Comparing Simulated and Observed Galaxies

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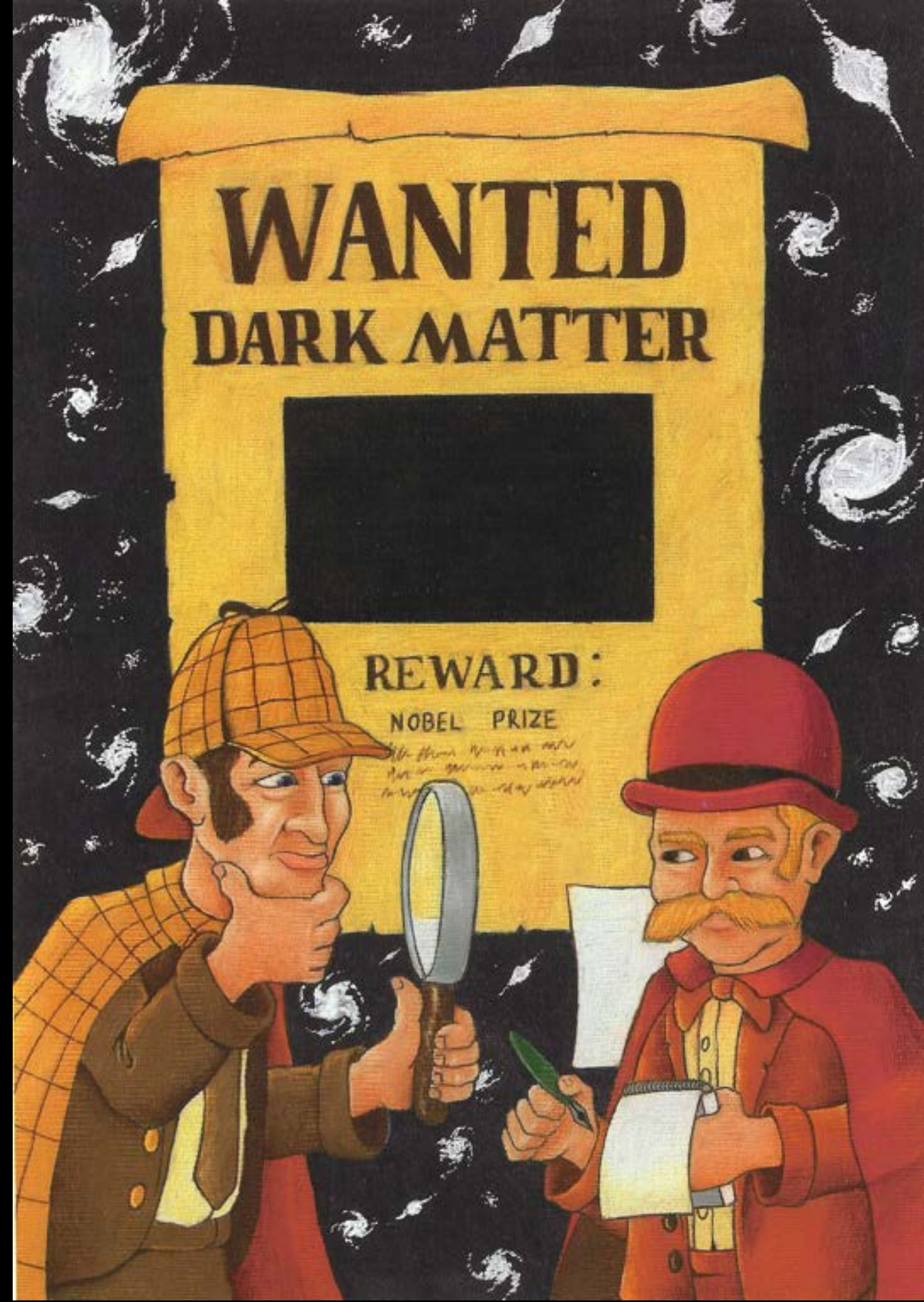
High-Performance AstroComputing Center
(UC-HiPACC)

"The Case of the Dark Matter"

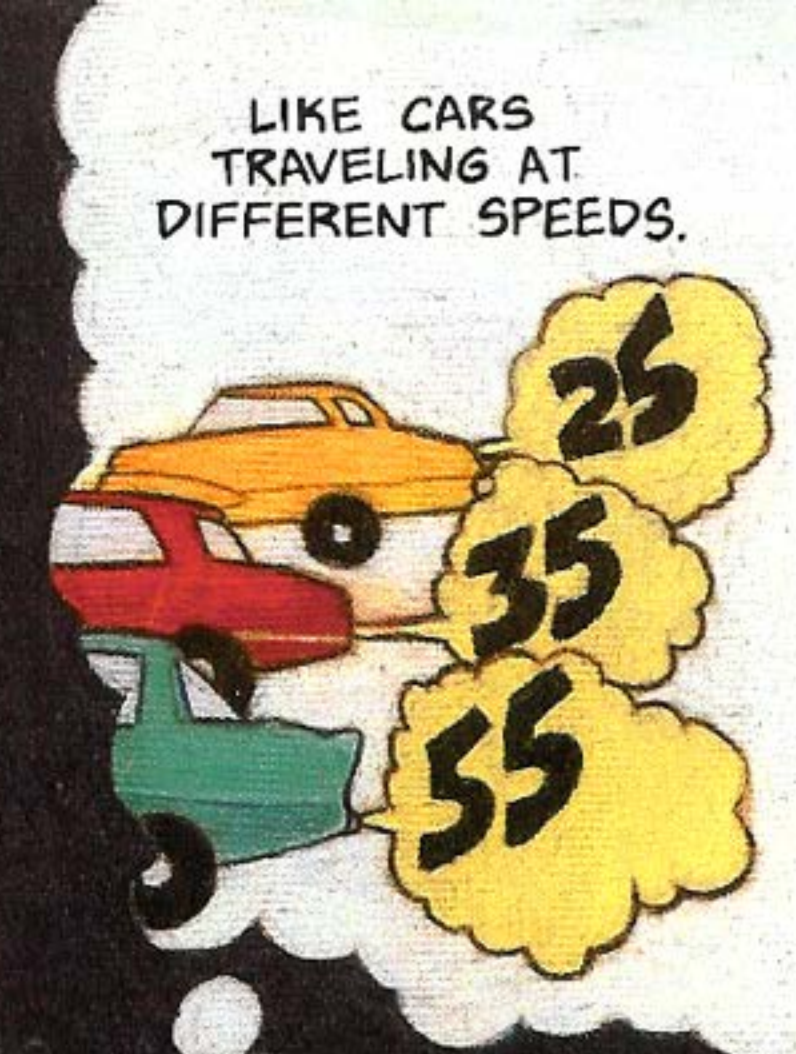
from *World Book Science Year 1990*

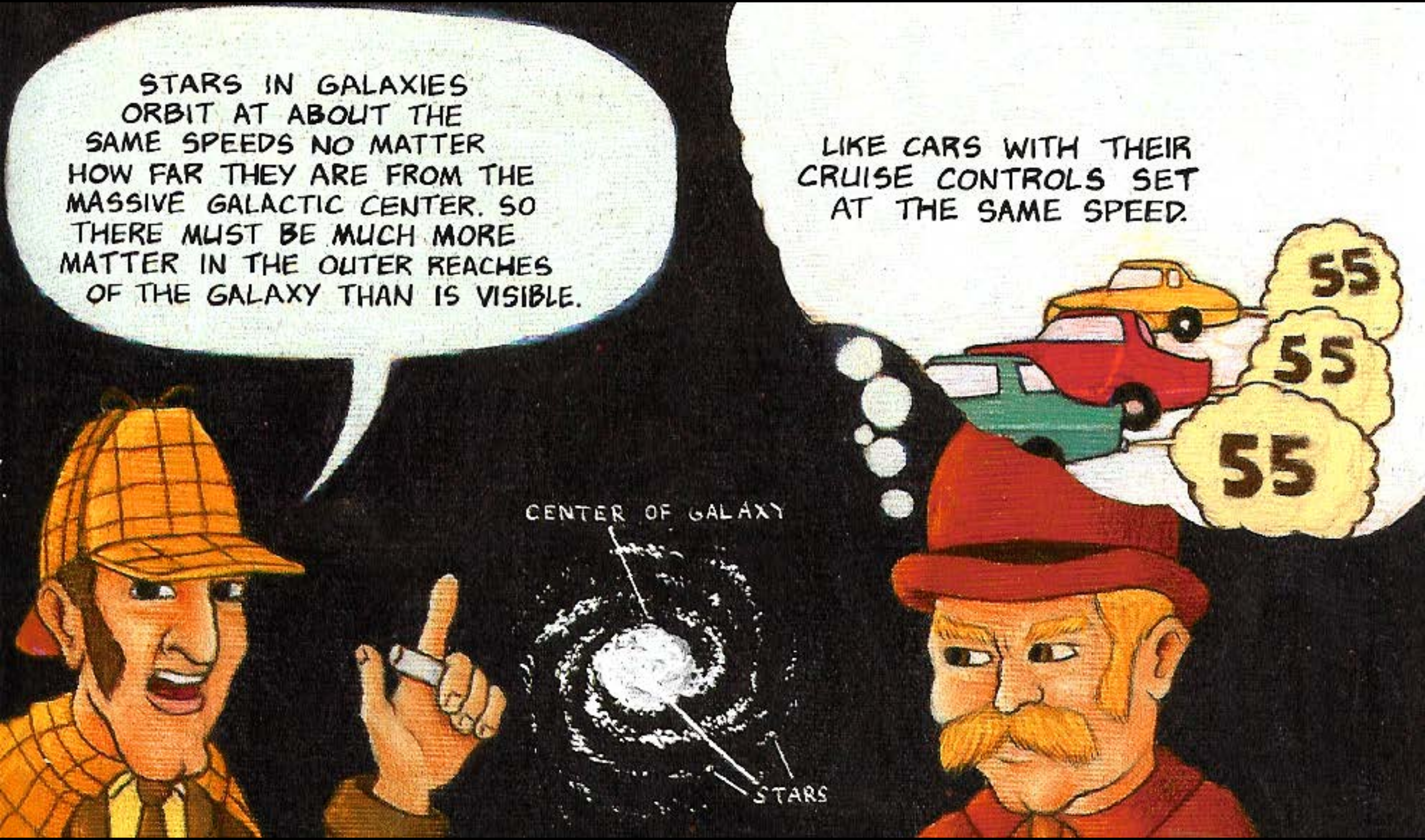
by Joel R. Primack



Evidence for Dark Matter

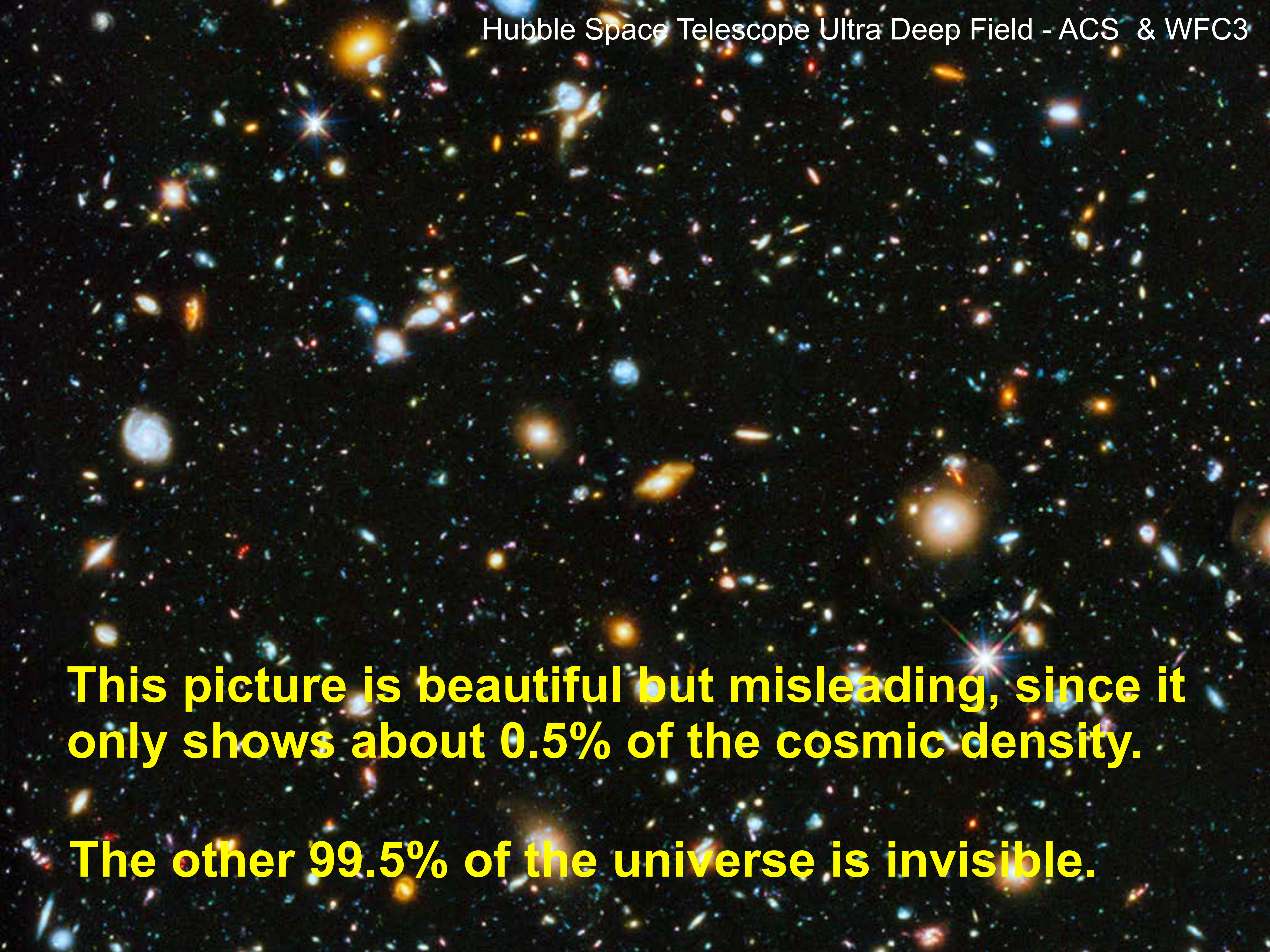
Evidence that there is more matter in the universe than is visible rests on a theory of gravity, the force that keeps planets, stars, and other celestial objects in their orbits. The strength of this force depends on the mass of the orbiting objects and the distance between them. The amount of mass in the objects and their distance from each other determine the orbital speeds of the objects. Knowing orbital speeds and the distance between objects, astronomers can calculate the total mass in the orbital system.



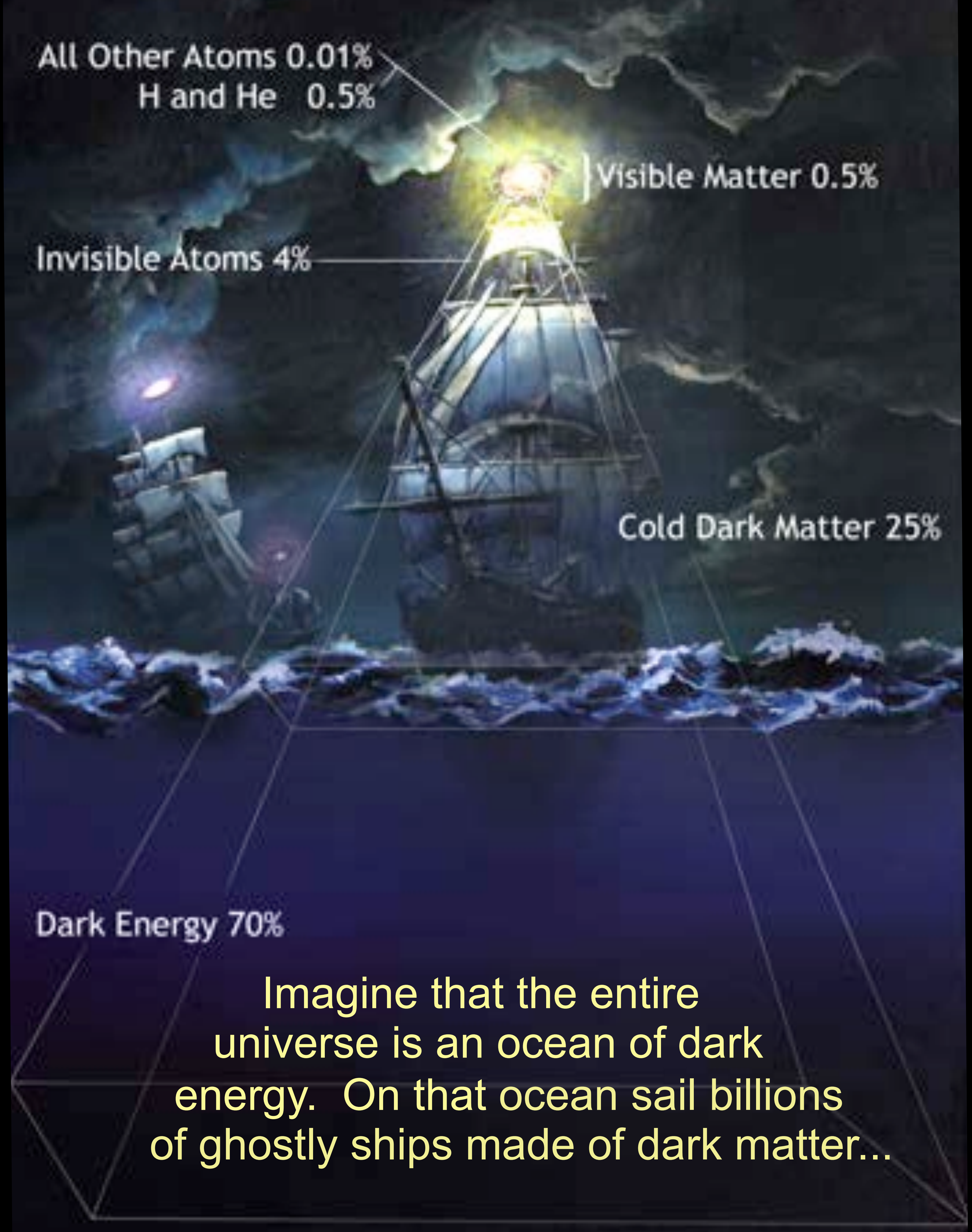

STARS IN GALAXIES ORBIT AT ABOUT THE SAME SPEEDS NO MATTER HOW FAR THEY ARE FROM THE MASSIVE GALACTIC CENTER. SO THERE MUST BE MUCH MORE MATTER IN THE OUTER REACHES OF THE GALAXY THAN IS VISIBLE.
CENTER OF GALAXY
STARS
LIKE CARS WITH THEIR CRUISE CONTROLS SET AT THE SAME SPEED.
55
55
55

Outline

- The Universe is Mostly Dark Matter & Dark Energy
- Large Scale Simulations - Bolshoi
  - Halo Abundance Matching vs. Observations
  - Semi-Analytic Models vs. Galaxies Near and Far
- High Resolution Galaxy Simulations
  - Making Mock Observations with Sunrise
  - Comparing Mocks with CANDELS Galaxies
  - Galaxy Evolution Revisited
- The AGORA Galaxy Simulation Comparison Project
- Supercomputing the Universe: Challenges


Hubble Space Telescope Ultra Deep Field - ACS & WFC3
This picture is beautiful but misleading, since it only shows about 0.5% of the cosmic density.
The other 99.5% of the universe is invisible.

Matter and Energy Content of the Universe



Dark Matter Ships

on a

Dark Energy Ocean

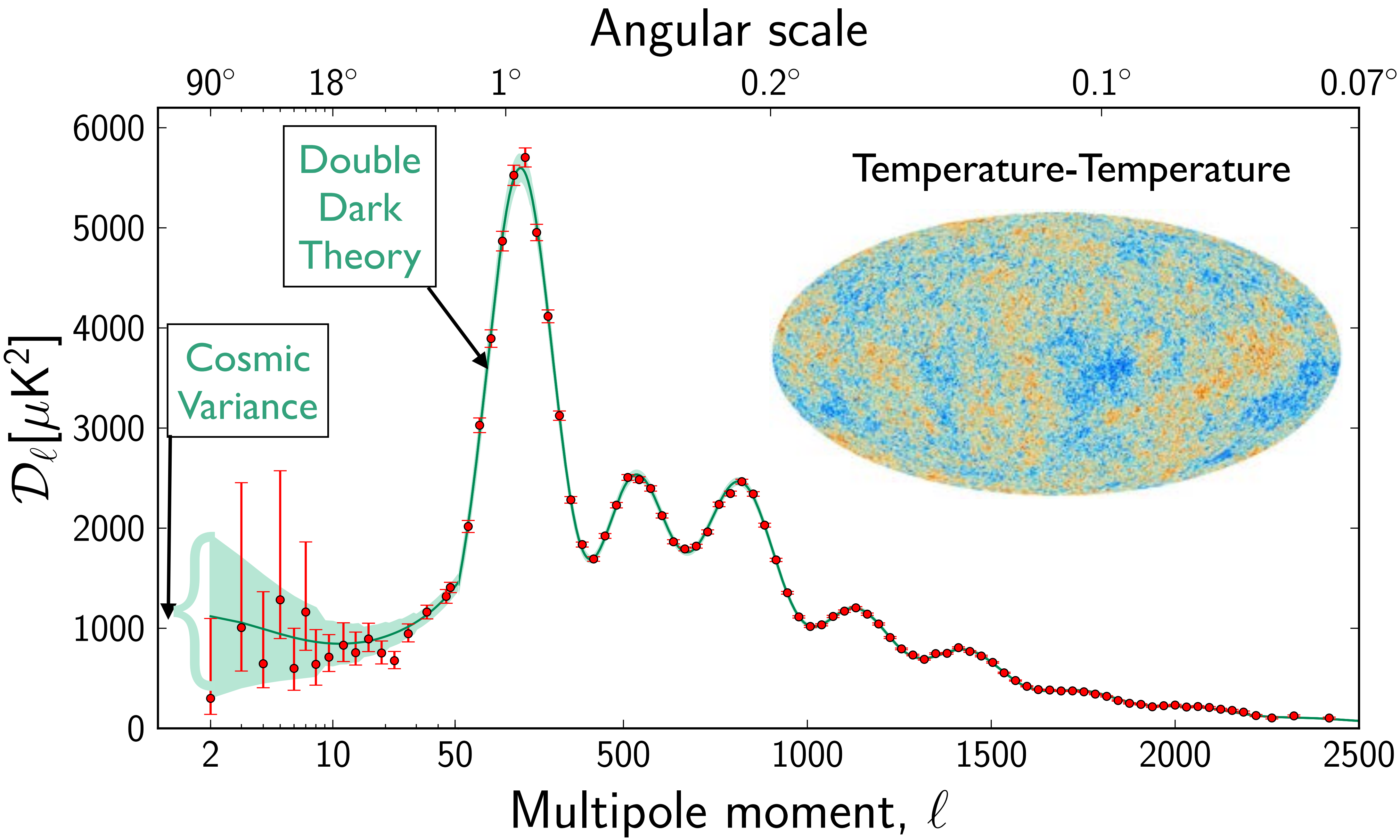
Matter and Energy Content of the Universe

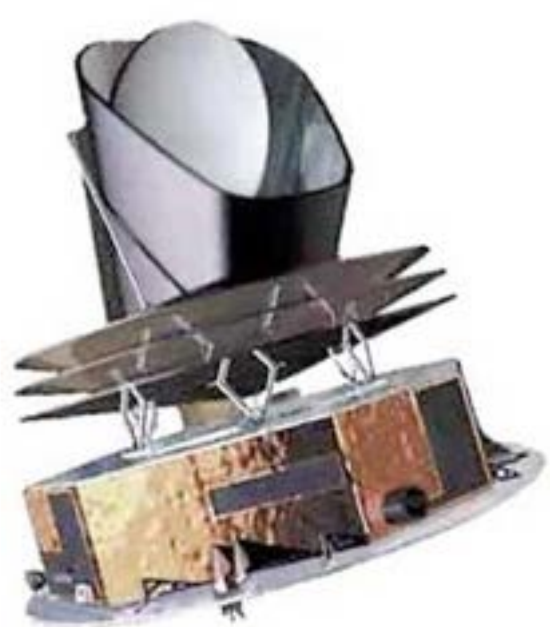
ΛCDM

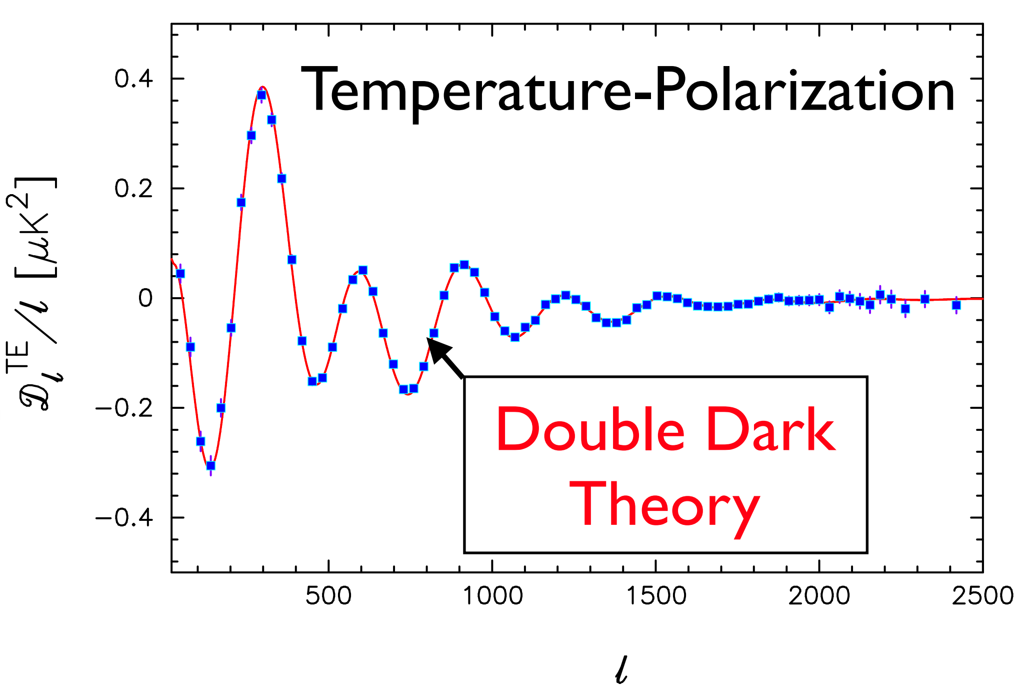
Double Dark Theory

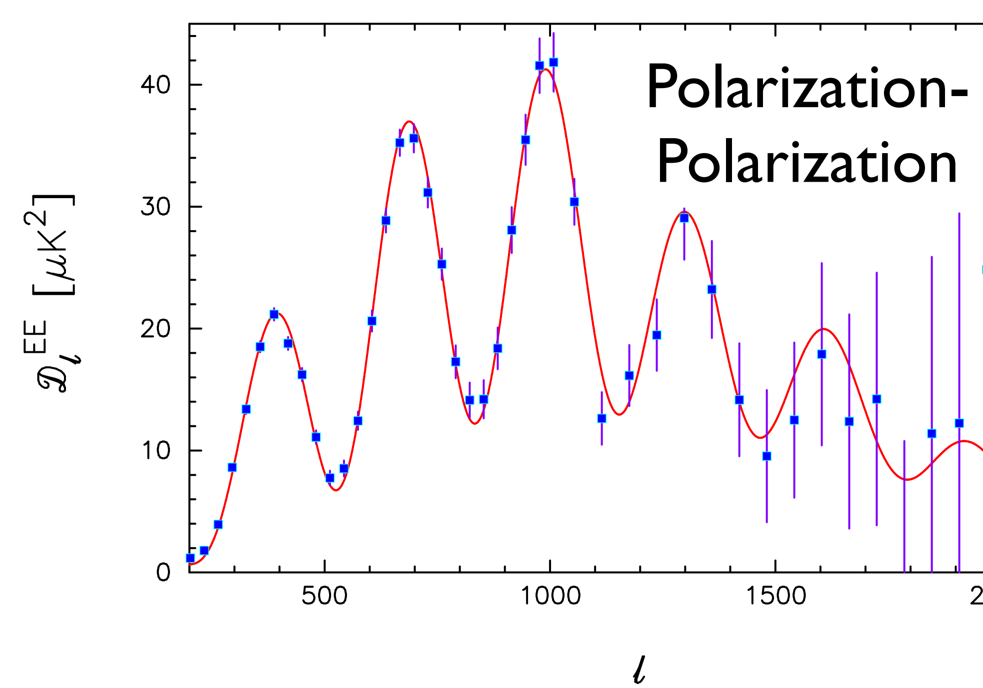
European Space Agency PLANCK Satellite Data

Released March 21, 2013

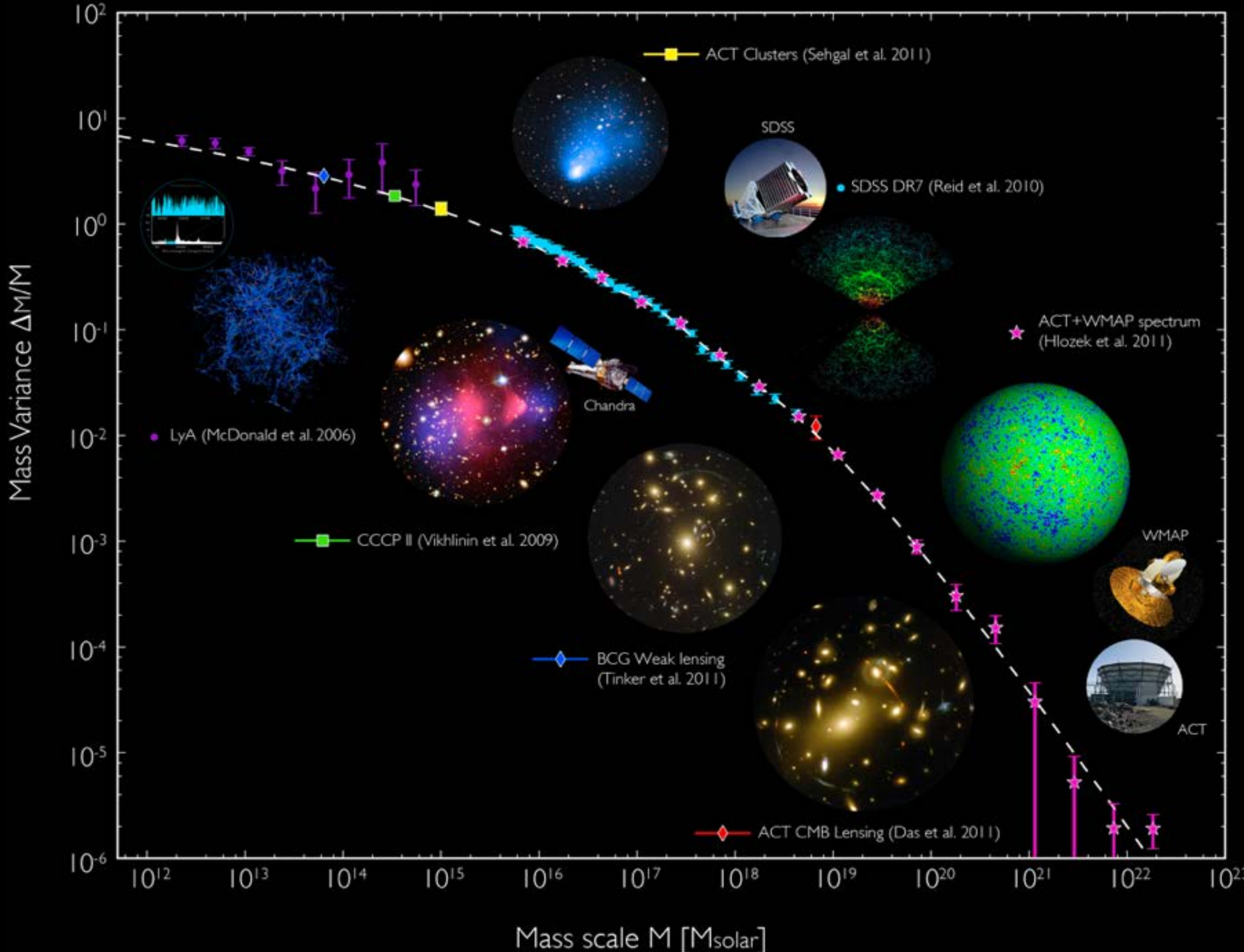








Matter Distribution Agrees with Double Dark Theory!

