Interrogating Methodologies

UCSB April 18, 2014

Exploring Boundaries in Art & Science

Supercomputing the Universe

Joel R. Primack

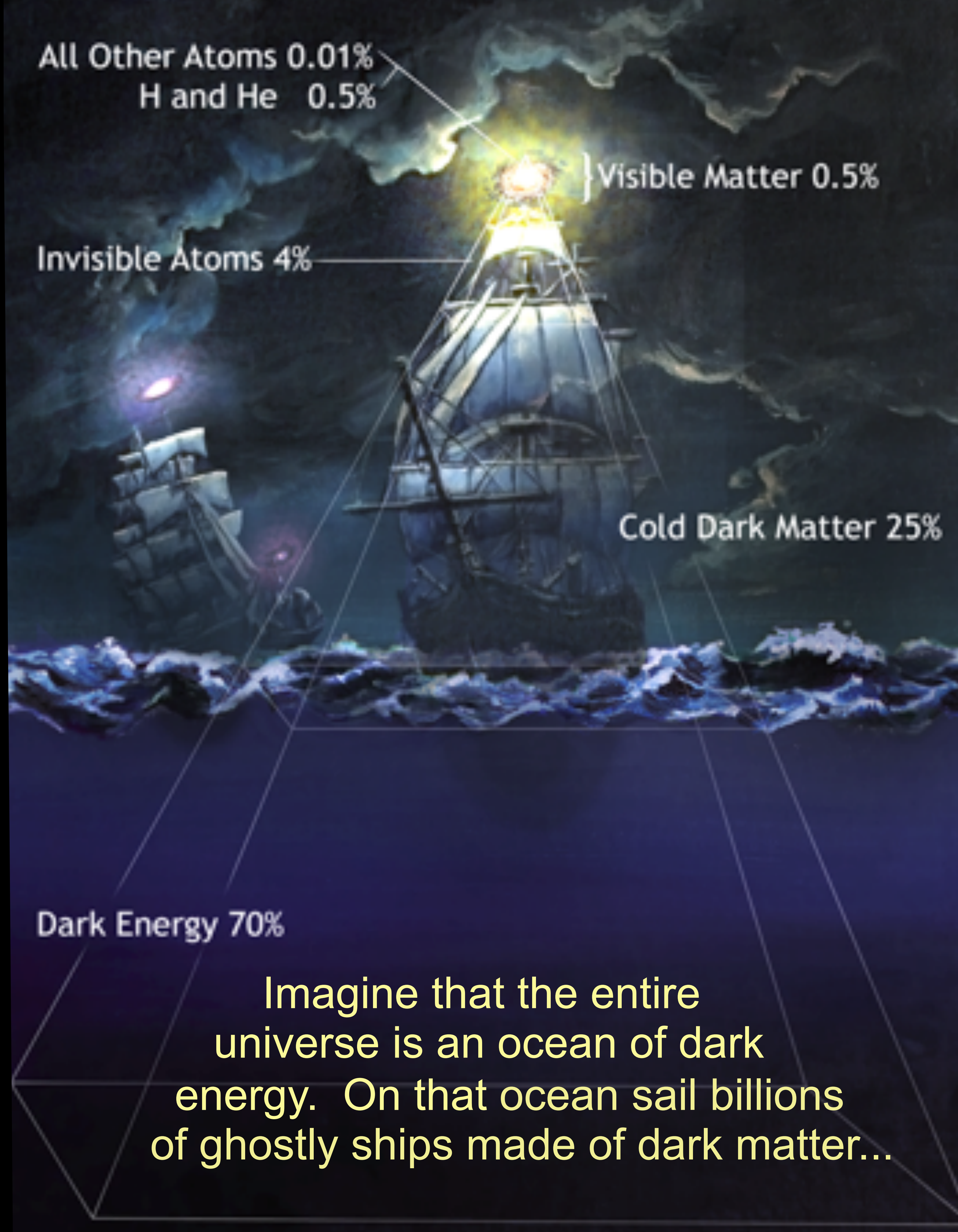
Distinguished Professor of Physics, University of California, Santa Cruz

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

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.

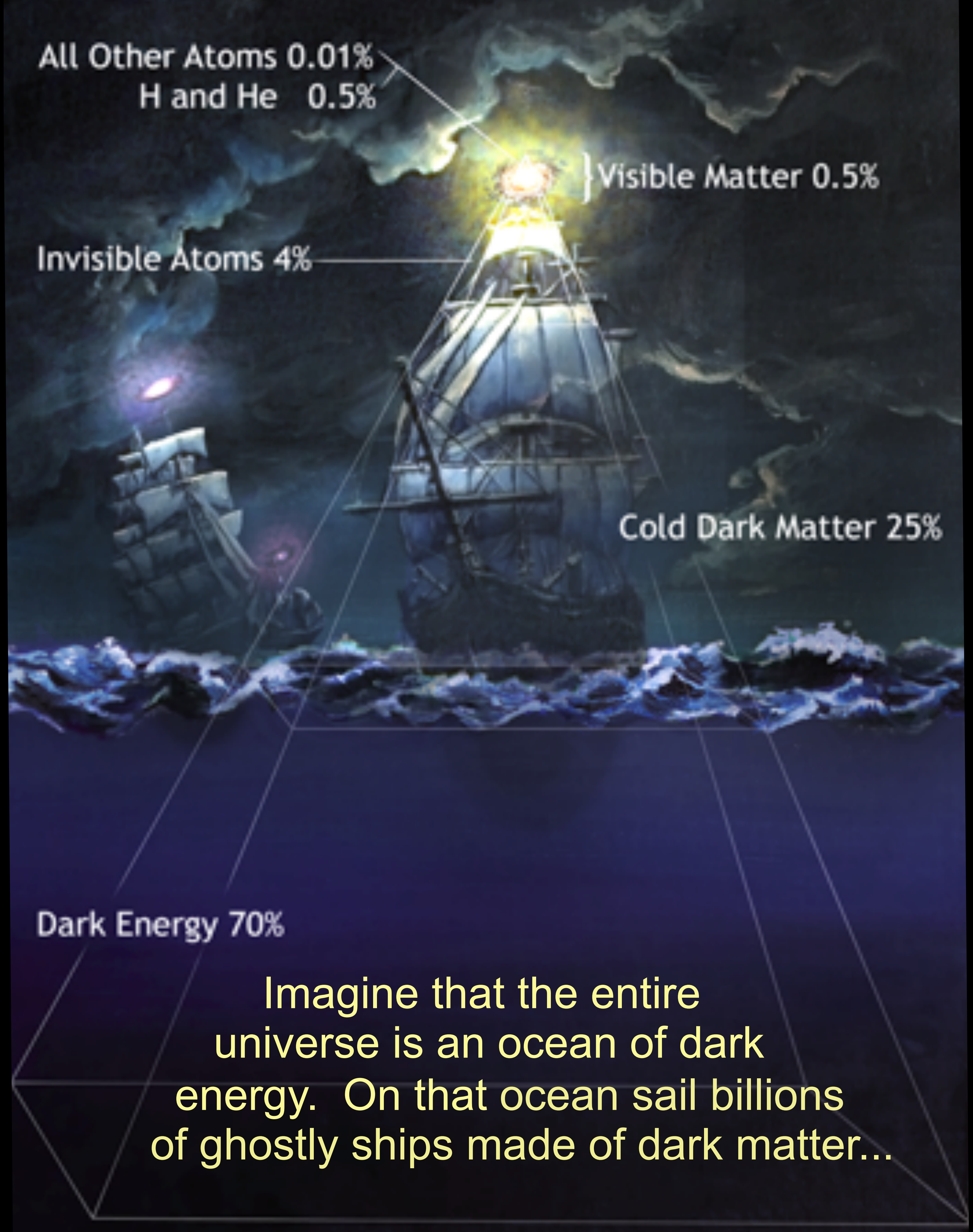
Matter and Energy Content of the Universe



Dark Matter Ships

on a

Dark Energy Ocean



Matter and Energy Content of the Universe

ΛCDM

Double Dark Theory

DARK MATTER + DARK ENERGY = DOUBLE DARK THEORY

Technical Name:
Lambda Cold Dark Matter (ΛCDM)

Cosmology 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.

