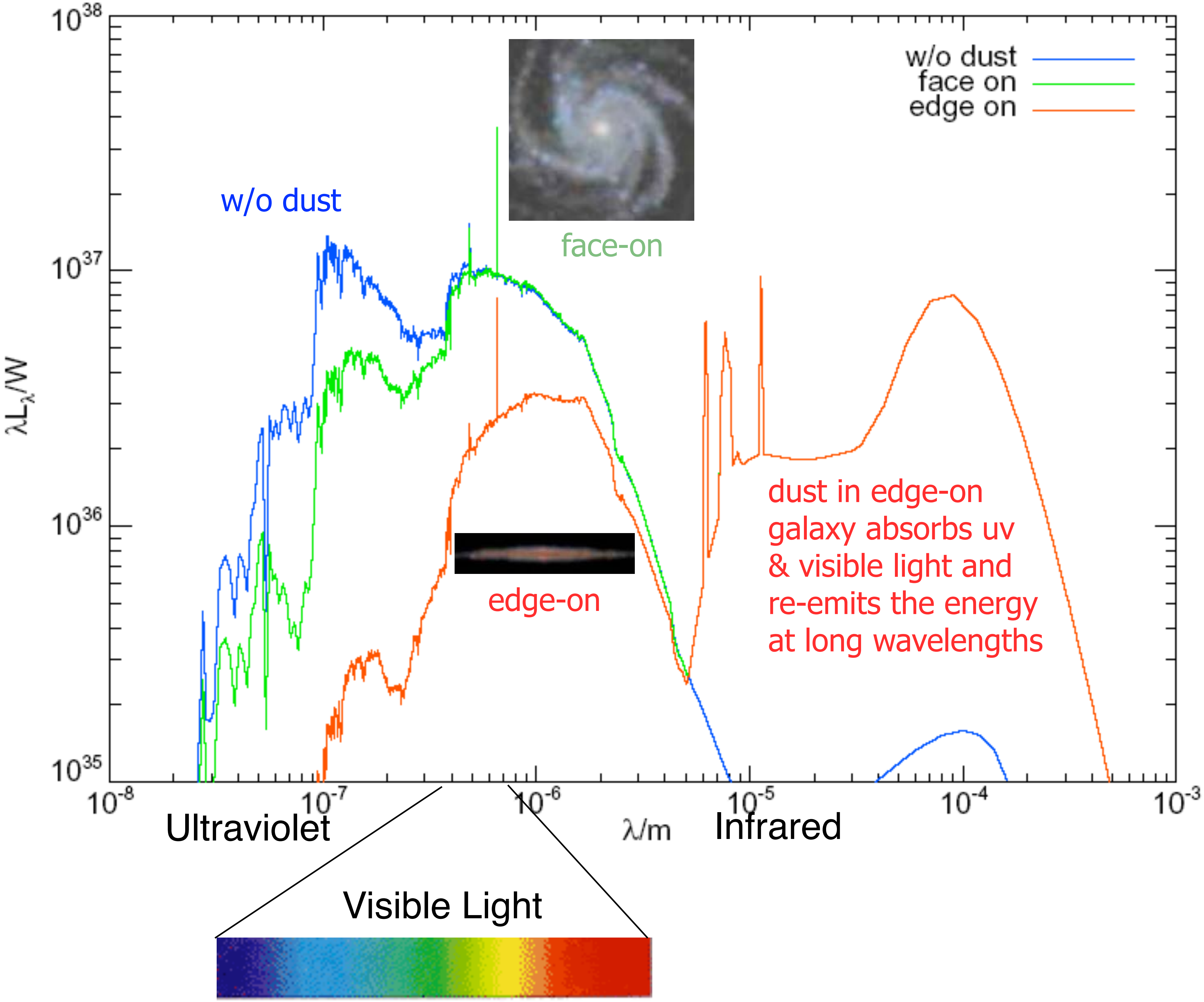
For every simulation snapshot:

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



"Photons" are emitted and scattered/ absorbed stochastically

Spectral Energy Distribution



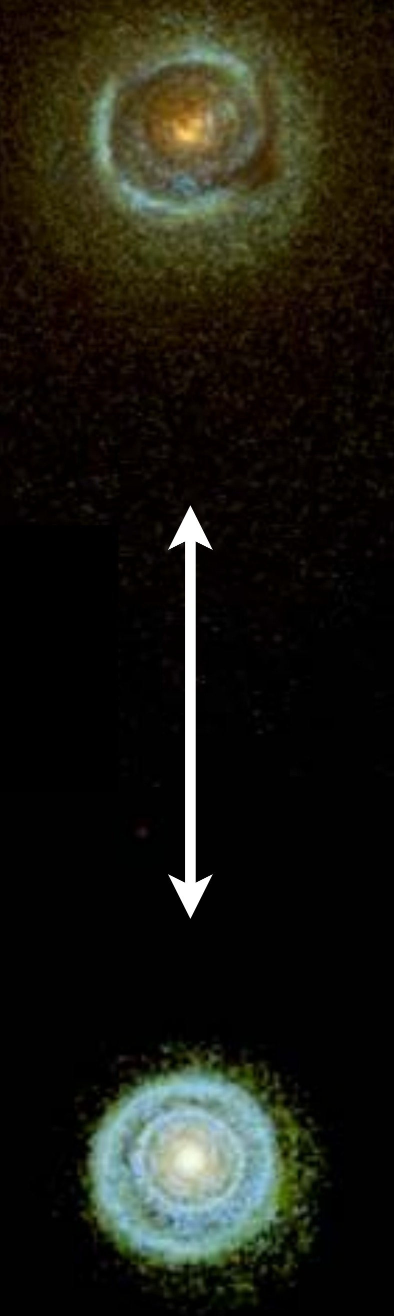
dust in edge-on galaxy absorbs uv & visible light and re-emits the energy at long wavelengths

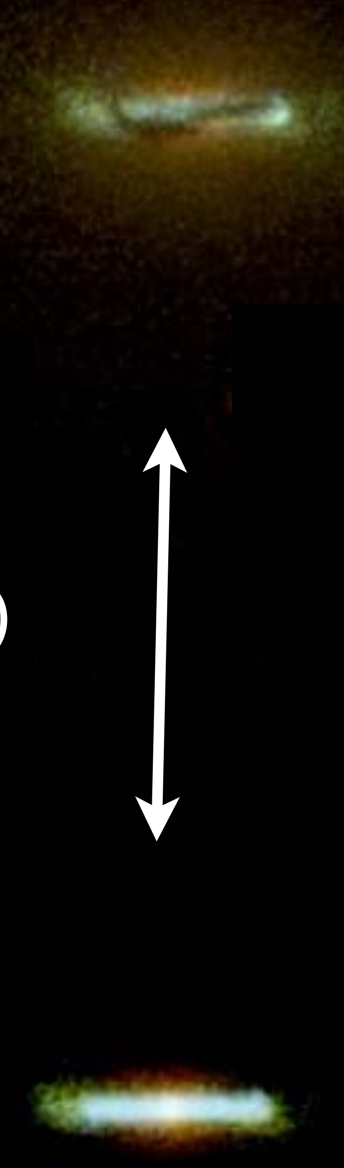
What’s the effect of including dust?

with
dust

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

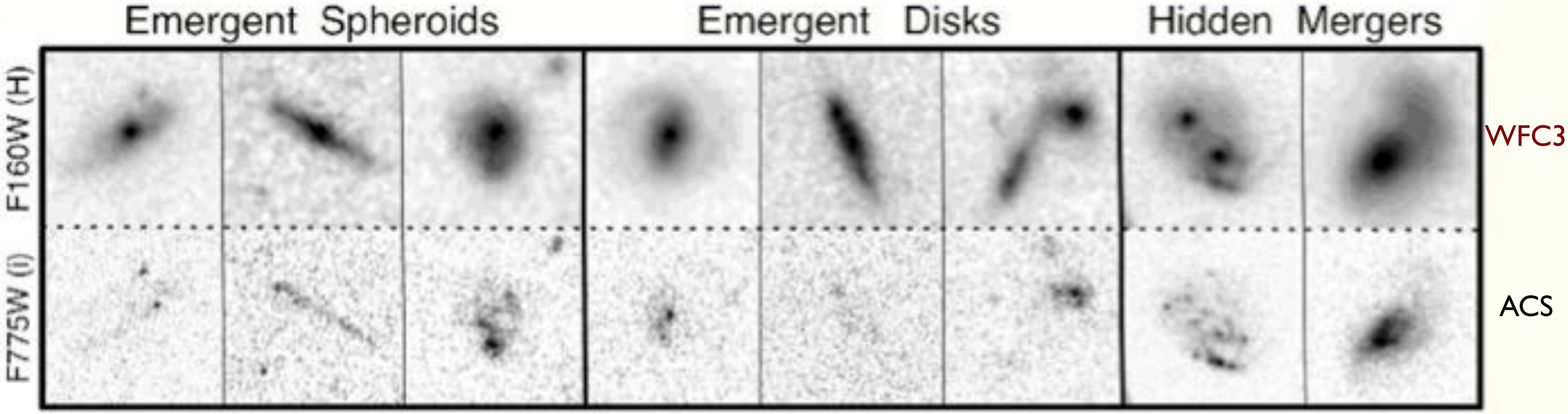
stars
only


face-on


edge-on

The CANDELS Survey with new near-ir camera WFC3

NEGATIVE IMAGES OF GALAXIES ~10 BILLION YEARS AGO



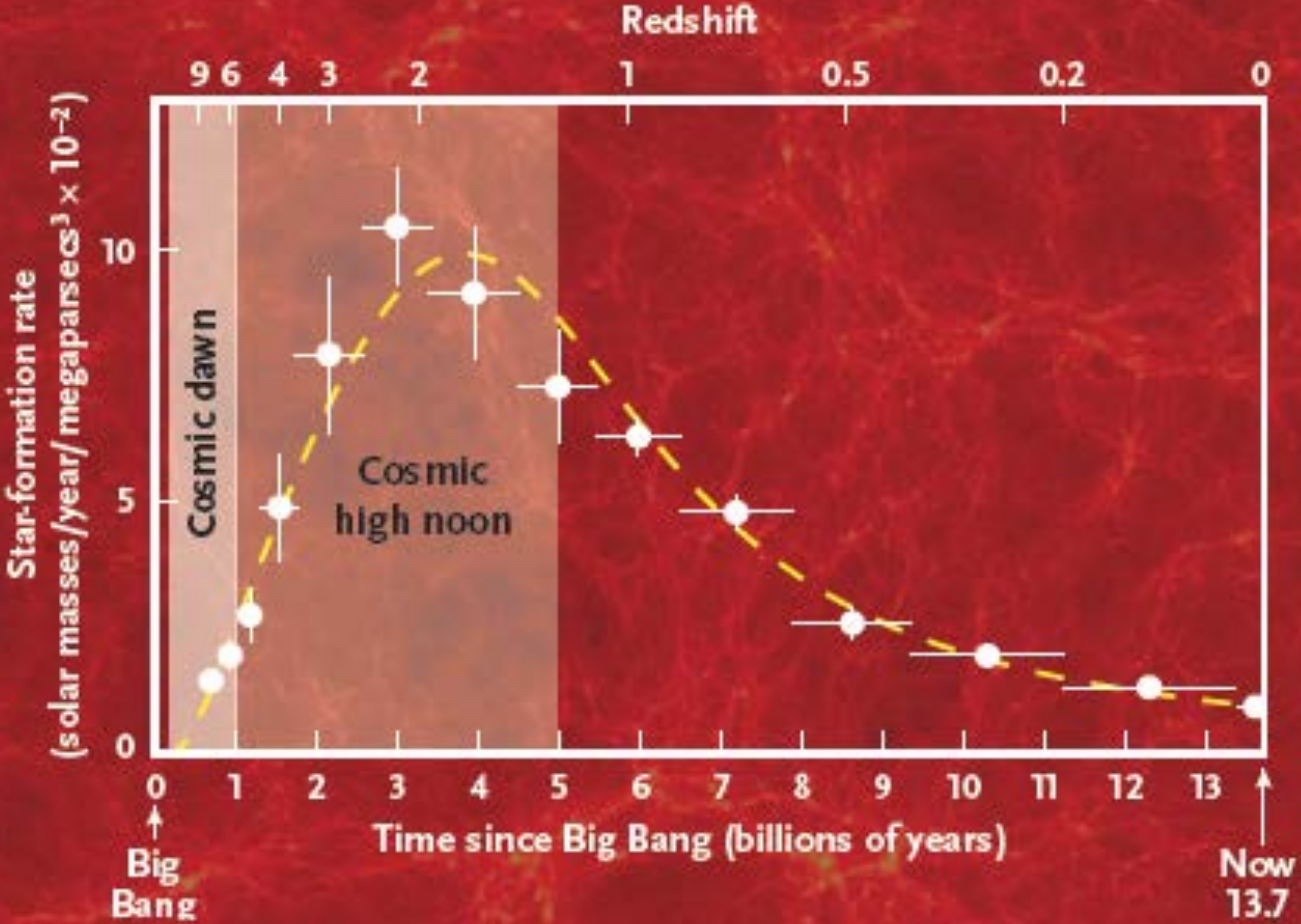
CANDELS makes use of the near-infrared WFC3 camera (top row) and the visible-light ACS camera (bottom row). Using these two cameras, CANDELS will reveal new details of the distant Universe and test the reality of cosmic dark energy.

Hubble
Space
Telescope

http://candels.ucolick.org

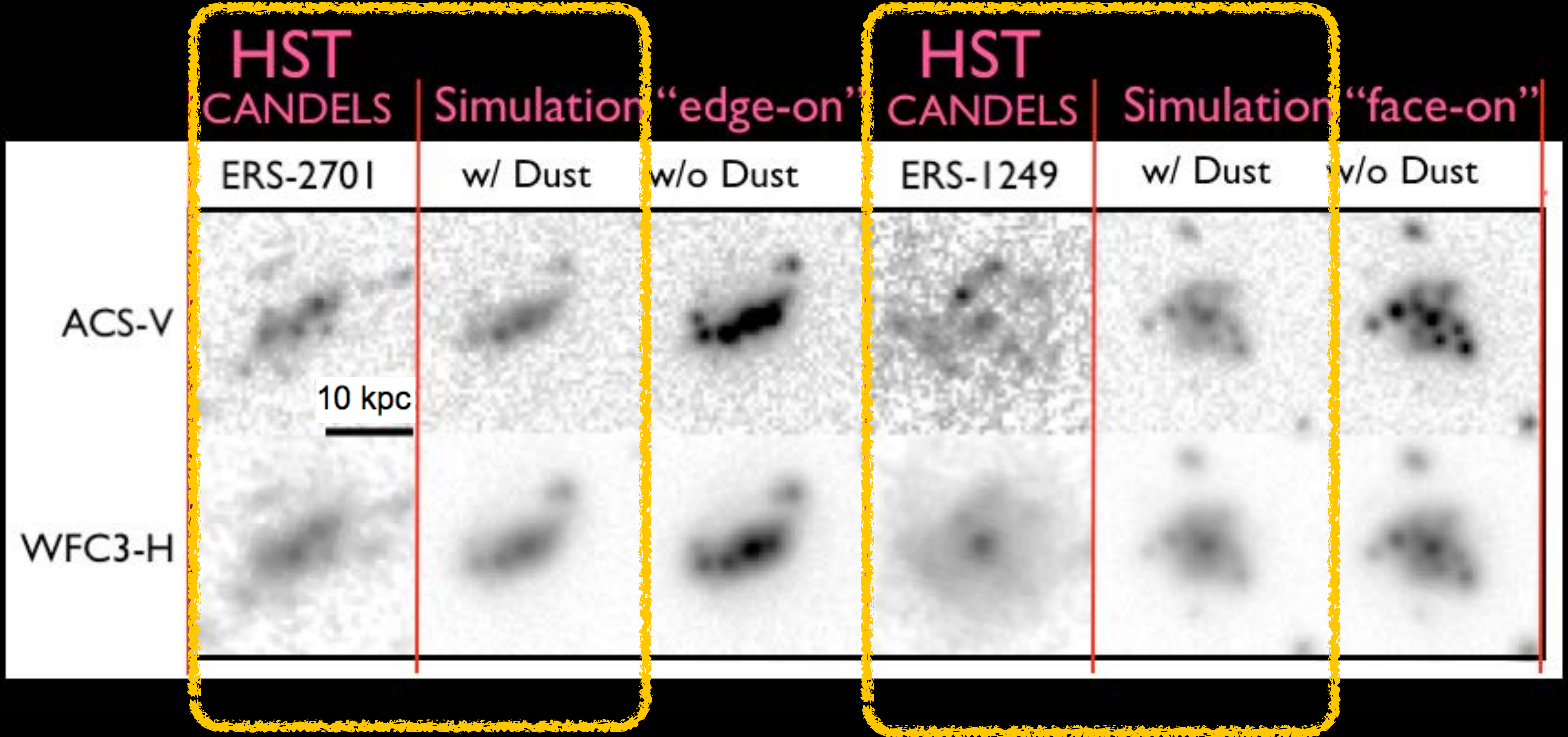
CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

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



STARBIRTH RATE Using data from many surveys, including CANDELS, astronomers have plotted the rate of star formation through cosmic history. The rate climbed rapidly at cosmic dawn and peaked at cosmic high noon.