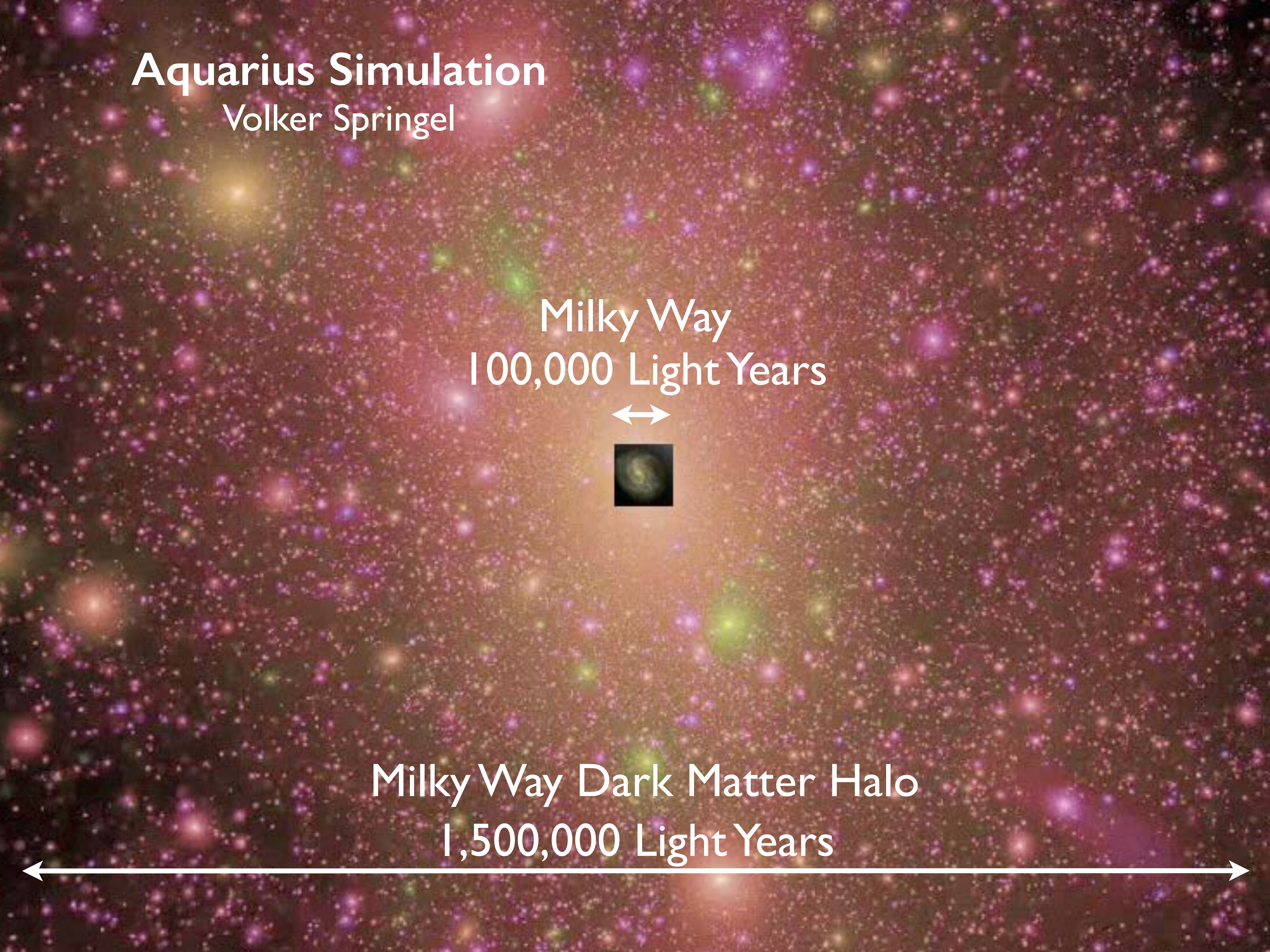


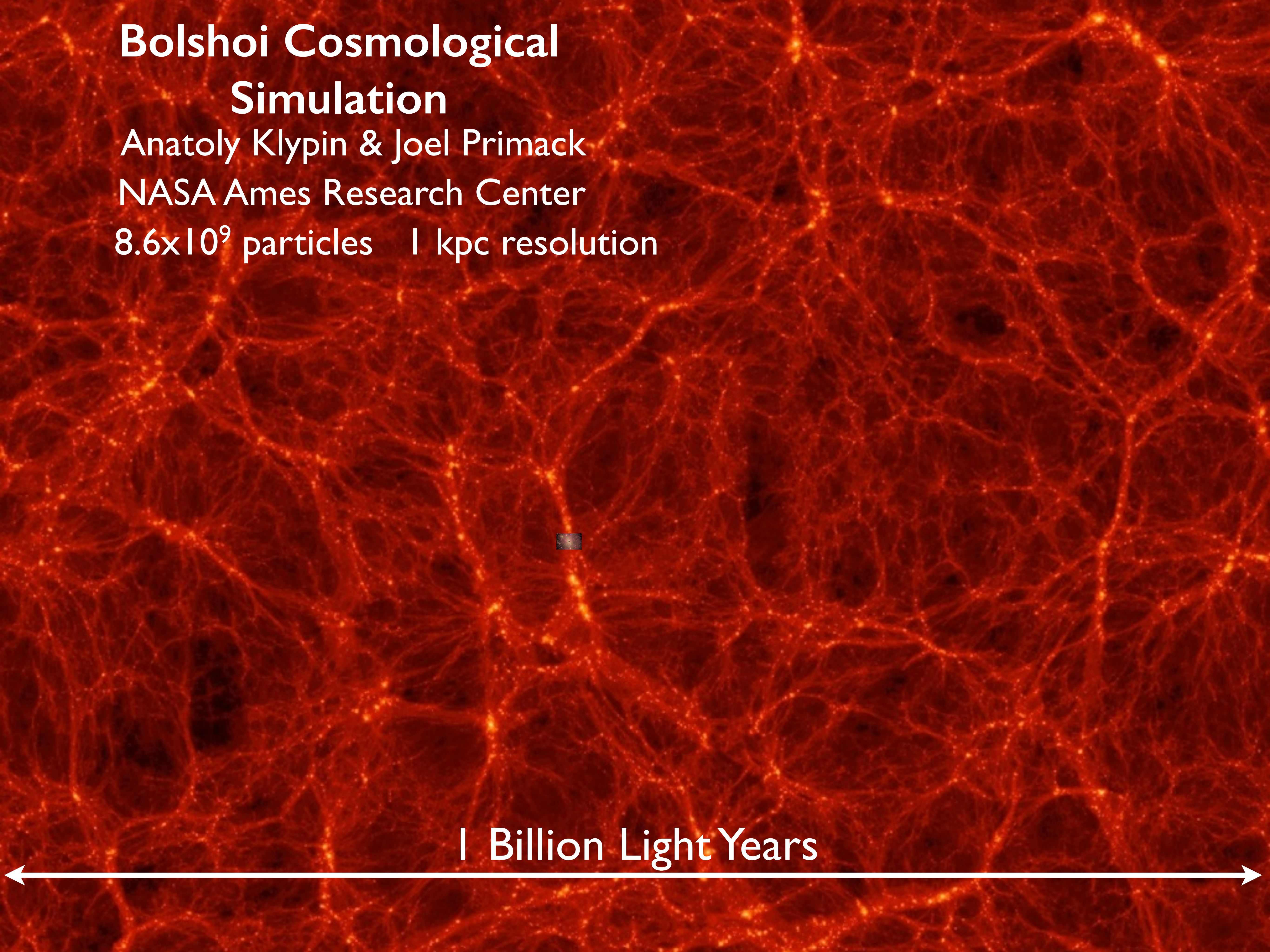
Cosmological Simulations

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.

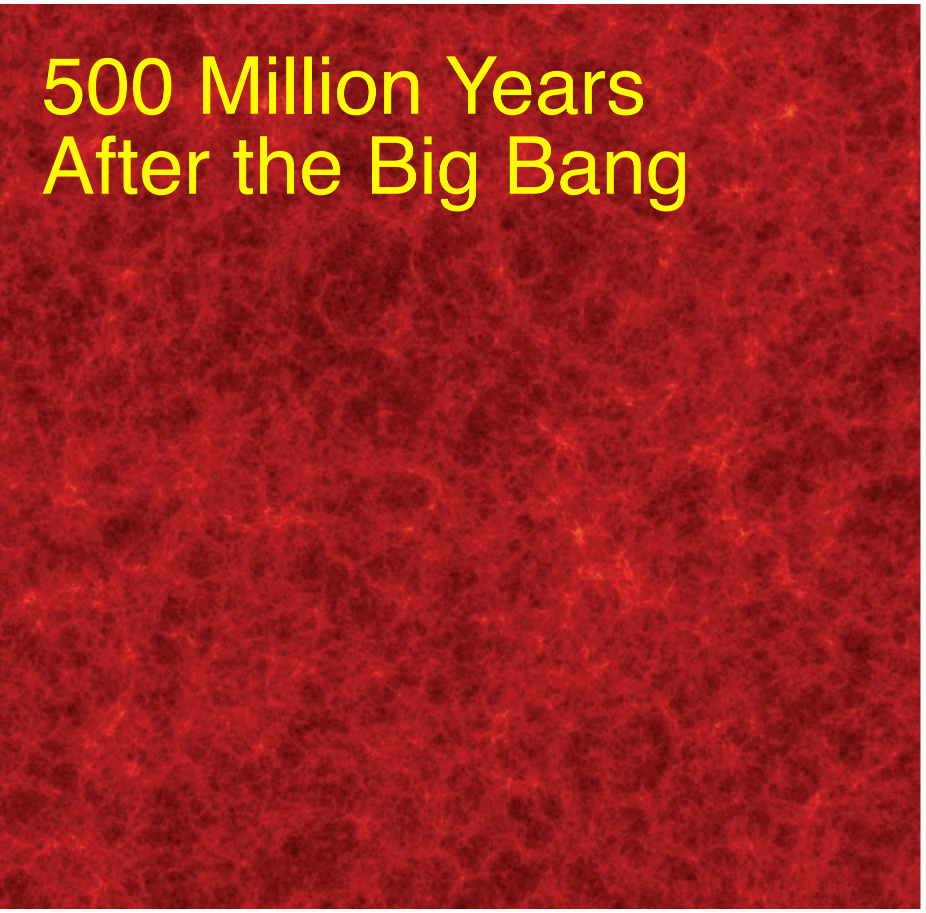
Cosmological dark matter simulations show large scale structure, growth of structure, and dark matter halo properties

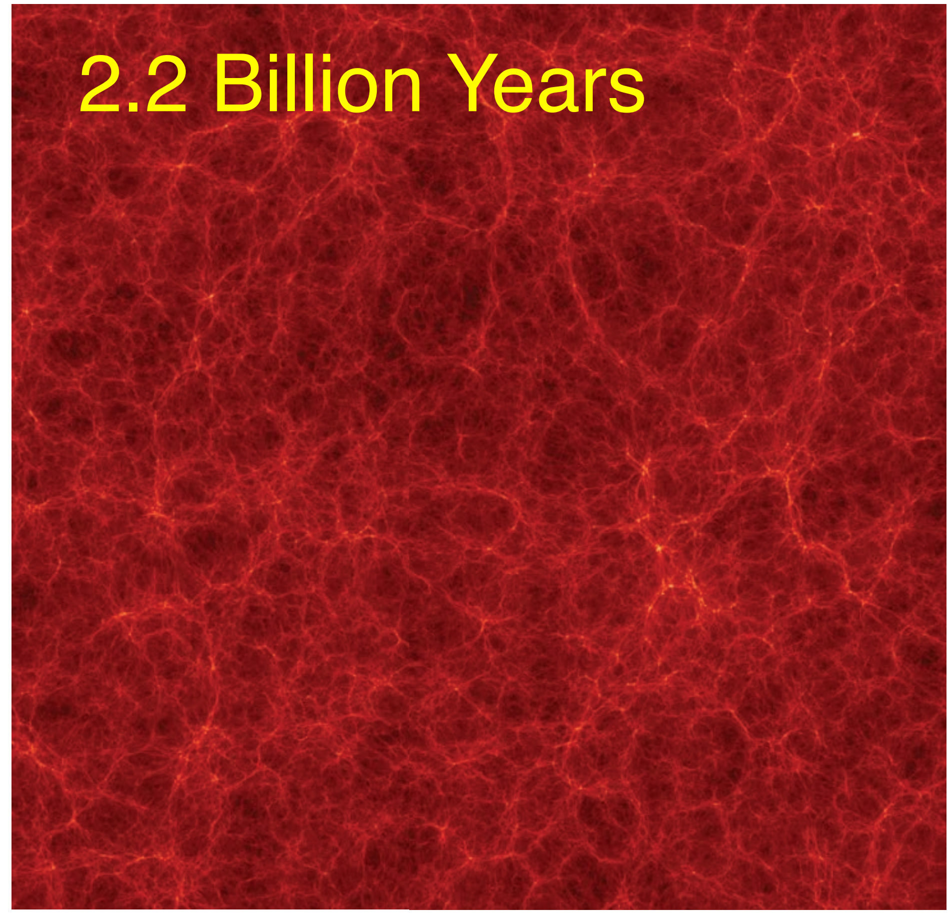
Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images in all wavebands including stellar evolution and dust


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

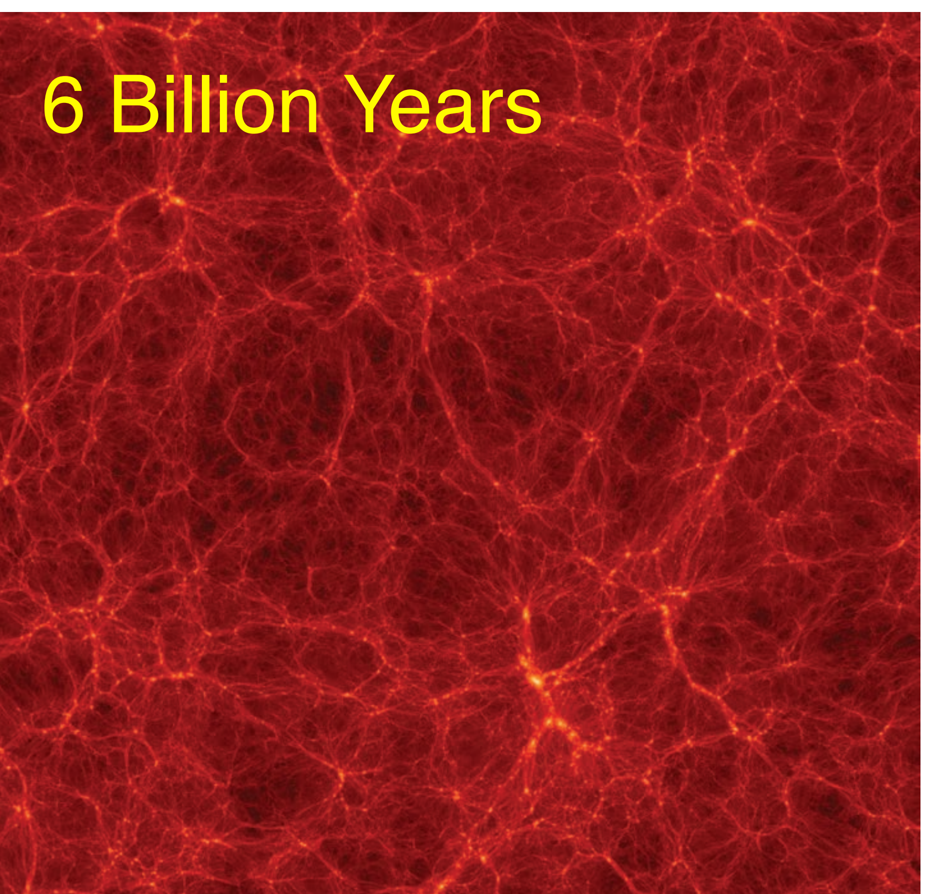

Bolshoi Cosmological Simulation
Anatoly Klypin & Joel Primack
NASA Ames Research Center
8.6x10^9 particles 1 kpc resolution
1 Billion Light Years

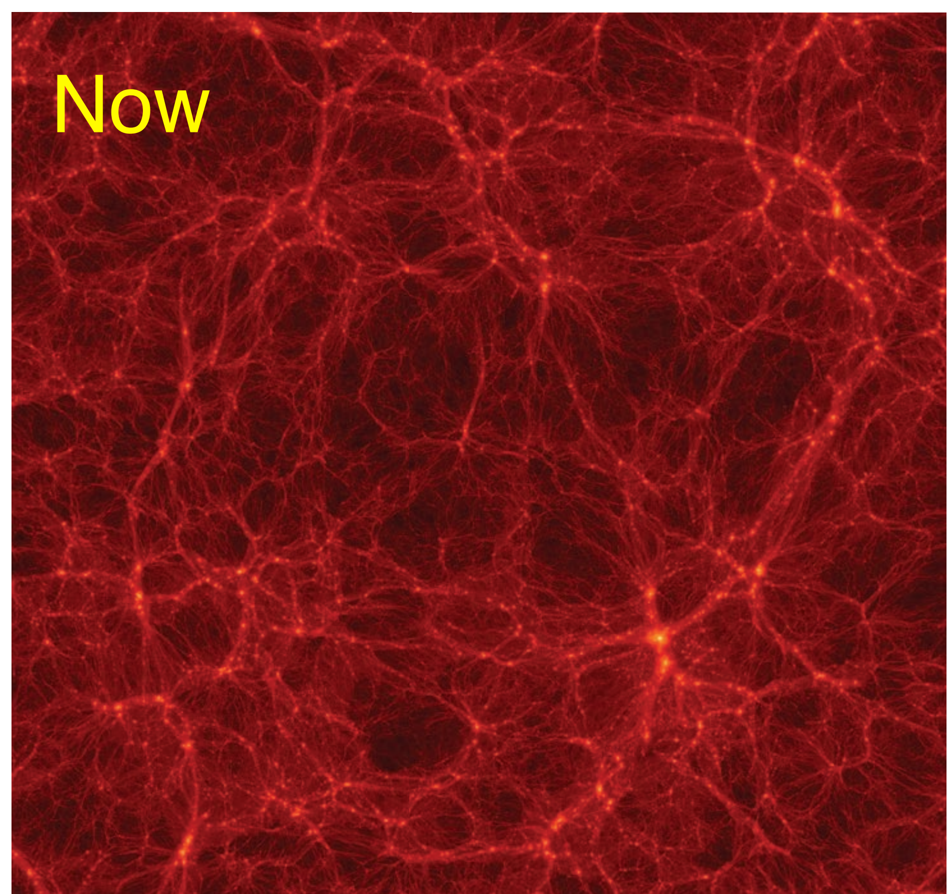
IEEE Spectrum - October 2012





THE UNIVERSE IN A SUPERCOMPUTER





COSMIC WEB: The Bolshoi simulation models the evolution of dark matter, which is responsible for the large-scale structure of the universe. Here, snapshots from the simulation show the dark matter distribution at 500 million and 2.2 billion years [top] and 6 billion and 13.7 billion years [bottom] after the big bang. These images are 50-million-light-year-thick slices of a cube of simulated universe that today would measure roughly 1 billion light-years on a side and encompass about 100 galaxy clusters.

SOURCES: SIMULATION, ANATOLY KLYPIN AND JOEL R. PRIMACK; VISUALIZATION, STEFAN GOTTLÖBER/LEIBNIZ INSTITUTE FOR ASTROPHYSICS POTSDAM

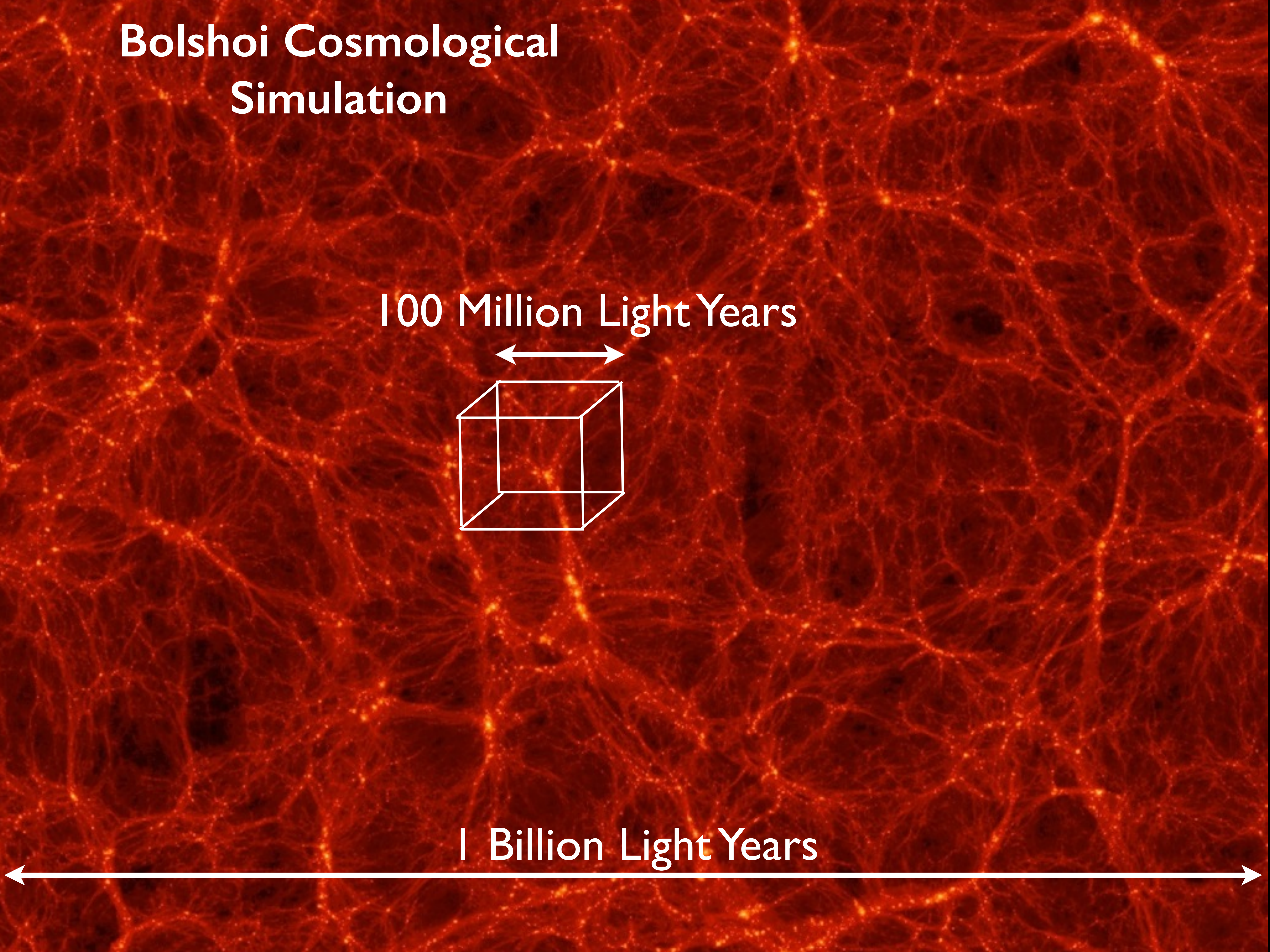
To understand the cosmos, we must evolve it all over again

By Joel R. Primack

WHEN IT COMES TO RECONSTRUCTING THE PAST, you might think that astrophysicists have it easy. After all, the sky is awash with evidence. For most of the universe's history, space has been largely transparent, so much so that light emitted by distant galaxies can travel for billions of years before finally reaching Earth. It might seem that all researchers have to do to find out what the universe looked like, say, 10 billion years ago is to build a telescope sensitive enough to pick up that ancient light.

Actually, it's more complicated than that. Most of the ordinary matter in the universe—the stuff that makes up all the atoms, stars, and galaxies astronomers can see—is invisible, either sprinkled throughout intergalactic space in tenuous forms that emit and absorb little light or else swaddled inside galaxies in murky clouds of dust and gas. When astronomers look out into the night sky with their most powerful telescopes, they can see no more than about 10 percent of the ordinary matter that's out there.