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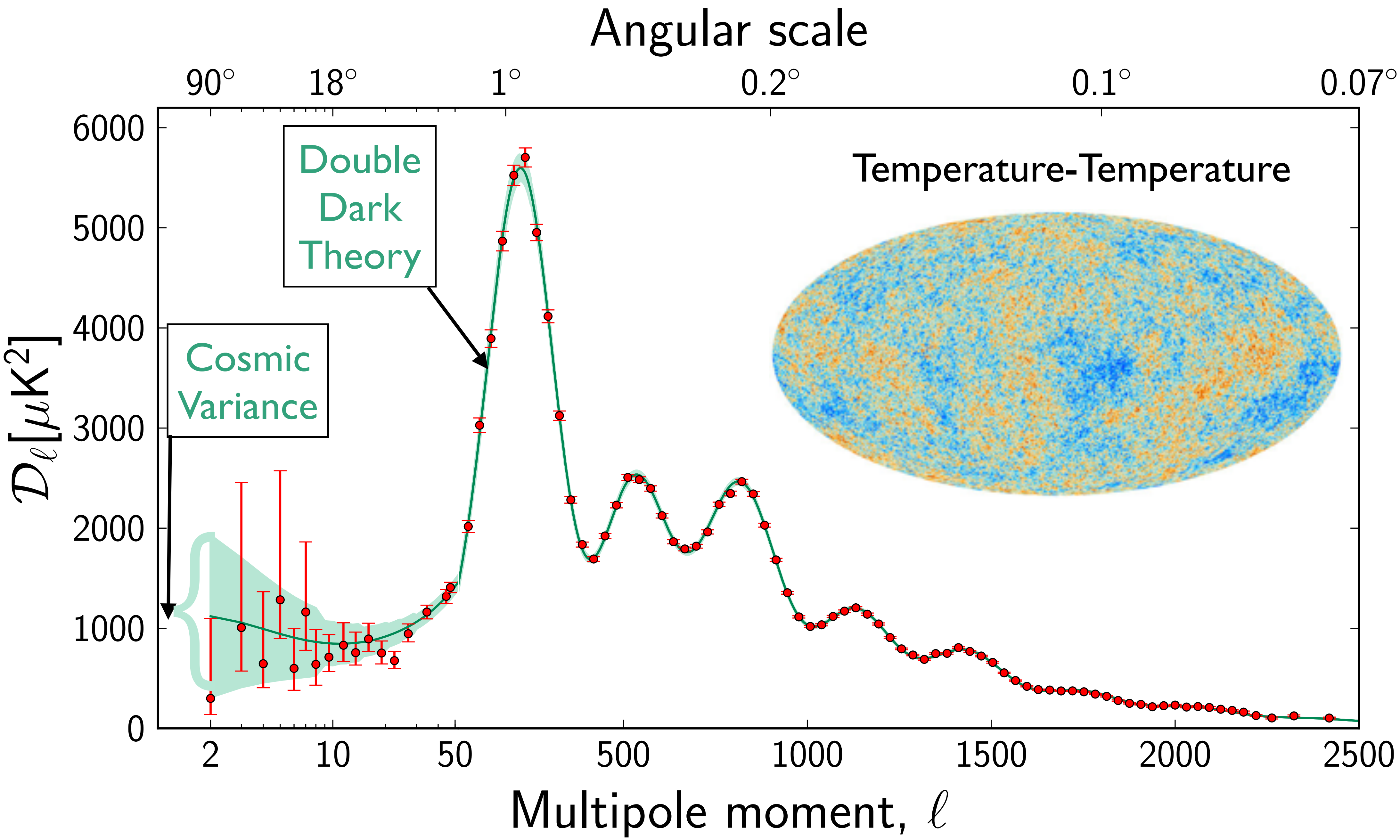
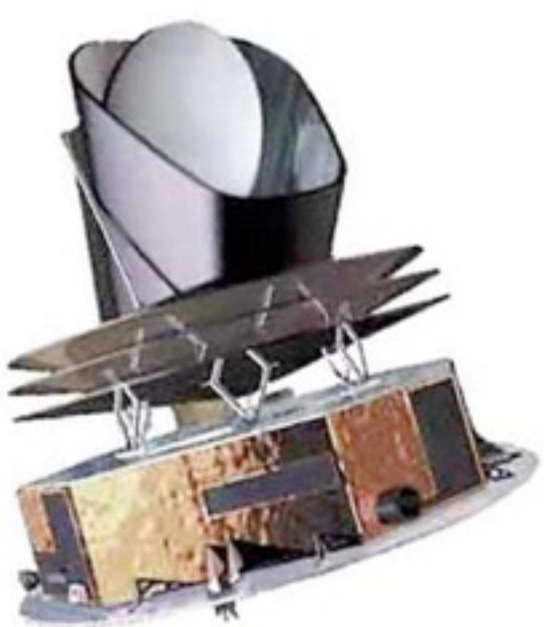
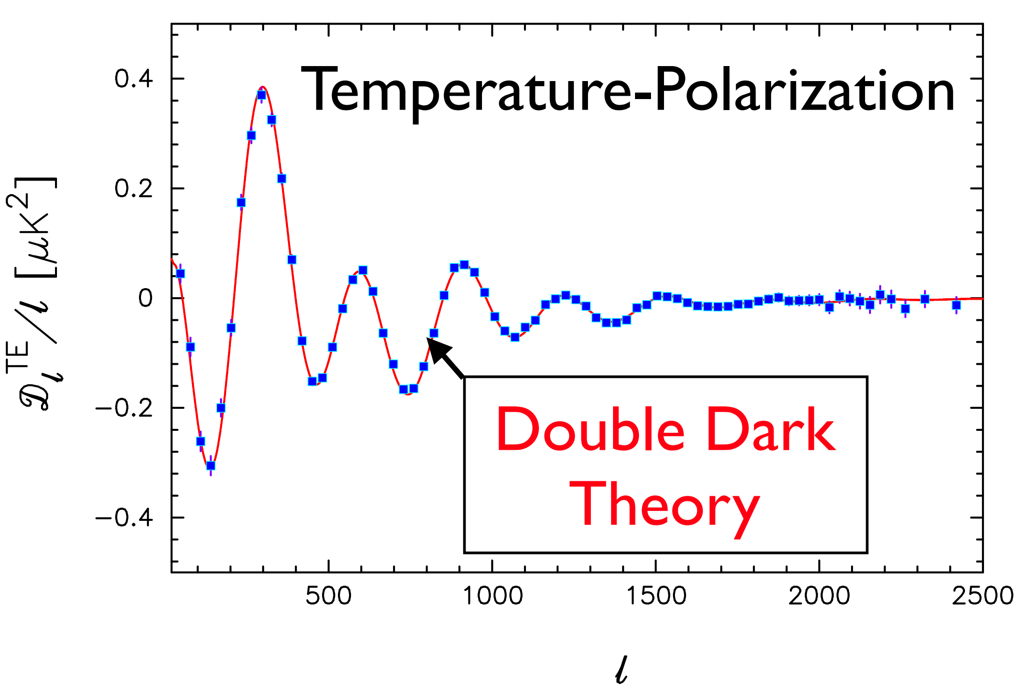
- Starting from the Big Bang, we simulate the evolution of a representative part of the universe according to the Double Dark theory to see if the end result matches what astronomers actually observe.
- On the large scale the simulations produce a universe just like the one we live in. We're always looking for new phenomena to predict — every one of which tests the whole theory!