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

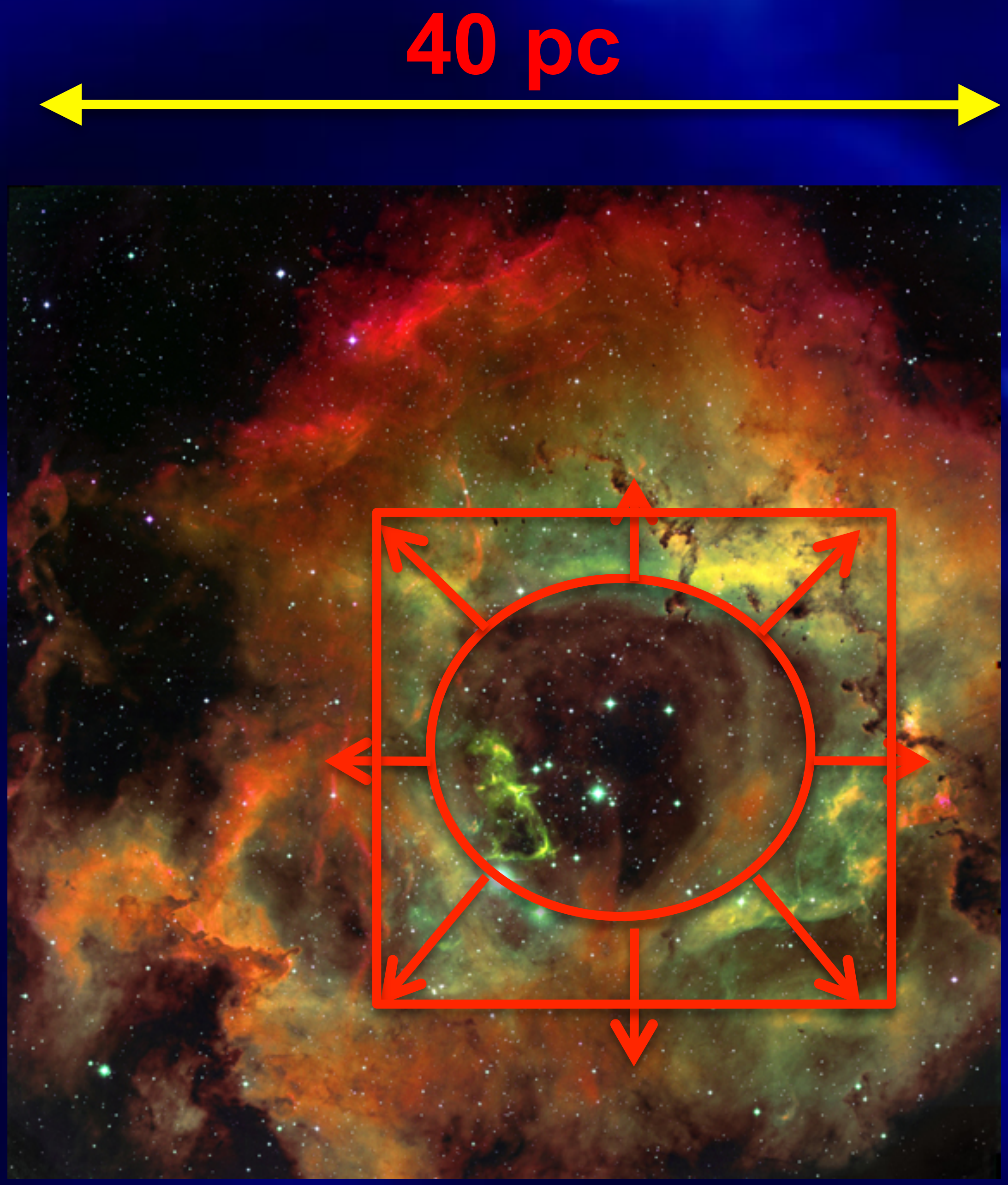


We are now systematically comparing simulated and observed galaxy images

(*Note: these are negative images.*)

Radiative feedback

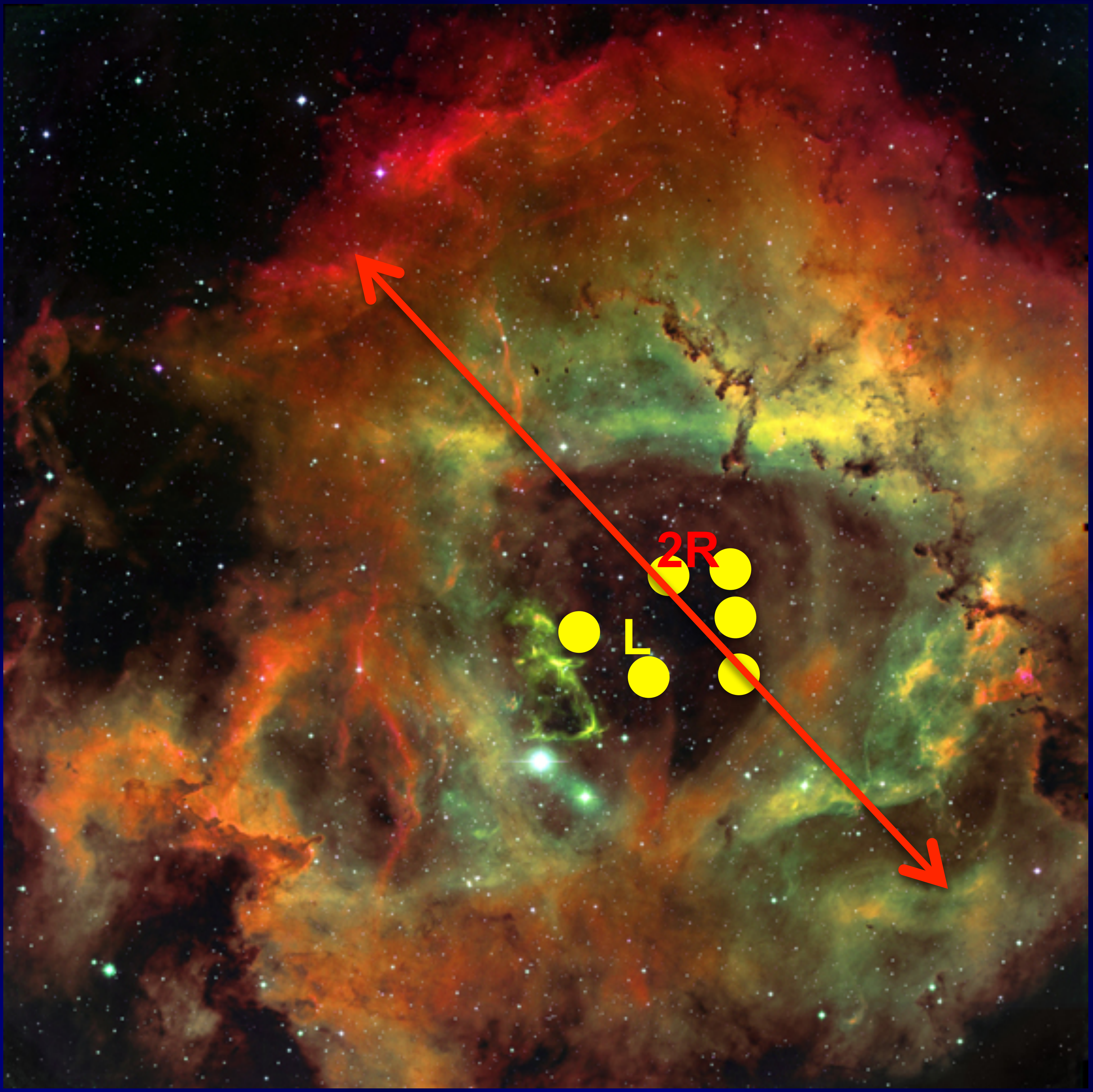
Rosette Nebula



No Supernova explosion yet
- Stellar winds
- Thermal pressure
- Radiation pressure
  from ionizing photons

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

Daniel Ceverino



- At high column densities
- Add pressure

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

$$L = M_* \Gamma$$

Γ = cte for 5 Myr

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

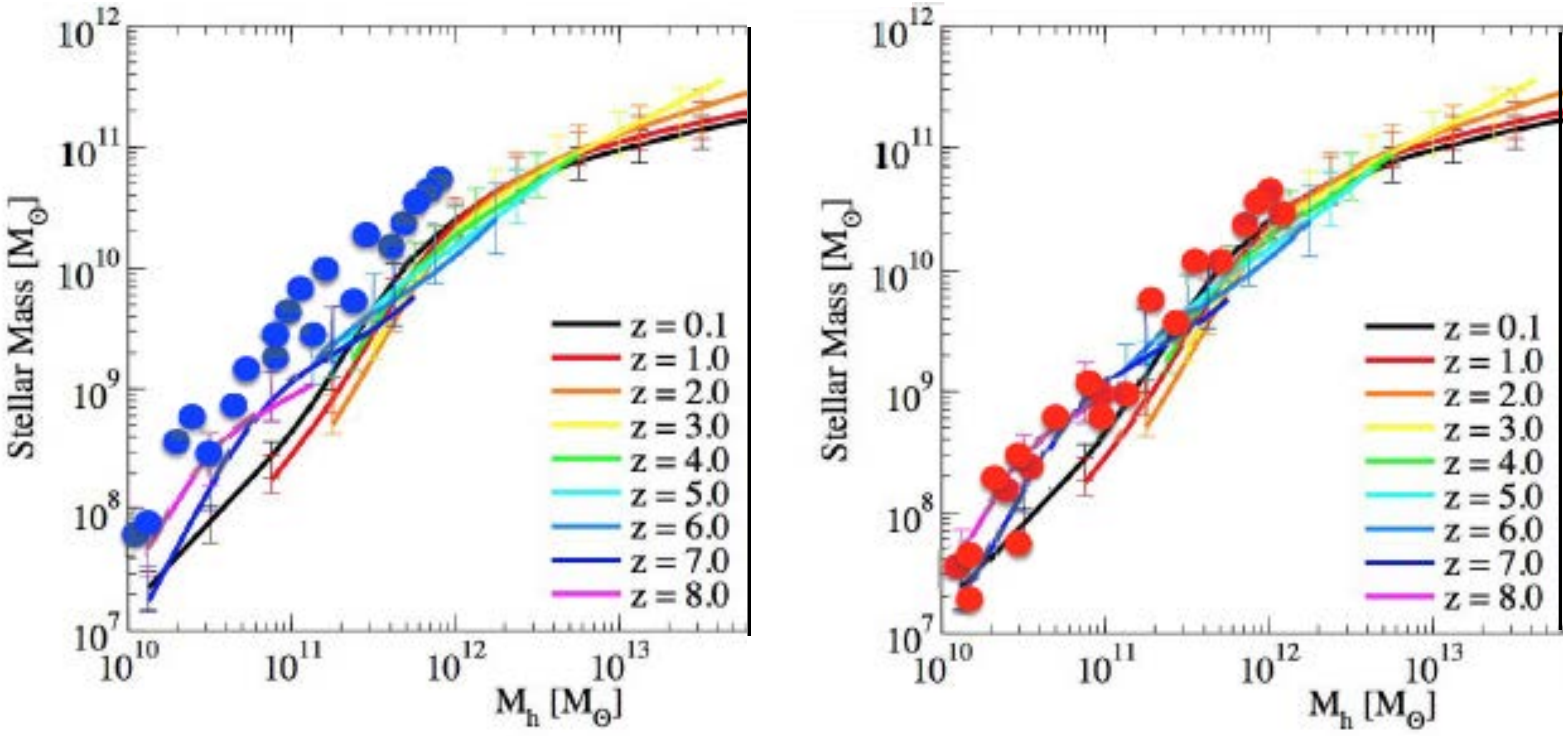
No free parameters

Daniel Ceverino

Radiative Feedback Decreases Star Formation, Improving Agreement with Observations