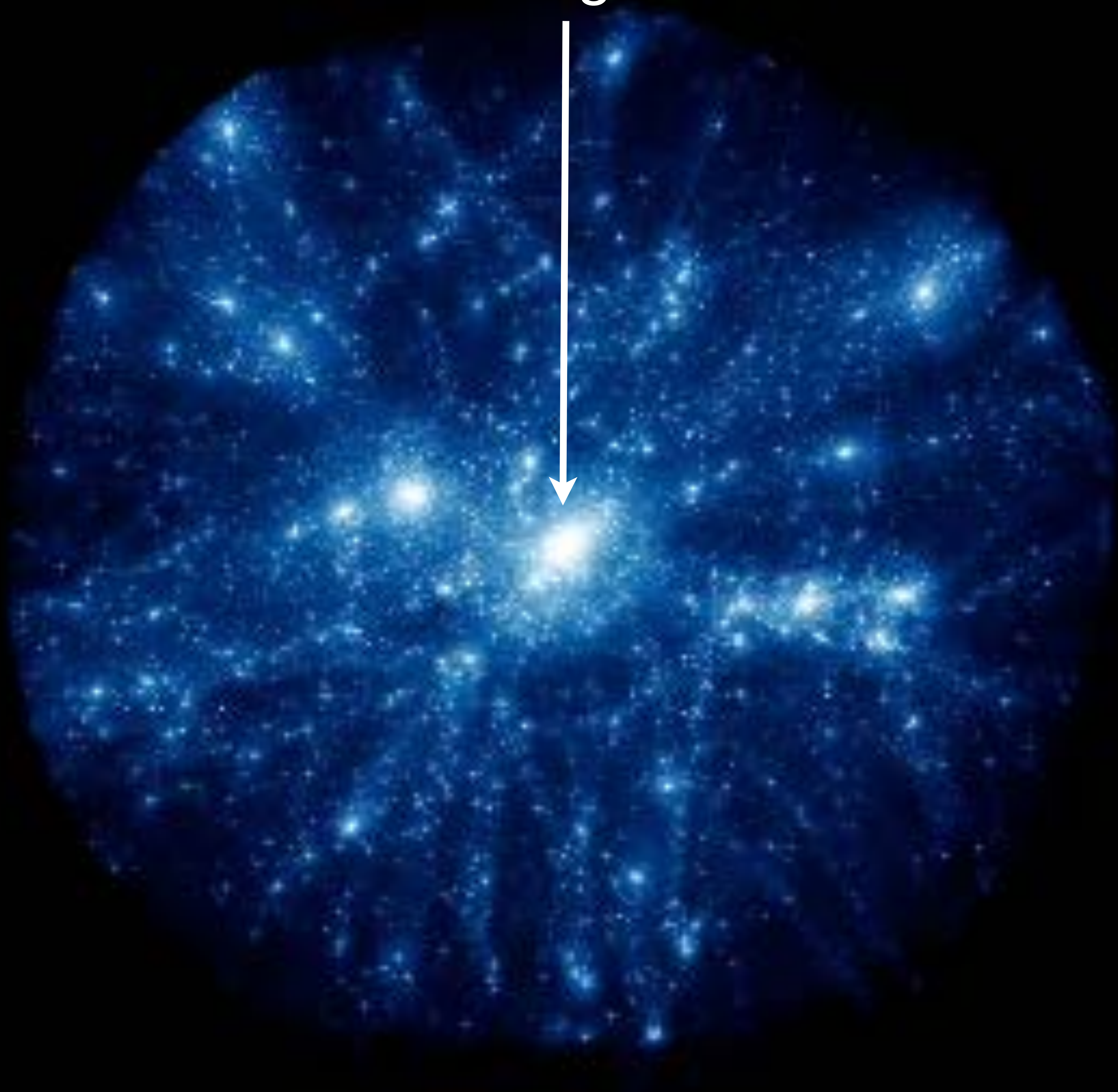
To make matters worse, cosmologists have discovered that if you add up all the mass and energy in the universe, only a small fraction is composed of ordinary matter. A good 95 percent of the cosmos is made up of two very different kinds of invisible and as-yet-unidentified stuff that is "dark," meaning that it emits and absorbs no light at all. One of these mysterious components, called dark matter, seems immune to all fundamental forces except gravity and perhaps the weak interaction, which is responsible for


Bolshoi Cosmological Simulation
100 Million Light Years
1 Billion Light Years

Bolshoi Cosmological Simulation

100 Million Light Years

How the Halo of the Big Cluster Formed



How the Halo of the Big Cluster Formed

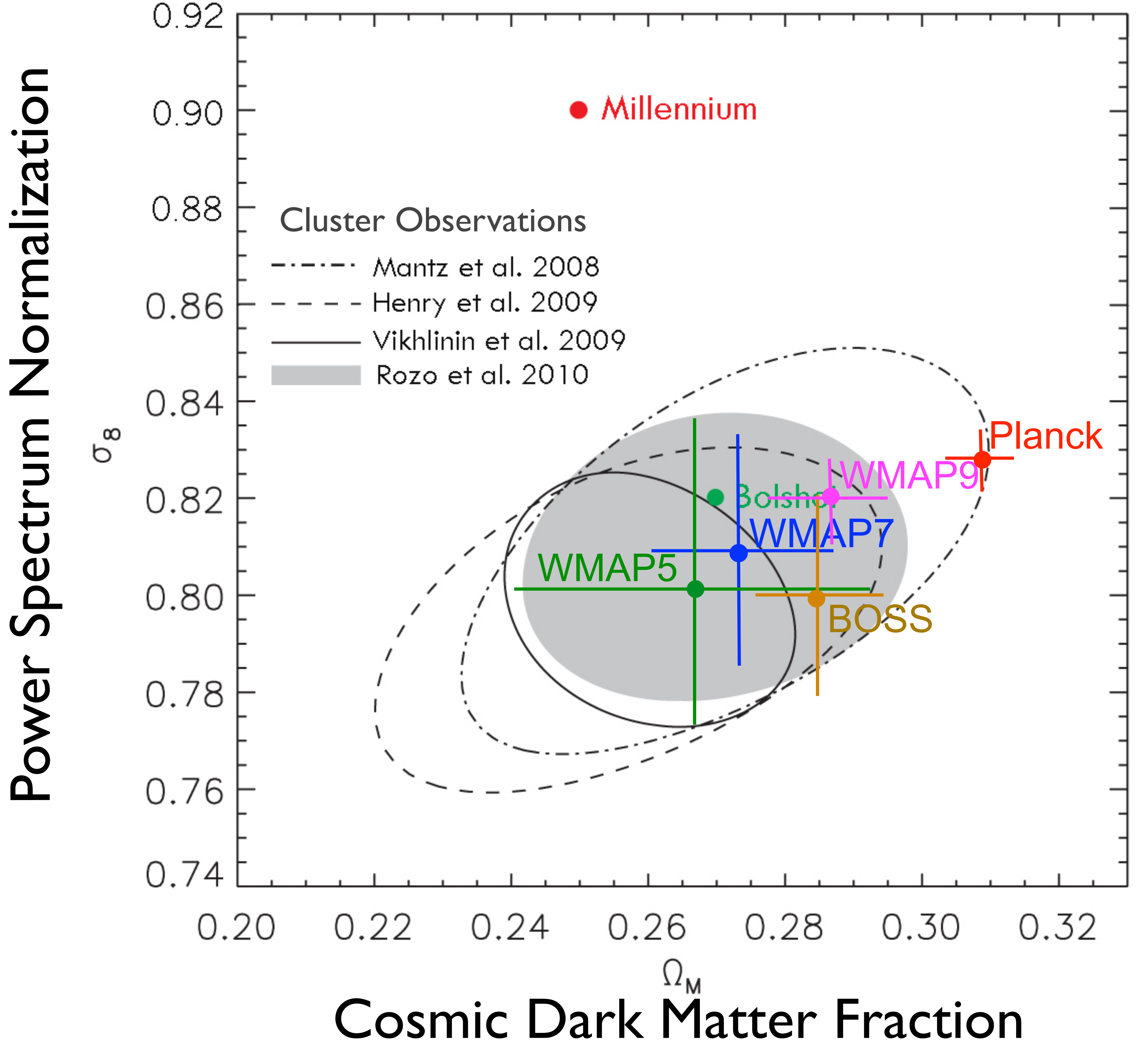
Merger Tree (History) of All the Halos that Have Merged by Today

Peter Behroozi


SKY
& TELESCOPE
Dive Deep In
the Lagoon p. 61
JULY 2012
Universe in
a Box
From the Big Bang to Now p. 26

Determination of σ_8 and Ω_M from CMB+

WMAP+SN+Clusters   Planck+WP+HighL+BAO



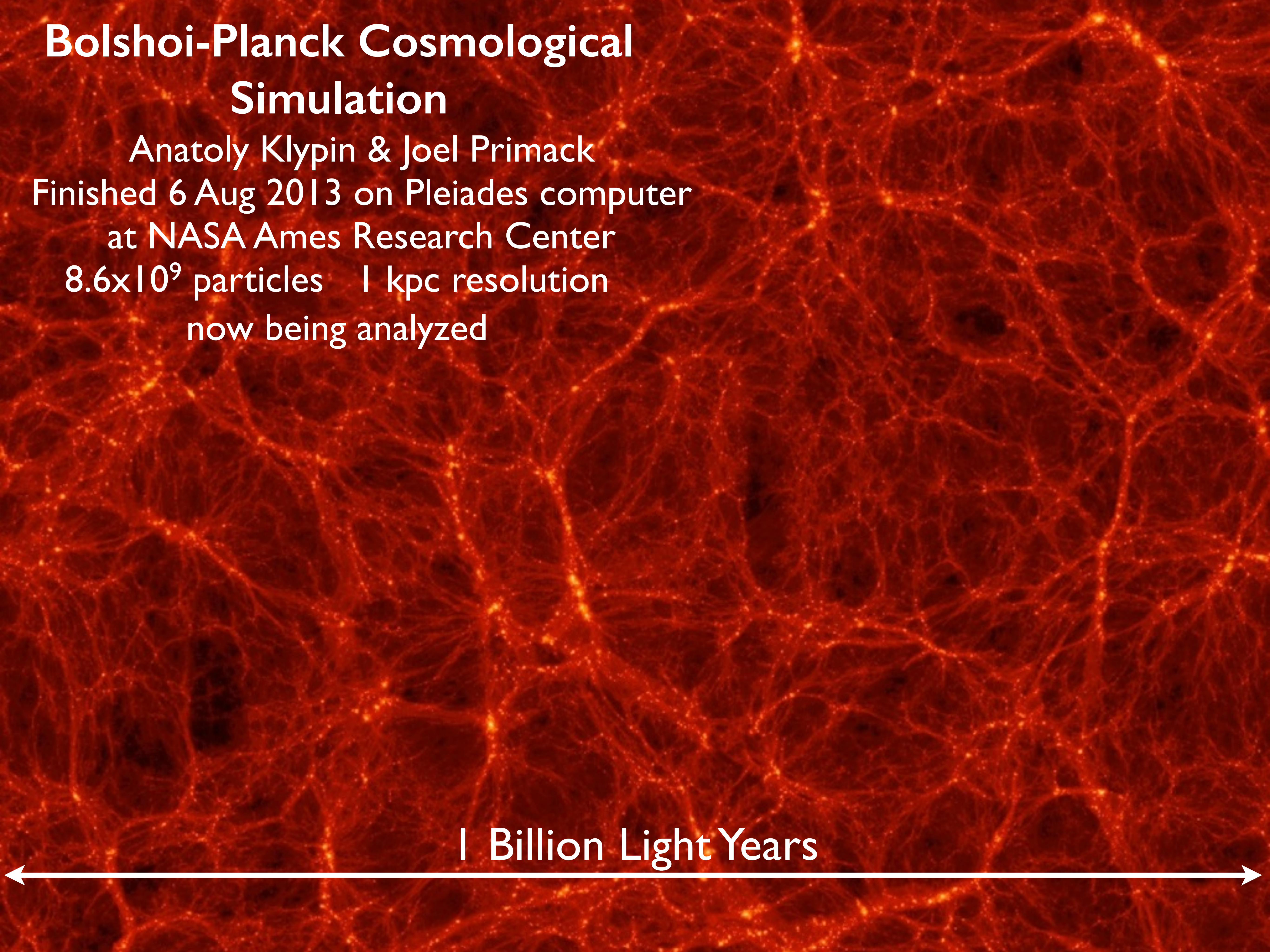
Bolshoi-Planck Cosmological Simulation

Anatoly Klypin & Joel Primack

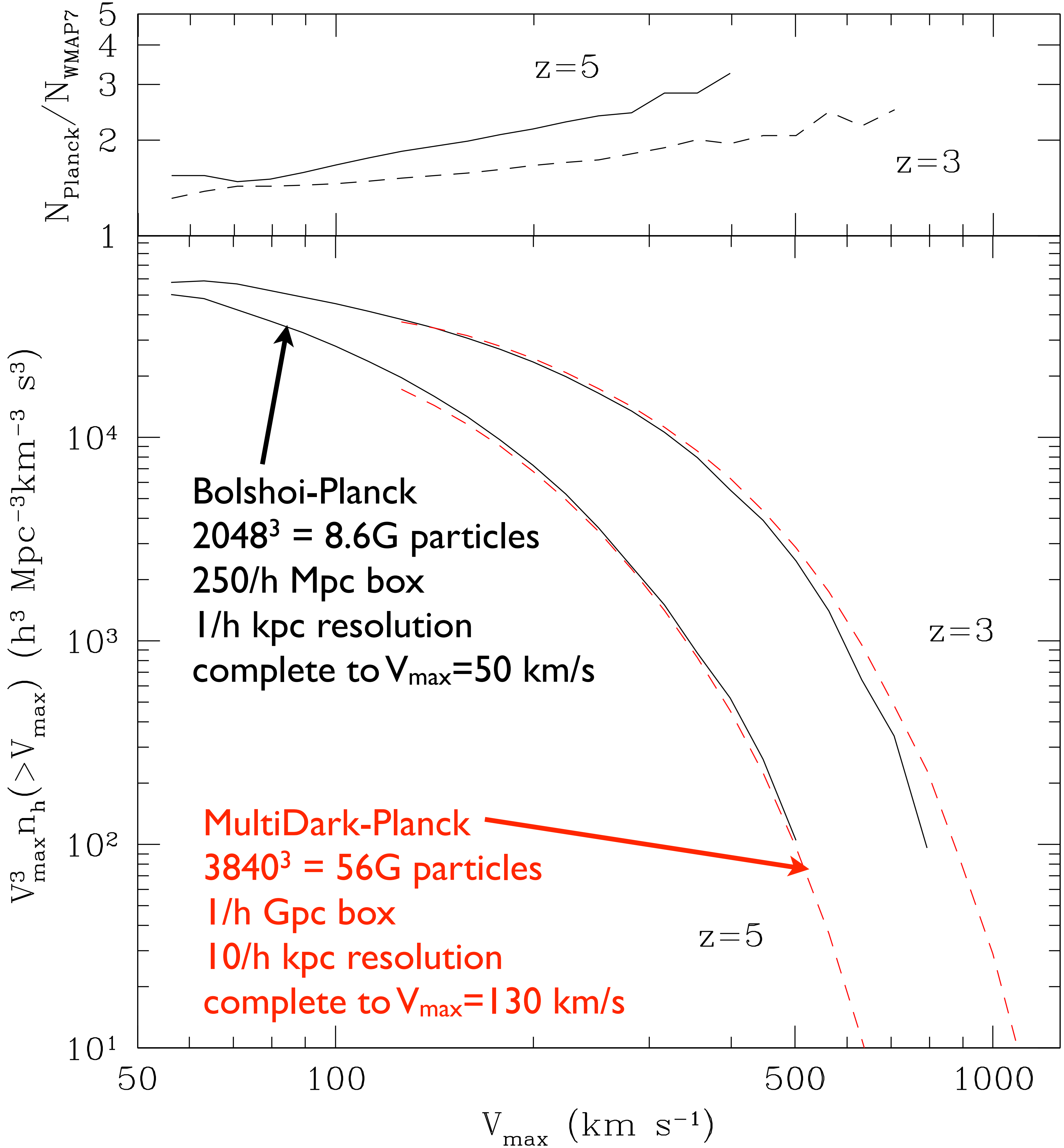
Finished 6 Aug 2013 on Pleiades computer at NASA Ames Research Center

8.6×10^9 particles   1 kpc resolution

now being analyzed

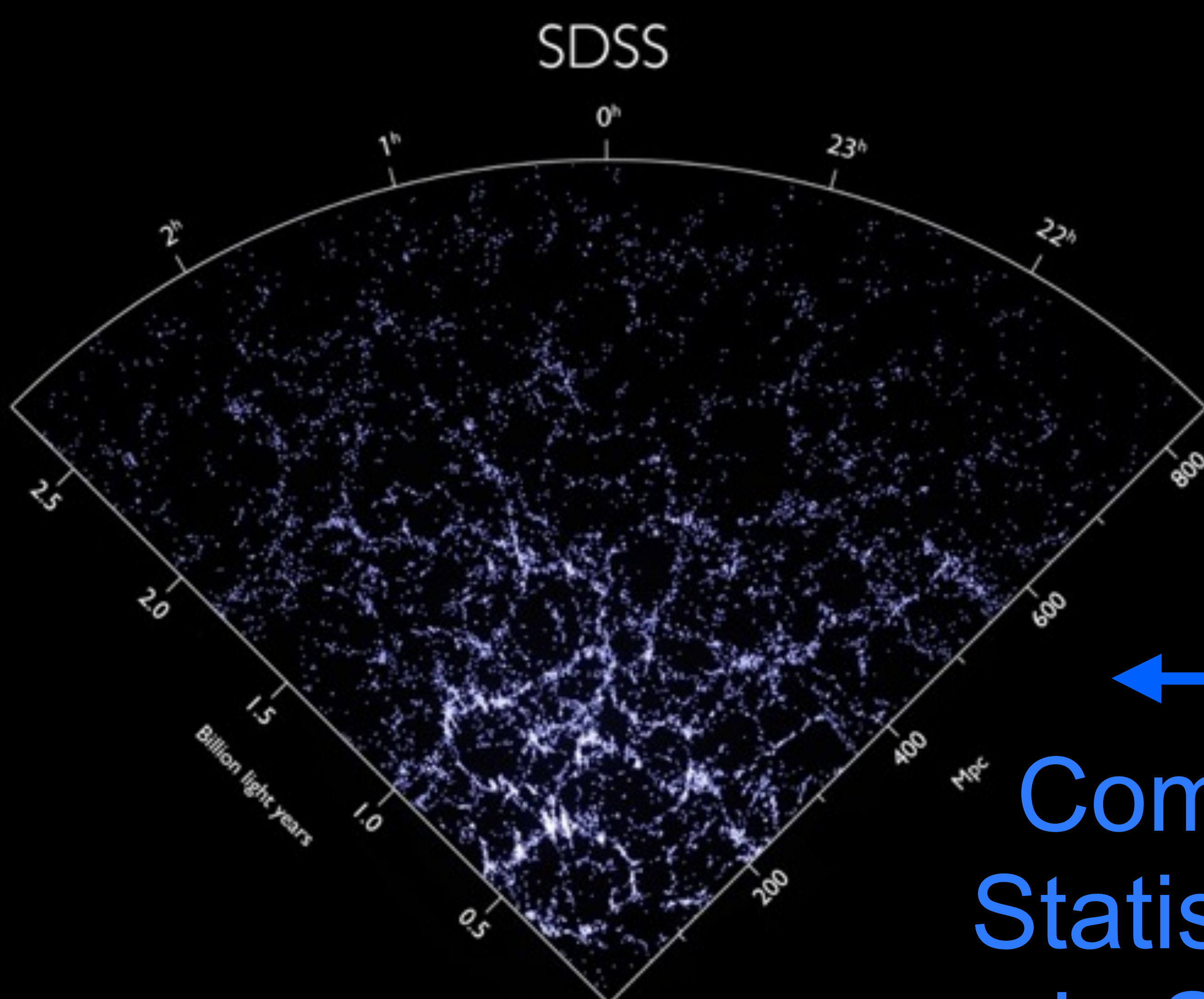


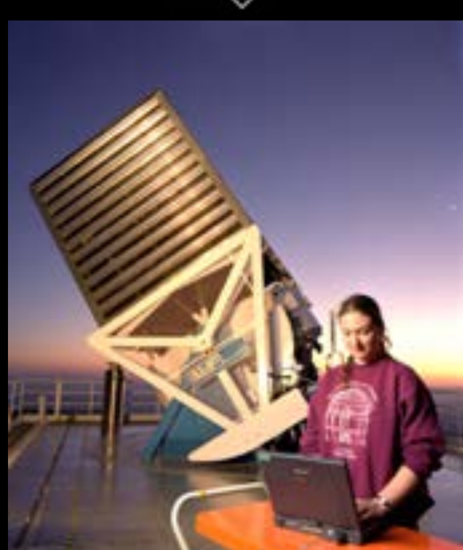
Bolshoi-Planck has a lot more massive halos at high redshifts than Bolshoi!



Observational Data

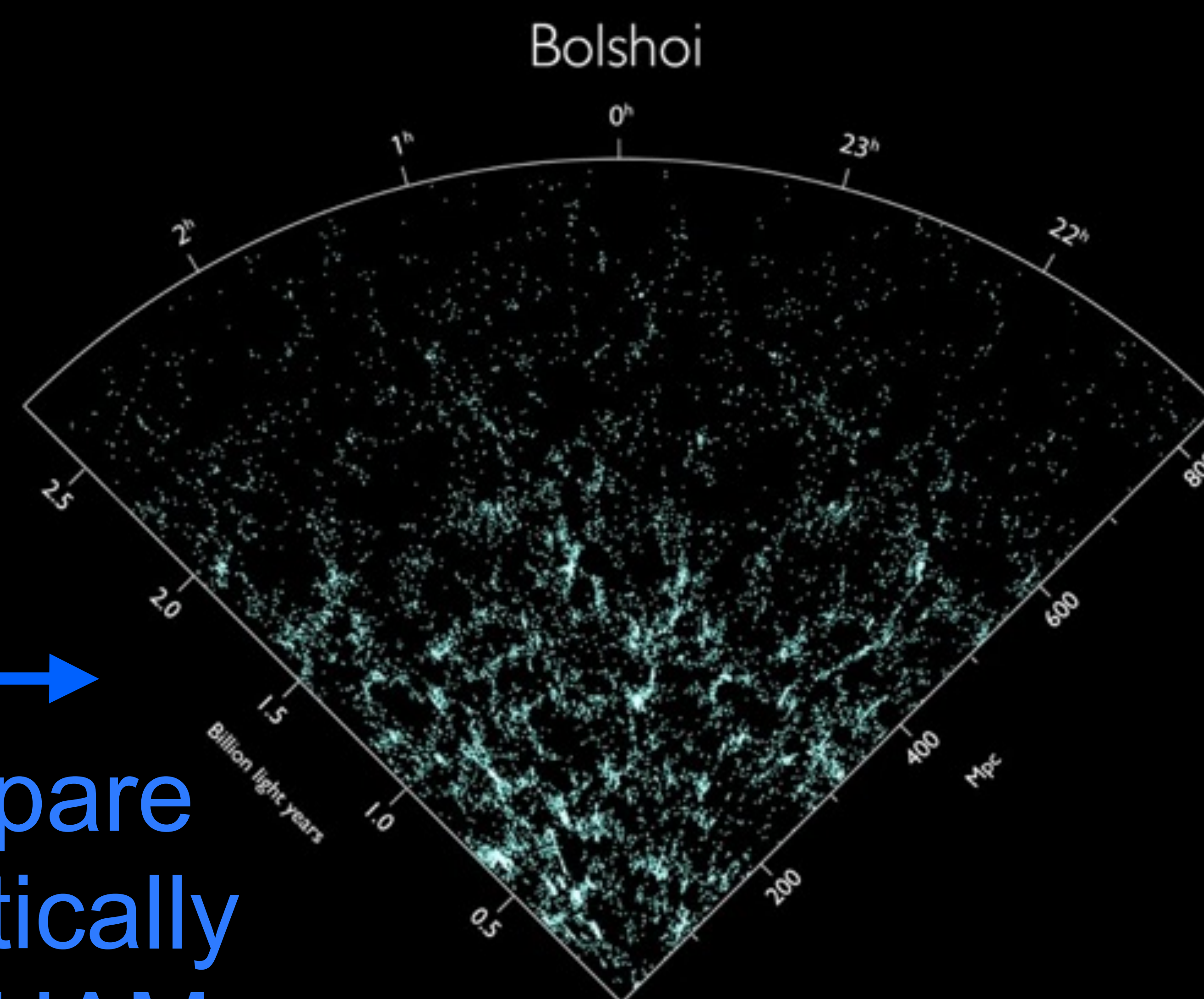
Sloan Digital Sky Survey





Bolshoi Simulation

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



Compare Statistically via SHAM

ΛCDM PREDICTS EVOLUTION IN THE GALAXY CORRELATION FUNCTION

$\xi_{gg}(r)$

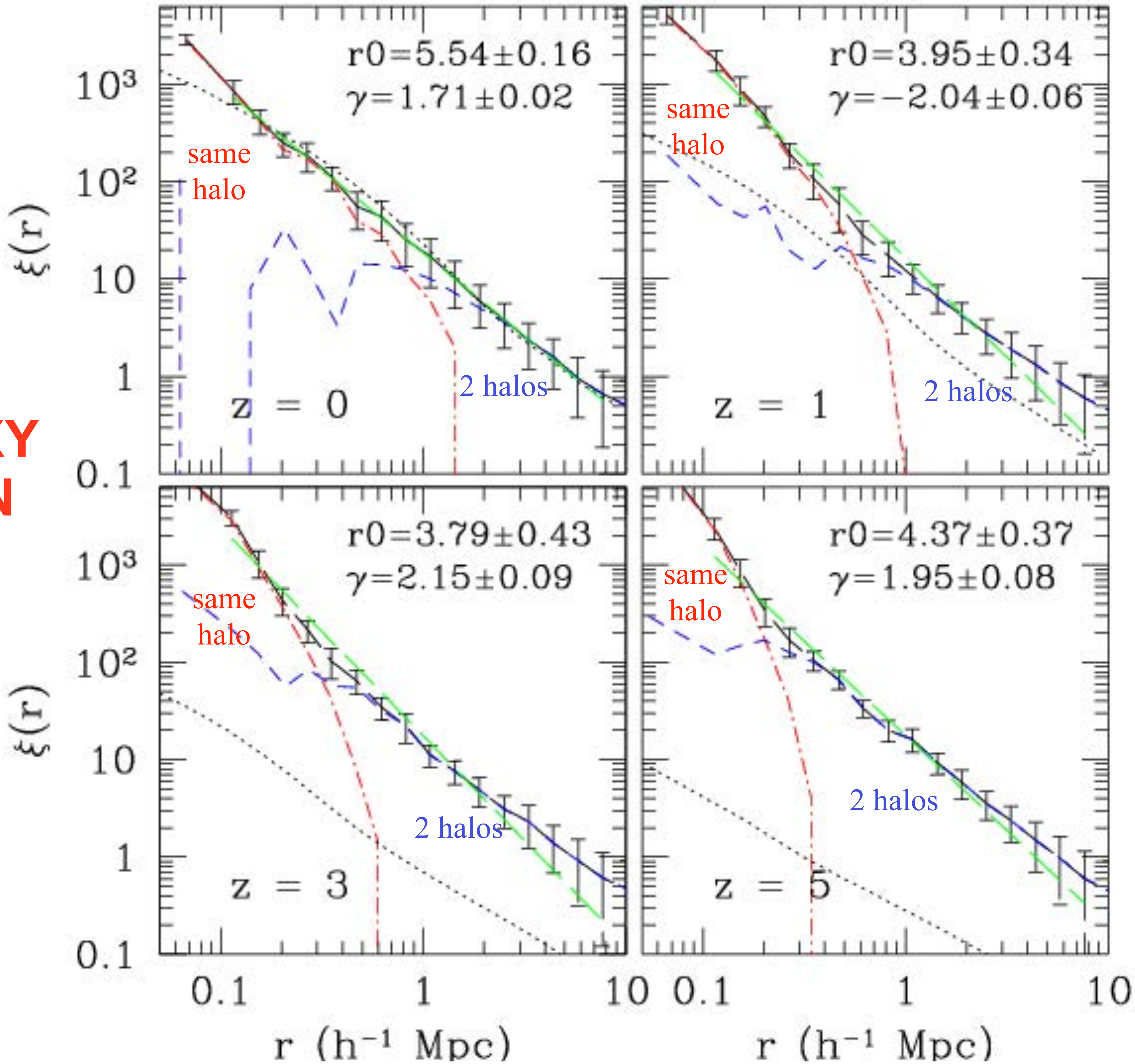
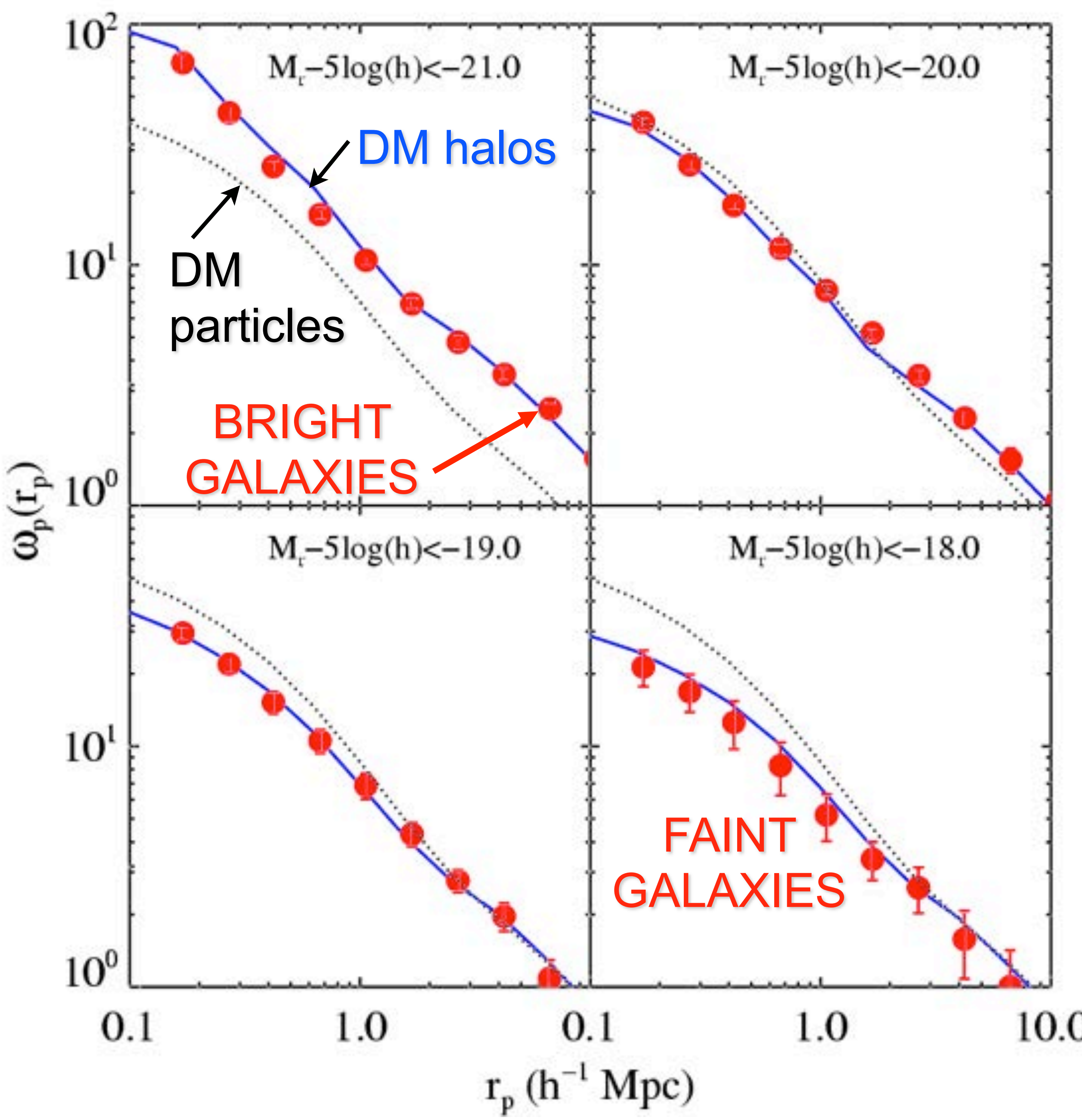


FIG. 8.— Evolution of the two-point correlation function in the $80h^{-1}$ Mpc simulation. The solid line with error bars shows the clustering of halos of the fixed number density $n = 5.89 \times 10^{-3}h^3$ Mpc^{-3} at each epoch. The error-bars indicate the "jack-knife" one sigma errors and are larger than the Poisson error at all scales. The dot-dashed and dashed lines show the corresponding one- and two-halo term contributions. The long-dashed lines show the power-law fit to the correlation functions in the range of $r = [0.1 - 8h^{-1}$ Mpc$]$. Although the correlation functions can be well fit by the power law at $r \gtrsim 0.3h^{-1}$ Mpc in each epoch, at $z > 0$ the correlation function steepens significantly at smaller scales due to the one-halo term.