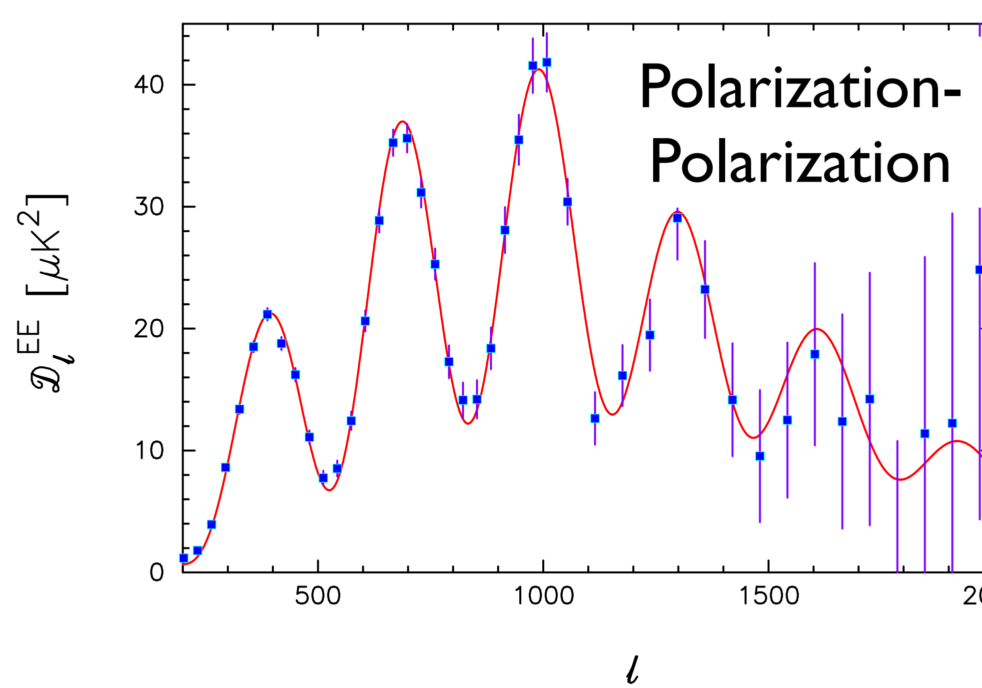
European Space Agency PLANCK Satellite Data

Released March 21, 2013

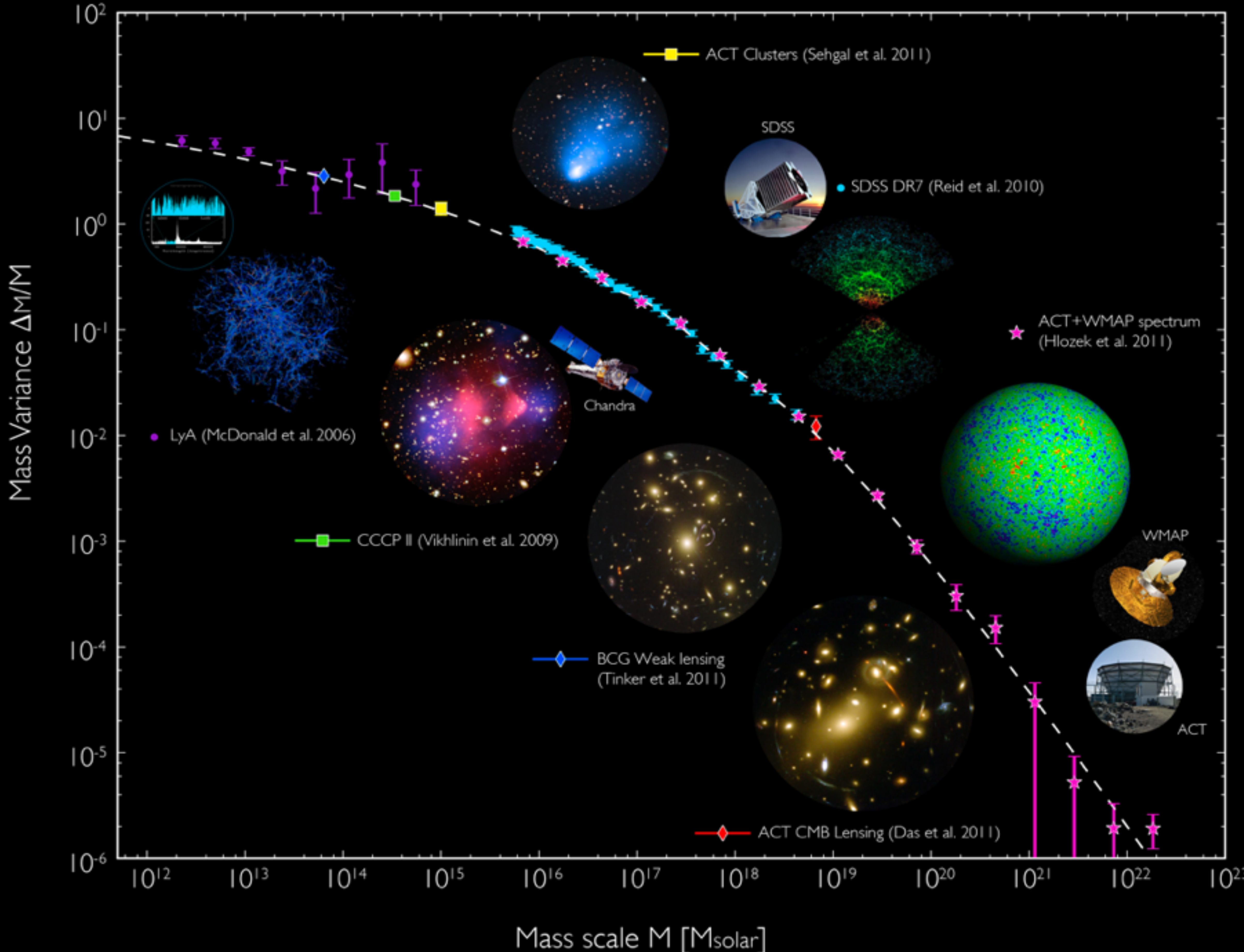








Matter Distribution Agrees with Double Dark Theory!