SNe Feedback

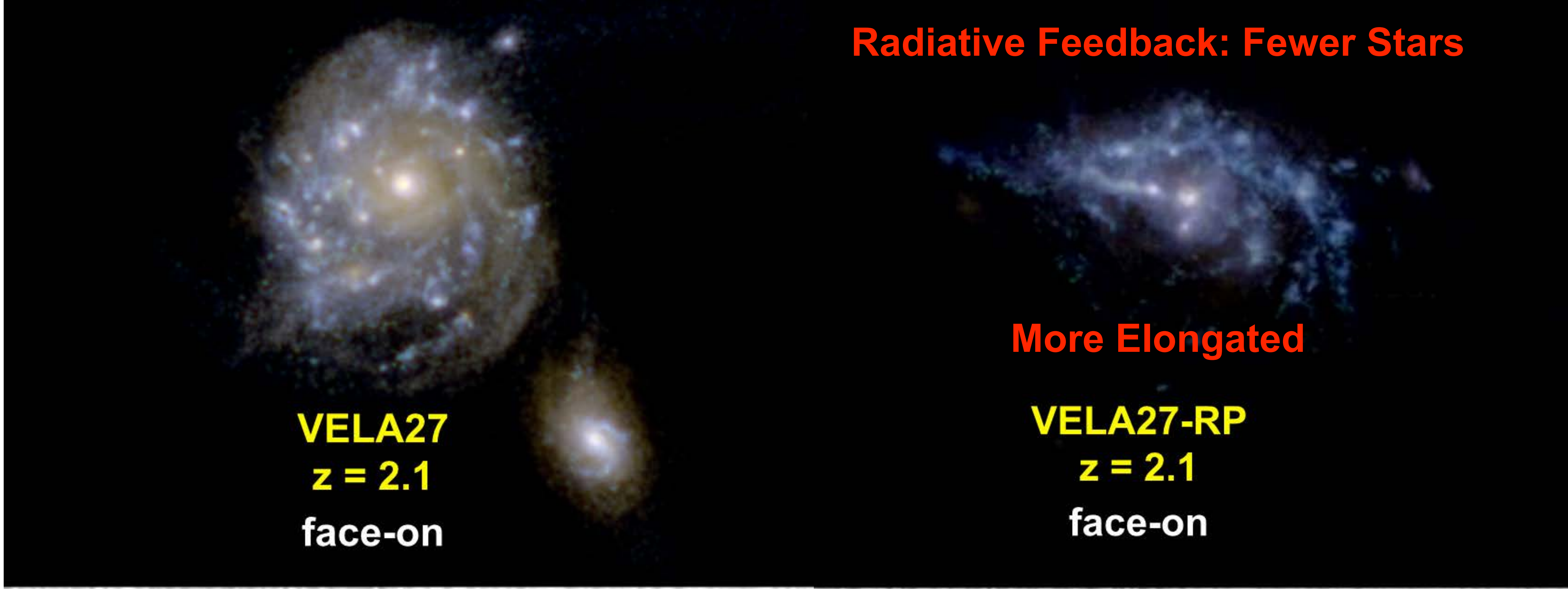
SNe & Radiative Feedback



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

Simulated Galaxy 10 billion years ago

as it would appear nearby to our eyes



Radiative Feedback: Fewer Stars

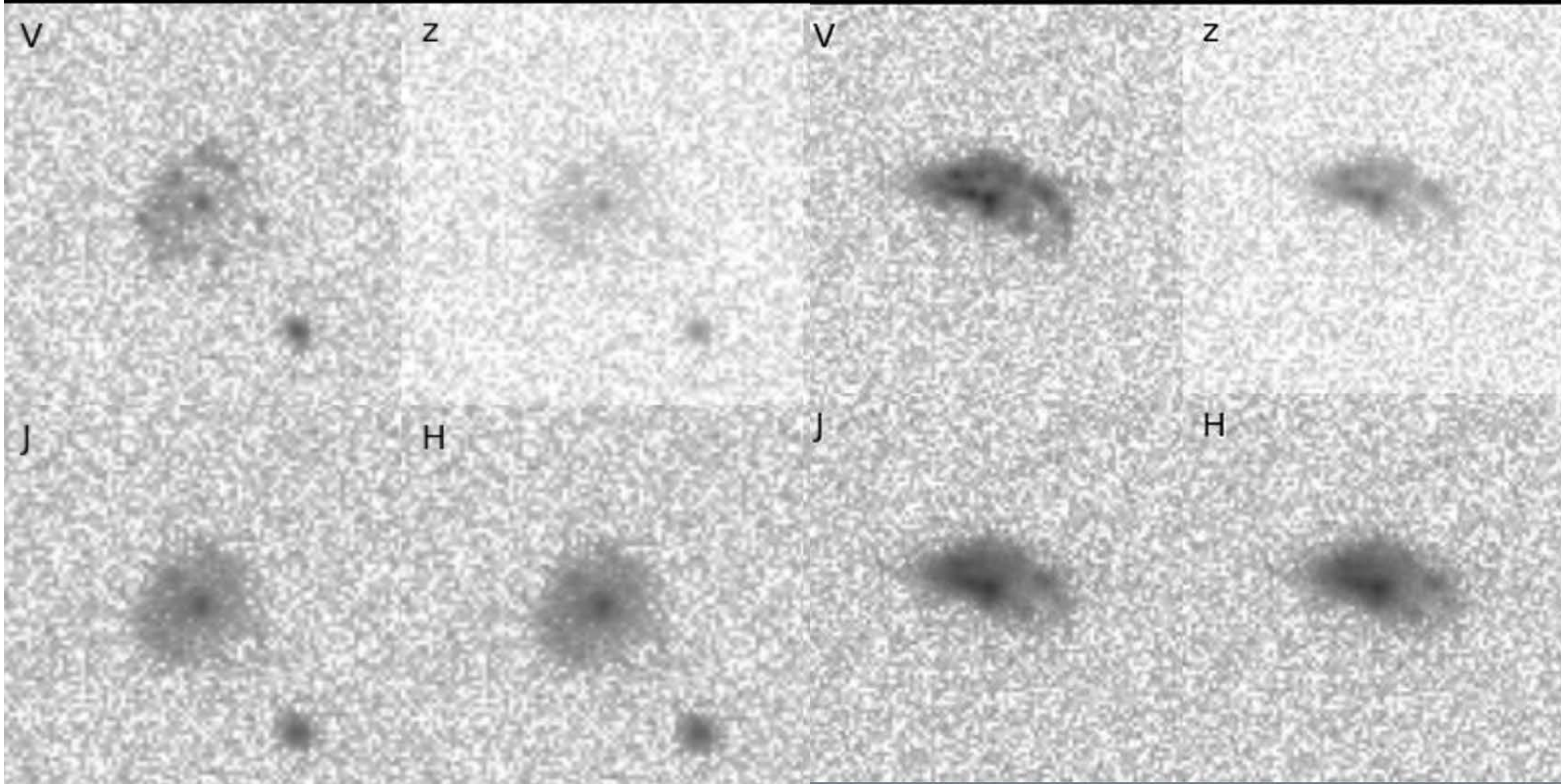
More Elongated

VELA27
z = 2.1
face-on

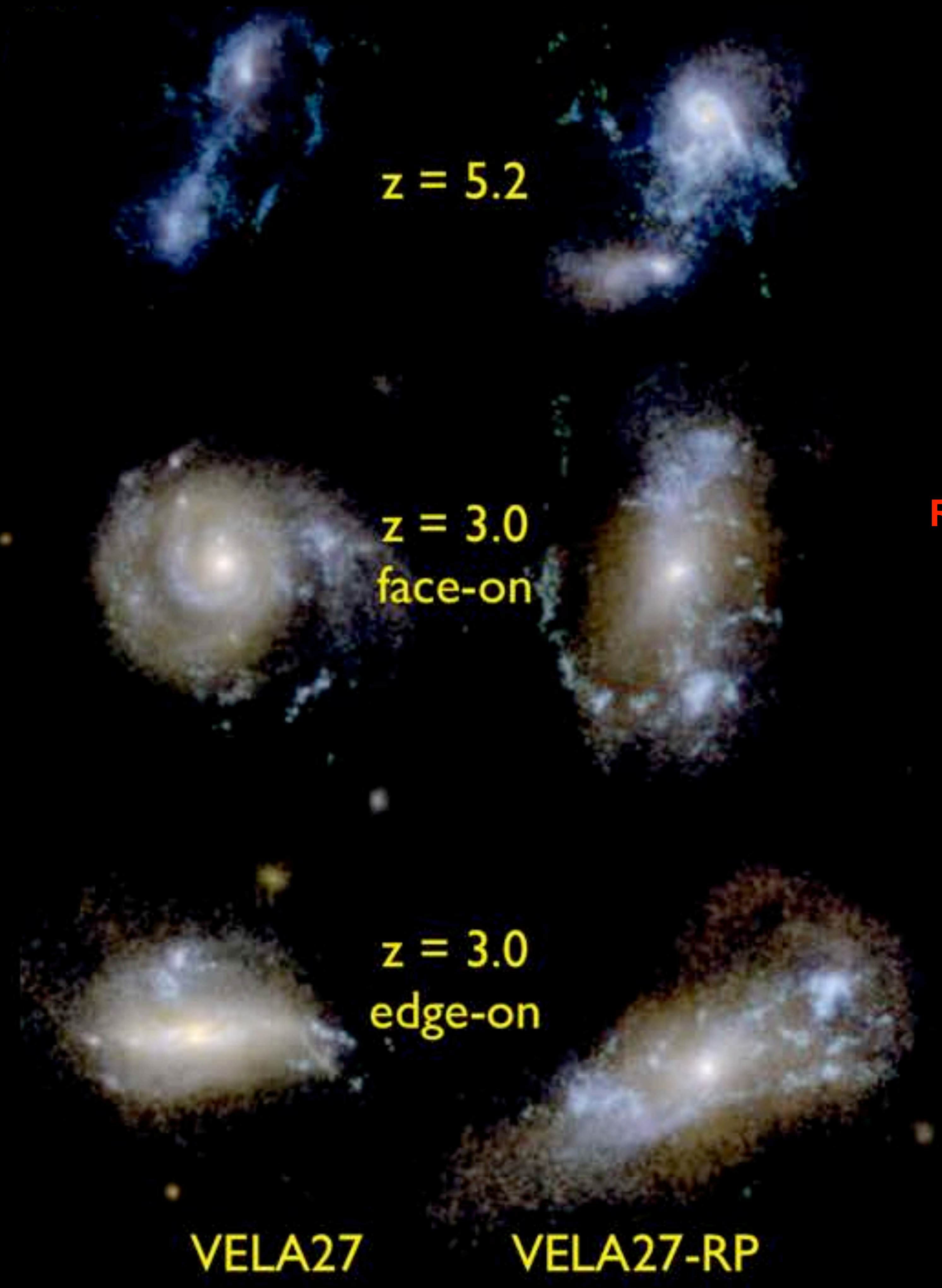
VELA27-RP
z = 2.1
face-on

as it would appear to Hubble's ACS visual camera

as it would appear to Hubble's WFC3 infrared camera



Left:
Simulation
without
Radiation
Pressure
feedback

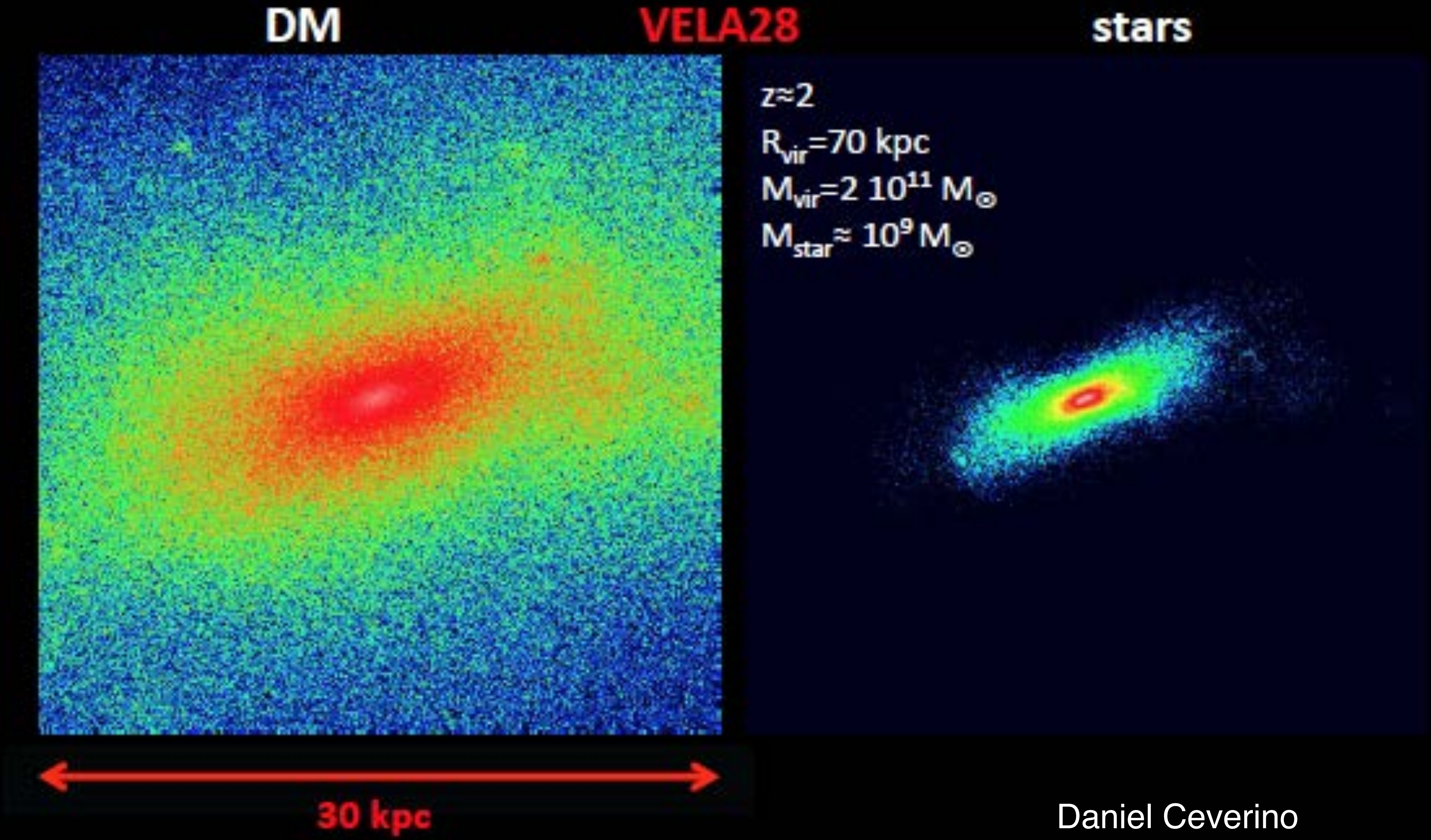


Right: Same
Simulation
with
Radiation
Pressure
feedback

Radiative Feedback Makes Galaxies More Elongated

van der Wel + SDSS, CANDELS & 3D HST: galaxy elongation observed

Prolate DM halo → elongated galaxy



$z \approx 2$

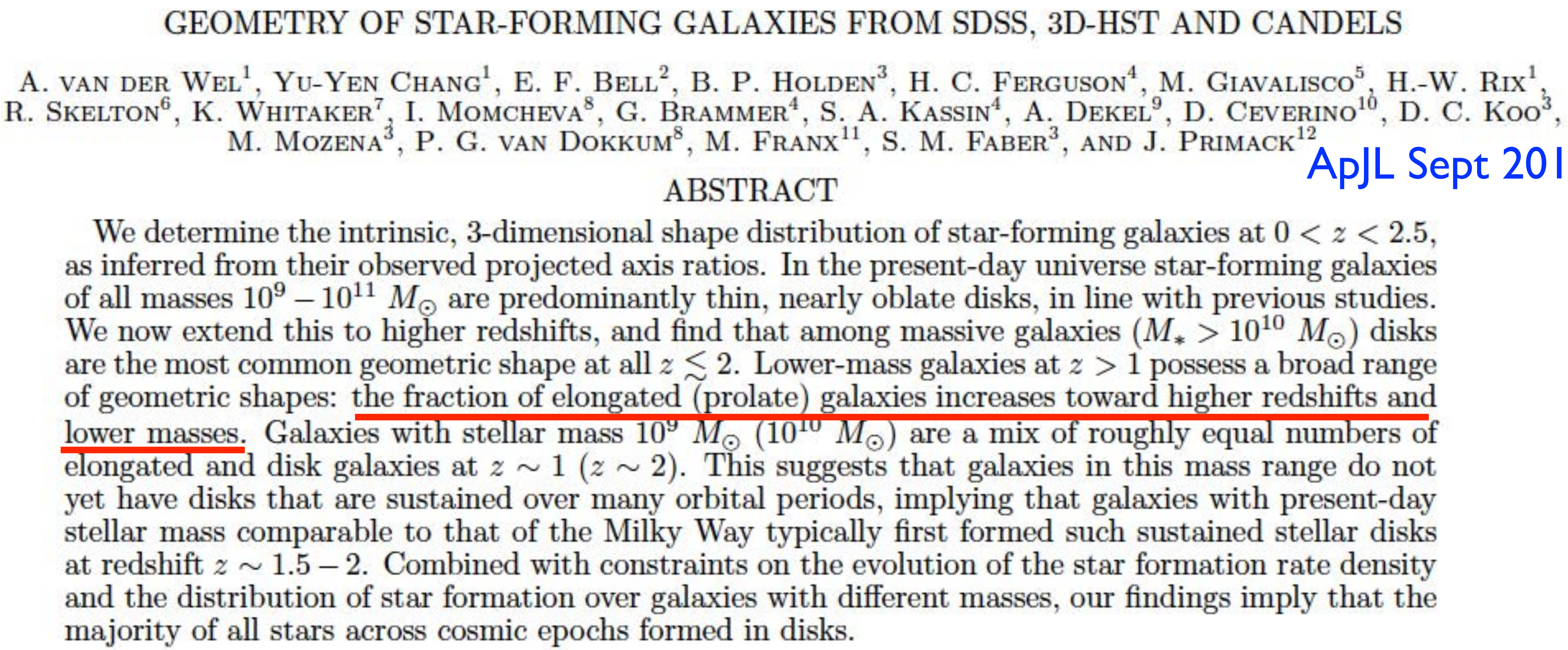
$R_{vir} = 70$ kpc

$M_{vir} = 2\ 10^{11}\ M_\odot$

$M_{star} \approx 10^9\ M_\odot$

Daniel Ceverino

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



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

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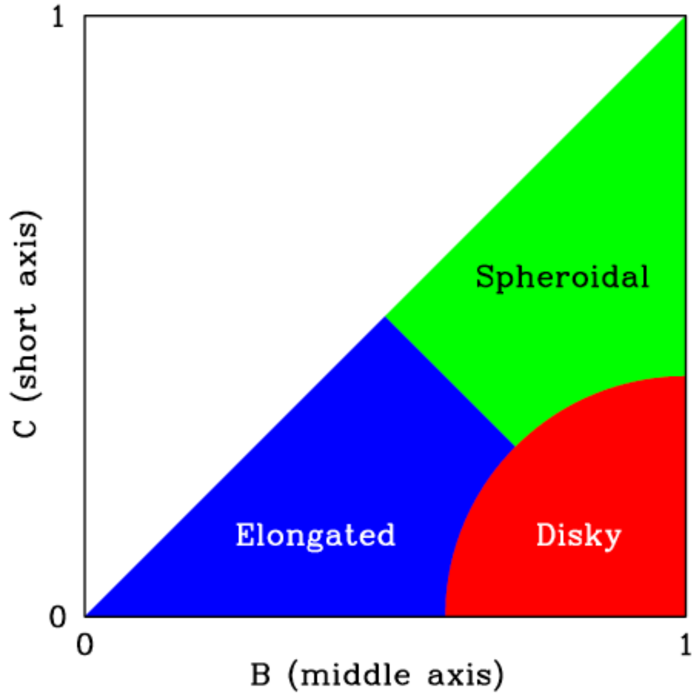
ApJL Sept 2014

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.