Kravtsov, Berlind, Wechsler, Klypin, Gottloeber, Allgood, & Primack 2004

Galaxy clustering in SDSS at z~0 agrees with ΛCDM simulations

projected 2-point correlation function



projected separation

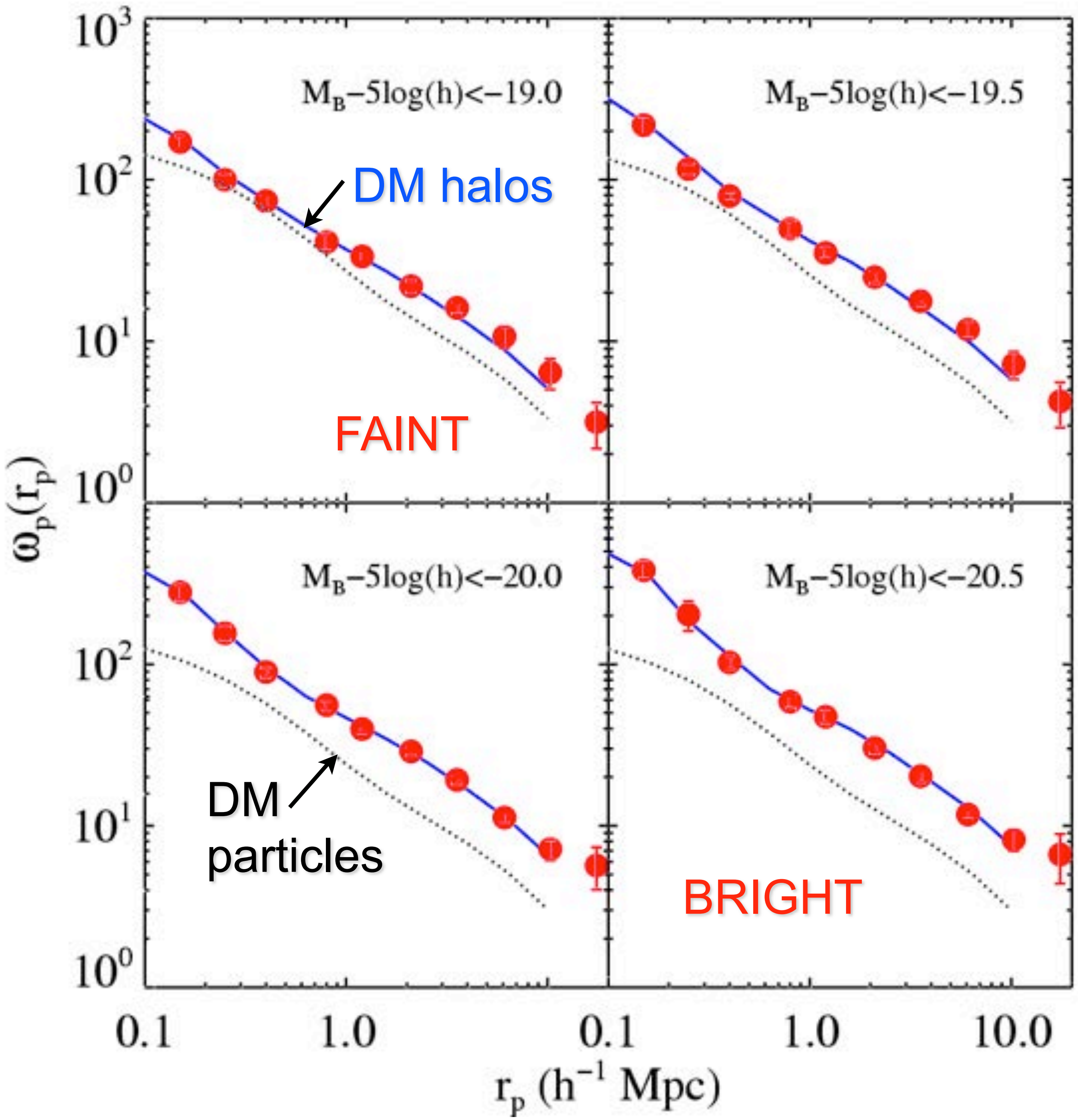
$n(>V_{max,acc}) = n(>L)$

Conroy, Wechsler & Kravtsov 2006, ApJ 647, 201

and at redshift z~1 (DEEP2)

$n(>V_{\rm max,acc})=n(>L)$

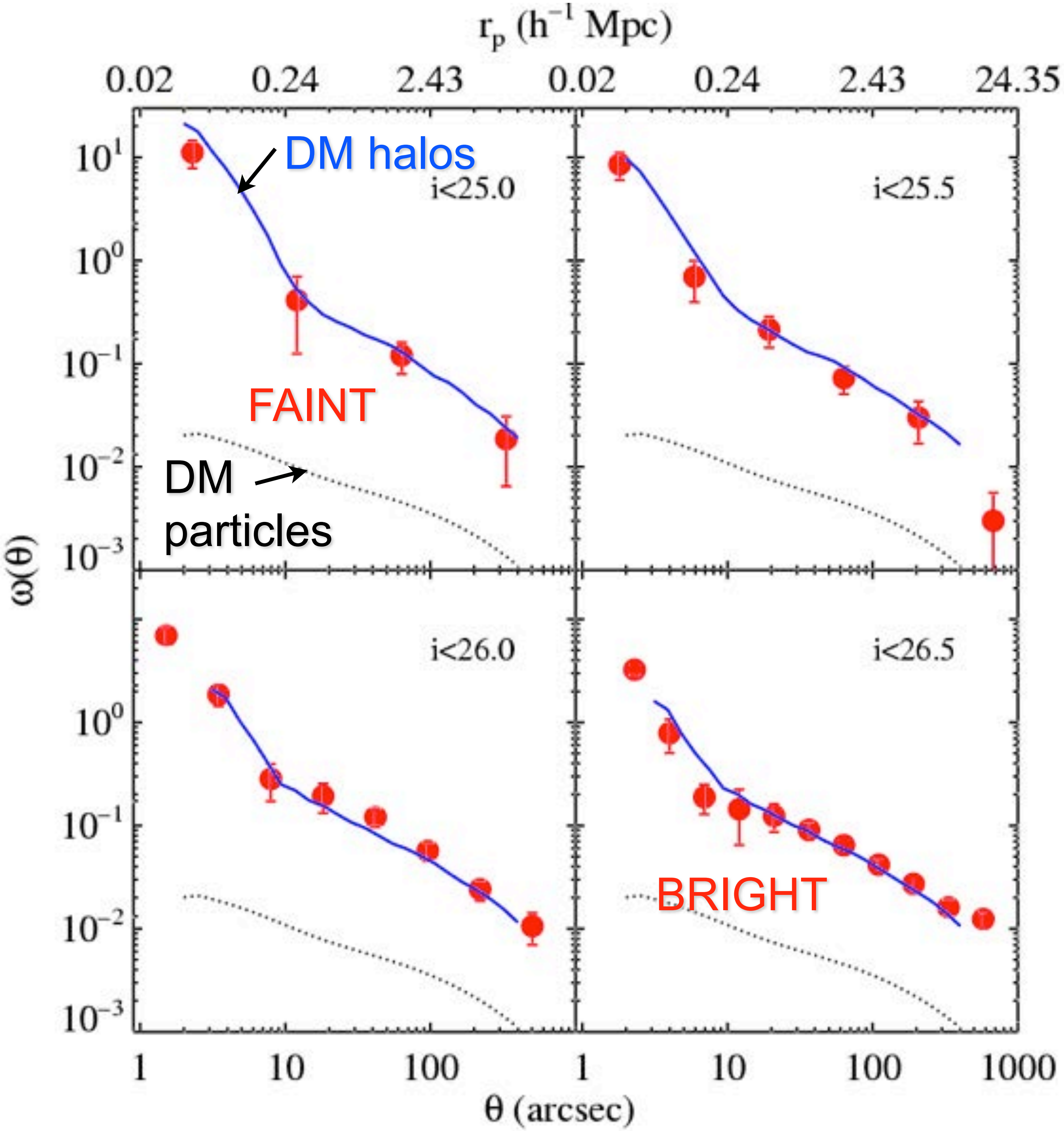
projected 2-point correlation function



projected separation

Conroy, Wechsler & Kravtsov 06

and at z~4-5 (LBGs, Subaru)!



$n(>V_{\rm max,acc})=n(>L)$

angular 2-point correlation function

projected separation

Conroy, Wechsler & Kravtsov 06

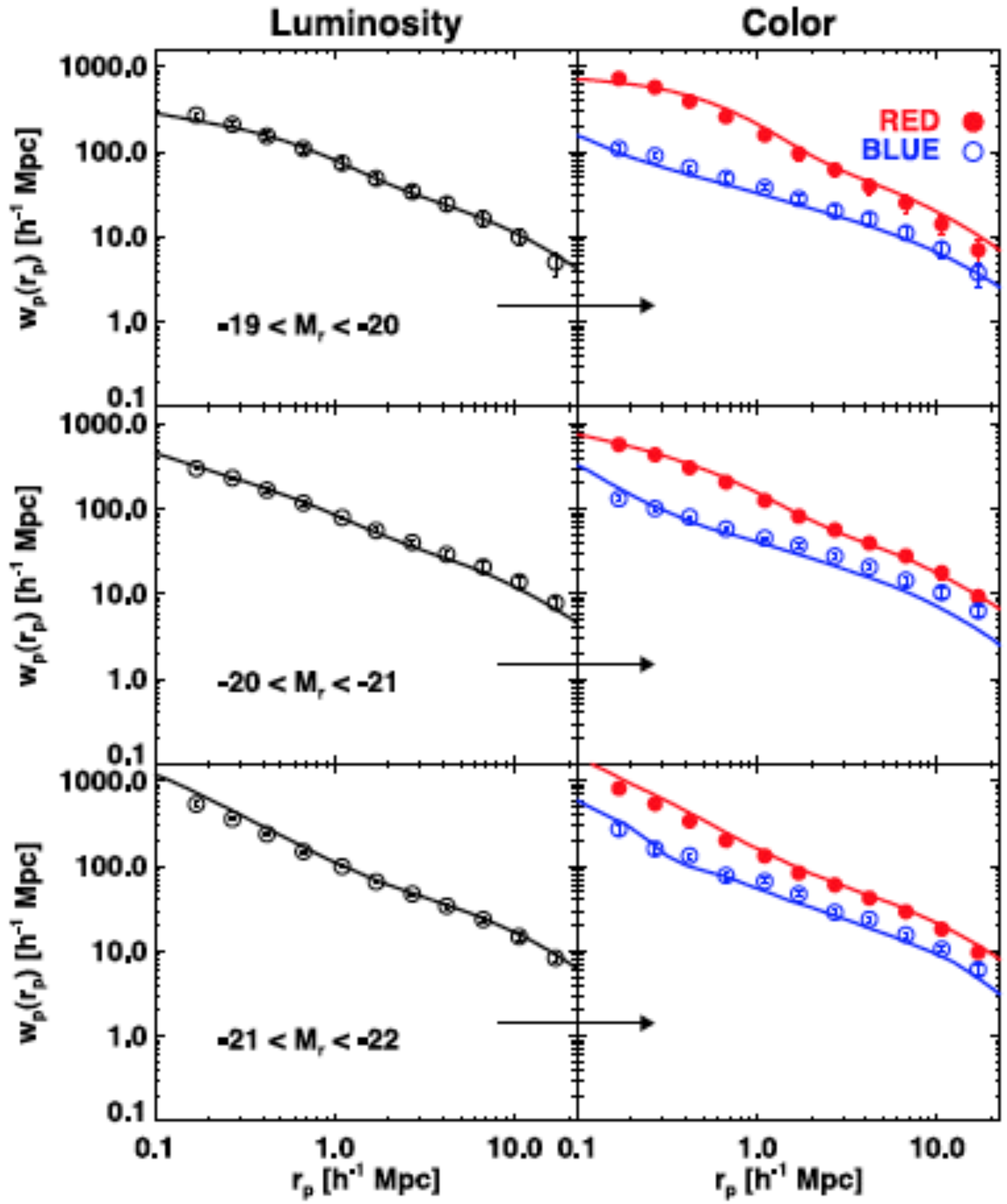
The dark side of galaxy colour

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



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

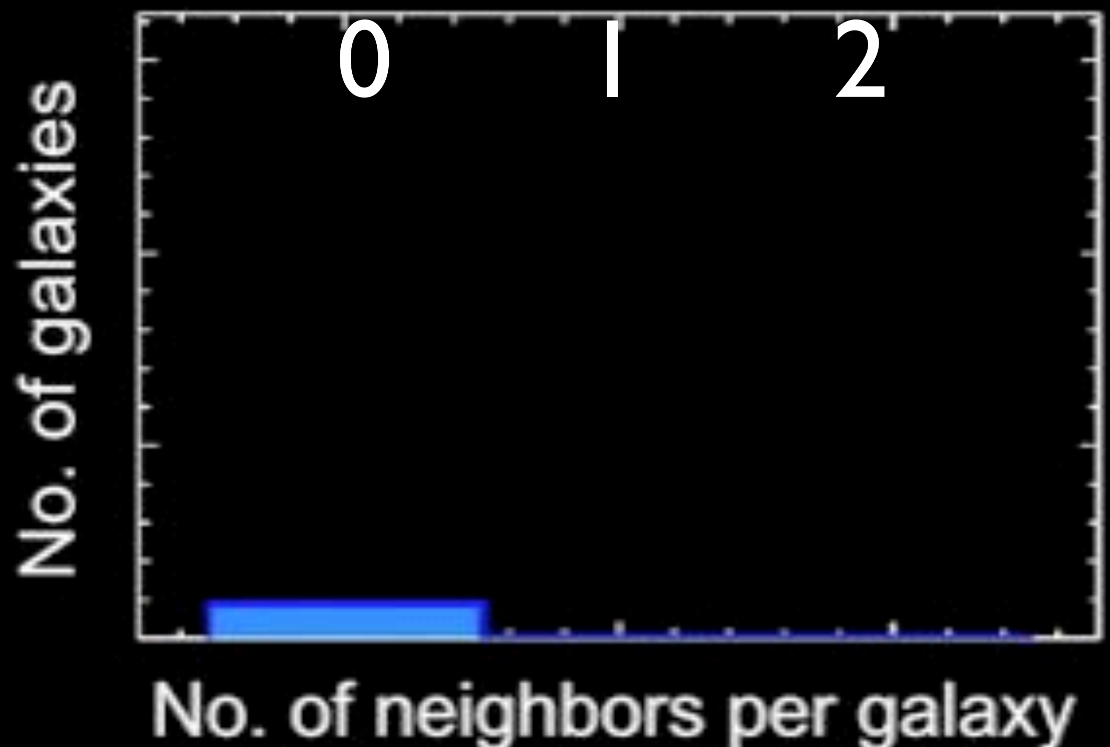
How common is this?

The Bolshoi simulation + sub-halo abundance matching predicts the likelihood of 0, 1, 2, 3, ... large satellites

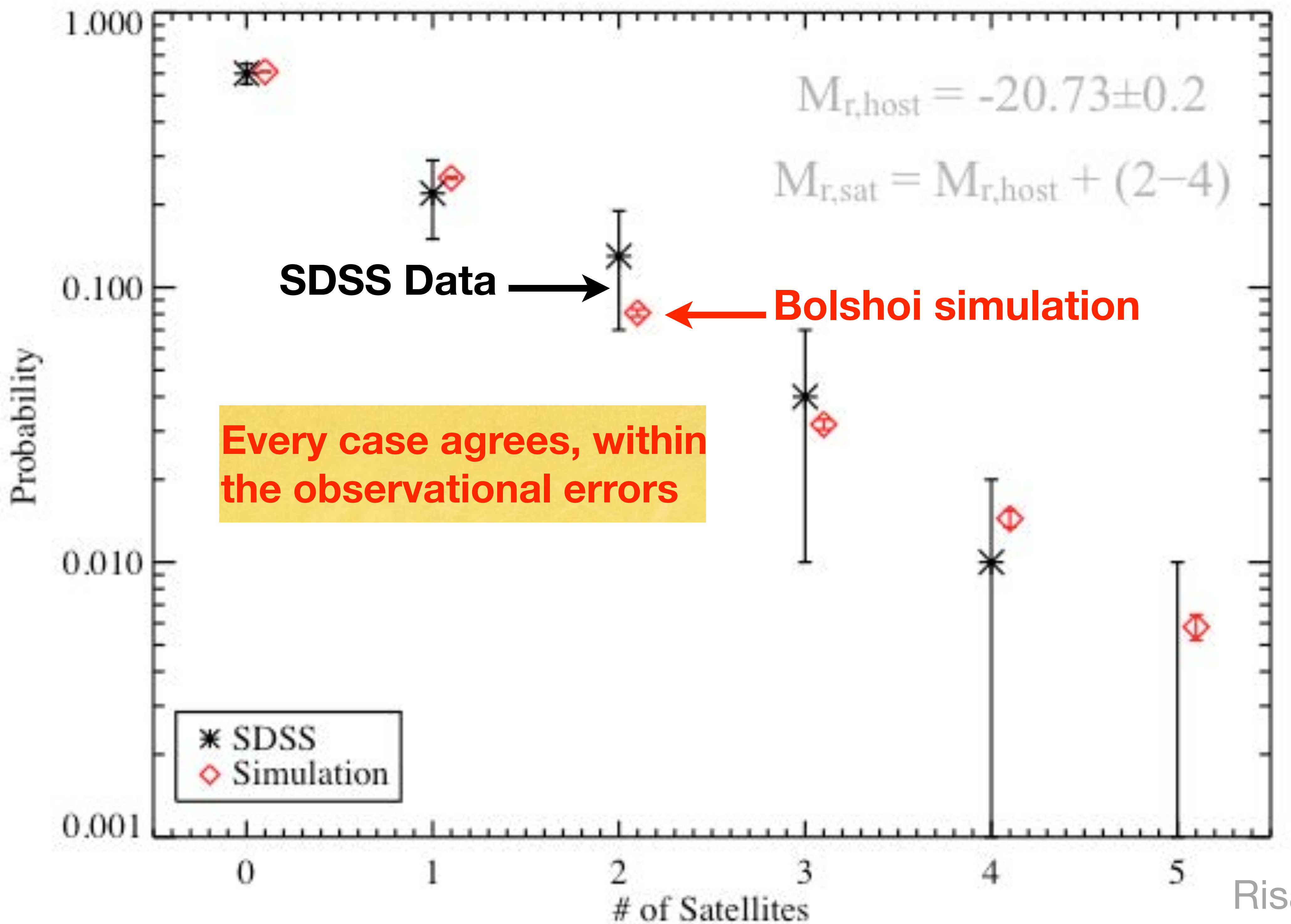

SDSS sky


Bolshoi simulation


0
1
2
No. of galaxies
No. of neighbors per galaxy


0
1
2
No. of galaxies
No. of neighbors per galaxy

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

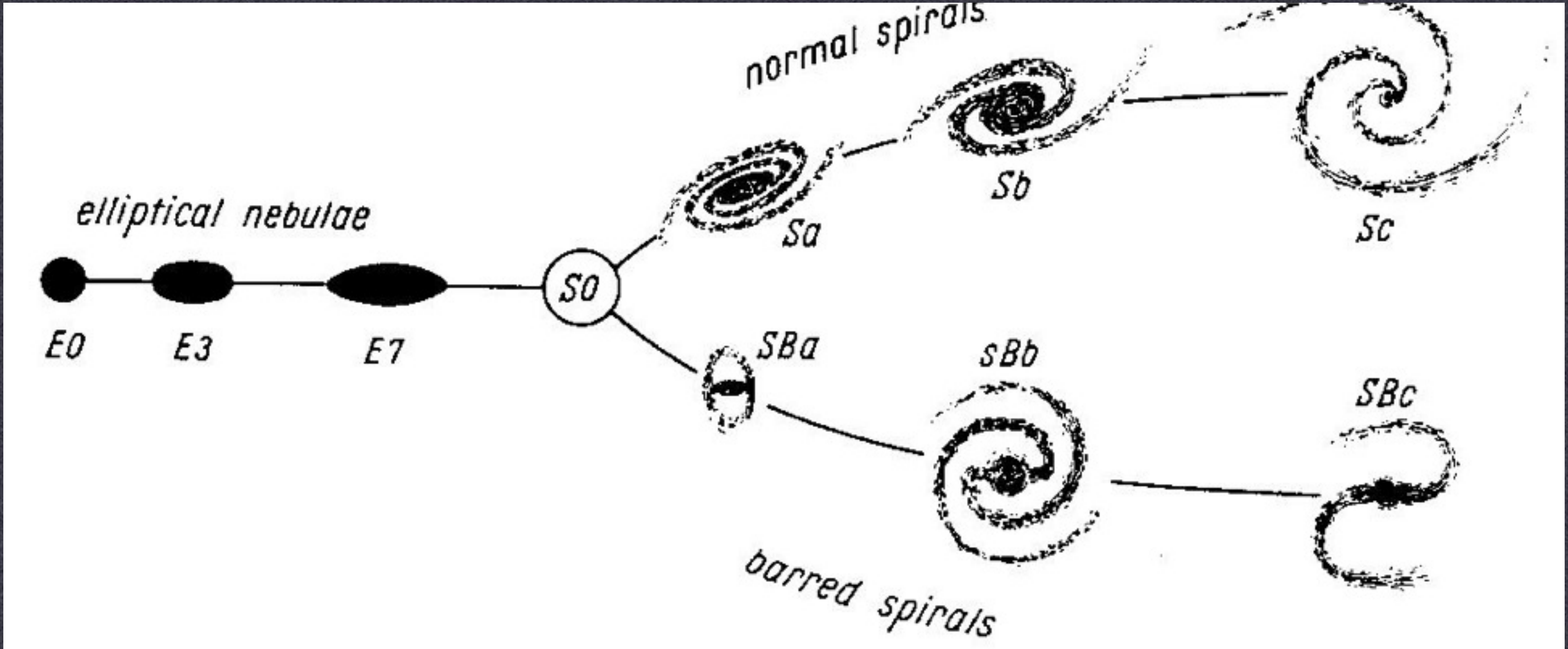


Risa Wechsler

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

ORIGIN OF HUBBLE SEQUENCE

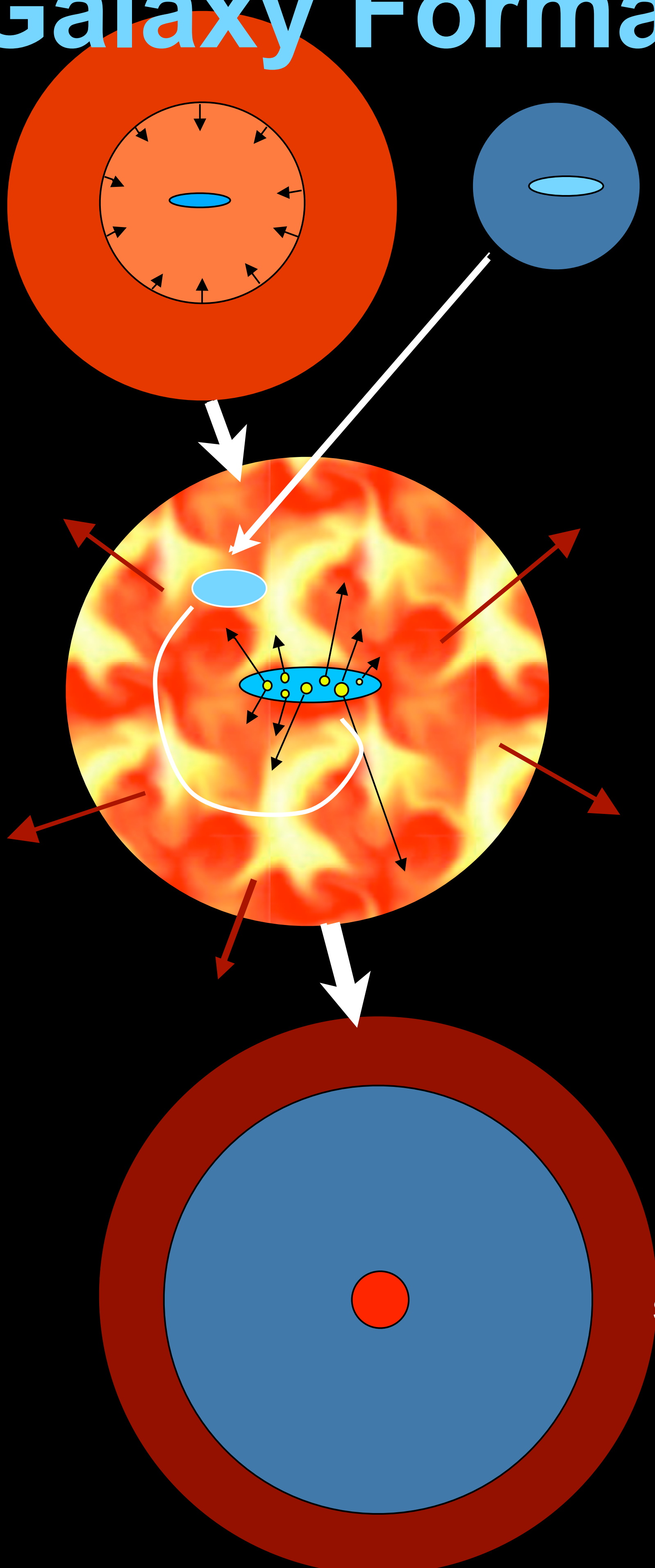
CIRCA 1930



ORIGIN OF HUBBLE SEQUENCE

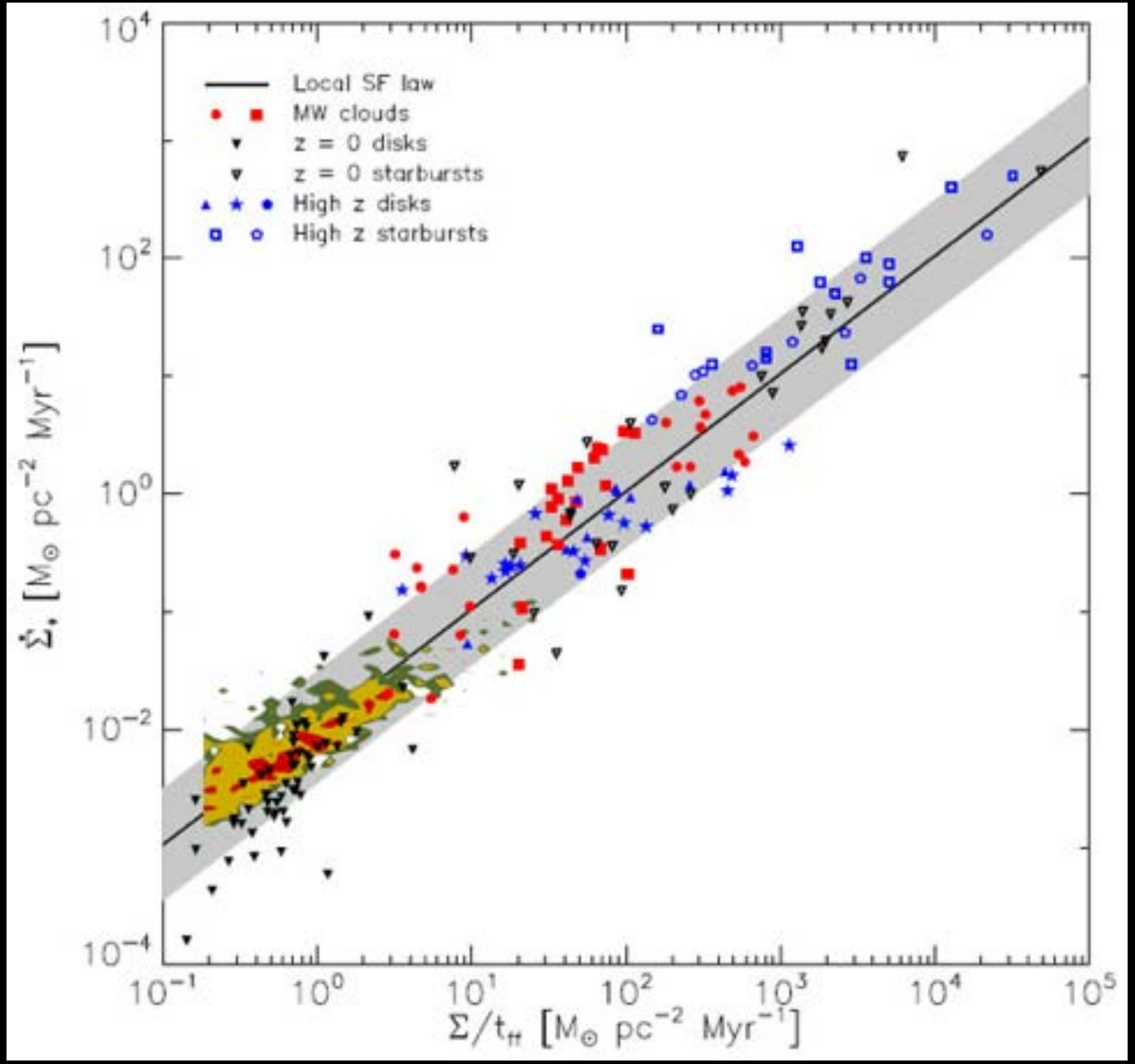
CIRCA 1930

Galaxy Formation via SemiAnalytic Models

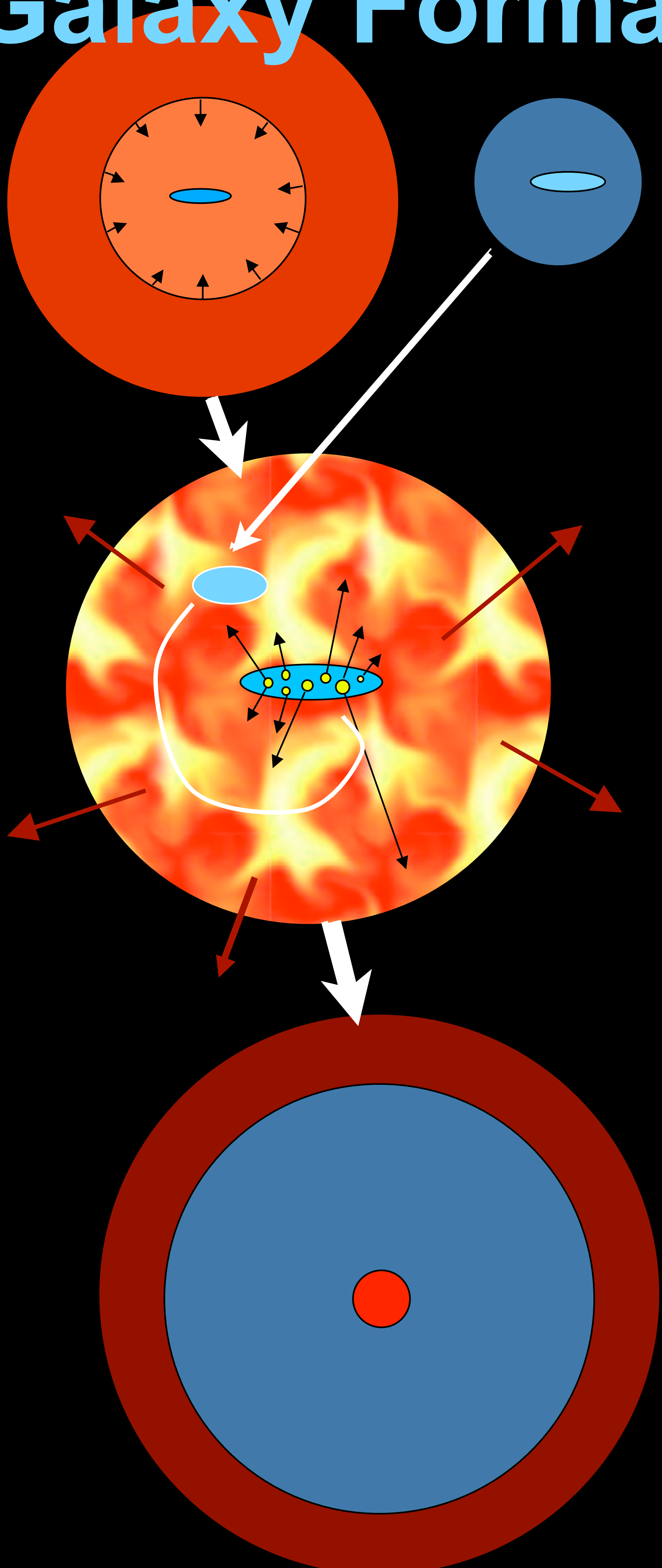


- gas is collisionally heated when perturbations 'turn around' and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law, metallicity effects?)