Cosmology 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

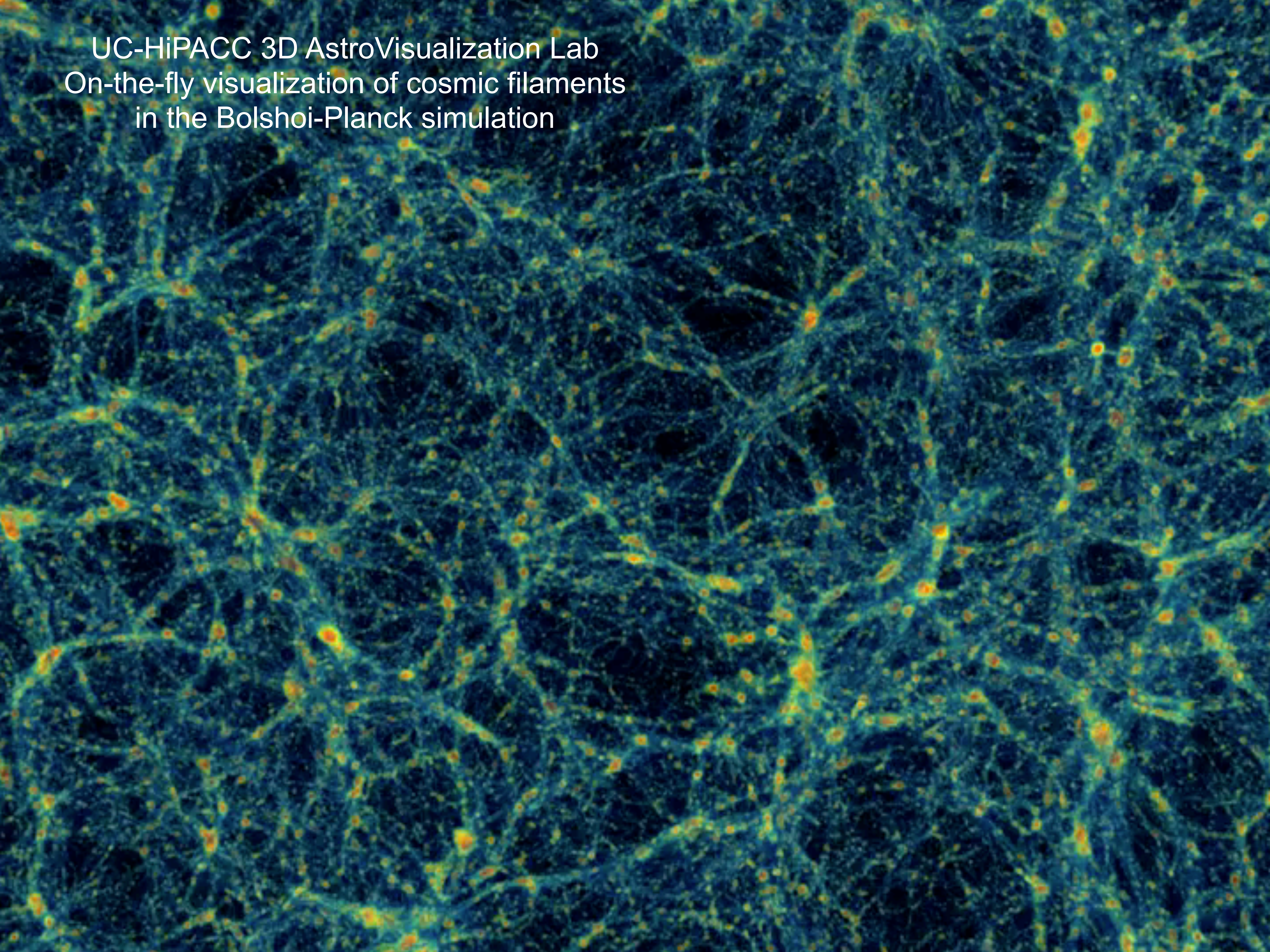
Hydrodynamic galaxy formation simulations: formation and evolution of galaxies, galaxy images in all wavebands and galaxy spectra including stellar evolution and dust effects

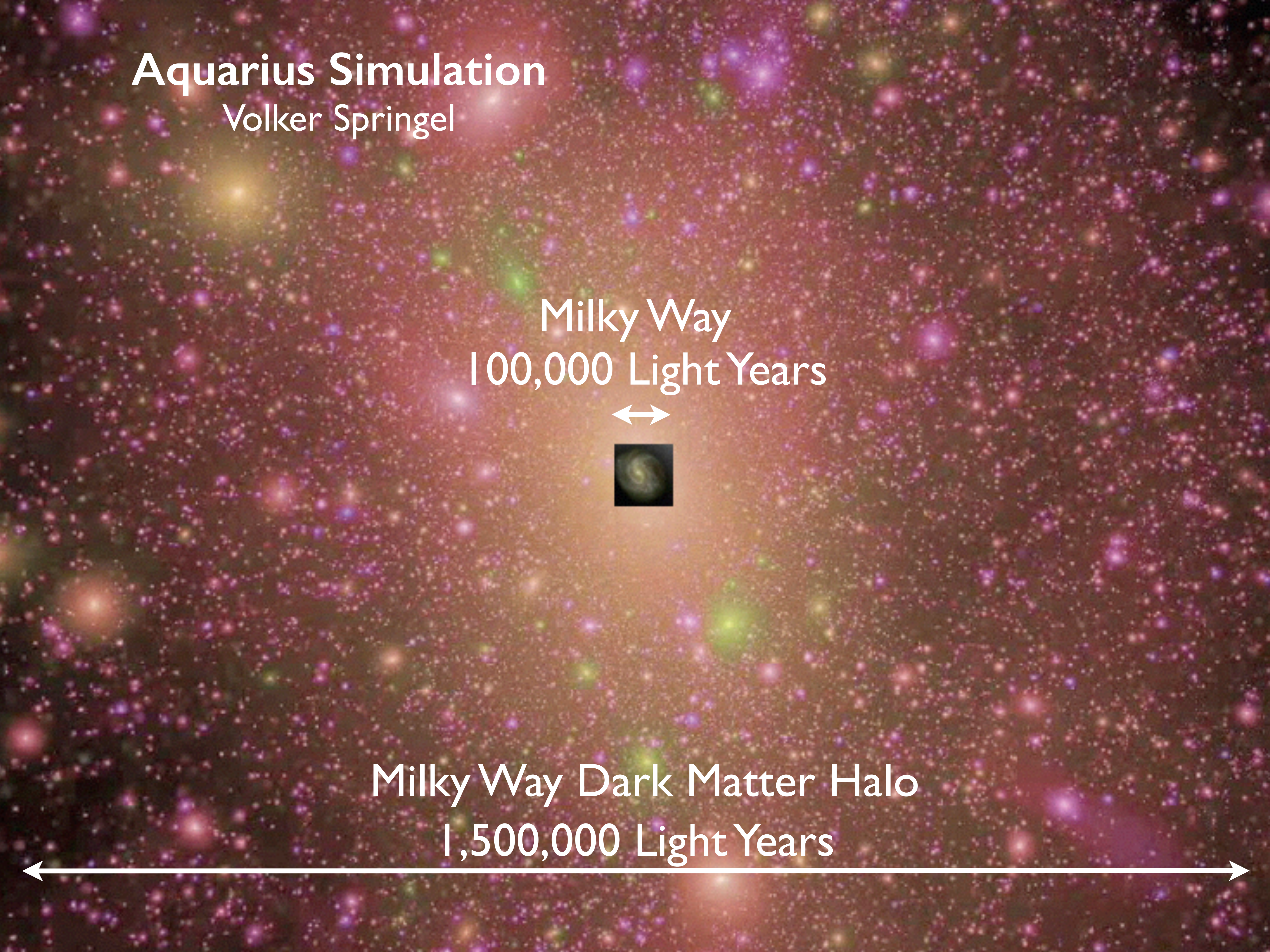
"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