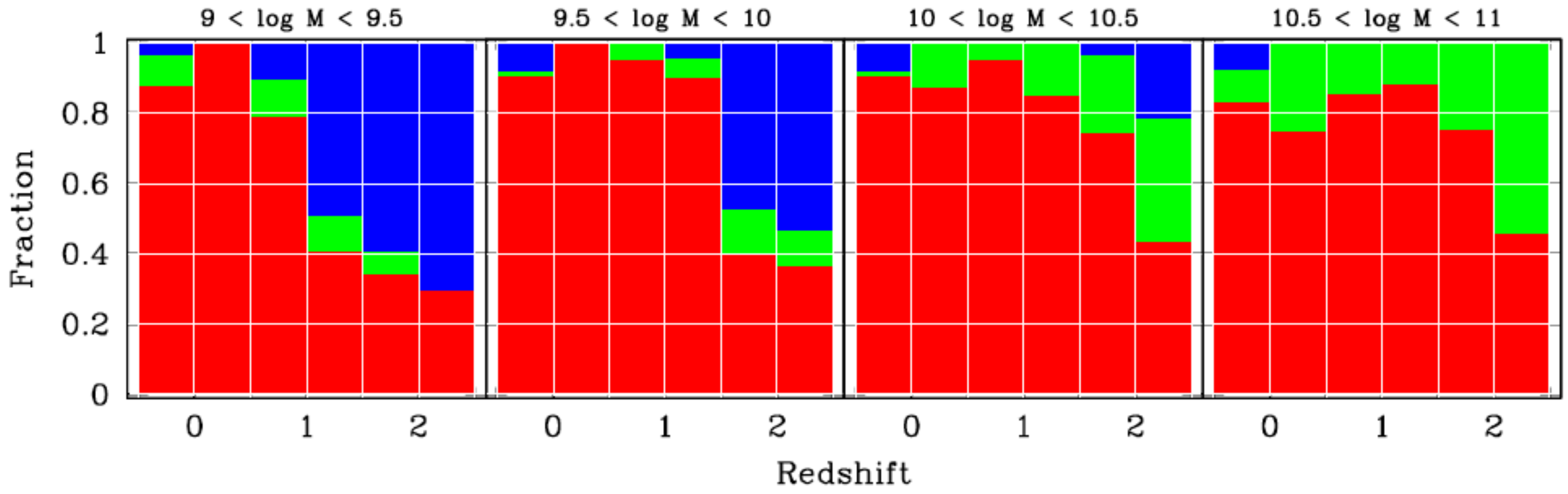


Figure 4. Color bars indicate the fraction of the different types of shape defined in Figure 2 as a function of redshift and stellar mass. The negative redshift bins represent the SDSS results for $z < 0.1$; the other bins are from 3D-HST/CANDELS.

$10^{8\text{-}9}$ $M_\odot$ Clumps in Simulated Galaxies

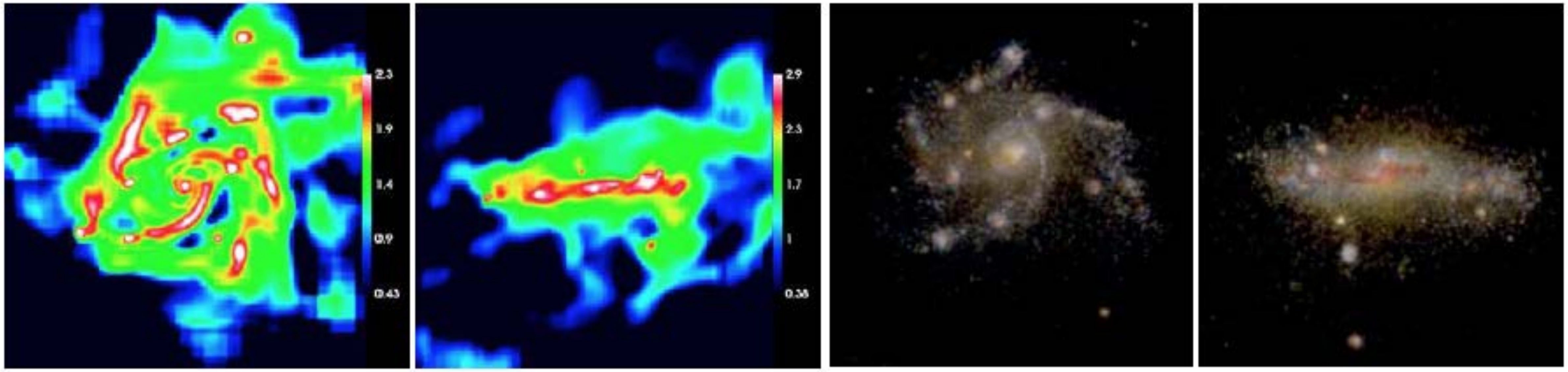


Figure 1: Violently unstable disks in $\sim 10^{11} M_\odot$ halos with $\sim 10^9 M_\odot$ clumps at $z = 2.3$: (a) face-on, (b) edge-on (Ceverino et al. 2009, resolution 70 pc, images 10 kpc across). RGB color images of the same simulated galaxy through dust using *Sunrise*: (c) face-on, (d) edge-on,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

Recall: Semi-Analytic Models find that a majority of galactic spheroids form by violently unstable disks forming clumps and bars that drive stars and gas to the galactic center, rather than by galaxy mergers.

$10^{8\text{-}9}$ $M_\odot$ Clumps in Real and Simulated Galaxies

CANDELS observations

ART simulations

3D-HST data

ART sims

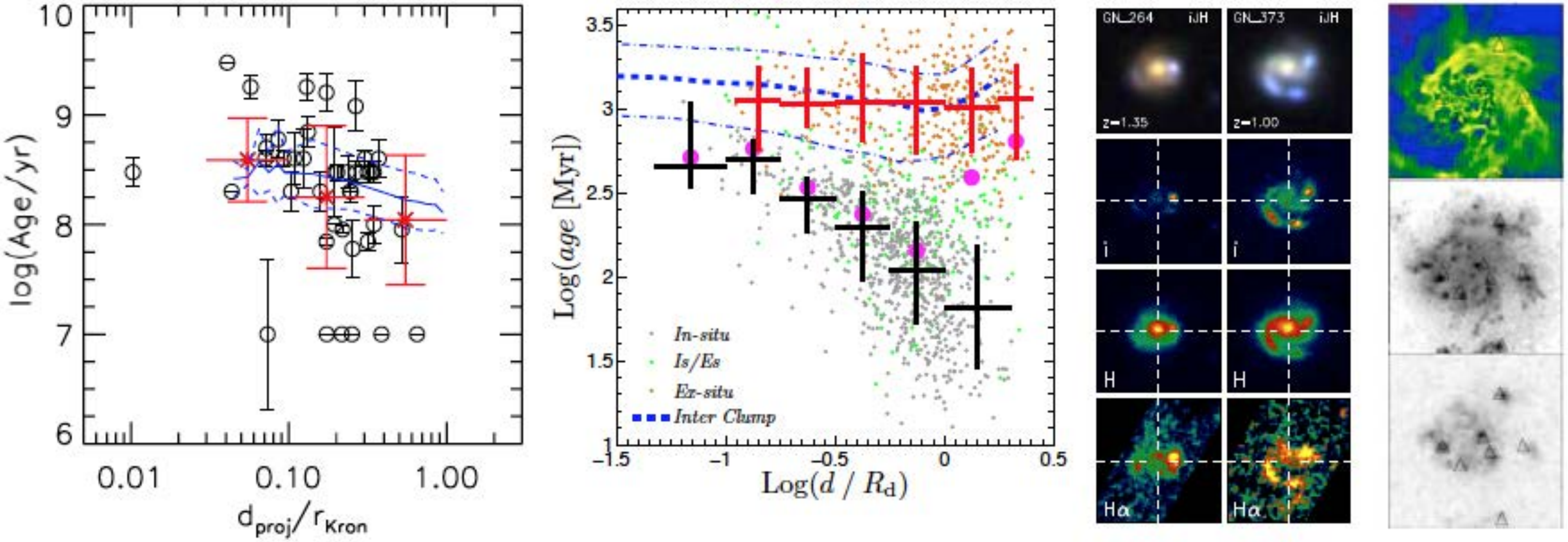
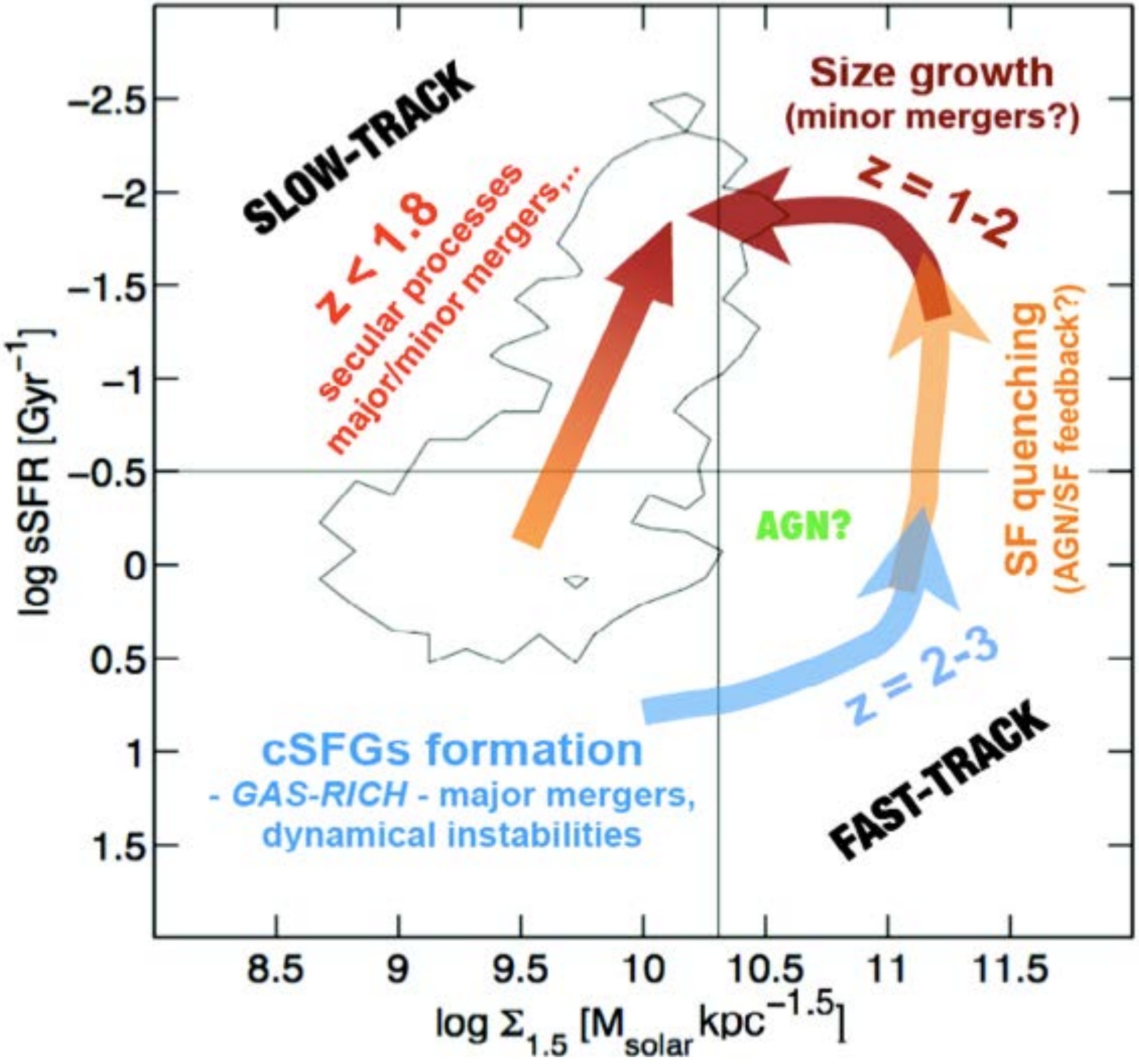


Figure 3: Clump stellar age vs. radius in (a) CANDELS observations (Guo et al. 2012, with black points showing individual clumps and red points showing mean and 1σ range) and (b) analysis of our generation 1 simulations, with black and red crosses showing in situ and ex situ clumps, respectively, and magenta points showing median values for all clumps, both in situ and ex situ (Mandelker et al. 2013). In both figures, the blue curves show the disk inter-clump stellar age and 1σ scatter. (c) 3D-HST observations of two clumpy galaxies (Wuyts et al. 2013); comparing Hα from the grism observations with i and H band images allows estimation of the dust extinction. (d) (*bottom*) Clumps (triangles) found by Yicheng Guo's automated method on CANDELized V-band image, and the same clumps plotted on (*middle*) the V-band image before CANDELization and (*top*) on the projected gas map (Moody et al. 2014).