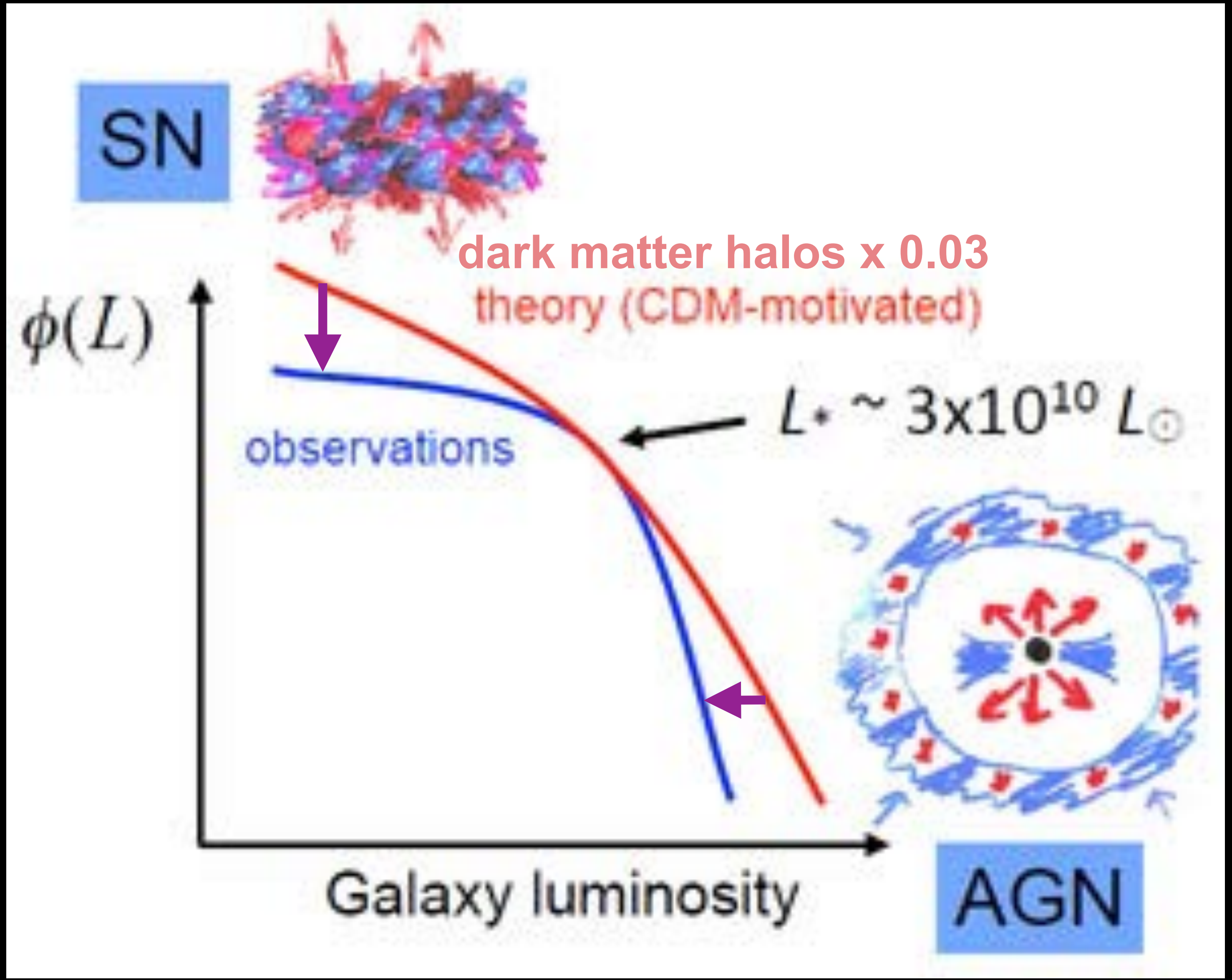
Schmidt-Kennicutt laws on nearby (including Local Group galaxies as shaded regions) and distant galaxies, as well as Milky Way Giant Molecular Clouds (Krumholz et al. 2012): Rate of change of stellar surface density is proportional to gas surface density divided by free-fall time $t_{ff}=(G\rho)^{-1/2}$



Galaxy Formation via SemiAnalytic Models



- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. 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 feedback cuts off star formation



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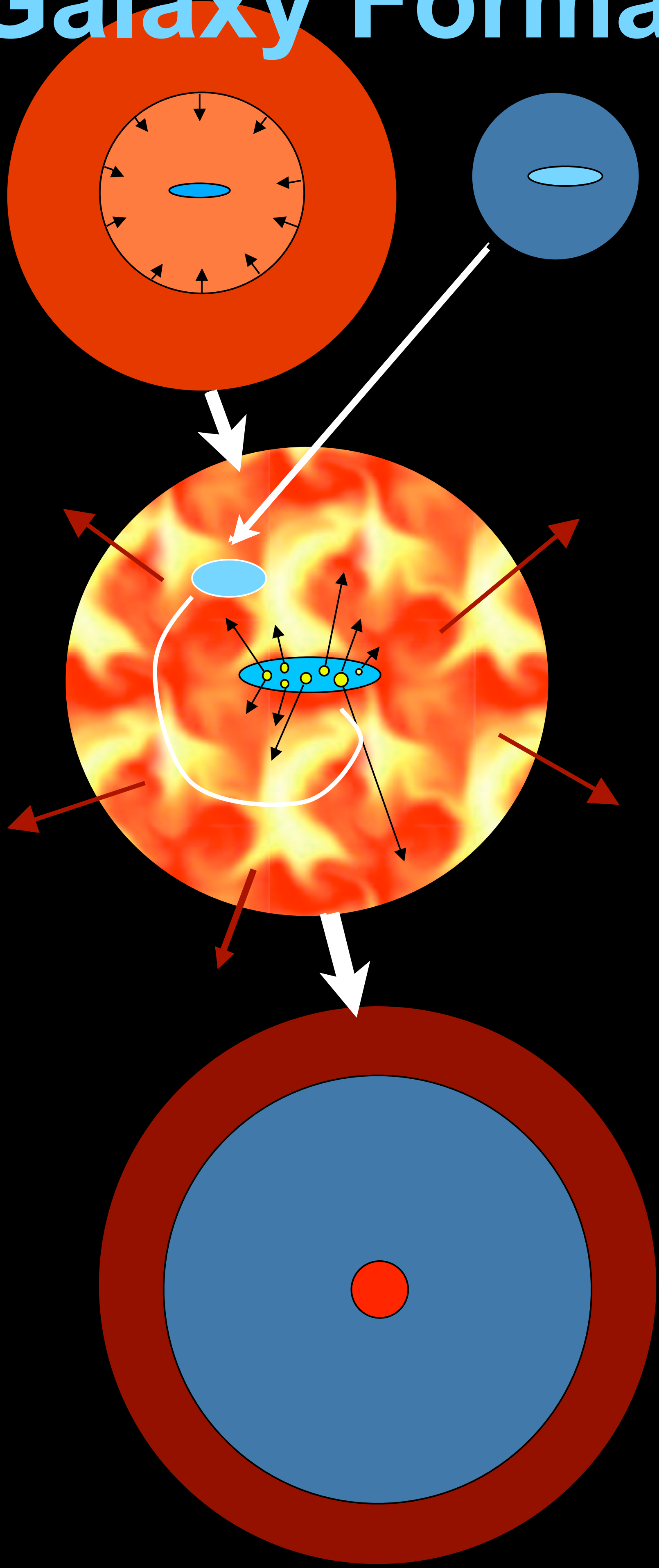

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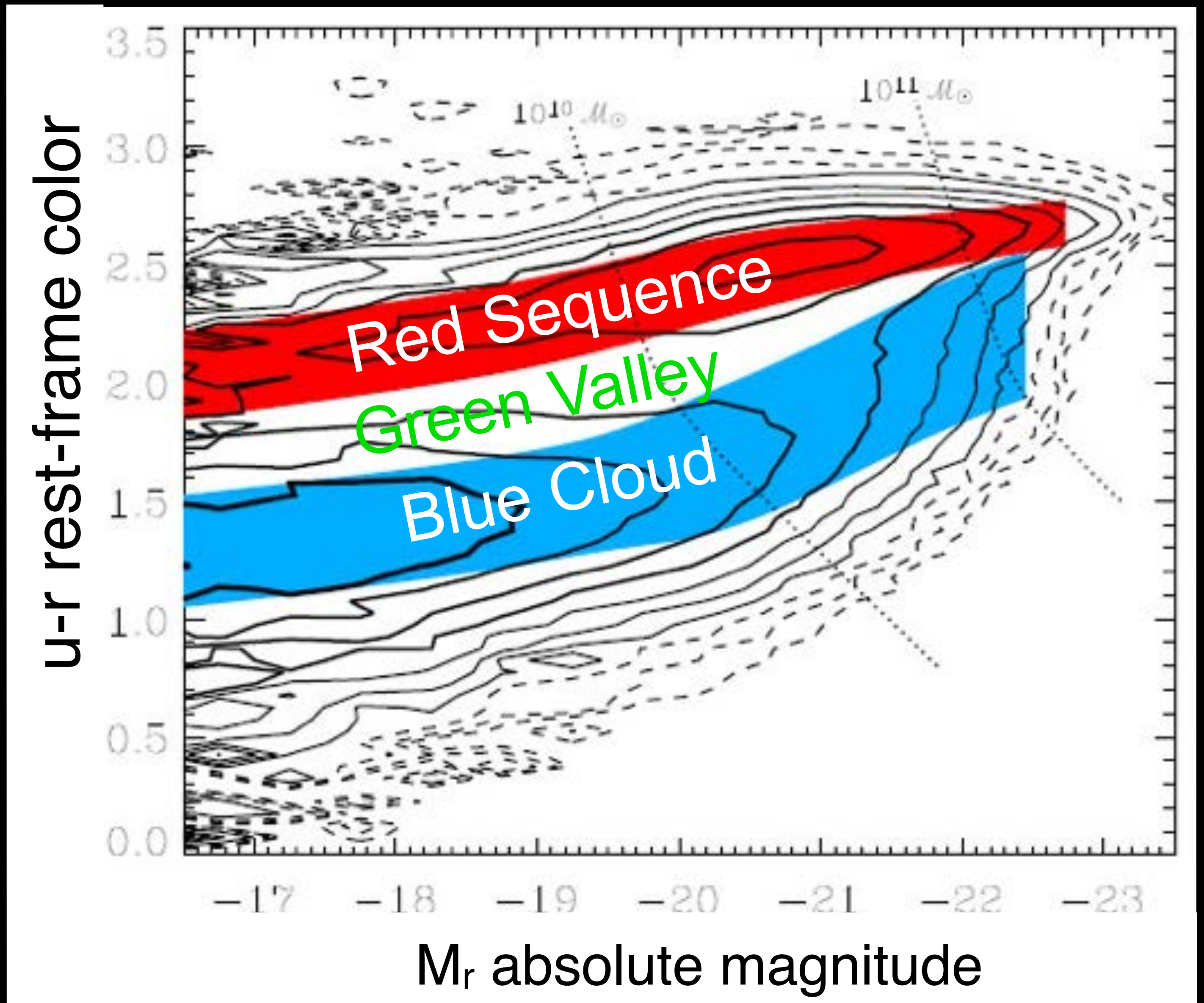
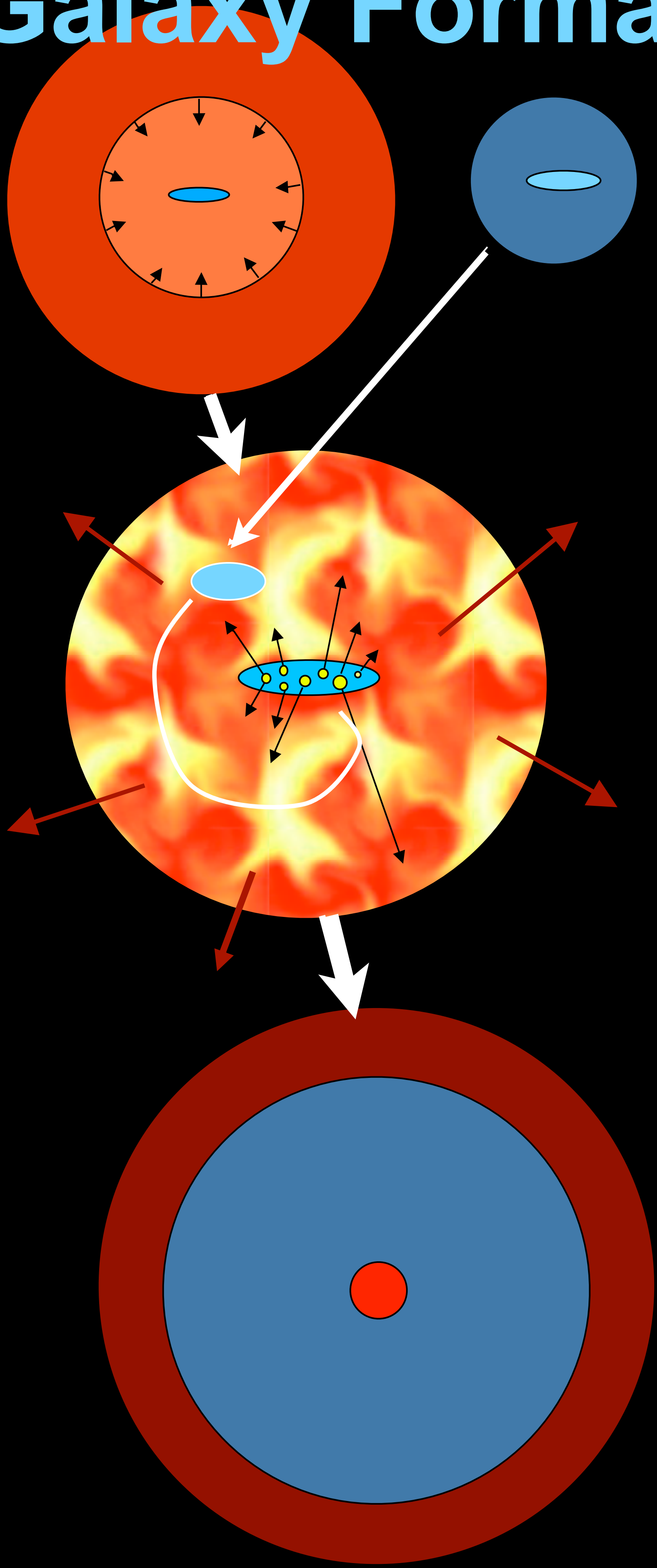
- Illustration of galaxy bimodality. The contours are the density of SDSS galaxies in color-luminosity space, after correction for selection effects (Baldry et al. 2004).



Galaxy Formation via SemiAnalytic Models



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- AGN feedback cuts off 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.

- 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.

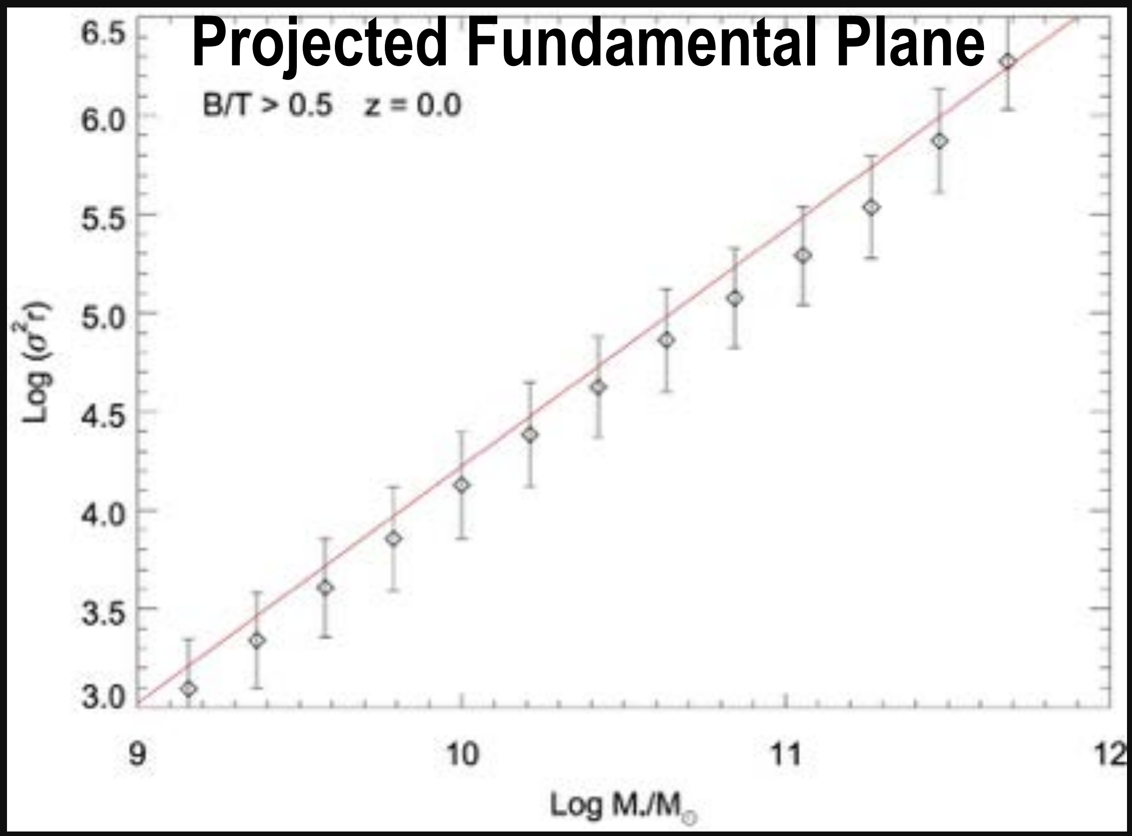




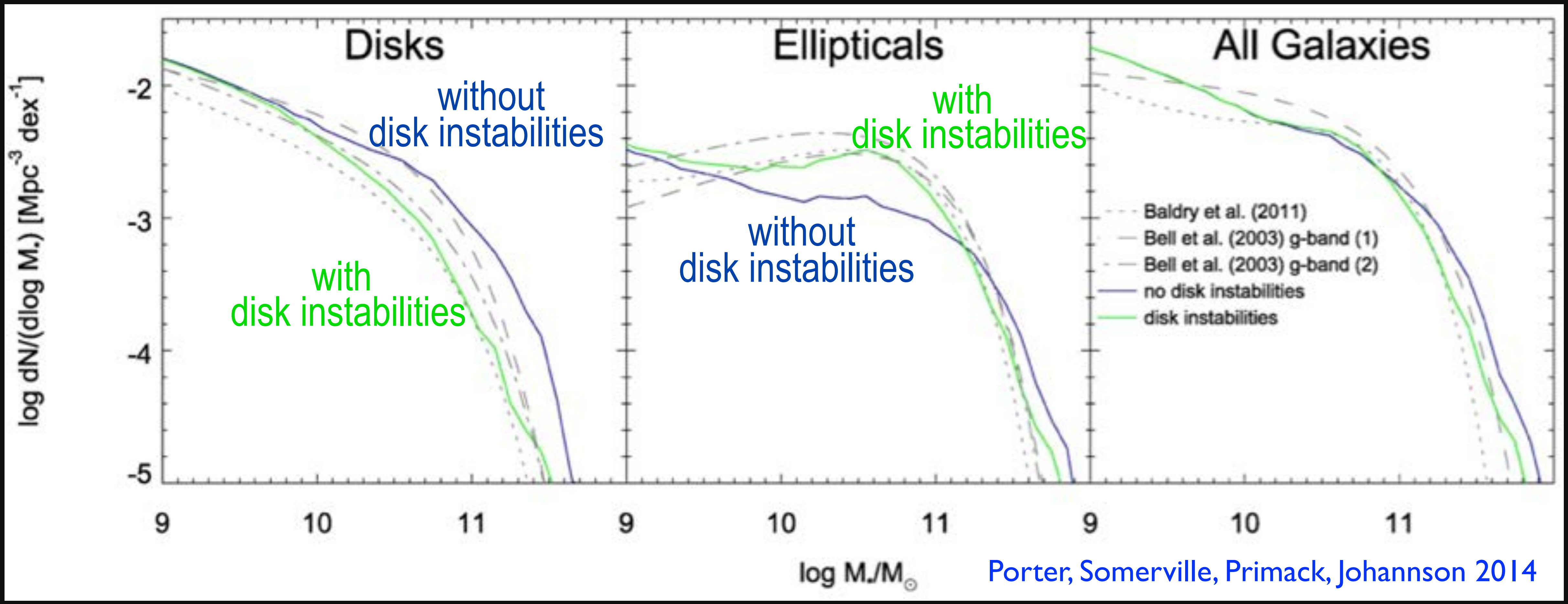



- Our semi-analytic model also correctly predicts the numbers of Disk galaxies and Elliptical galaxies of all masses.

SemiAnalytic Model Low-Redshift Galaxies



- Correctly reproduces the z=0 size-mass, Faber-Jackson, and Fundamental Plane relations
- Forming spheroids with major mergers + disk instabilities reproduces the morphology-selected z=0 mass function



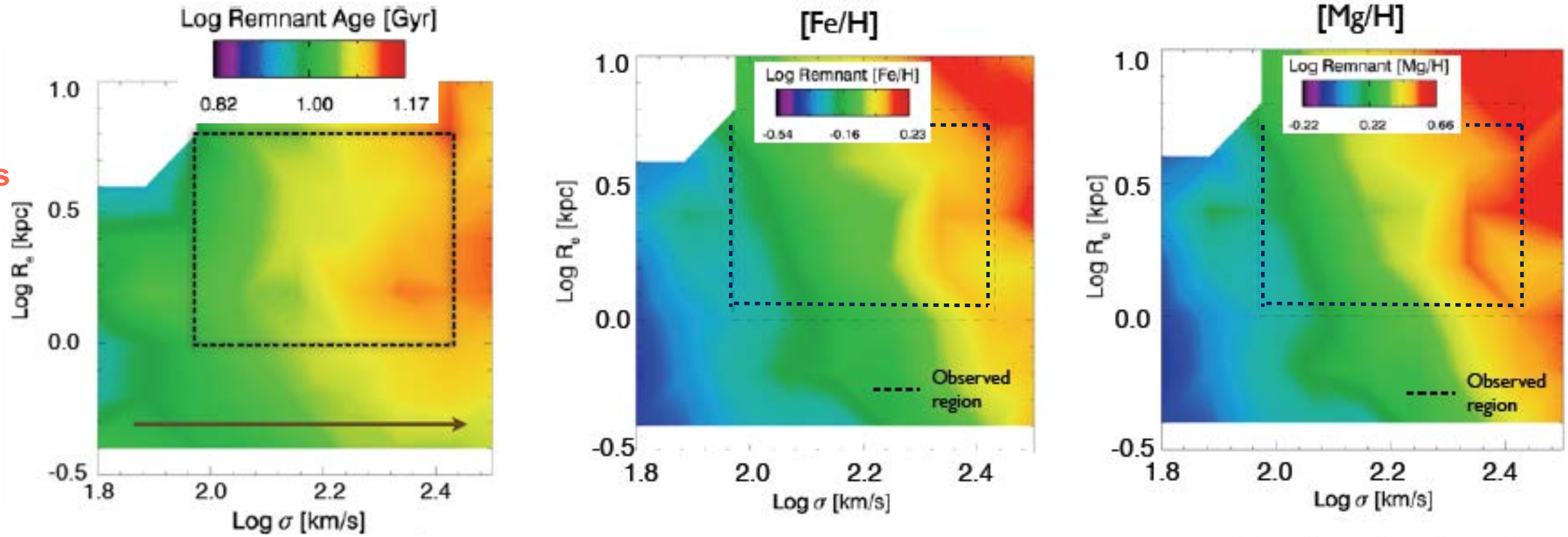
Porter, Somerville, Primack, Johannson 2014