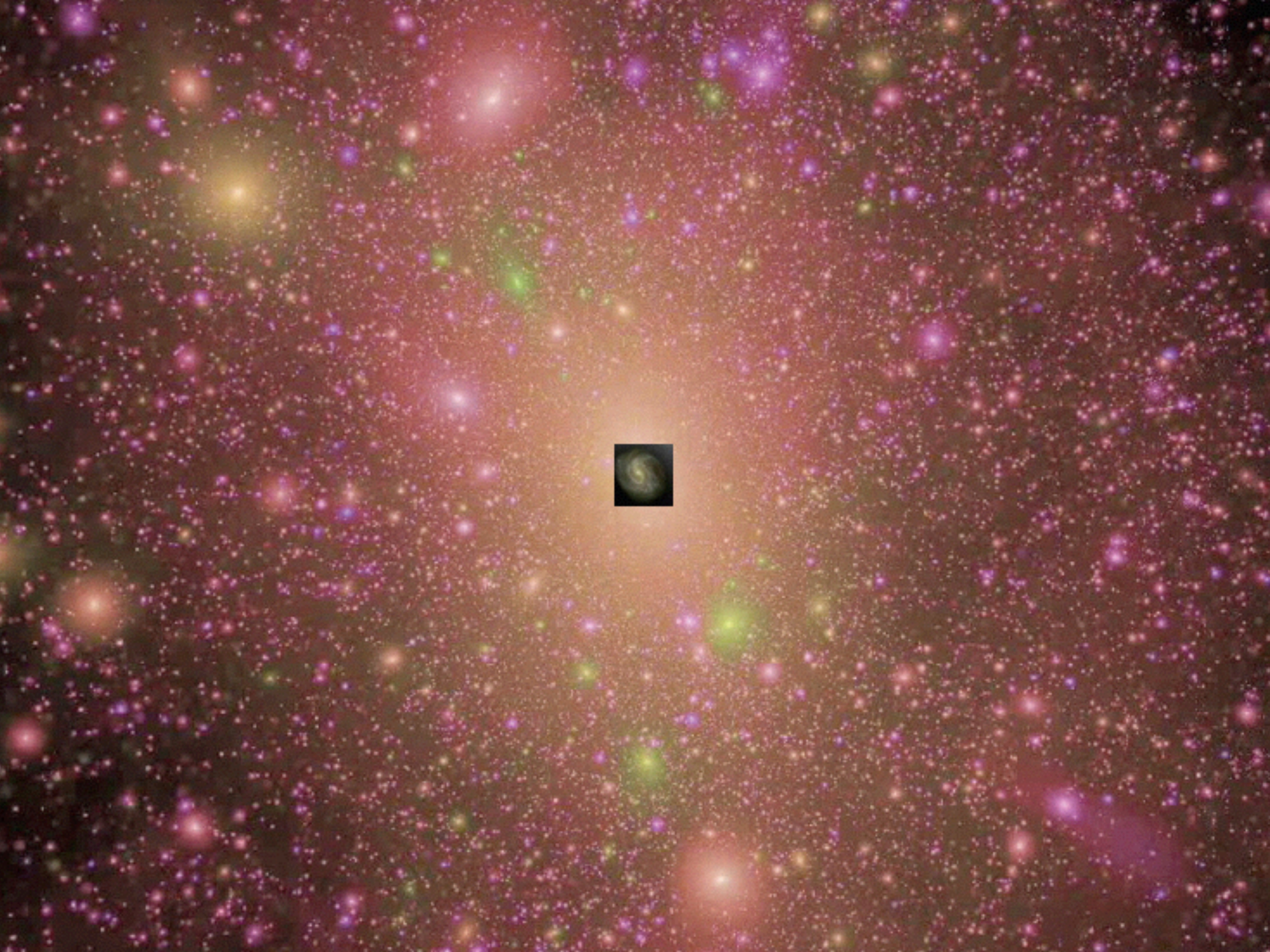
CONSTRAINED LOCAL UNIVERSE SIMULATION

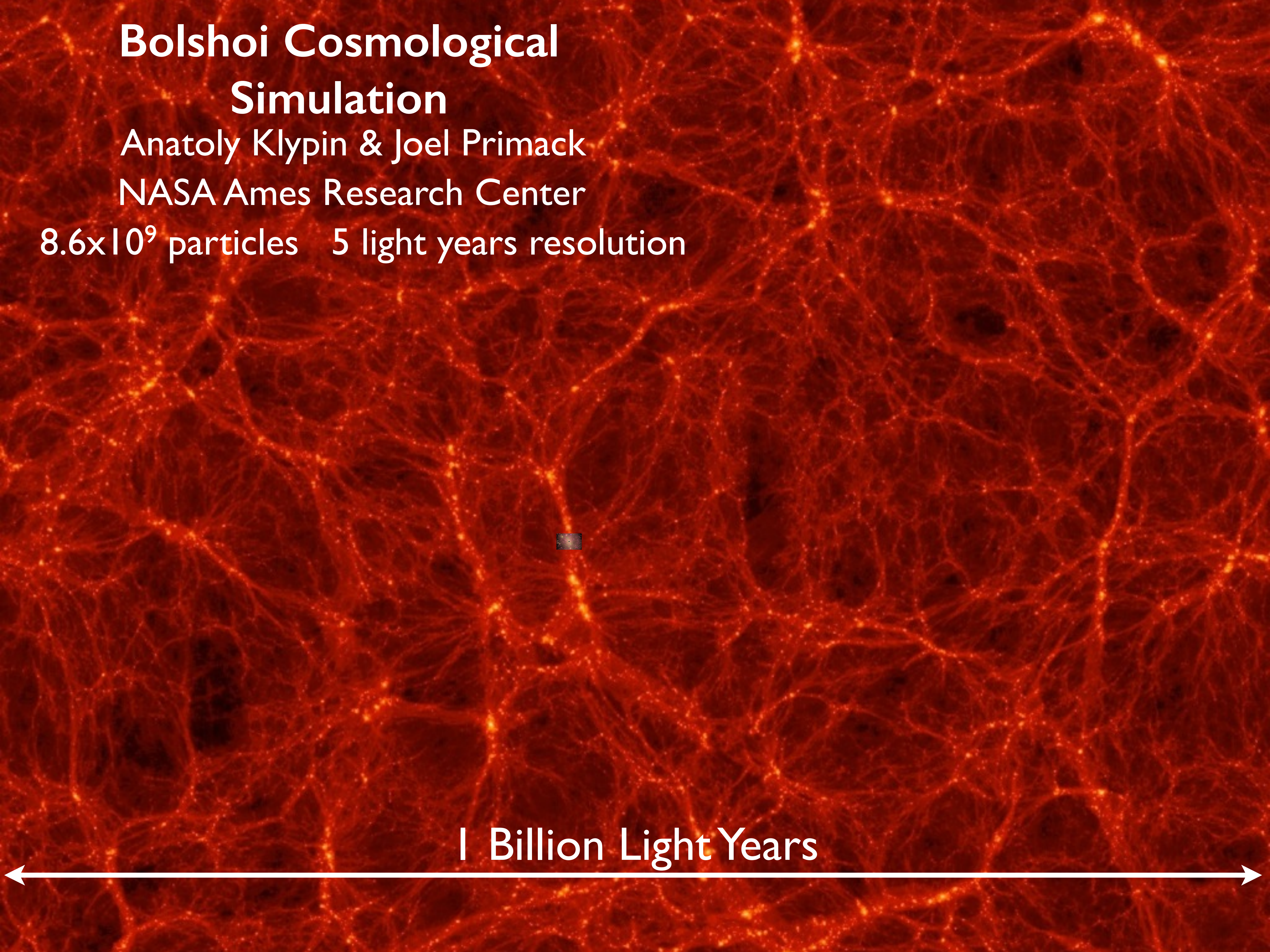
Stefan Gottloeber, Anatoly Klypin, Joel Primack