Barro+ (CANDELS) 2013

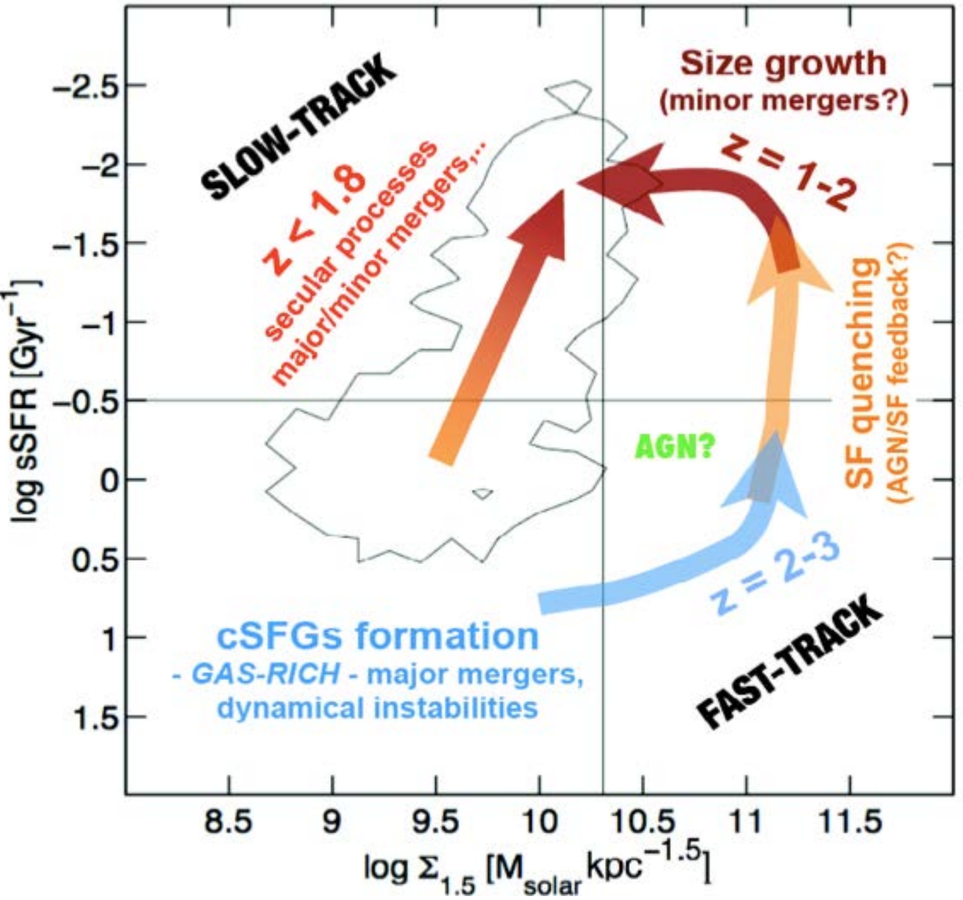


Increasing Star Formation ↓

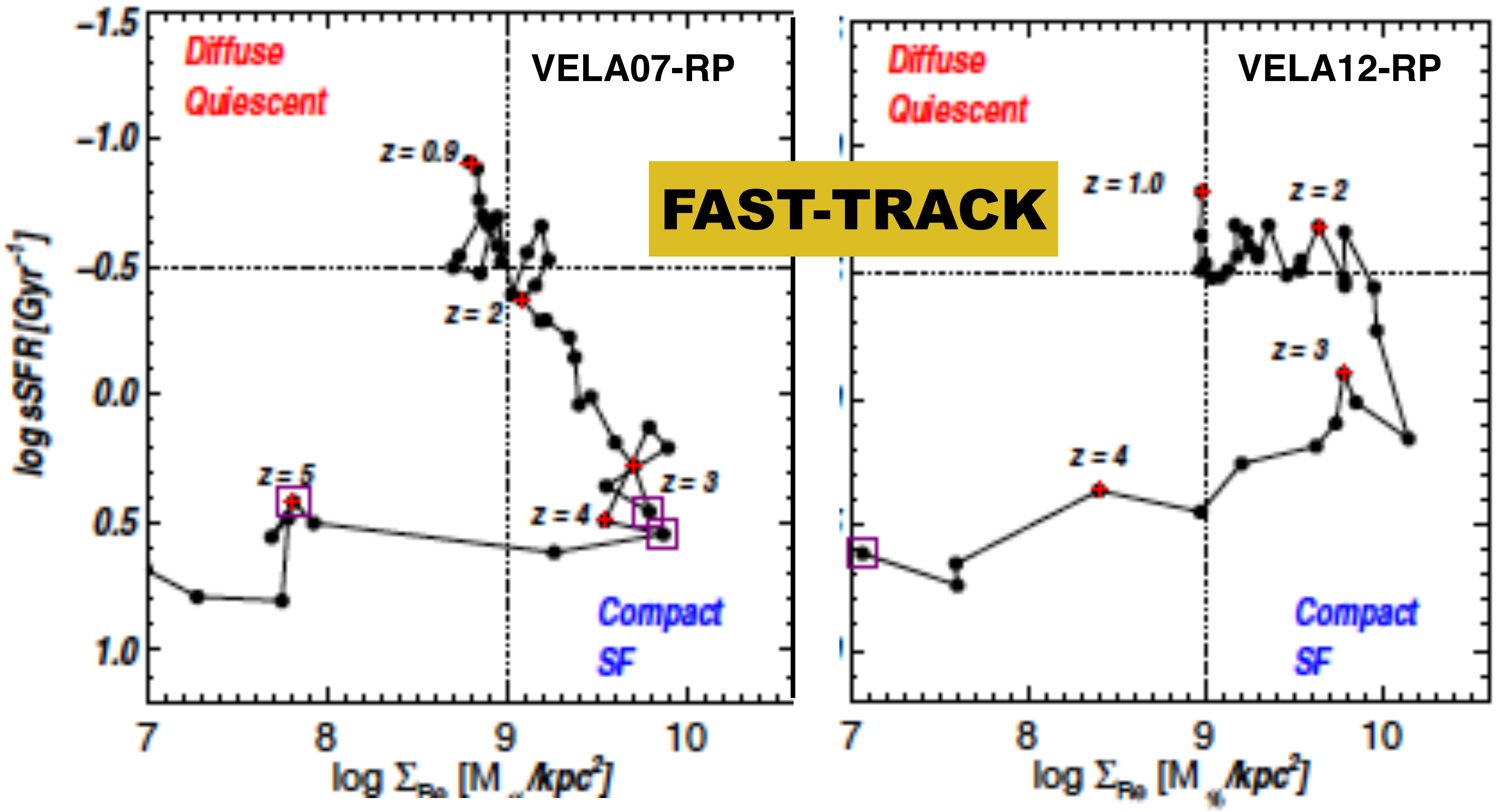
"Compactness" →

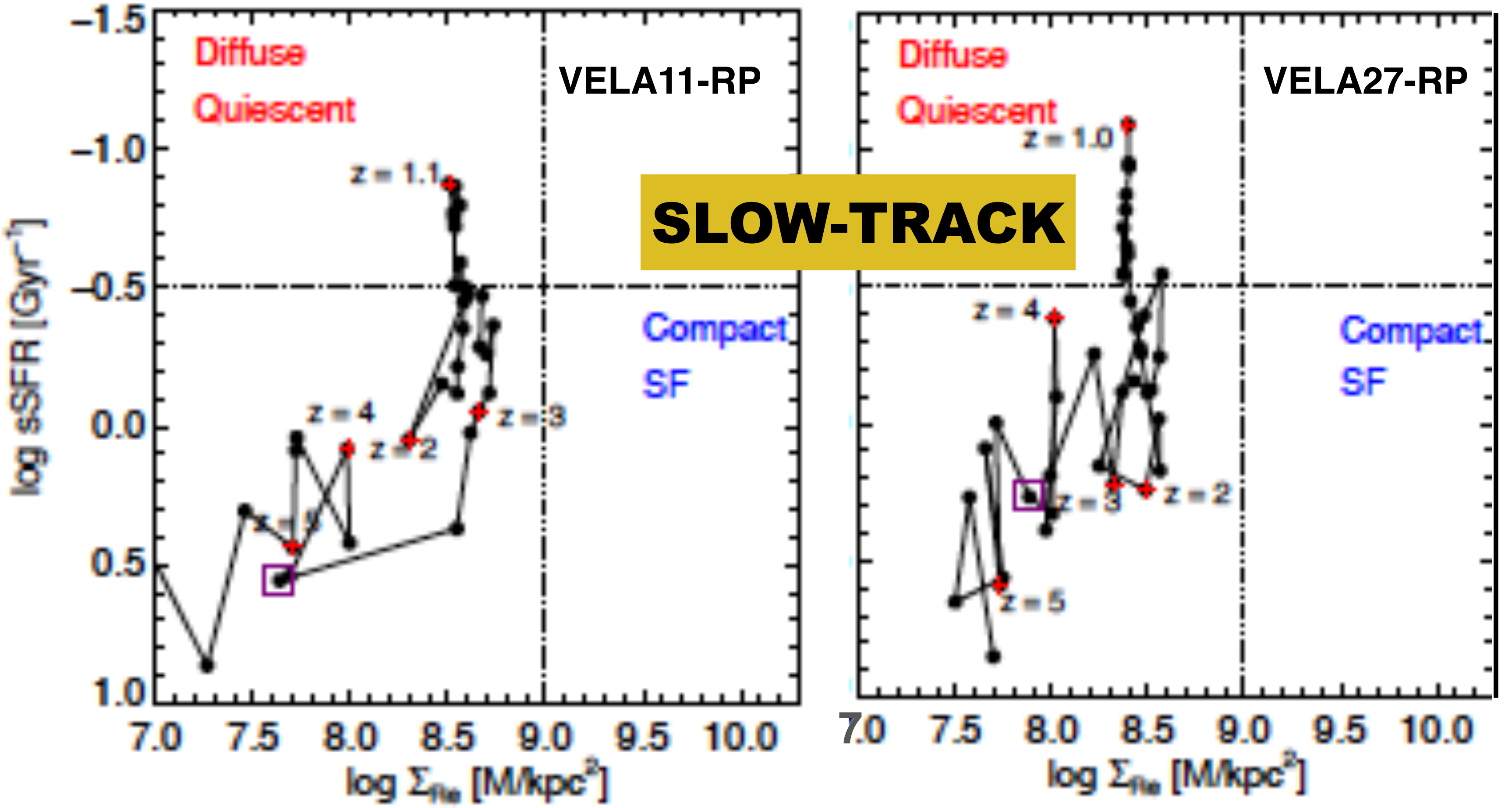
Ceverino+ RP simulations analyzed by Zolotov, Dekel, Tweed, Mandelker, Ceverino, & Primack (in prep.)