SAM Predictions vs. SDSS Observations

Galaxy Age | Galaxy Metallicity

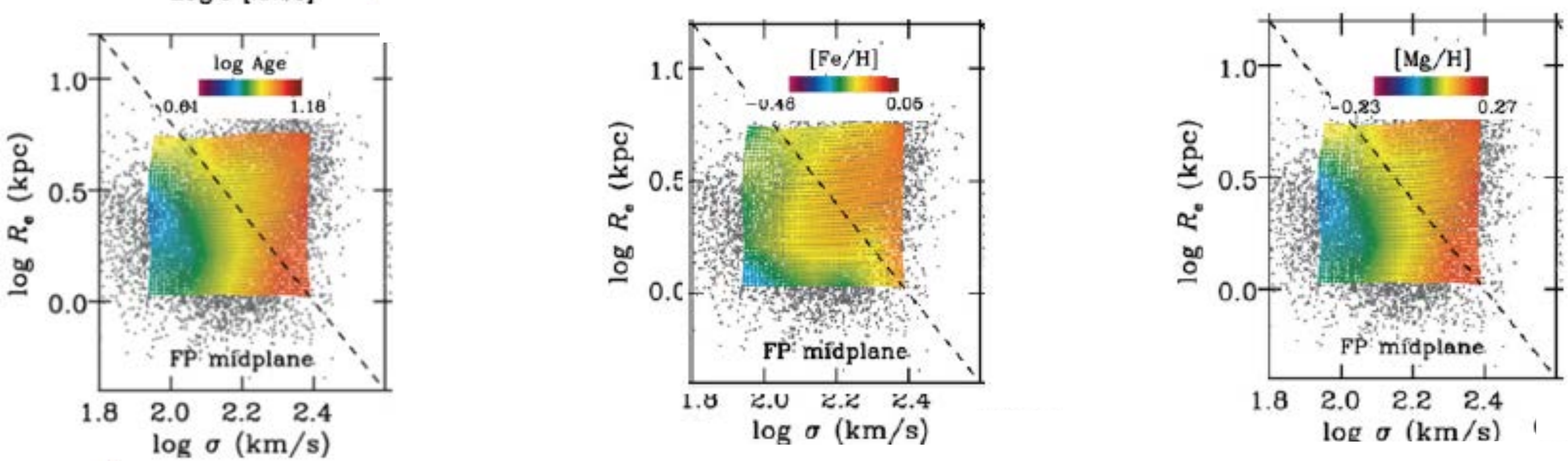
SAM
Predictions

Lauren Porter et al. 2013b



SDSS
Observations

Jenny Graves et al. 2009



Lauren Porter et al. 2014b

Cosmological Simulations

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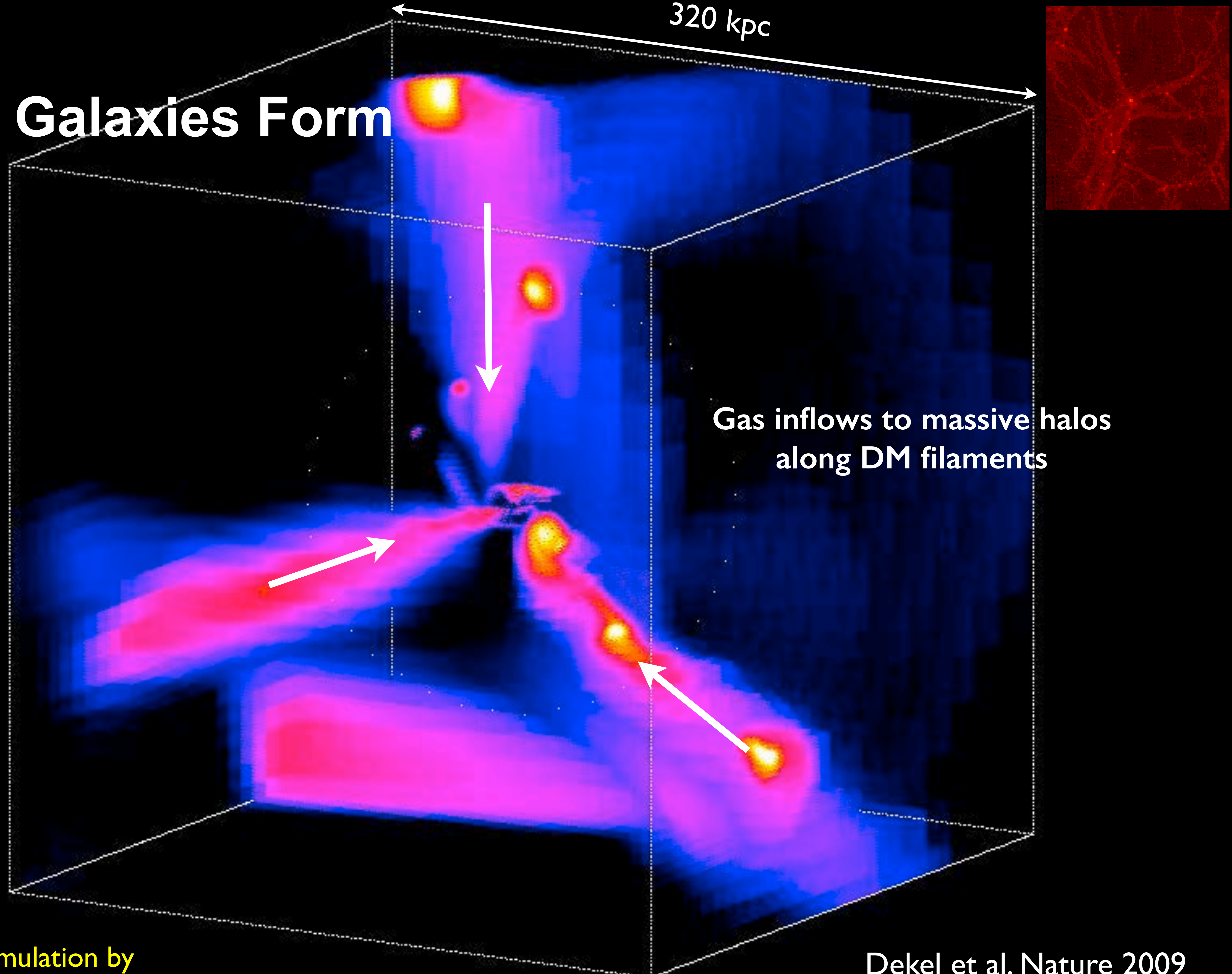
Cosmological dark matter simulations show large scale structure, growth of structure, and dark matter halo properties

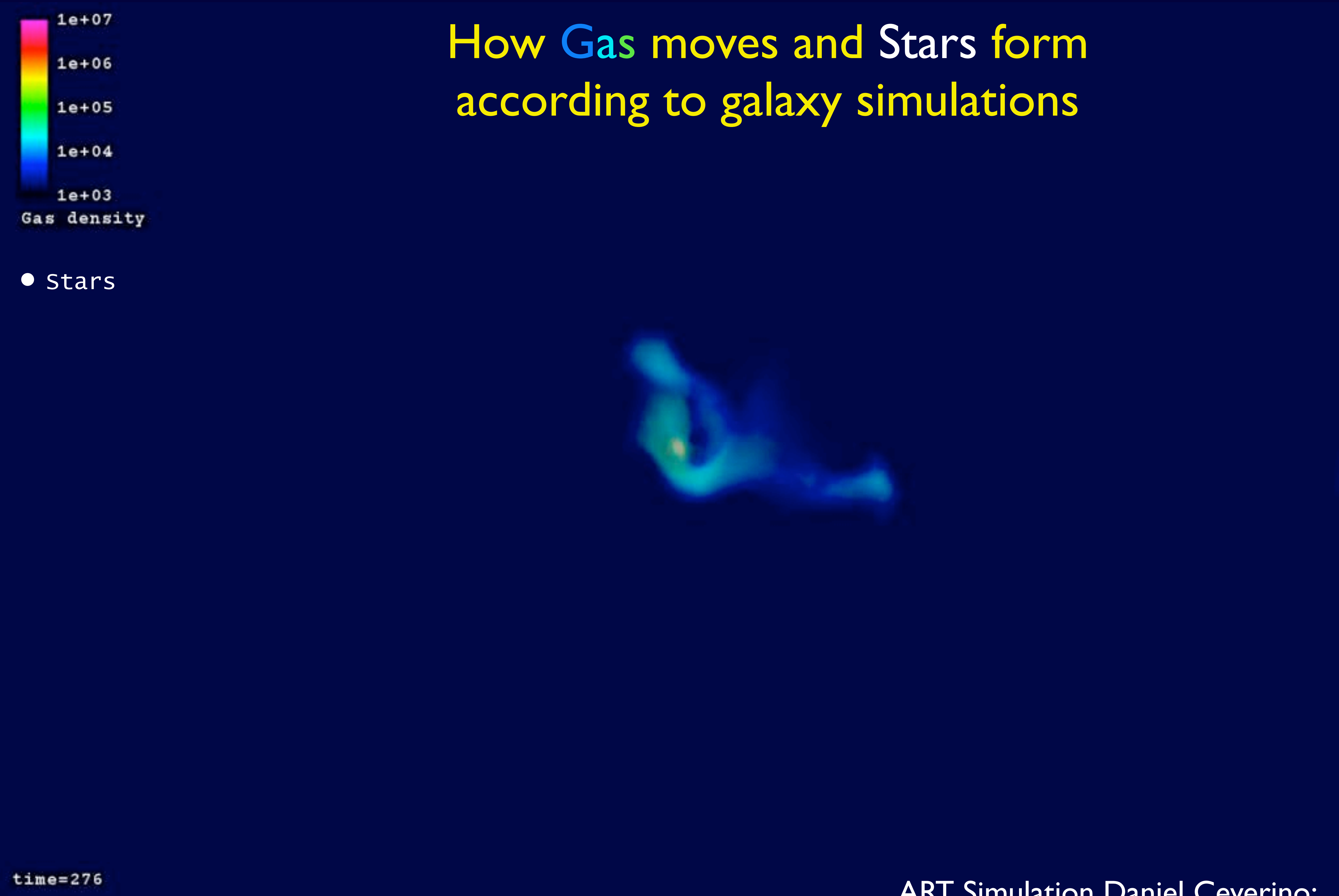
Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images in all wavebands including stellar evolution and dust

How Galaxies Form



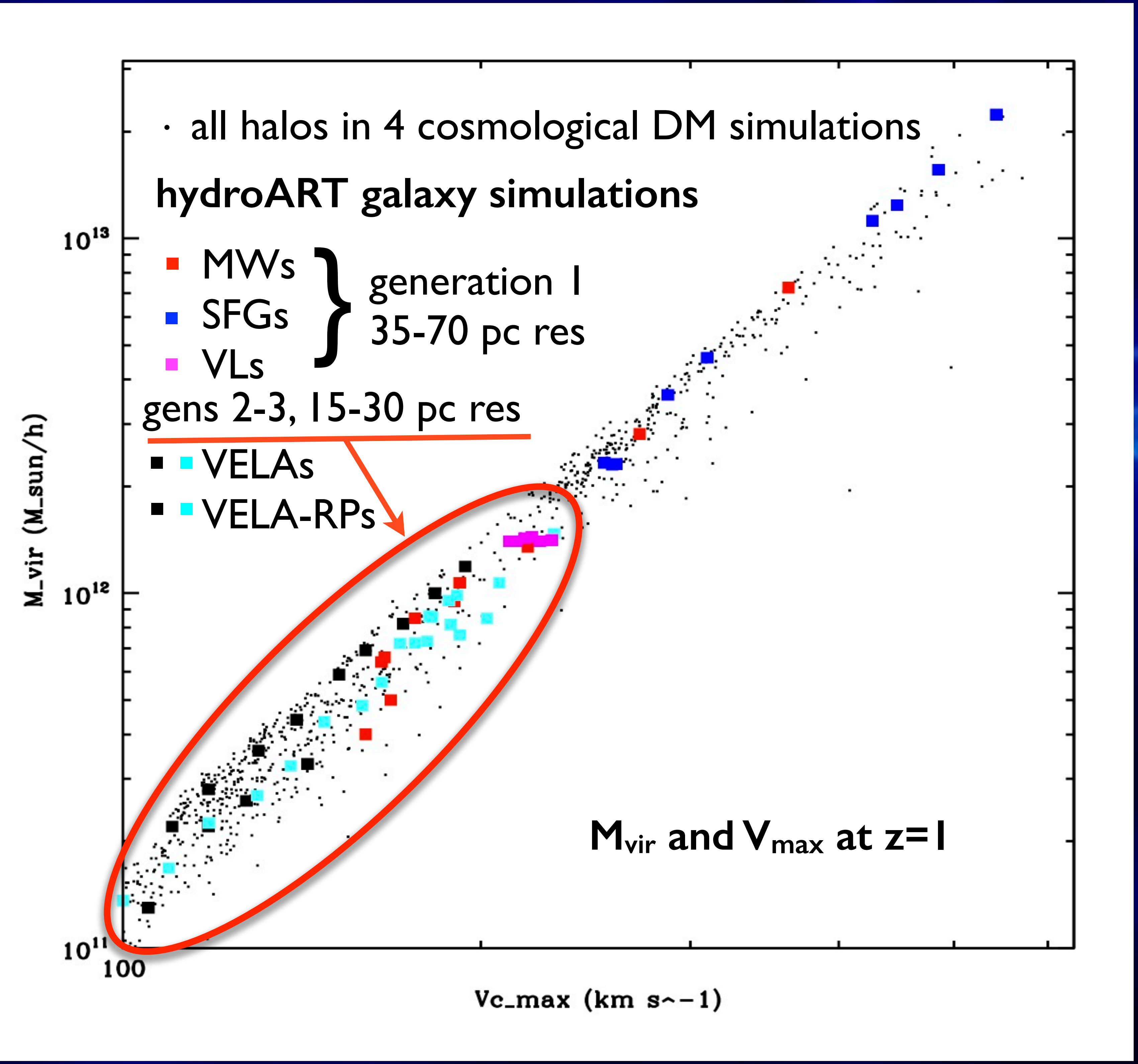
RAMSES simulation by
Romain Teyssier on Mare Nostrum supercomputer, Barcelona

Dekel et al. Nature 2009



ART Simulation Daniel Ceverino;
Visualization: David Ellsworth

3 Generations of hydroART simulations



Generations 2 & 3

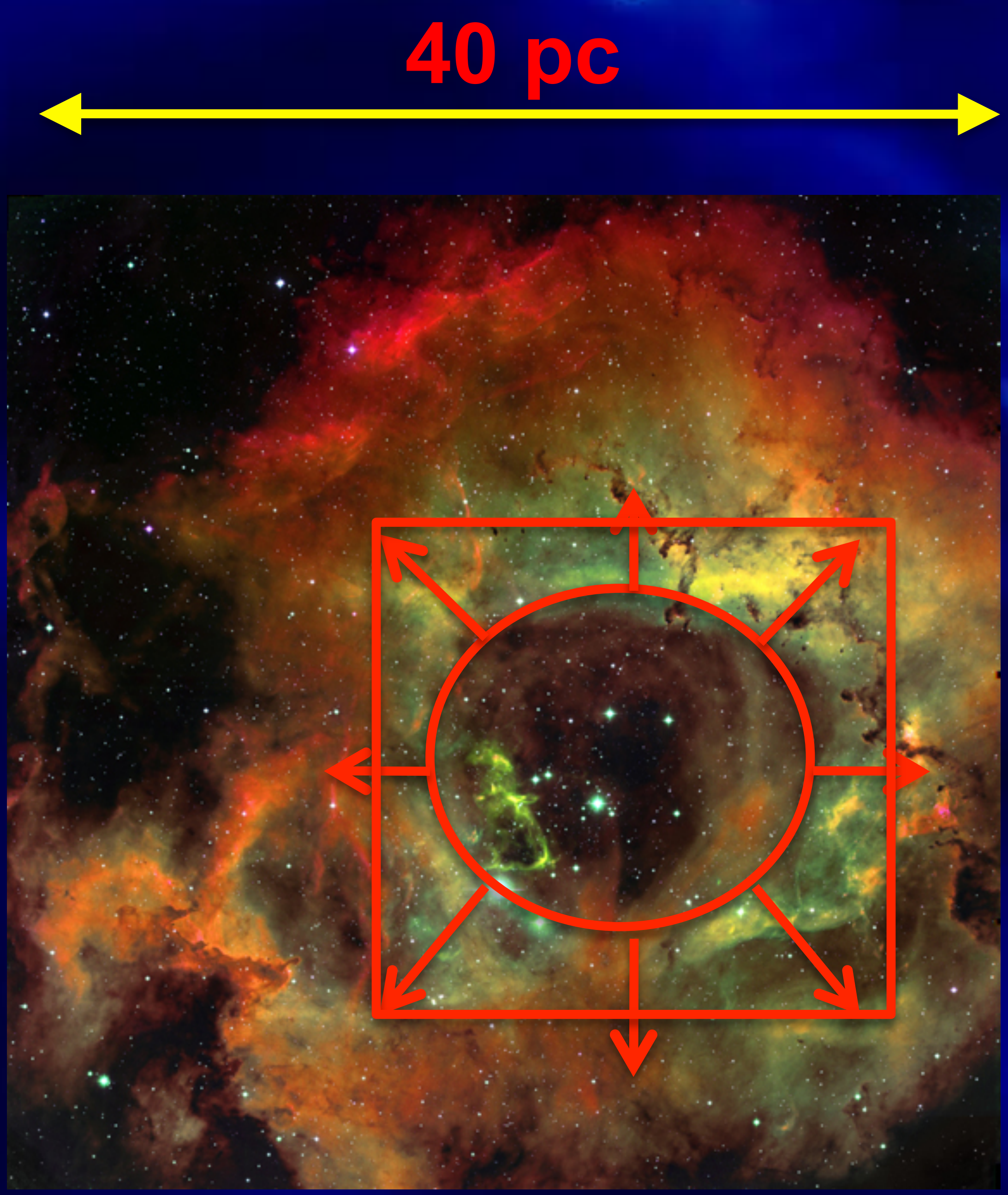
- ~35 zoom-in simulations
- 15-30 pc reso
- M_{DM}=8 10^4 Ms
- M_*=10^3 Ms
- z=1-3