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
8.6x10^9 particles 5 light years resolution
1 Billion Light Years

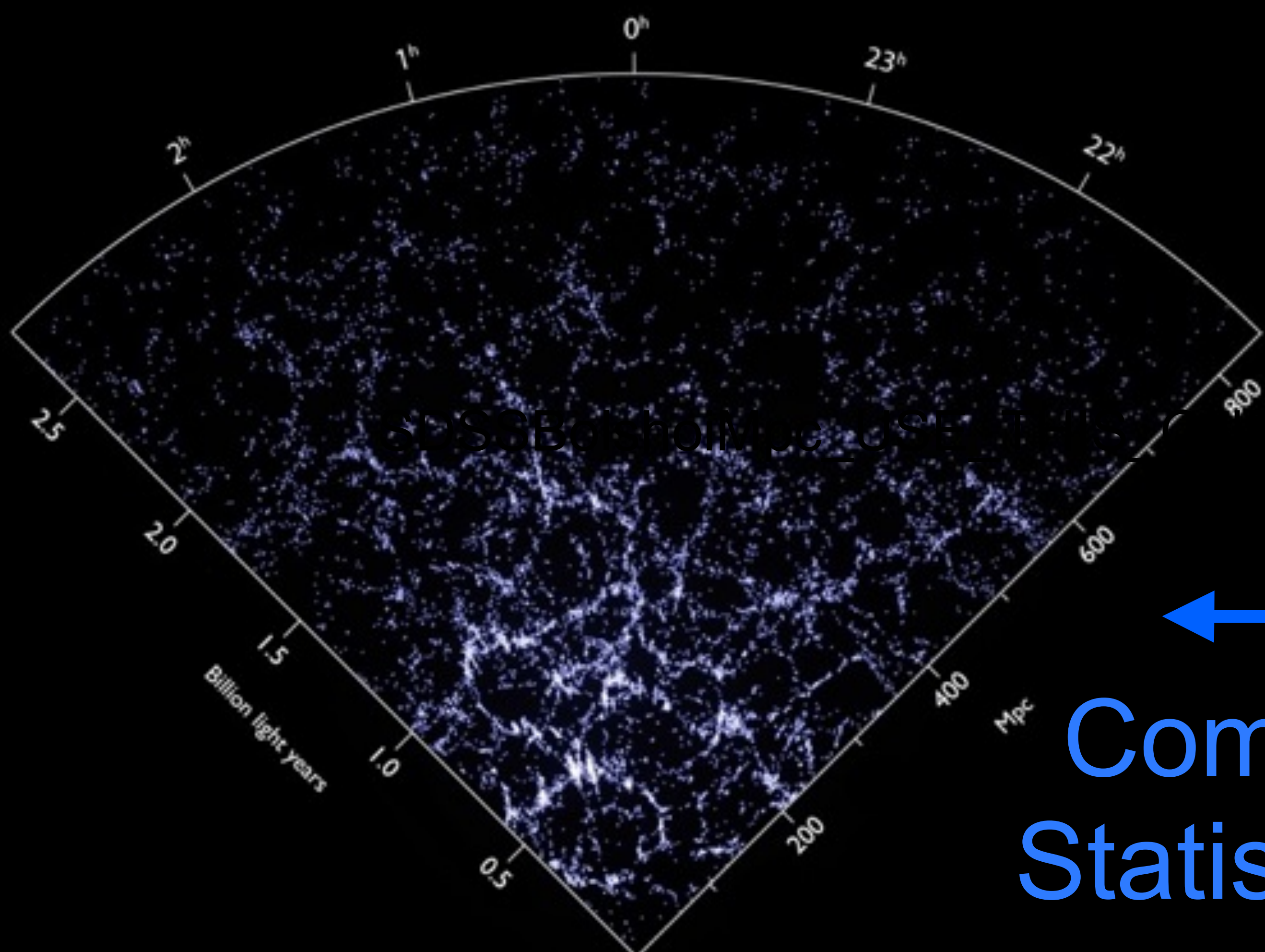
Observational Data

Sloan Digital Sky Survey

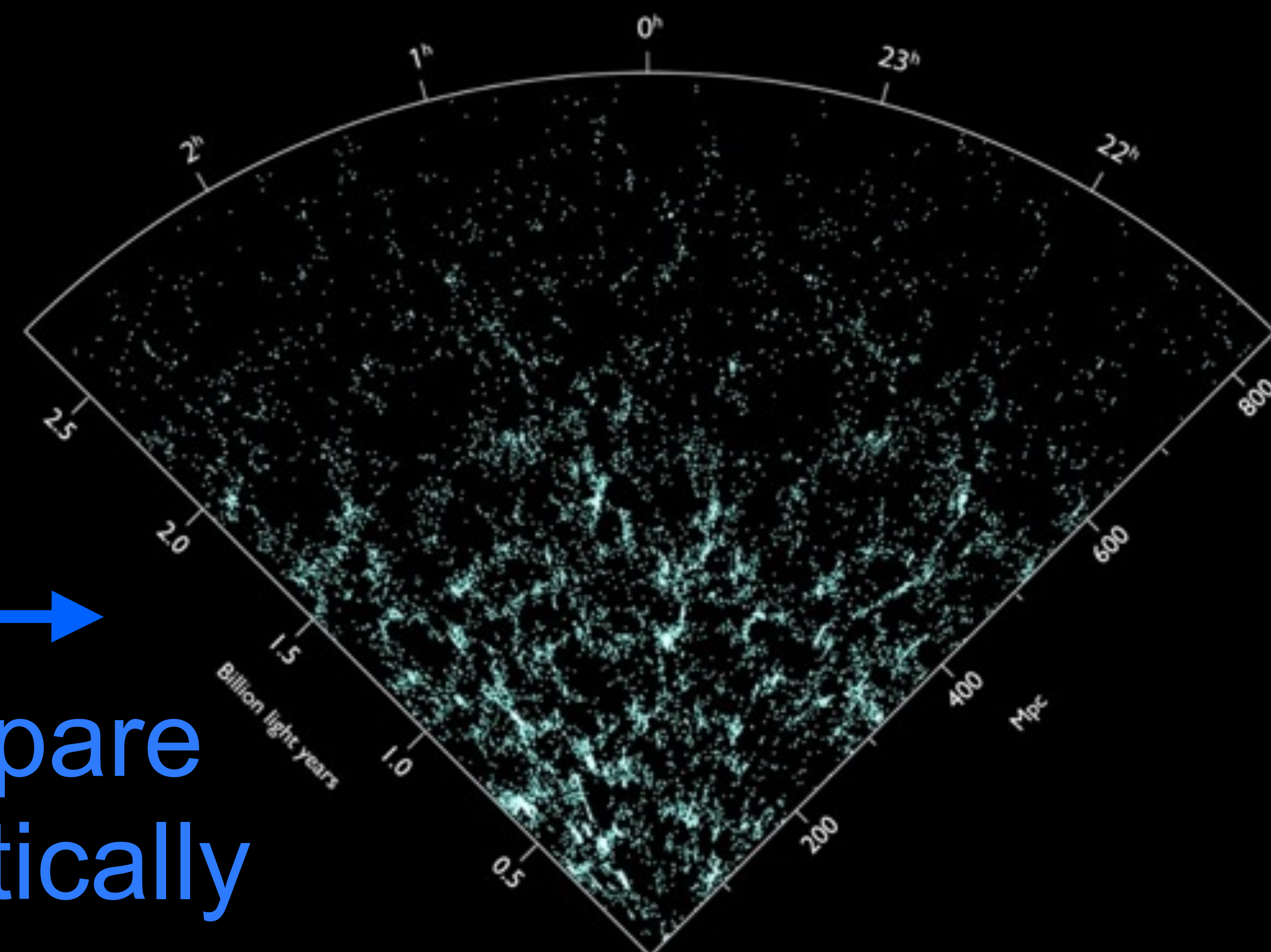
Bolshoi Simulation

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

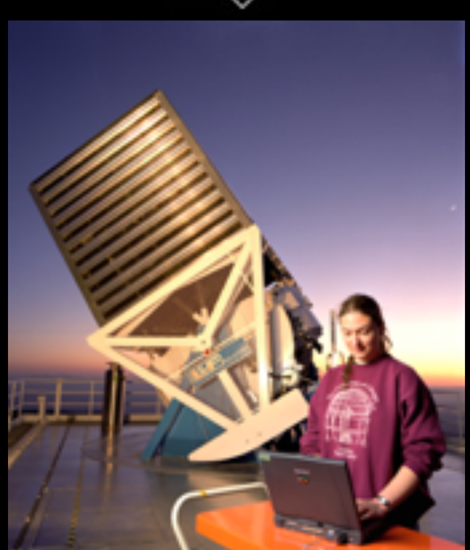