Barro+ (CANDELS) 2013



“Compactness” →





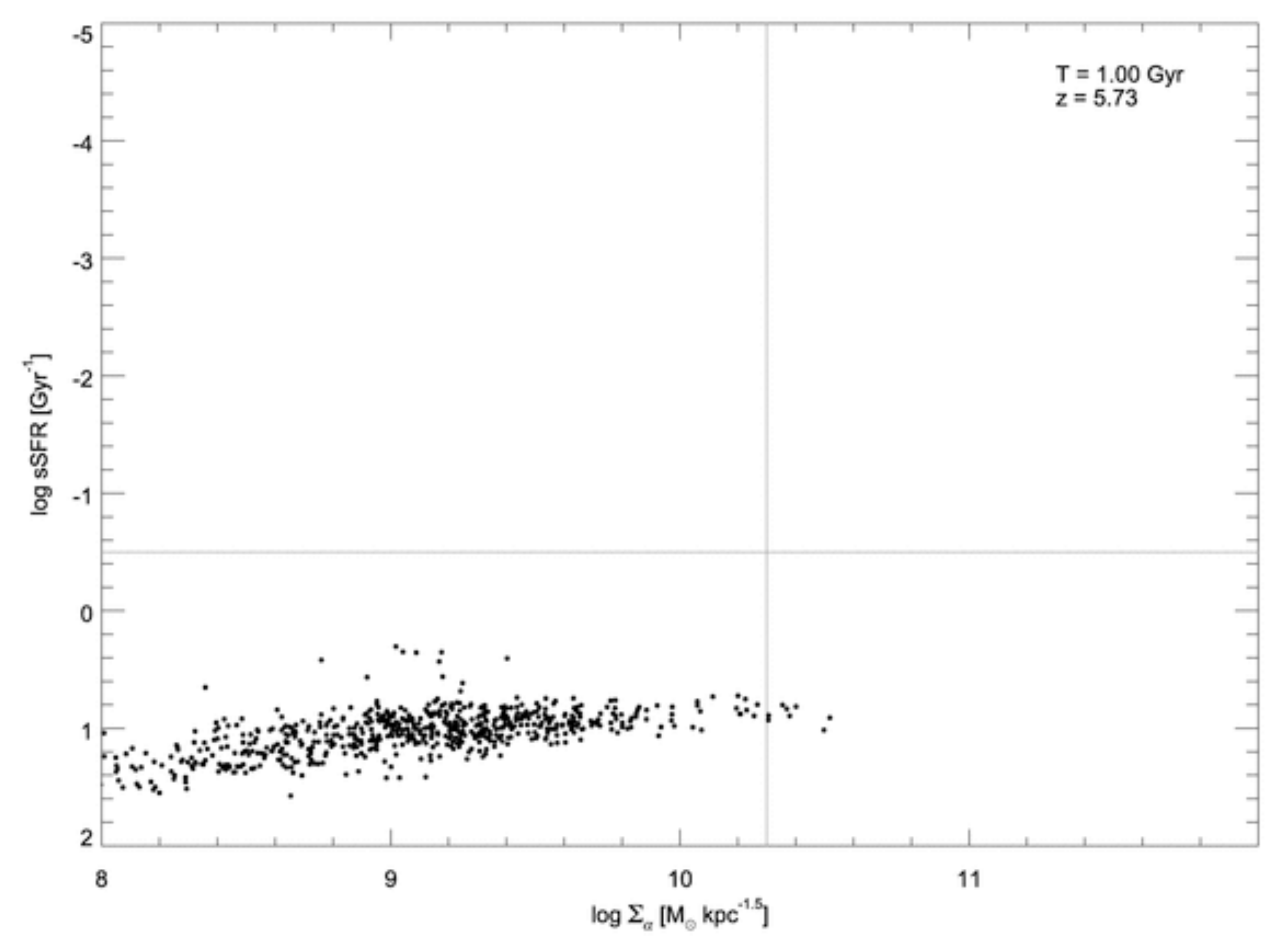
“Compactness” →   “Compactness” →

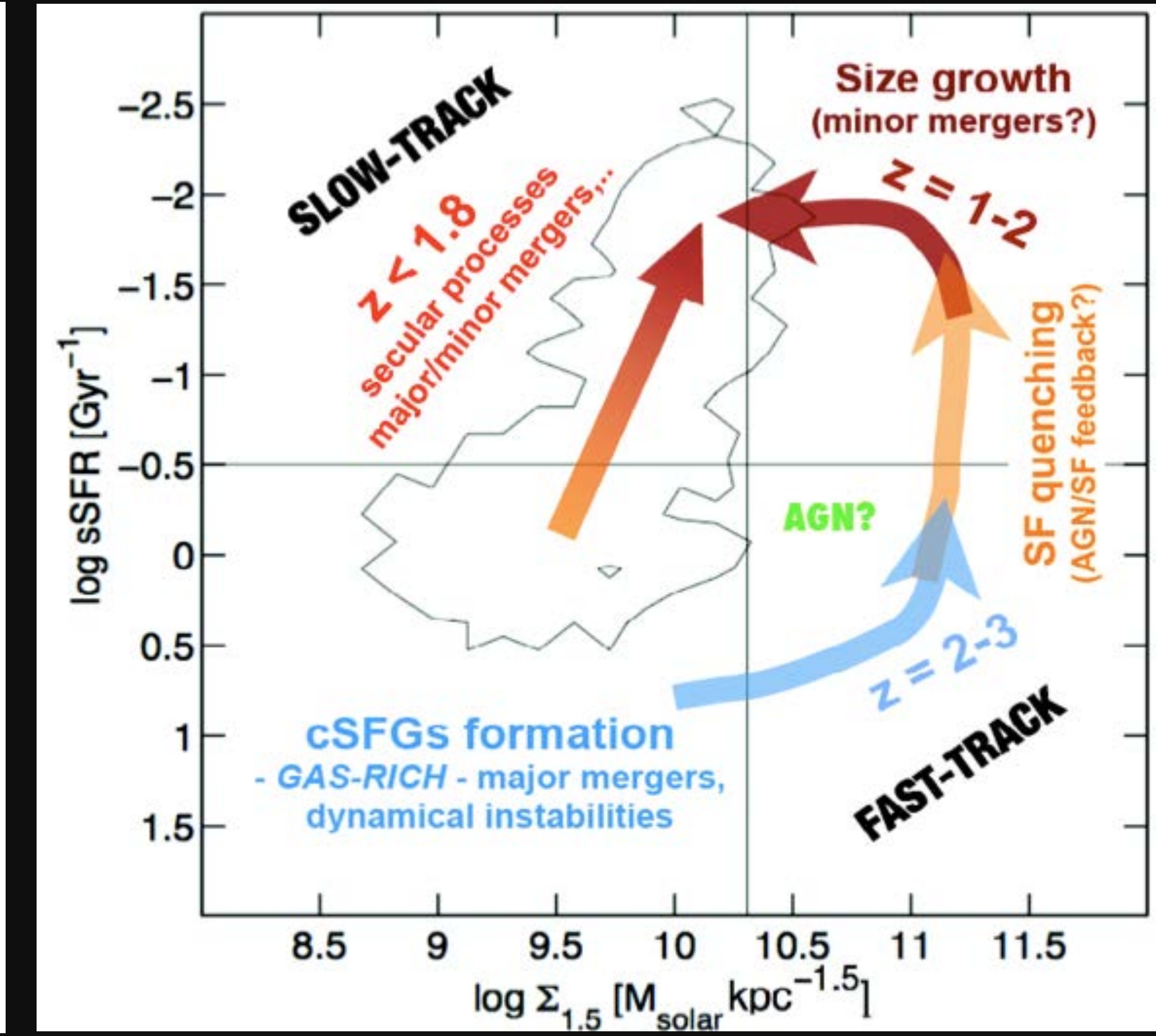
▣ minor merger

▣ major merger

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

Observed Evolution of Galaxies from Latest Hubble Telescope Data





Gas-rich merger in past Gyr

Gas-poor merger in past Gyr

cSFG at z = 2.4

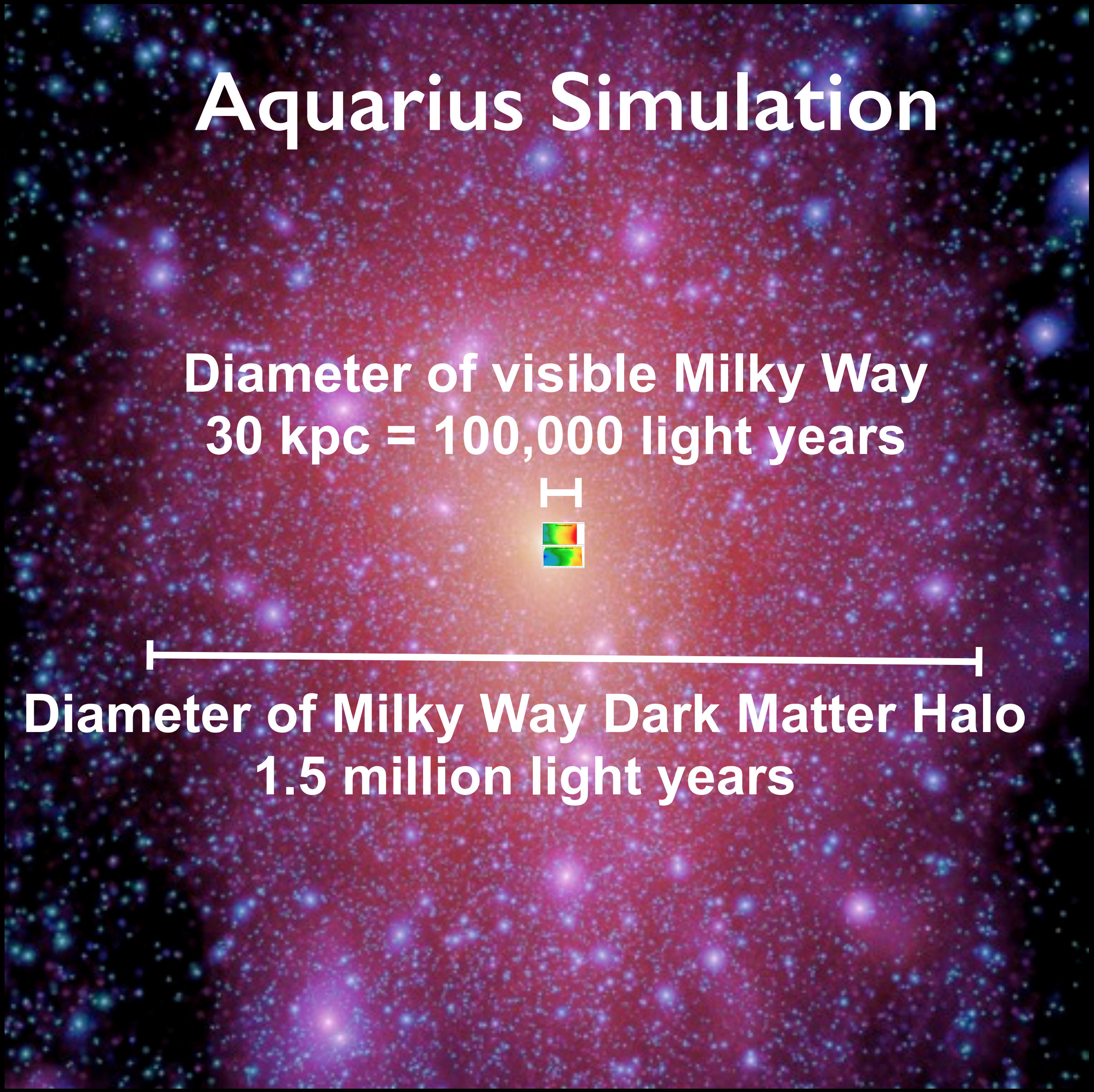
Barro et al. (2013 - Hubble Observations)

Somerville et al. (in prep.) - Bolshoi SAM

The “Too Big To Fail” problem

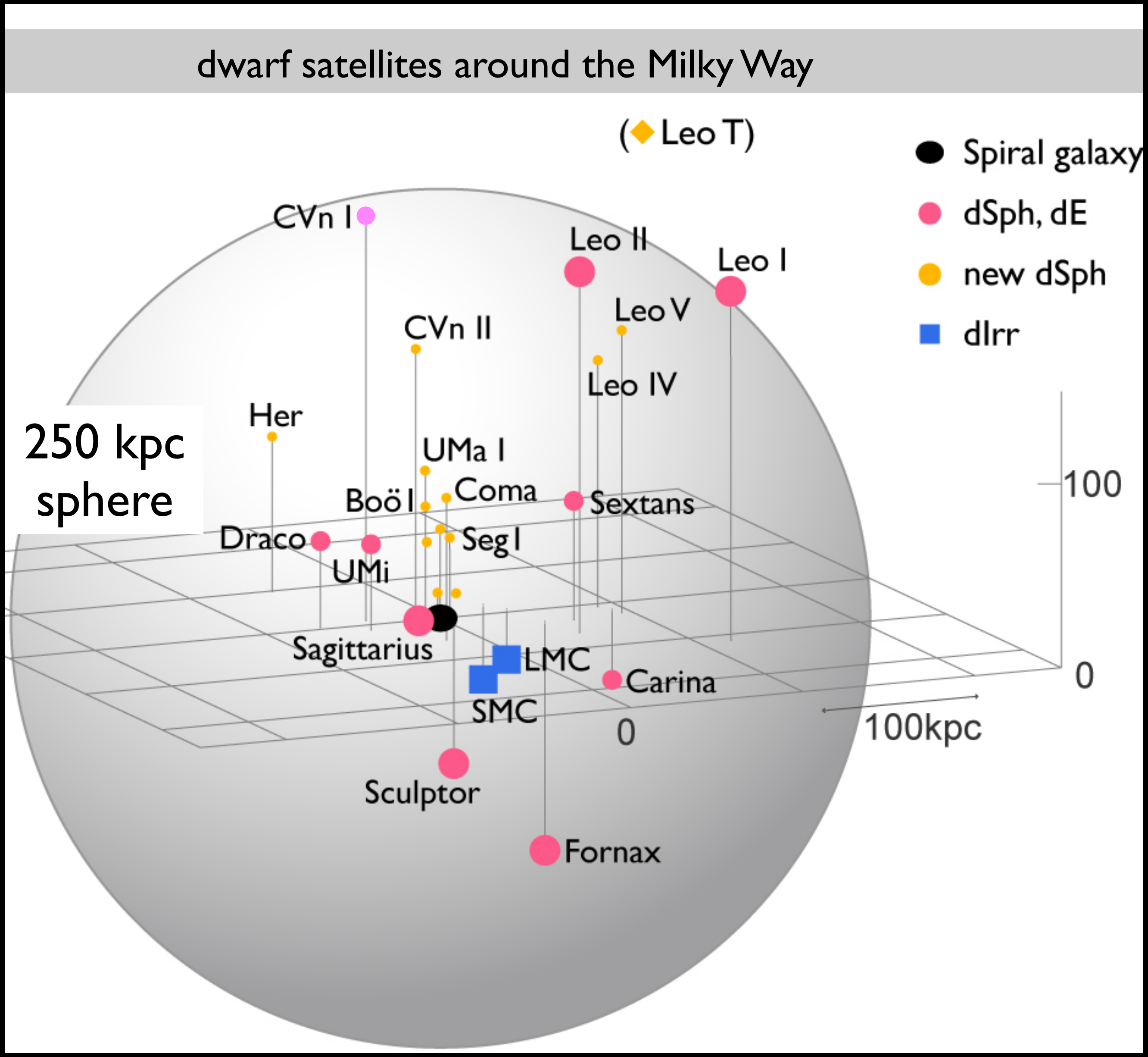
ΛCDM subhalos vs. Milky Way satellites

“Missing satellites”: Klypin et al. 1999, Moore et al. 1999



>10^5 identified subhalos

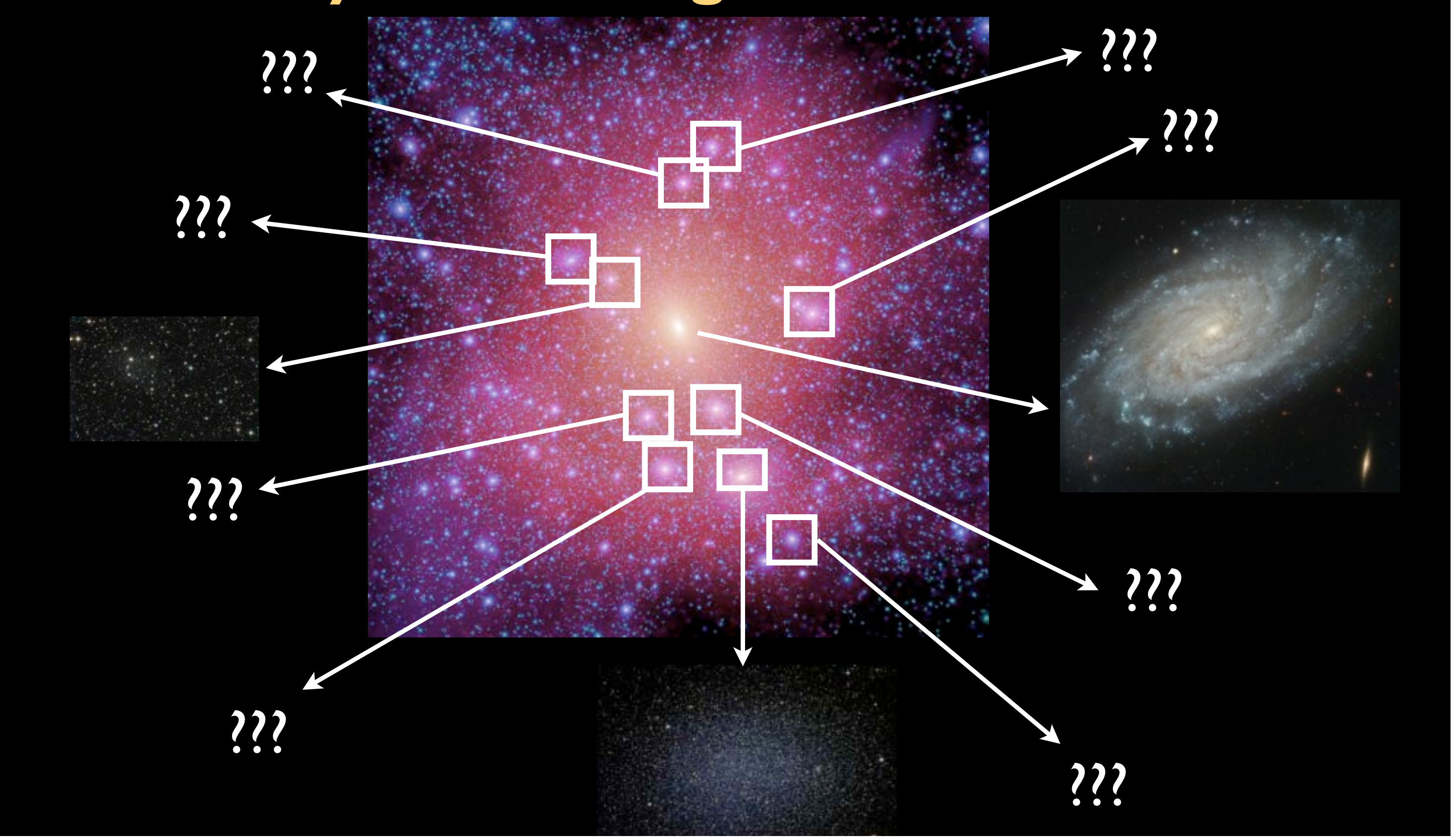
V. Springel / Virgo Consortium



12 bright satellites ($L_V > 10^5 L_\odot$)

S. Okamoto

Of the ~10 biggest subhalos, ~8 cannot host *any* known bright MW satellite

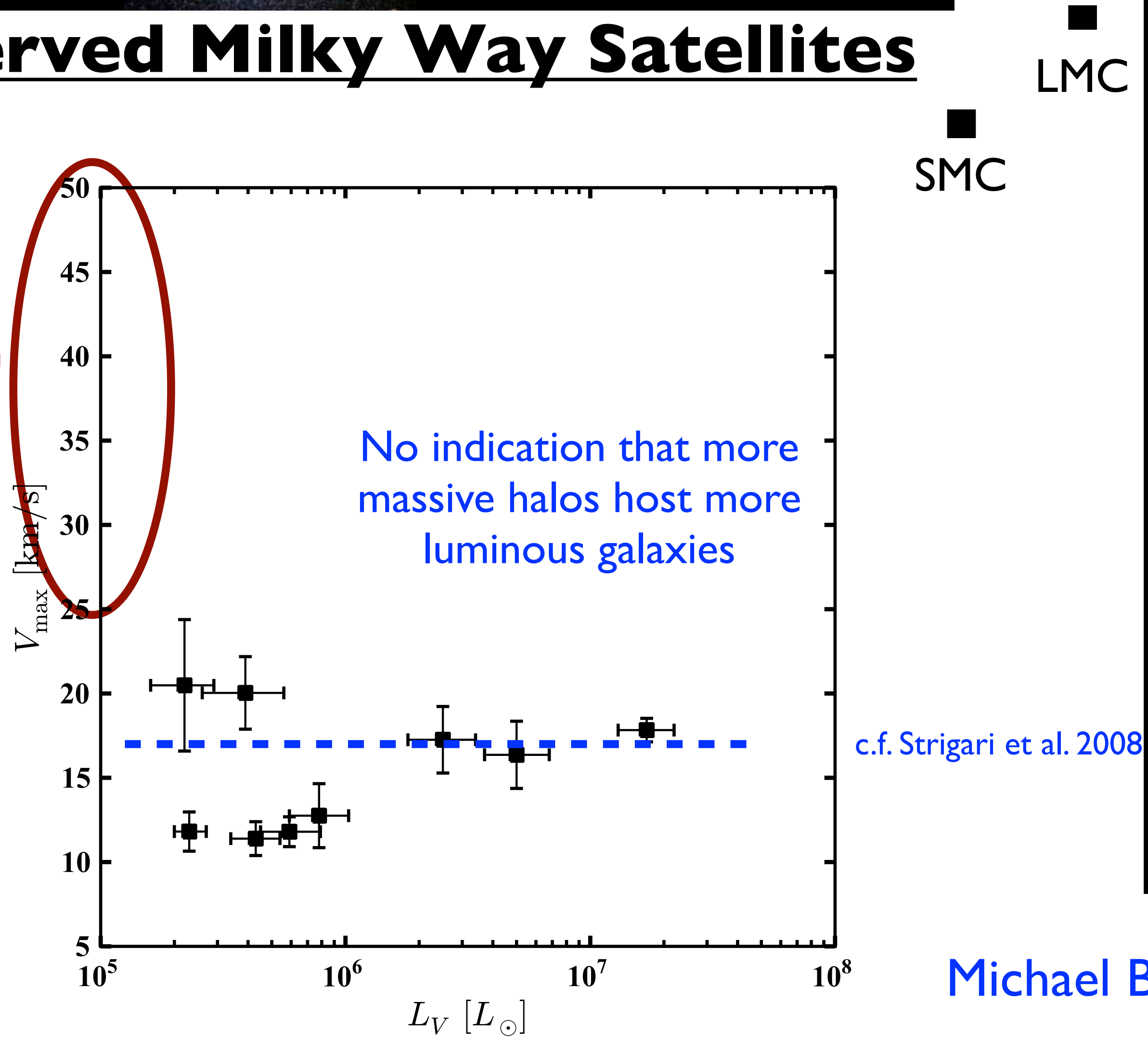


Observed Milky Way Satellites

"massive failures": highest resolution LCDM simulations predict ~10 subhalos in this range in the MW, but we don't see ***any*** such galaxies [except Sagittarius (?)]