10^{11} Ms/h < M_H < 10^{12} Ms/h
Vc_max =100-200 km/s @ z=1

Daniel Ceverino

Radiative feedback

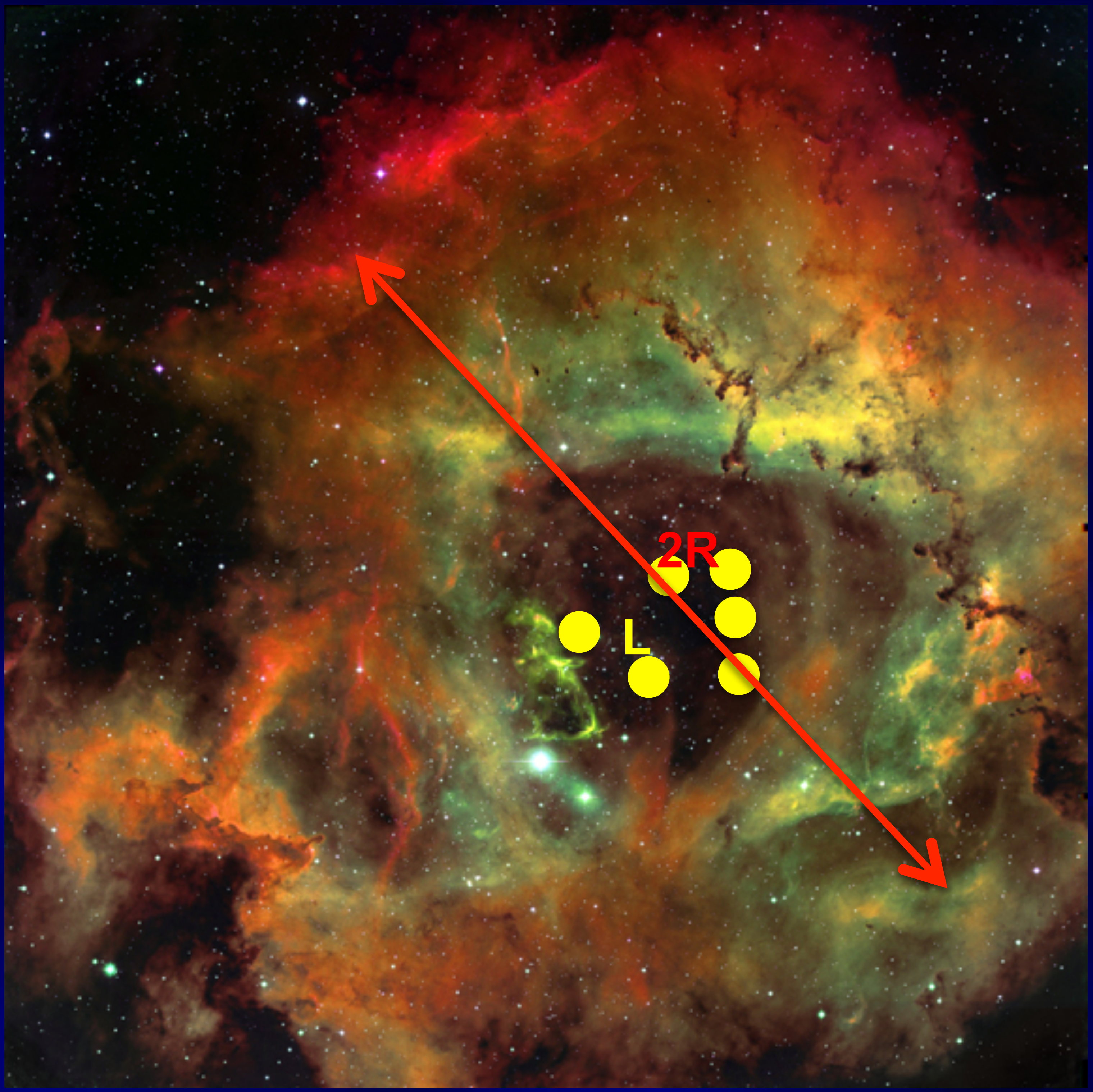
Rosette Nebula



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

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

$L = M_* \Gamma$

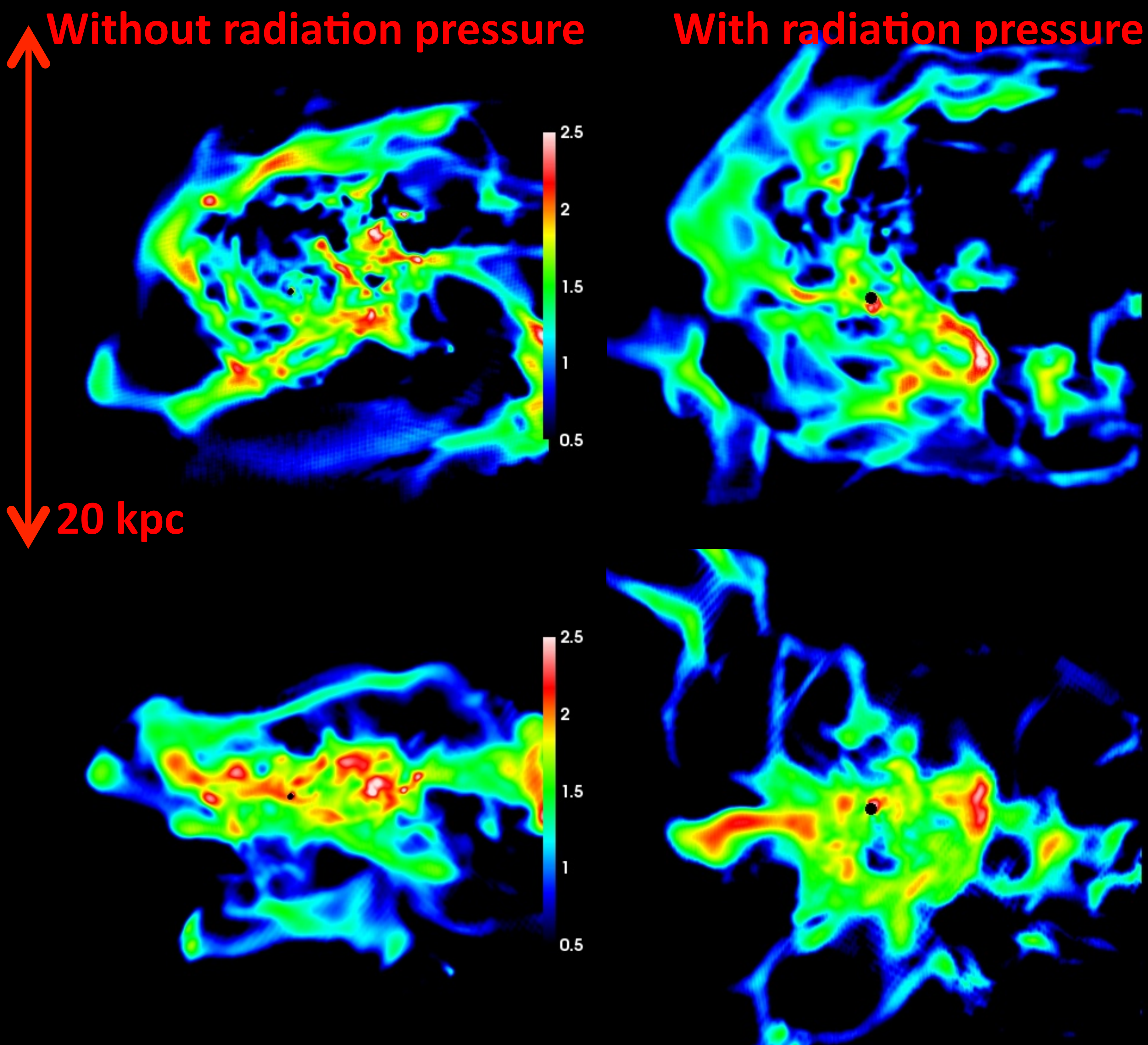
Γ = cte for 5 Myr

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

No free parameters

Daniel Ceverino

Gas distributions



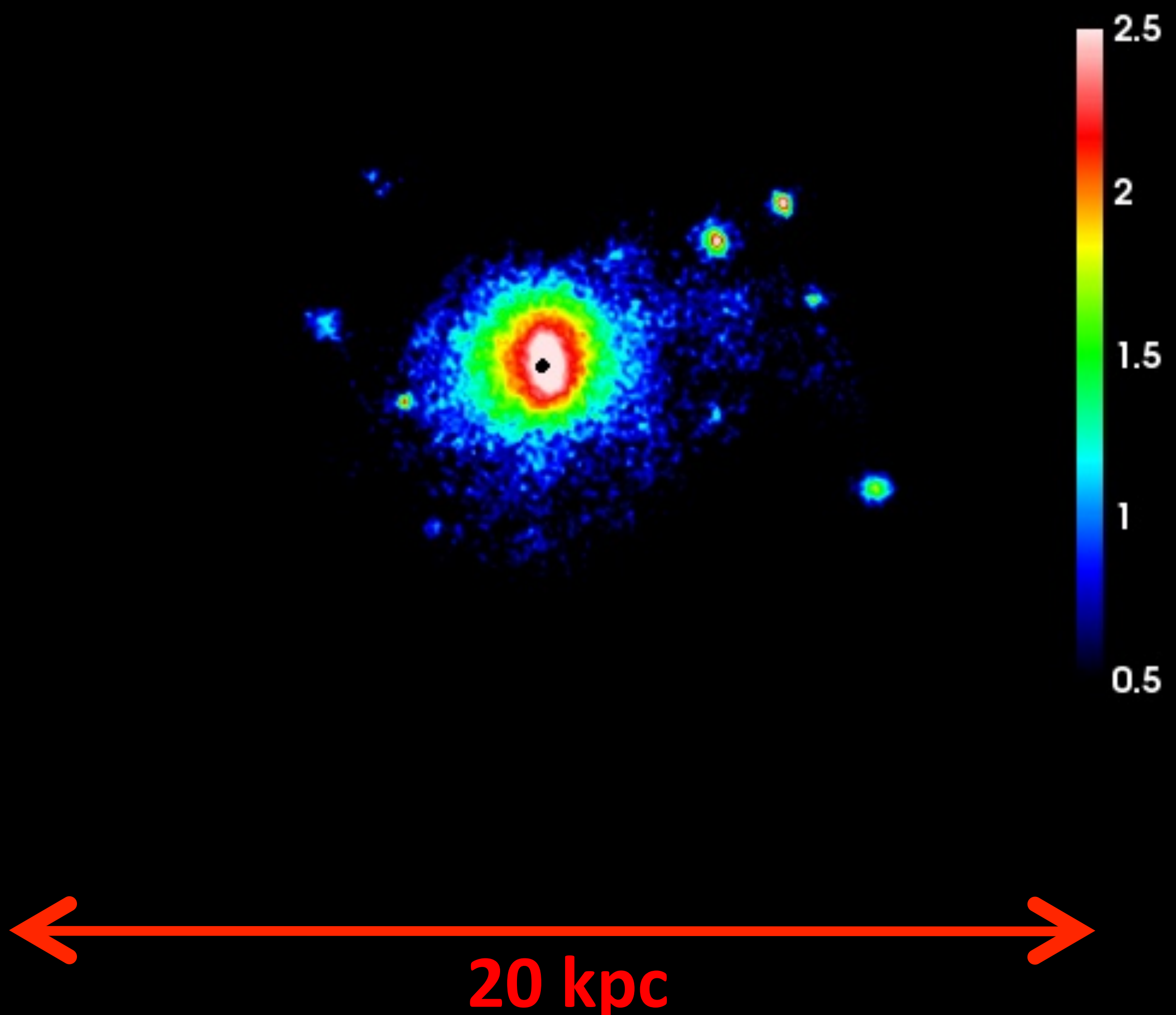
Gas face-on

Gas edge-on

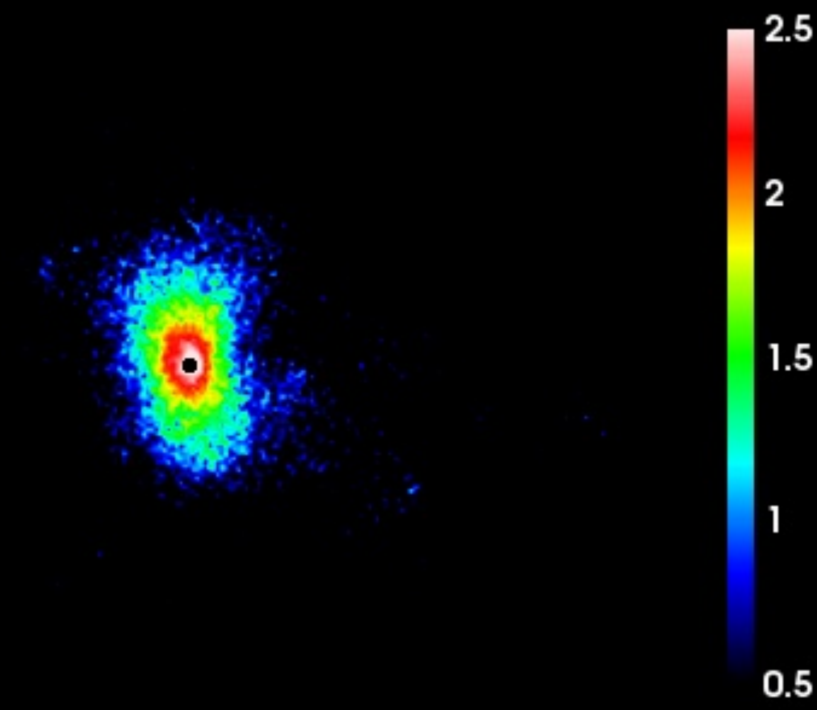
Daniel Ceverino

Stars face-on

Without radiation pressure

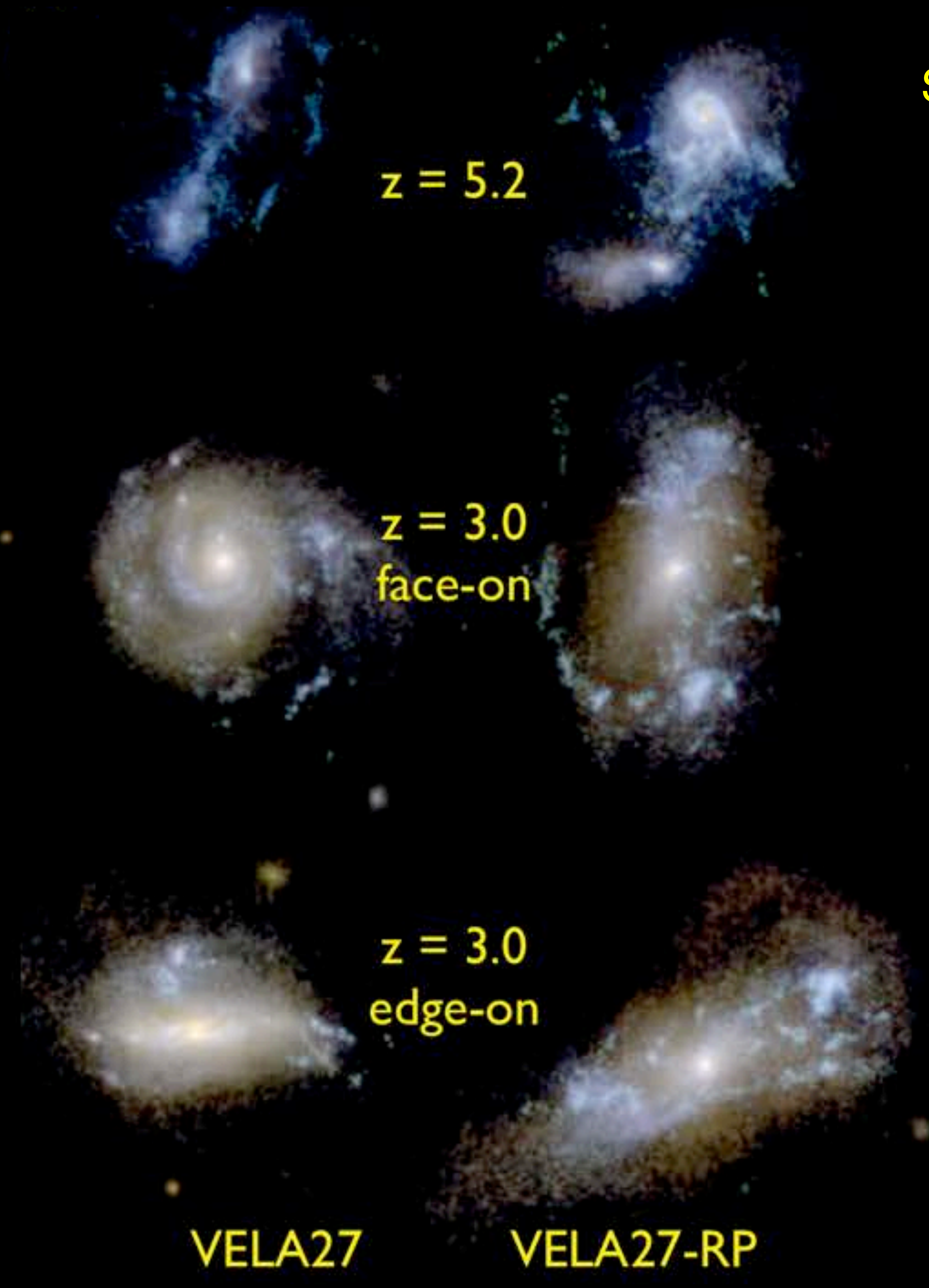


With radiation pressure



Daniel Ceverino

Simulation without Radiation Pressure feedback



Same Simulation with Radiation Pressure feedback

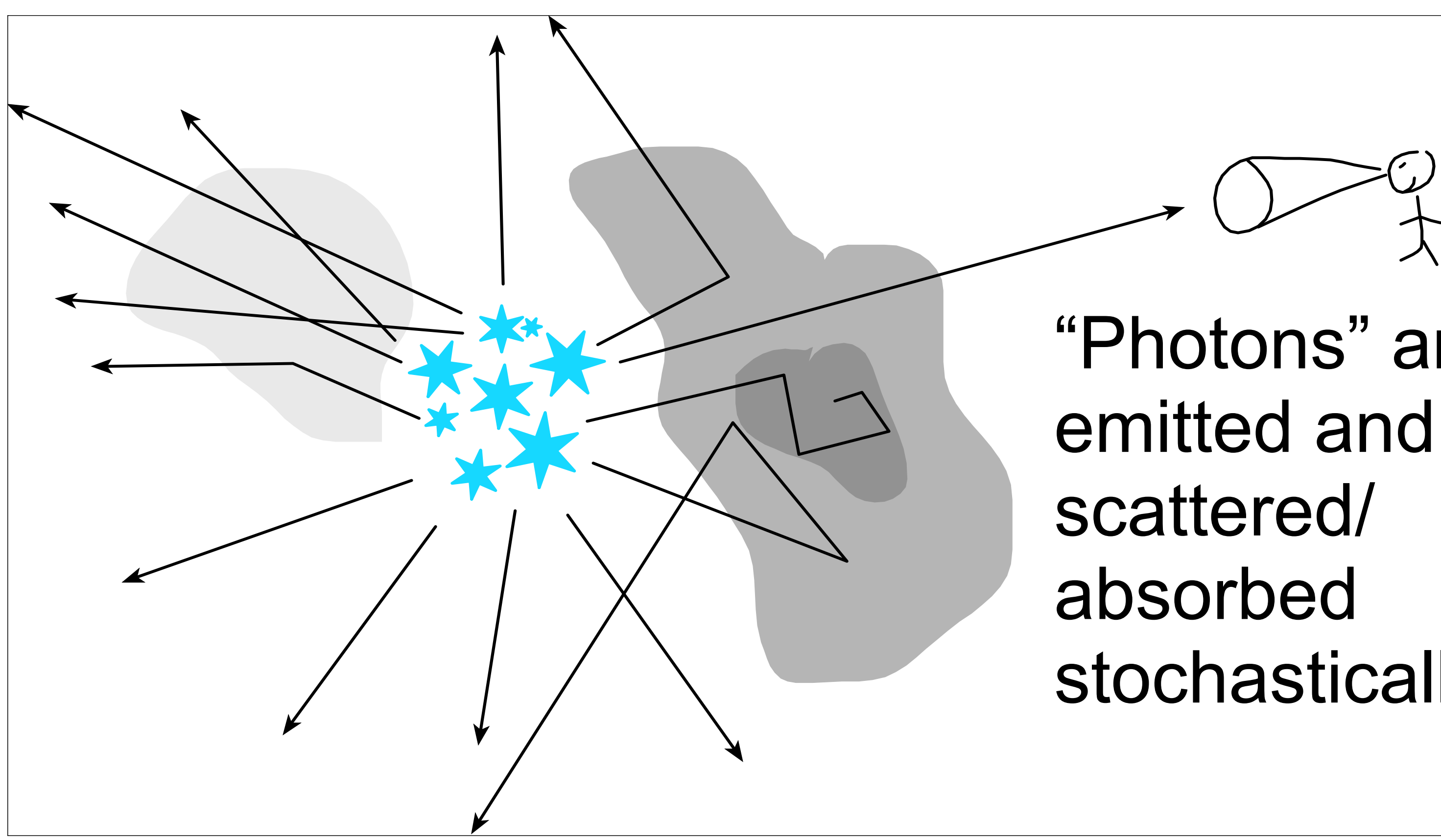
CANDELS paper in preparation: galaxy elongation observed

Sunrise Radiative Transfer Code

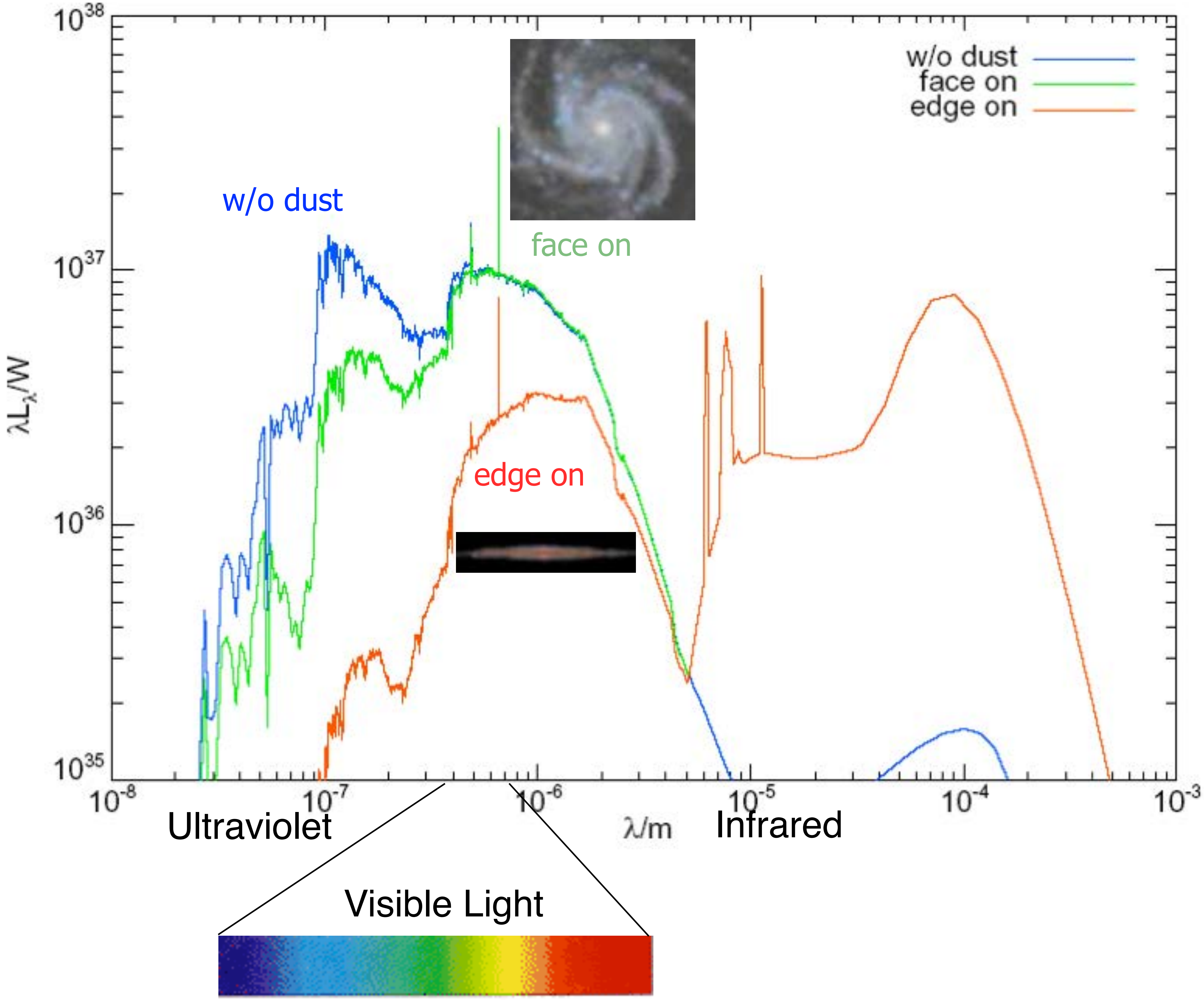
Patrik Jonsson
& Joel Primack

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

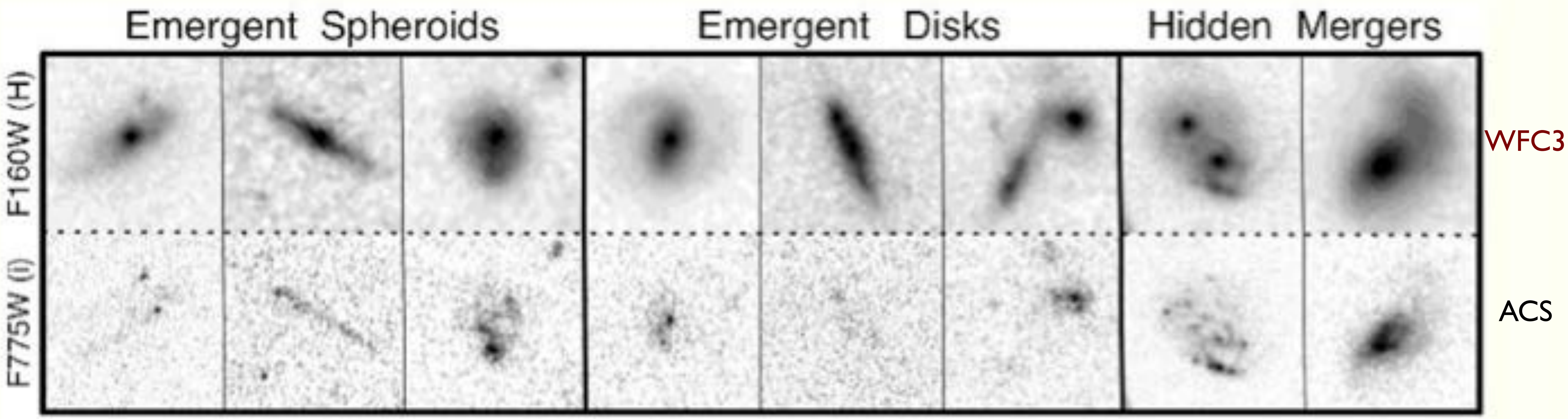


Spectral Energy Distribution



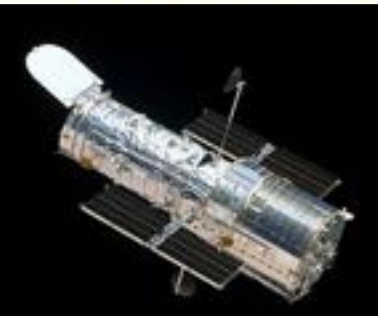
The CANDELS Survey with new near-IR camera WFC3

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

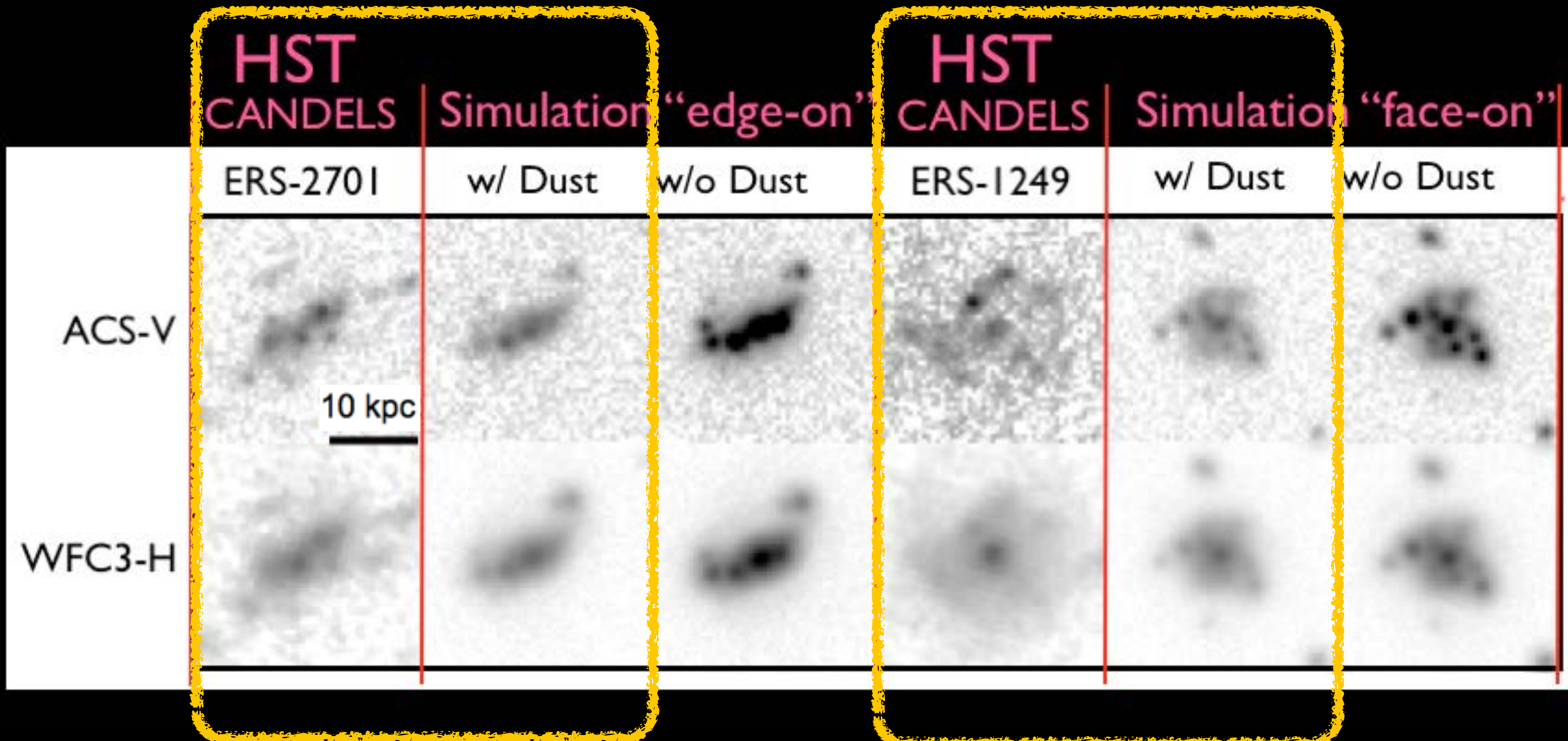


http://candels.ucolick.org

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

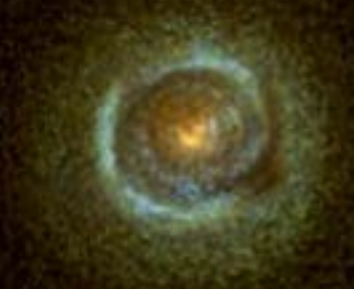
- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared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

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

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

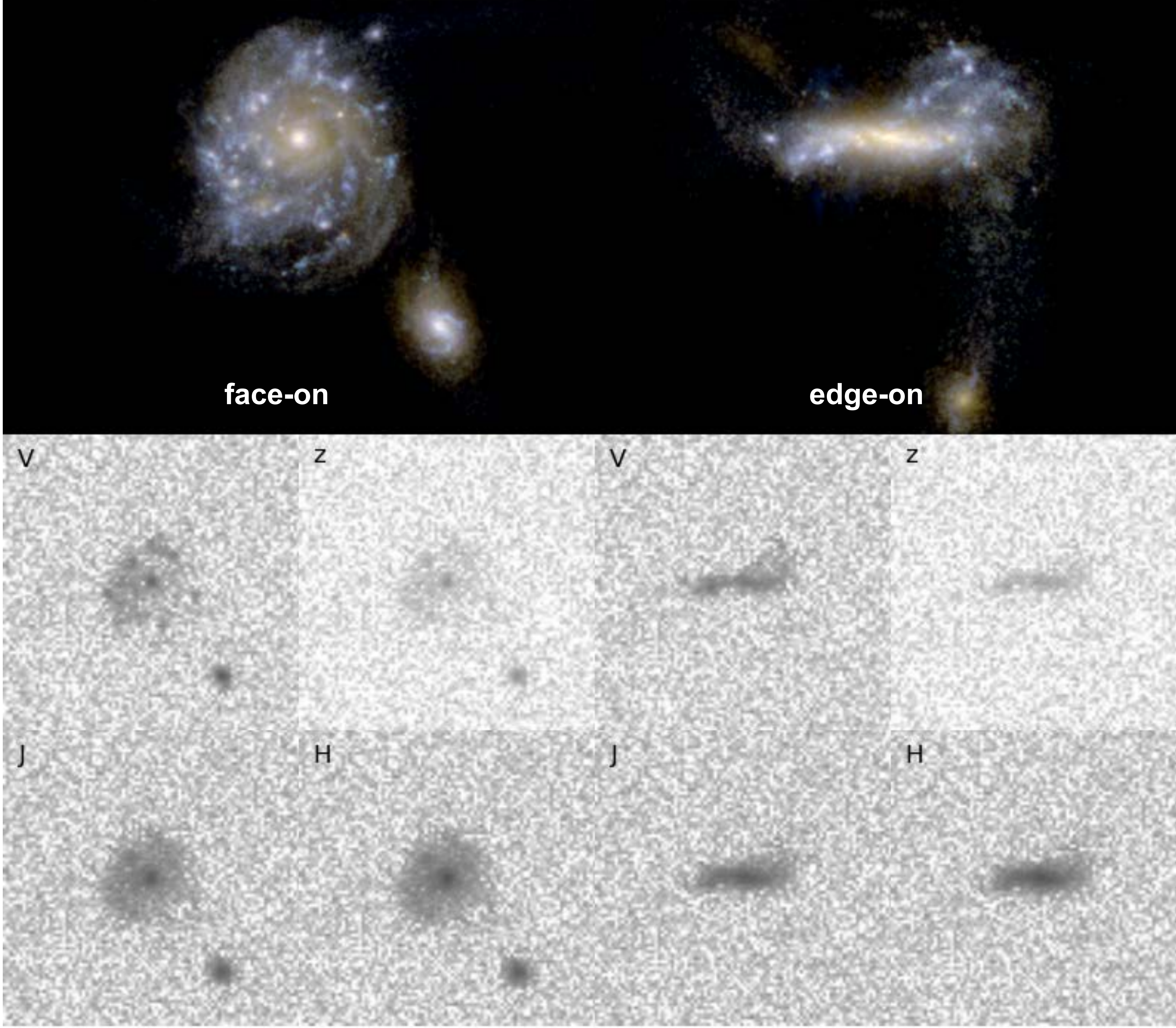
cemoody.imgur.com

Simulated Galaxy 10 billion years ago

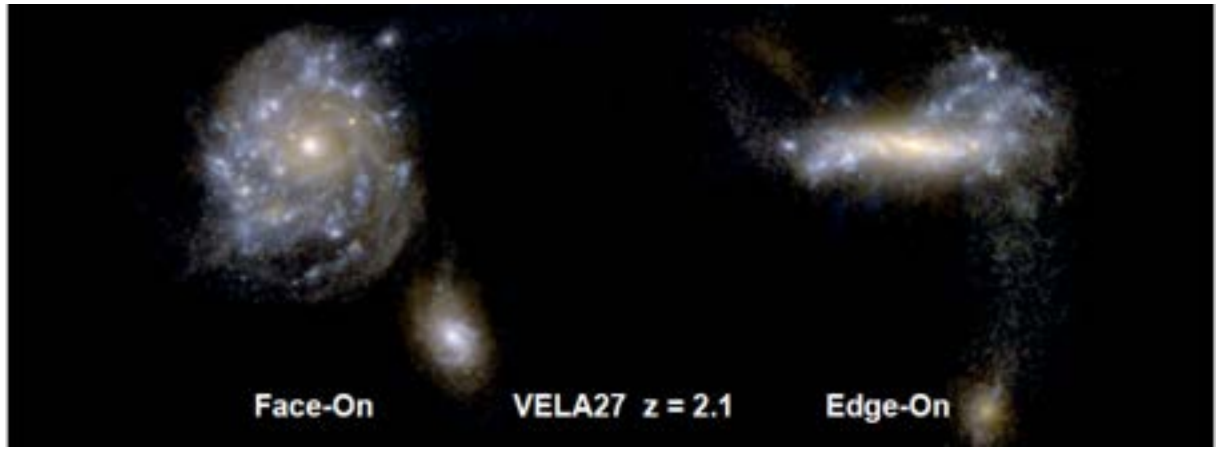
as it would appear nearby to our eyes

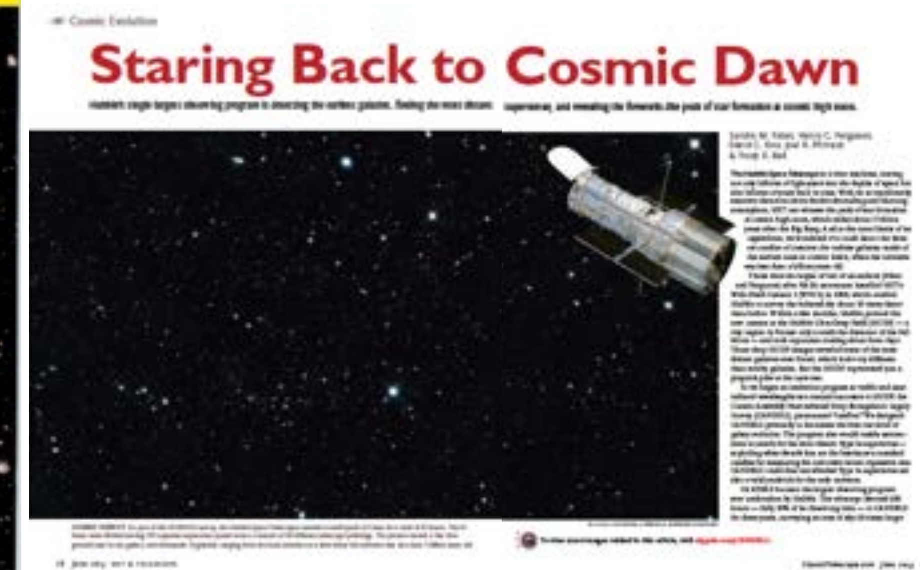
as it would appear to Hubble's ACS visual camera