All of the bright MW dSphs are consistent with $V_{\max} \lesssim 25\,\mathrm{km/s}$

(see also Strigari, Frenk, & White 2010)



No indication that more massive halos host more luminous galaxies

c.f. Strigari et al. 2008

Possible Solutions to "Too Big to Fail"

The Milky Way is anomalous?

The Milky Way has a low mass dark matter halo?

Galaxy formation is stochastic at low masses?

Dark matter is not just CDM -- maybe WDM or even repulsive self-interacting DM?

Or maybe high-resolution CDM-only simulations are being misinterpreted? Stellar feedback can strongly modify the central structure of subhalos, and may resolve the TBTF challenge to ΛCDM.

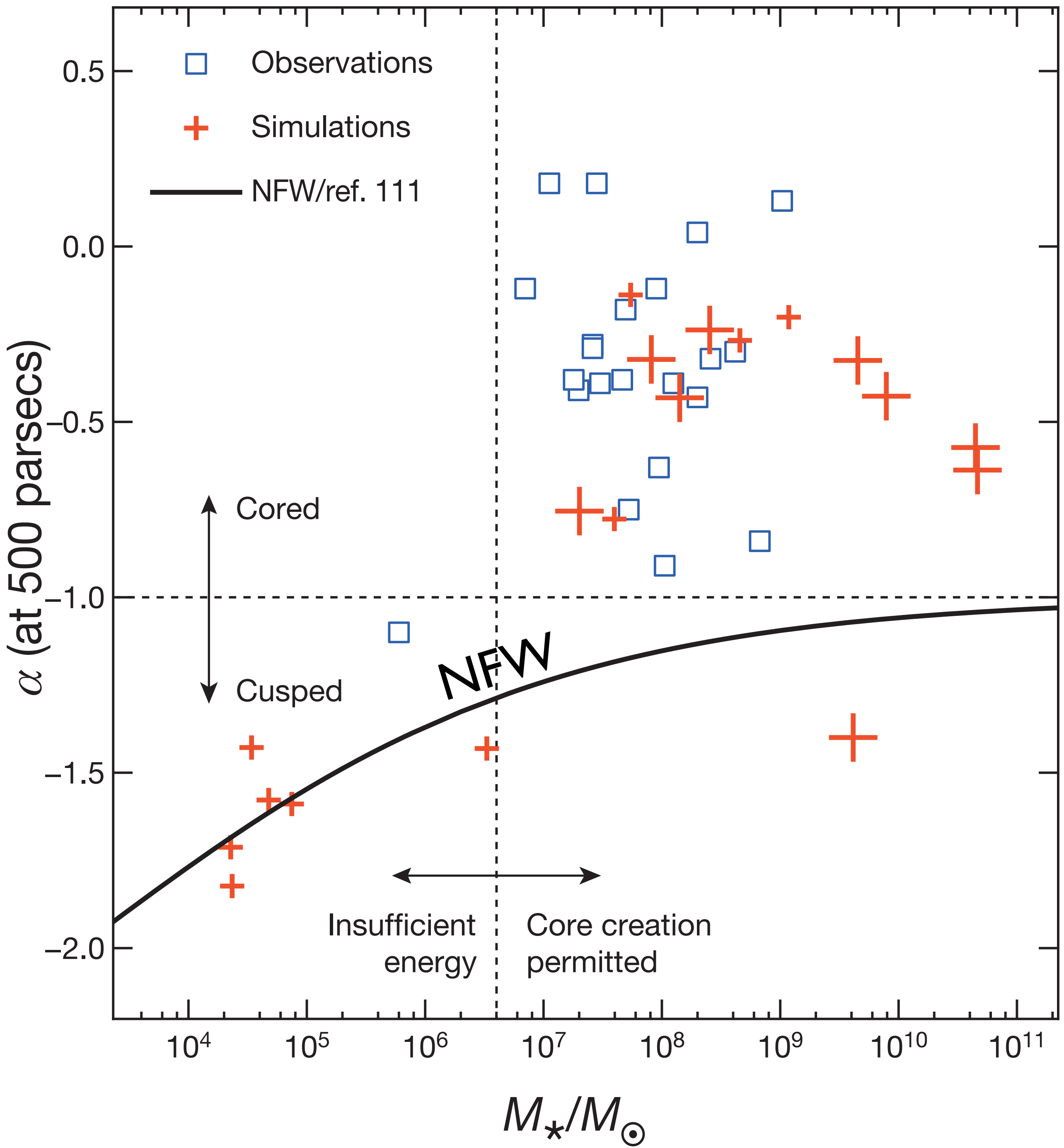
Michael Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012

Challenges: Cusp-Core, Too Big to Fail, Satellite Galaxies

Flores & Primack94 and Moore94 first pointed out that dark matter simulations have density ρ(r) ~ r^{α} at small r with α ≈ –1 (“cusp”) while observed small spiral galaxies and clusters appeared to have α ≈ 0 (“core”).

Governato+10,13 and the *Nature* review by Pontzen & Governato14 show that in high-resolution galaxy simulations, baryonic physics softens the central DM cusp to a core as long as enough stars form, M* ≥ 10^7 $M_\odot$. This happens because of repeated episodes when the baryons cool and slowly fall into the galaxy center, and are then expelled rapidly (in less than a dynamical time) by energy released by stars and supernovae.

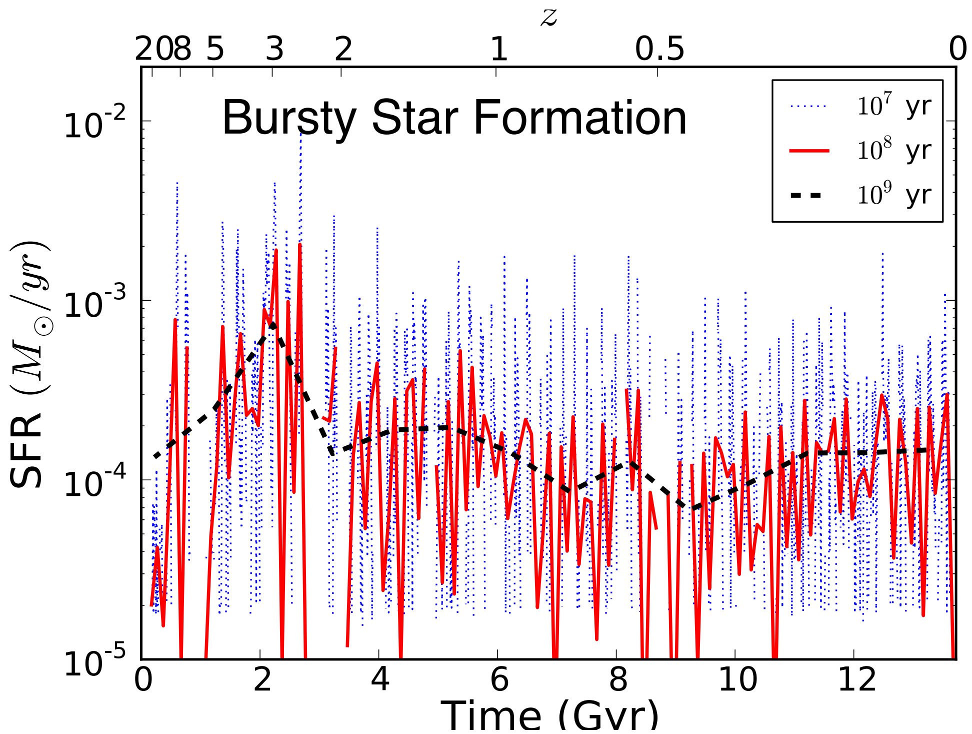
Observers (e.g., Walker & Peñarrubia11, Amorisco & Evans12) had agreed that the larger dwarf spheroidal Milky Way satellite galaxies such as Fornax (L ≈ 1.7x10^7 $L_\odot$) have cores, but recent papers (e.g., Breddels & Helmi13 A&A, Jardel & Gebhardt13, Richardson & Fairbairn14) have questioned this. **Thus the cusp-core question is now observational *and* theoretical.** Adams, Simon+14 find α ≈ 0.5 for dwarf spirals, in agreement with recent high-resolution simulations with baryons.

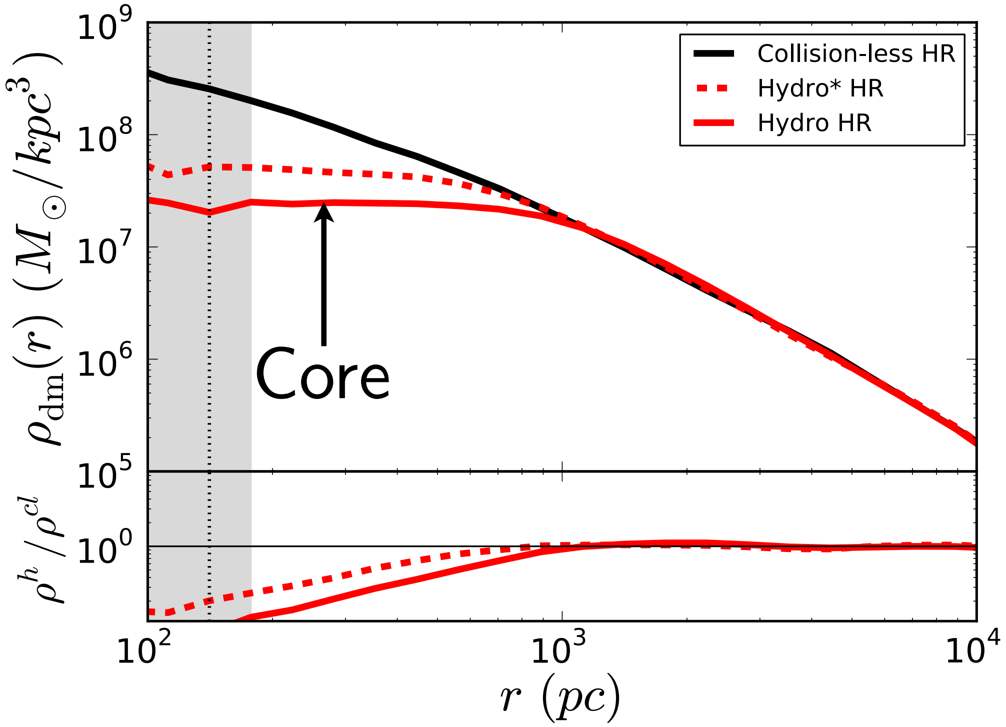


Pontzen & Governato14

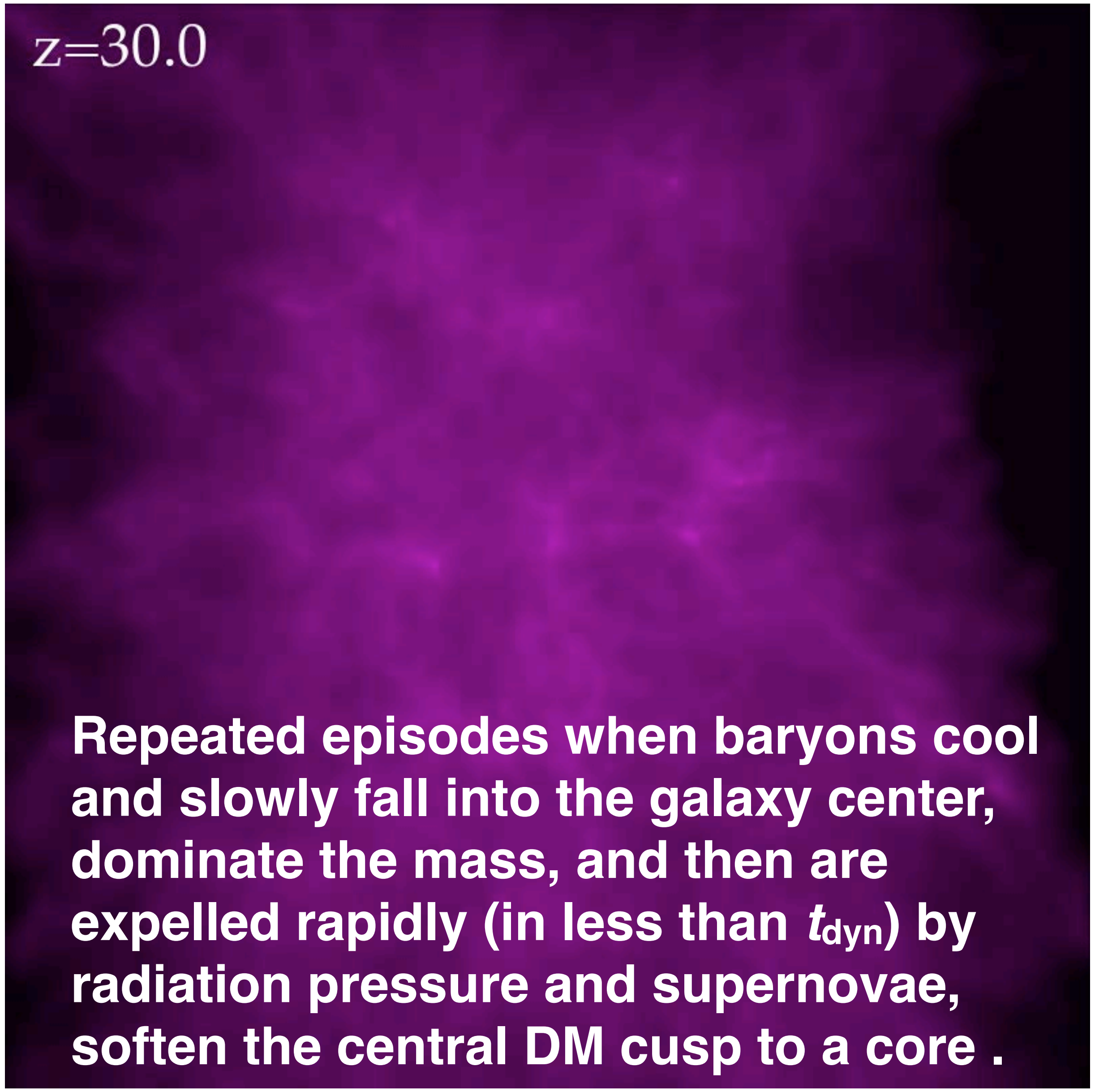
Challenges: Cusp-Core, Too Big to Fail, Satellite Galaxies

In addition to the Governato group's papers on this (including Zolotov+12, Brooks+13) there are several other important recent papers (e.g., Teyssier+13, Arraki+14, Trujillo-Gomez+14) arguing that baryonic effects convert the DM cusp to a core. **The highest-resolution simulation yet of a dwarf spiral was described by Jose Onorbe in his talk at the Near Field-Deep Field Connections conference at UC Irvine Feb 12-14. The central star formation converted the central cusp to a core, reducing the rotation velocity.**





$M_{vir} = 1E10 M_\odot$ at $z = 0$ $M_* = 4 \times 10^6 M_\odot$



Repeated episodes when baryons cool and slowly fall into the galaxy center, dominate the mass, and then are expelled rapidly (in less than $t_{\rm dyn}$) by radiation pressure and supernovae, soften the central DM cusp to a core .

Onorbe, Hopkins+14 FIRE (Feedback in Realistic Environments) simulations

Cusp-Core, Too Big to Fail, Satellite Galaxies

Stellar feedback can perhaps strongly modify the central structure of subhalos, soften the dark matter cusp, and resolve the TBTF challenge to ΛCDM. Semi-analytic models can reduce the number of satellites. But high-resolution galaxy simulations generally make too many satellites. They should be Too Small To Succeed!

Tensions in Galaxy Simulations

How can simulations have adequate SF and FB to solve cusp-core, reionize, and eject metals into the CGM, but not overproduce early stars and overpressurize disks?

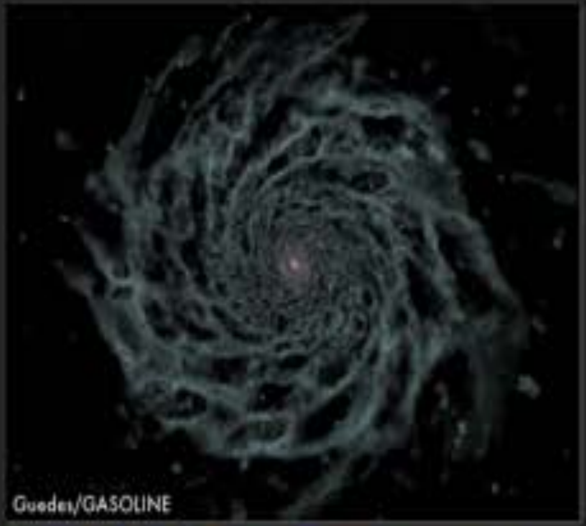
AGORA Assembling Galaxies of Resolved Anatomy

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

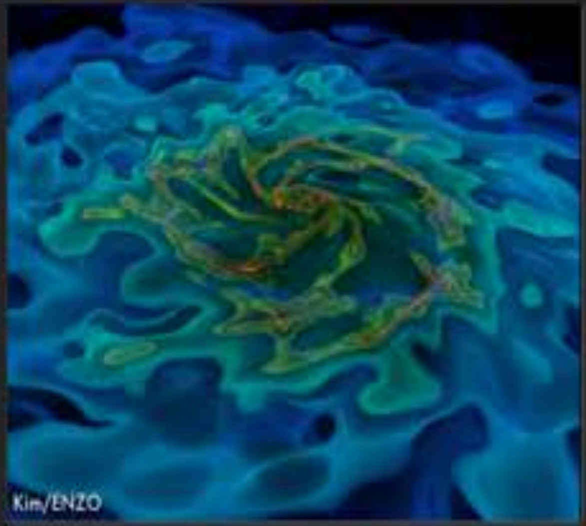
---

Steering Committee: Piero Madau & Joel Primack (UCSC), co-chairs; Tom Abel (Stanford), Nick Gnedin (Chicago), Romain Teyssier and Lucio Mayer (Zurich), James Wadsley (McMaster)

High-res Galaxy Simulations

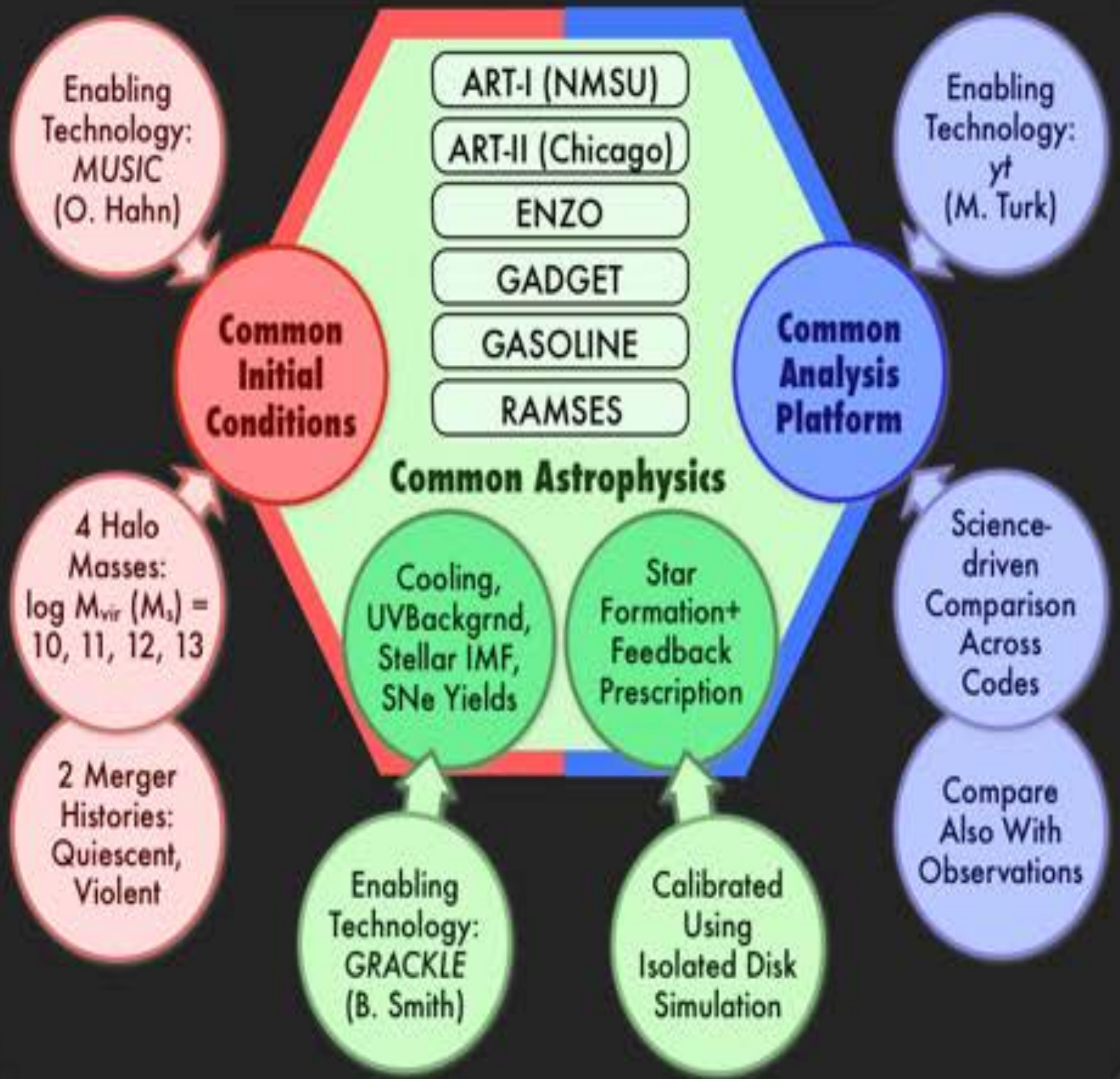


Guedes/GASOLINE



Kim/ENZO

AGORA Comparison Infrastructure



Enabling Technology: *MUSIC* (O. Hahn)

Common Initial Conditions

4 Halo Masses: $\log M_{vir}$ $(M_\odot)$ = 10, 11, 12, 13

2 Merger Histories: Quiescent, Violent

ART-I (NMSU)
ART-II (Chicago)
ENZO
GADGET
GASOLINE
RAMSES

Common Astrophysics

Cooling, UVBackgrnd, Stellar IMF, SNe Yields

Star Formation+ Feedback Prescription

Enabling Technology: *GRACKLE* (B. Smith)

Calibrated Using Isolated Disk Simulation

Enabling Technology: *yt* (M. Turk)

Common Analysis Platform

Science-driven Comparison Across Codes

Compare Also With Observations

AGORA Goal & Team

- GOAL: A multi-platform study to raise the realism and predictive power of high-resolution (<100 pc) galaxy simulations collectively
- TEAM: 4 task working groups and 9+ science working groups, 110 participants from 8 countries as of September 2014
- DATA SHARE: Simulation data will be radpily available to public

- AGORA First light: Flagship paper by Ji-hoon Kim et al. ApJS, 210, 14 (2014); www.AGORAsimulations.org)
- 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)
cooling function (based on ENZO and Eris cooling)

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

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

www.AGORAsimulations.org

www.AGORAsimulations.org

AGORA Task-Oriented Working Groups

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

AGORA Science Working Groups

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

Cosmological Structure Formation

Large Scale Structure agrees with ΛCDM predictions

Cosmological Structure Formation

Large Scale Structure agrees with ΛCDM predictions

Cosmological simulations the basis for Abundance Matching, Age Matching, and Semi-Analytic Models

Cosmological Structure Formation

Large Scale Structure agrees with ΛCDM predictions

Cosmological simulations the basis for Abundance Matching, Age Matching, and Semi-Analytic Models

Galaxy formation and evolution - disk instability in simulations appears to resemble observations

Cosmological Structure Formation

Large Scale Structure agrees with ΛCDM predictions

Cosmological simulations the basis for Abundance Matching, Age Matching, and Semi-Analytic Models

Galaxy formation and evolution - disk instability in simulations appears to resemble observations

Tensions on small scales call for better observations and better simulations

Thanks!

Cosmological Structure Formation

Joel R. Primack, UCSC

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

Websites related to this talk:

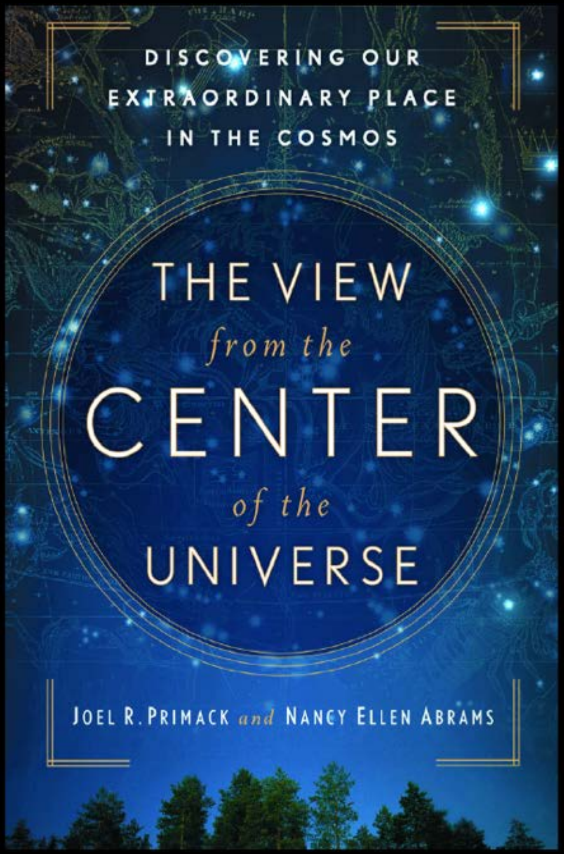
http://hipacc.ucsc.edu University of California High-Performance AstroComputing Center (UC-HiPACC)
http://hipacc.ucsc.edu/v4/ International Astronomy Visualization Gallery
http://hipacc.ucsc.edu/Bolshoi Bolshoi simulations
http://candels.ucolick.org CANDELS survey
http://code.google.com/p/sunrise/ Sunrise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

Abrams & Primack Book Websites with images and videos:

ViewfromtheCenter.com

New-Universe.org

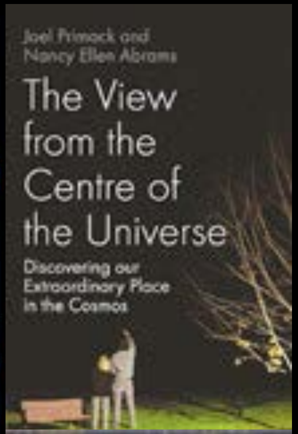
El-Nuevo-Universo.org



DISCOVERING OUR EXTRAORDINARY PLACE IN THE COSMOS

THE VIEW *from the* CENTER *of the* UNIVERSE

JOEL R. PRIMACK *and* NANCY ELLEN ABRAMS



Joel Primack and Nancy Ellen Abrams

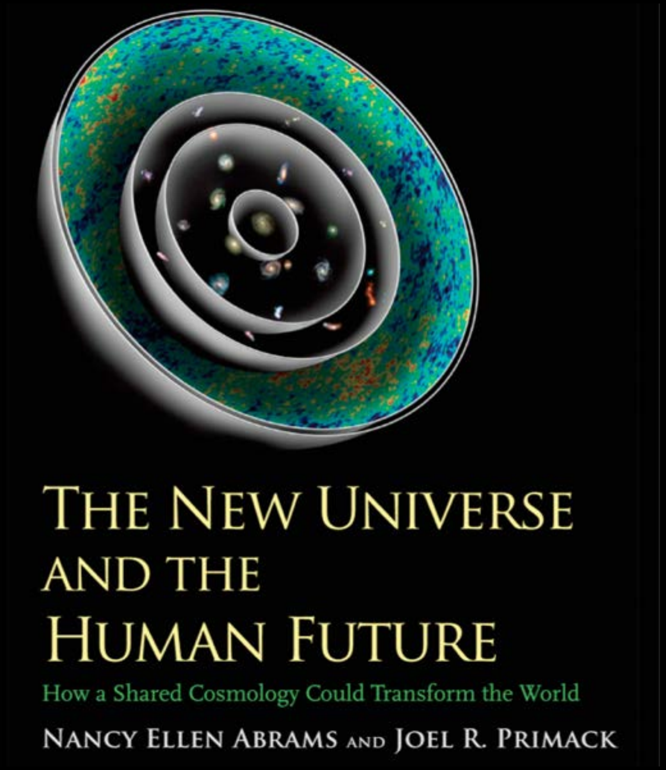
The View from the Centre of the Universe

Discovering our Extraordinary Place in the Cosmos

JOEL R. PRIMACK
NANCY ELLEN ABRAMS

DESTIN COSMIQUE

Pourquoi la nouvelle cosmologie place l'homme au centre de l'Univers



THE NEW UNIVERSE AND THE HUMAN FUTURE

How a Shared Cosmology Could Transform the World

NANCY ELLEN ABRAMS AND JOEL R. PRIMACK

EL NUEVO UNIVERSO Y EL FUTURO DE LA HUMANIDAD

Cómo la nueva ciencia del cosmos transformará el mundo

Nancy Ellen Abrams
y Joel R. Primack