as it would appear to Hubble's WFC3 infrared camera

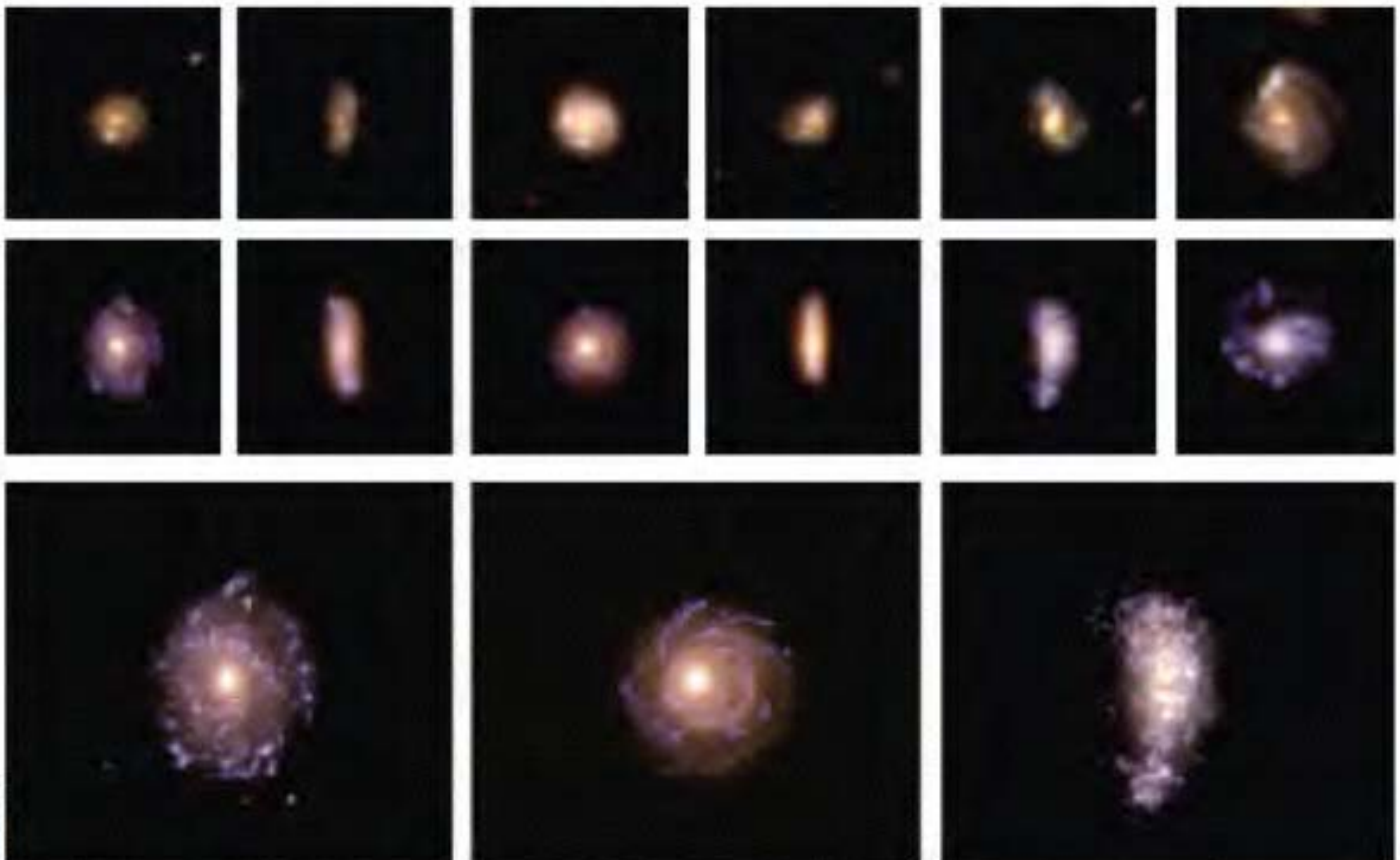


High-resolution Sunrise Images



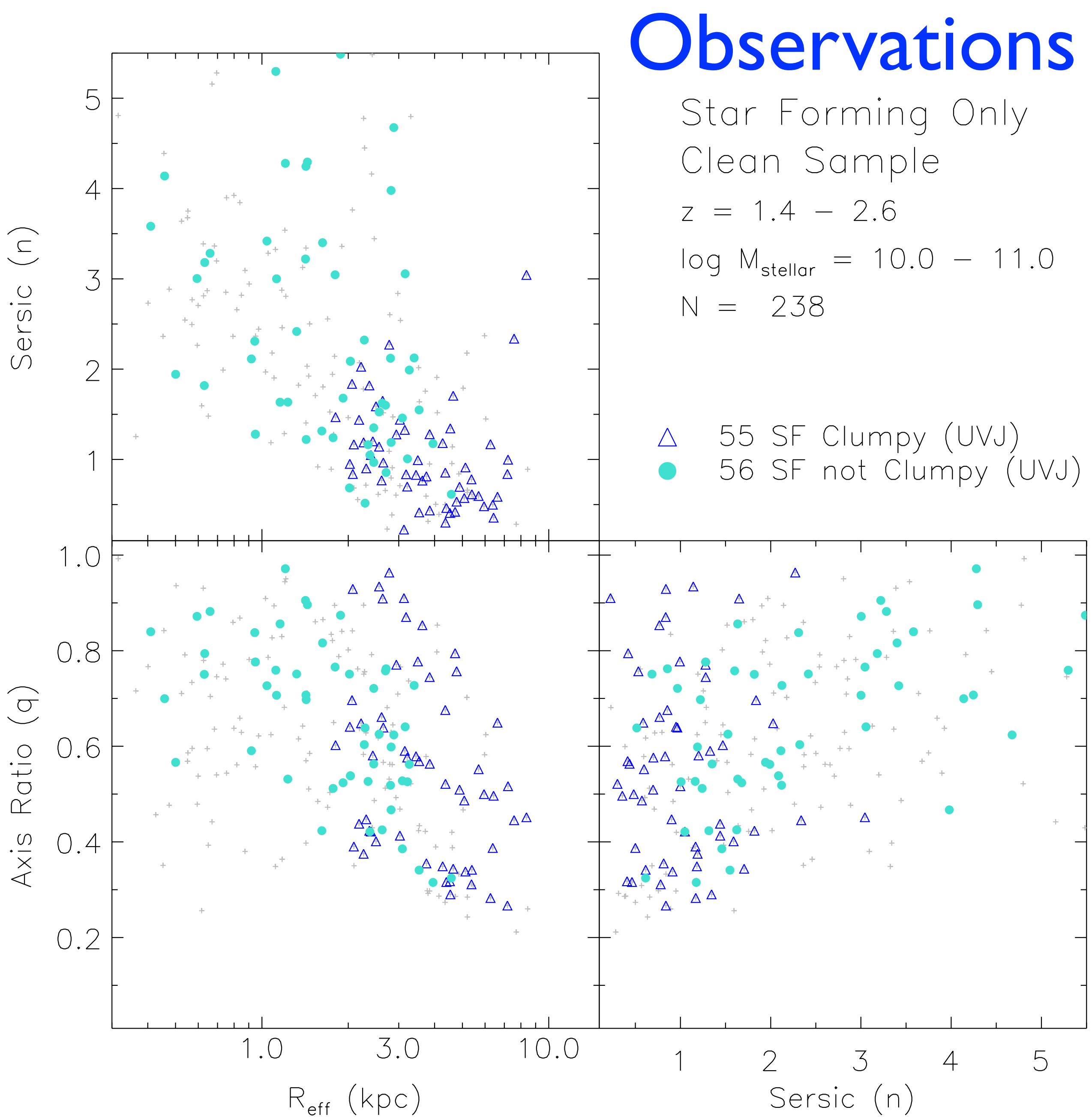


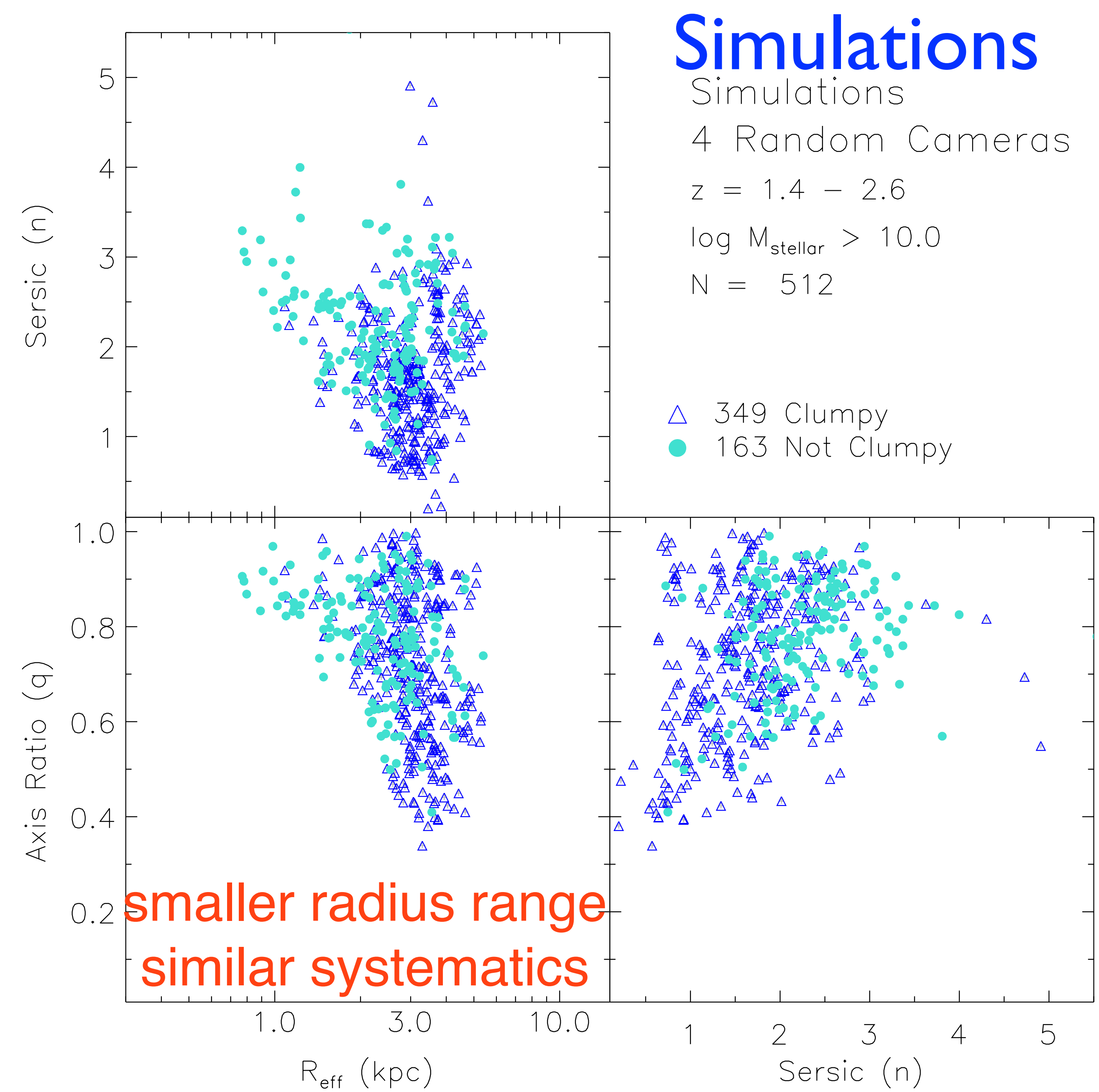
From June 2014 *Sky & Telescope* article



CLUMPY GALAXIES
Top row: Six galaxies from CANDELS are seen when the universe was 4 to 6 billion years old. *Middle row:* These computer simulation frames show three disk galaxies as if imaged by CANDELS when viewed roughly face-on (*left of pair*) and edge-on (*right*). *Bottom row:* This is how these galaxies would appear if we could see them closer up from one angle. All three are about 4 billion years old and have large clumps of rapidly forming stars ignited by instabilities in their disks.

CANDELS Galaxies Compared with Generations 1 & 2 hydroART simulations using R_{eff}, Axis Ratio q, Sersic n, with clumpy vs. not clumpy from by-eye classification

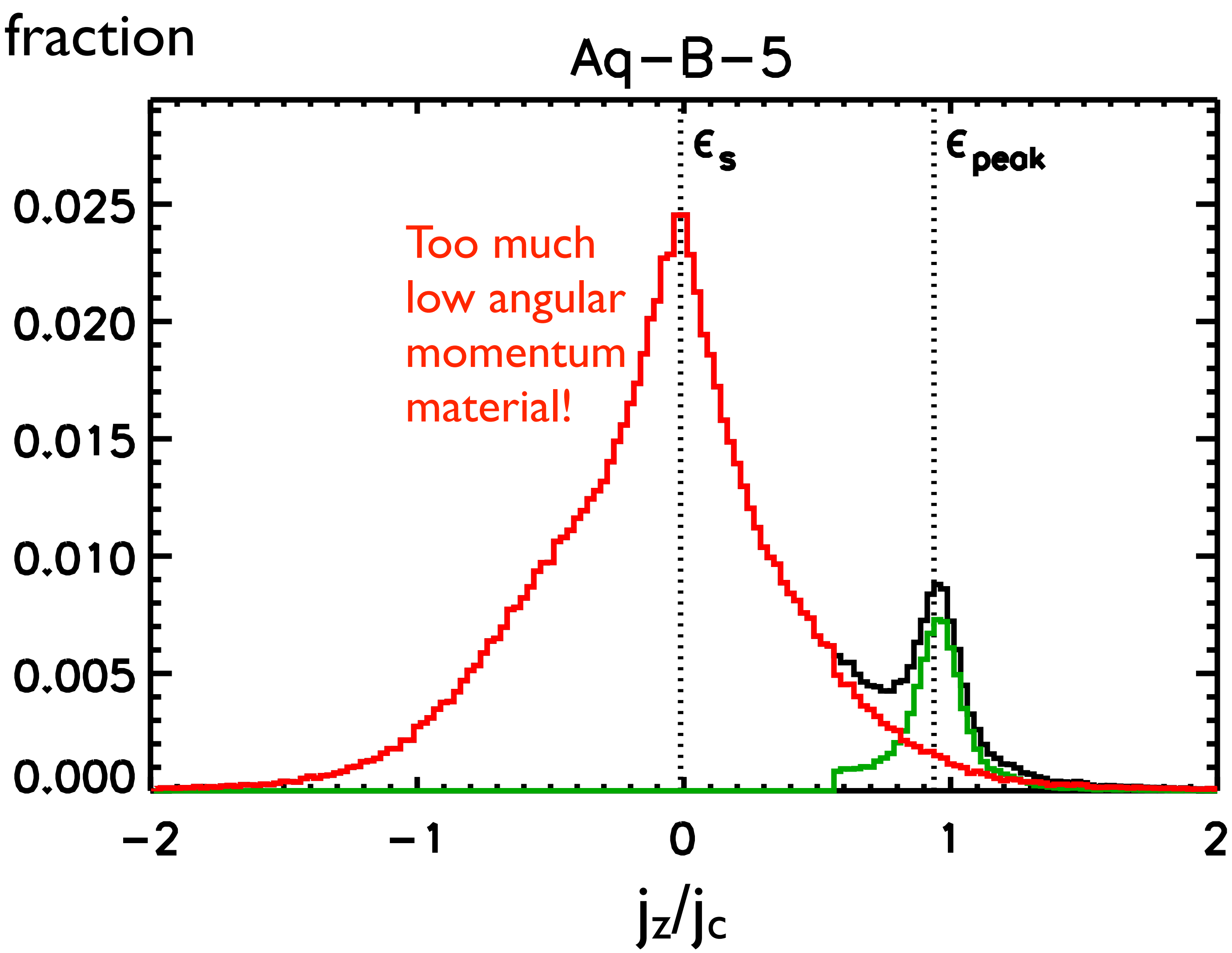




Mark Mozena (in prep)

The Angular Momentum Catastrophe

In practice it is not trivial to form galaxies with massive, extended disks and small spheroids. The angular momentum content of the disk determines its final structure.



≠

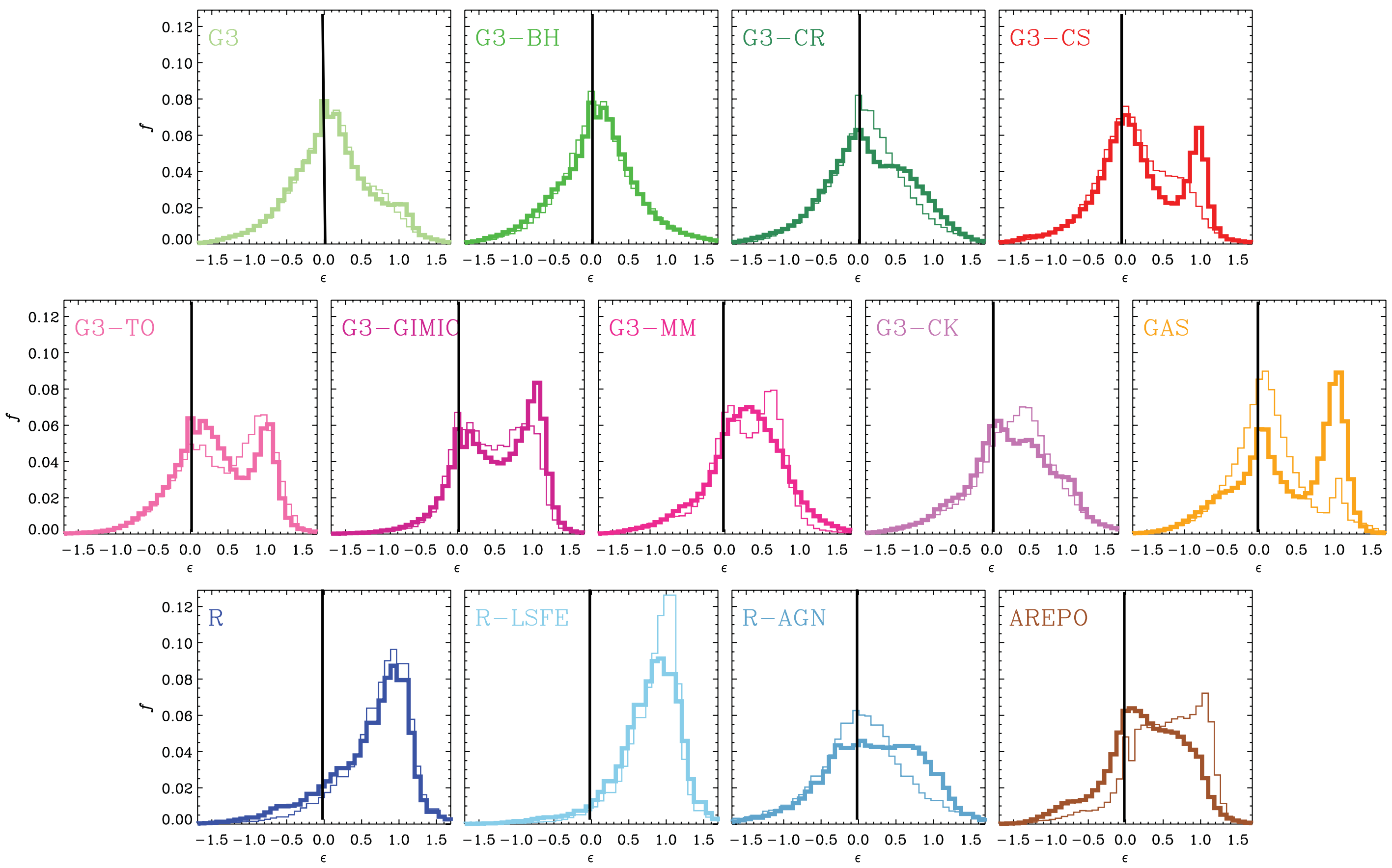
Scannapieco et al. 2009

angular momentum / ang mom needed for rotational support

The Angular Momentum Catastrophe

In practice it is not trivial to form galaxies with massive, extended disks and small spheroids. The angular momentum content of the disk determines its final structure. None of the 2012 Aquila low-resolution galaxy simulations had realistic disks.

fraction of stars with given angular momentum



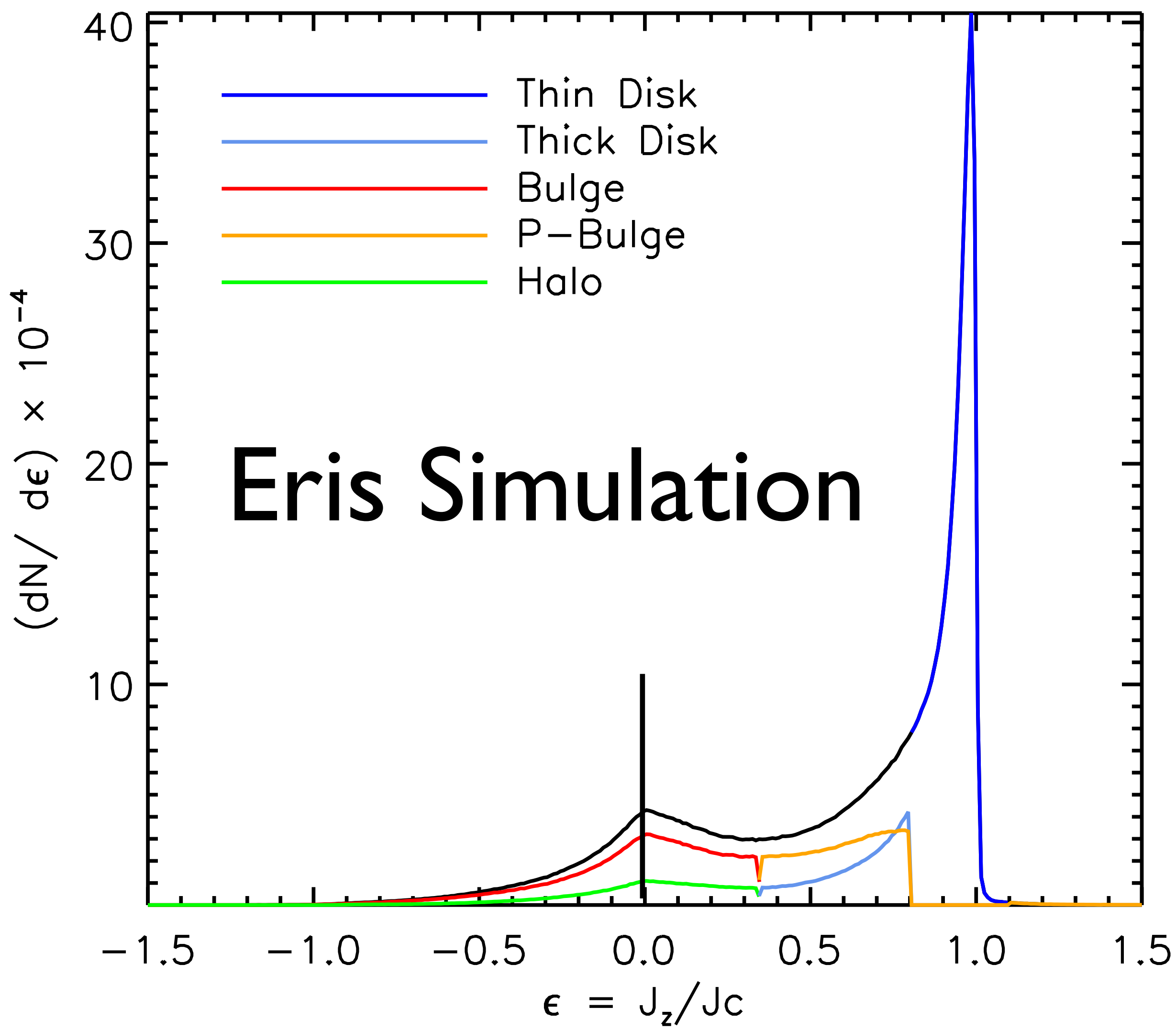
jz/jc

≠

Scannapieco et al., Aquila Galaxy Simulation Comparison, 2012

The Angular Momentum ~~Catastrophe~~

Eris, the first high-resolution simulation of formation of a ~10^{12} $M_\odot$ galaxy, produced a realistic spiral galaxy. Adequate resolution and physically realistic feedback appear to be sufficient.



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Guedes, Callegari, Madau, Mayer 2011 ApJ

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

Ji-hoon Kim, UCSC (Coordinator)

105 astrophysicists using 11 codes have joined AGORA

www.AGORAsimulations.org

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)

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

AstroComputing is Prototypical Scientific Computing

Astronomy has several advantages:

The data tends to be pretty clean

The data is (mostly) non-proprietary

The research is (mostly) funded

The data is pretty sexy

There's a lot of public involvement:

Big Challenges of AstroComputing

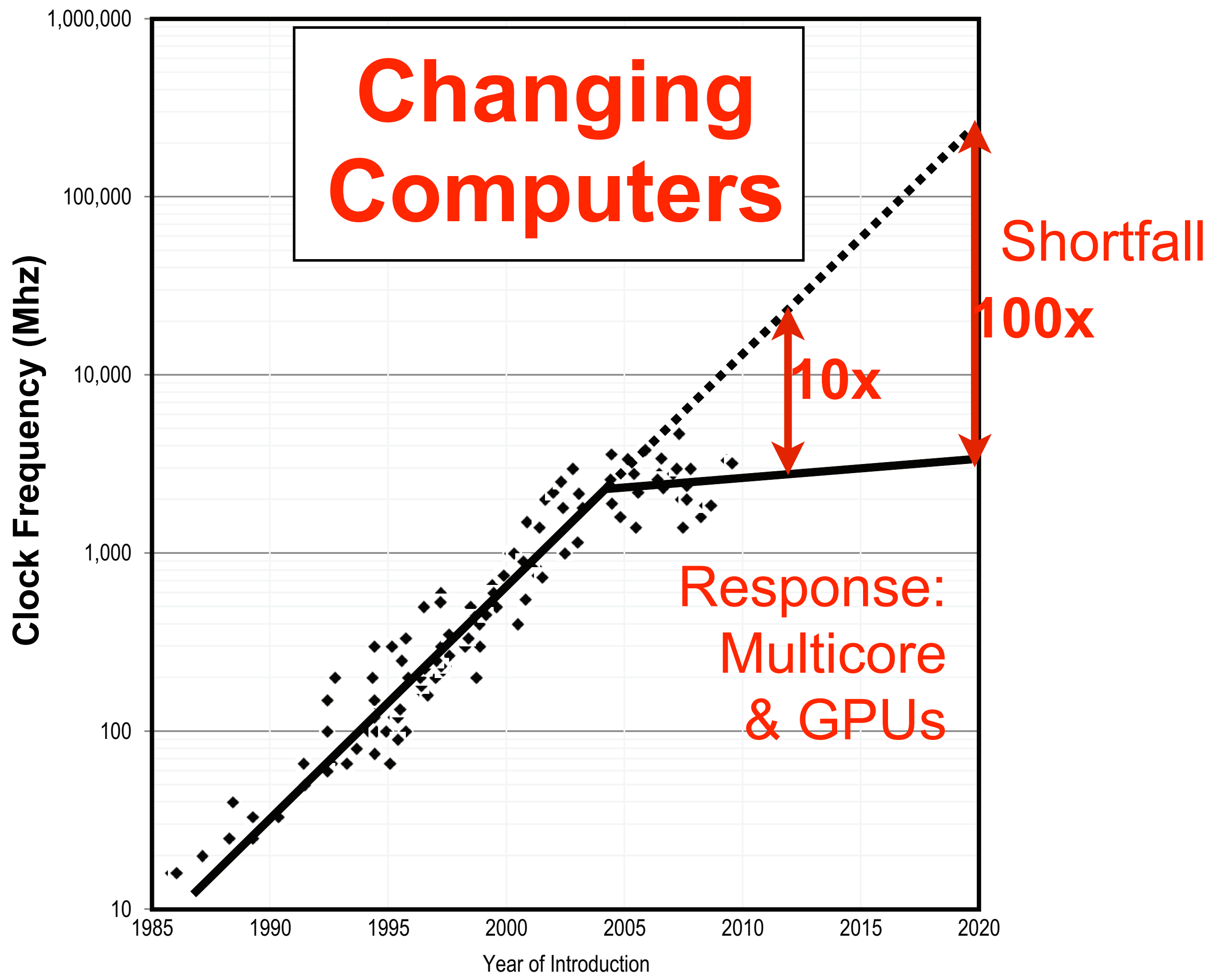
Big Data

Sloan Digital Sky Survey (SDSS) 2008
- 2.5 Terapixels of images
- 40 TB raw data ➠120 TB processed
- 35 TB catalogs

Mikulski Archive for Space Telescopes (MAST) 2013
- 185 TB of images
- 25 TB/year ingest rate
- >100 TB/year retrieval rate

Large Synoptic Survey Telescope (LSST) 2019
- 15 TB per night for 10 years
- 100 PB image archive
- 20 PB final database catalog

Square Kilometer Array (SKA) ~2024
- 1 EB per day (~ internet traffic today)
- 100 PFlop/s processing power
- ~1 EB processed data/year



Increasingly inhomogeneous computers are harder to program! We need computational scientists and engineers and new compilers that generate code for nodes with cores+accelerators with automatic load balancing and fault tolerance.

High Performance Scientific Computing Needs

The challenges facing us are

- "Big data" -- too large to move -- from more powerful observations, larger computer outputs, and falling storage costs
- Changing high-performance computer architecture -- from networked single processors to multicore and GPUs

These challenges demand new collaborations between natural scientists and computer scientists to develop

- Tools and scientific programmers to convert legacy code and write new codes efficient on multicore/GPU/MIC architectures, including fault tolerance and automatic load balancing
- New ways to visualize and analyze big data remotely
- Train new generations of scientific & engineering computer users
- Improve education and outreach

UC-HiPACC is proposing a California Scientific Computing Institute in Silicon Valley to work on these issues -- we welcome collaboration!

Double Dark Theory Successes

- Predicted Cosmic Background Radiation
- Predicted Large Scale Galaxy Distribution
- Predicted Abundance of Big Satellite Galaxies
- Explains Main Properties of Spiral & Elliptical Galaxies

Big Remaining Questions

- Nature of Dark Matter and Dark Energy
- Explanation of the Proportions of DE, DM, "Baryons"
- Galaxy Formation and Evolution in Detail
- Galaxy Details: Cusp-Core, Satellites, Substructure
- Supercomputing the Universe Challenges

Thanks!

Supercomputing the Universe

Joel R. Primack, UCSC

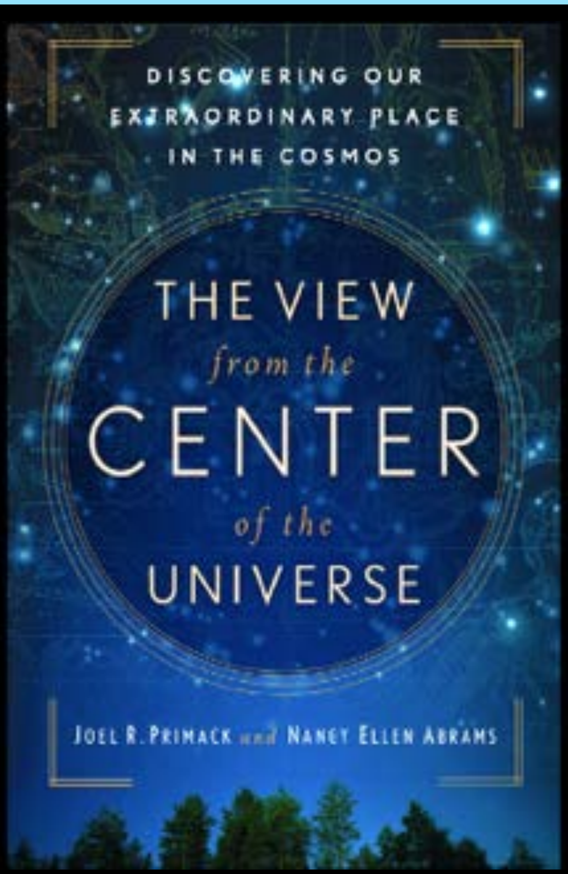
http://scipp.ucsc.edu/personnel/profiles/primack.html

Websites related to this talk:

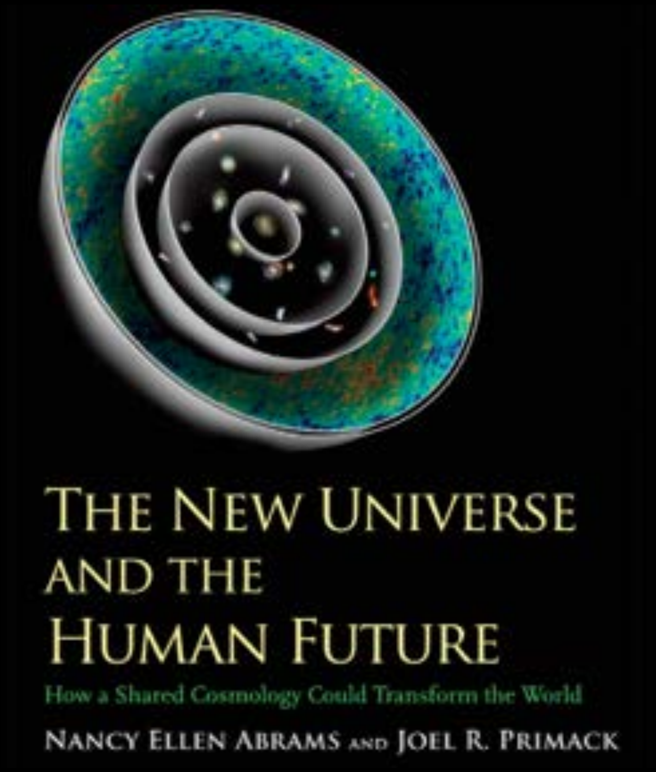
http://hipacc.ucsc.edu University of California High-Performance AstroComputing Center (UC-HiPACC)
http://hipacc.ucsc.edu/v4/ International Astronomy Visualization Gallery
http://hipacc.ucsc.edu/Bolshoi Bolshoi simulations
http://candels.ucolick.org CANDELS survey
http://code.google.com/p/sunrise/ Sunrise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

Nancy Abrams & Joel Primack Book Websites with images and videos:

ViewfromtheCenter.com



New-Universe.org



El-Nuevo-Universo.org