SDSS

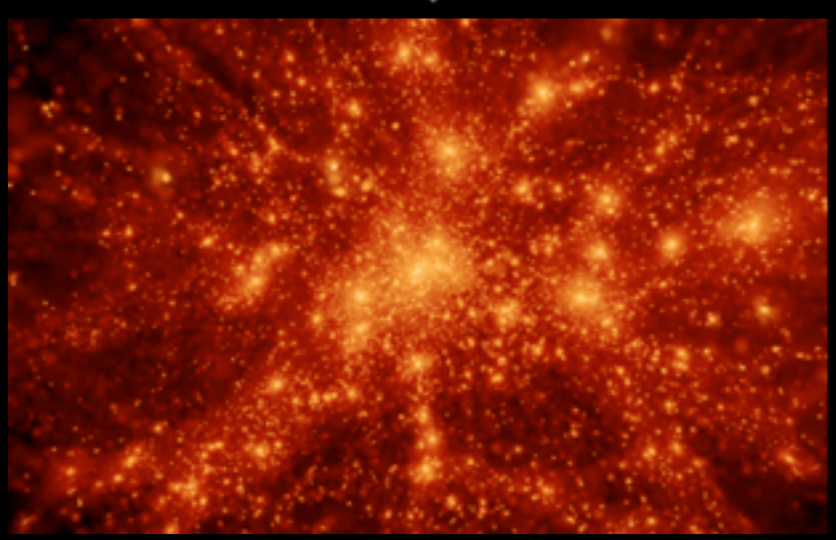


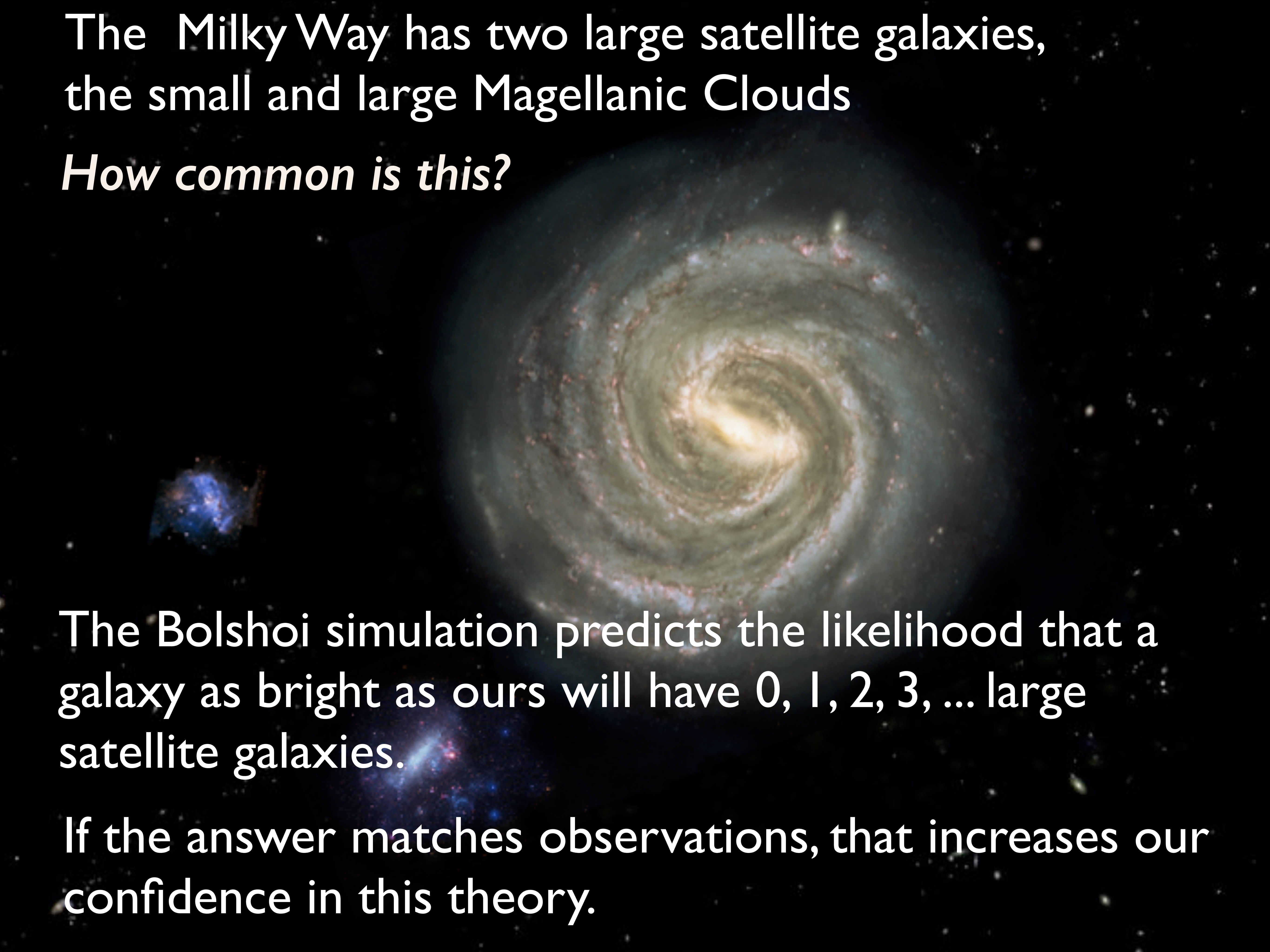
Bolshoi

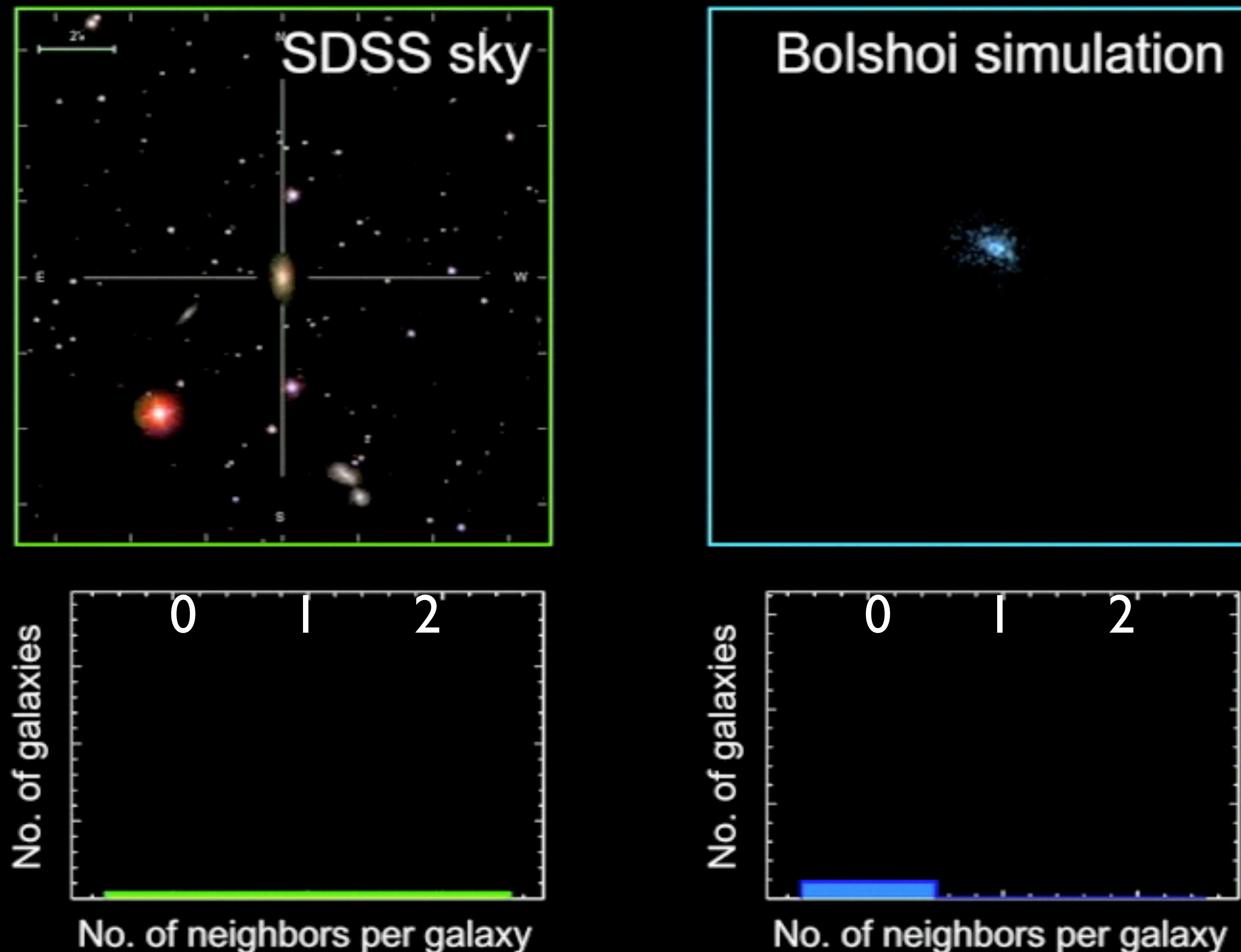


Compare Statistically



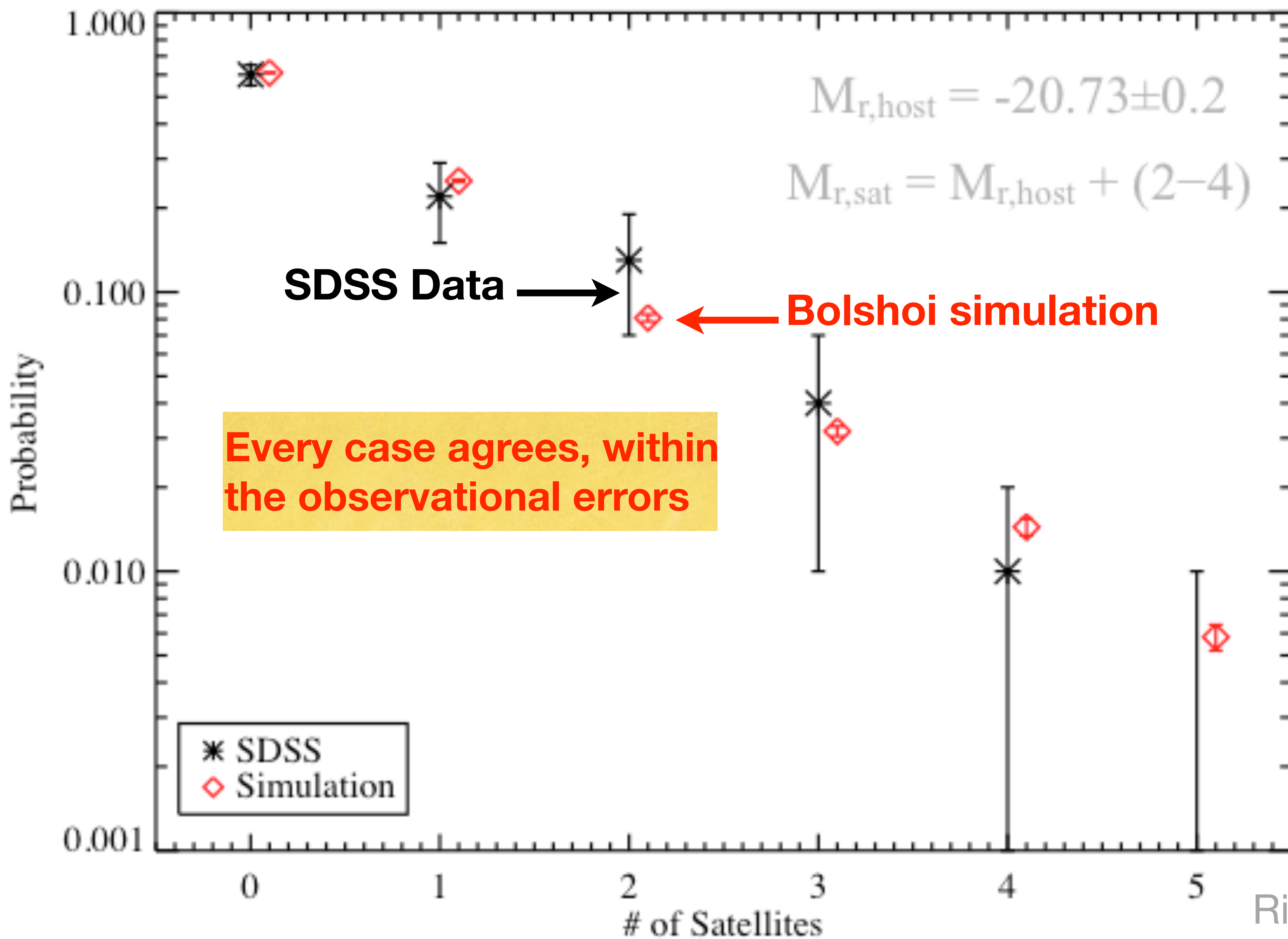



The Milky Way has two large satellite galaxies, the small and large Magellanic Clouds
How common is this?
The Bolshoi simulation predicts the likelihood that a galaxy as bright as ours will have 0, 1, 2, 3, ... large satellite galaxies.
If the answer matches observations, that increases our confidence in this theory.



SDSS sky
N
E
W
S
Bolshoi simulation
0
1
2
No. of galaxies
No. of neighbors per galaxy
0
1
2
No. of galaxies
No. of neighbors per galaxy

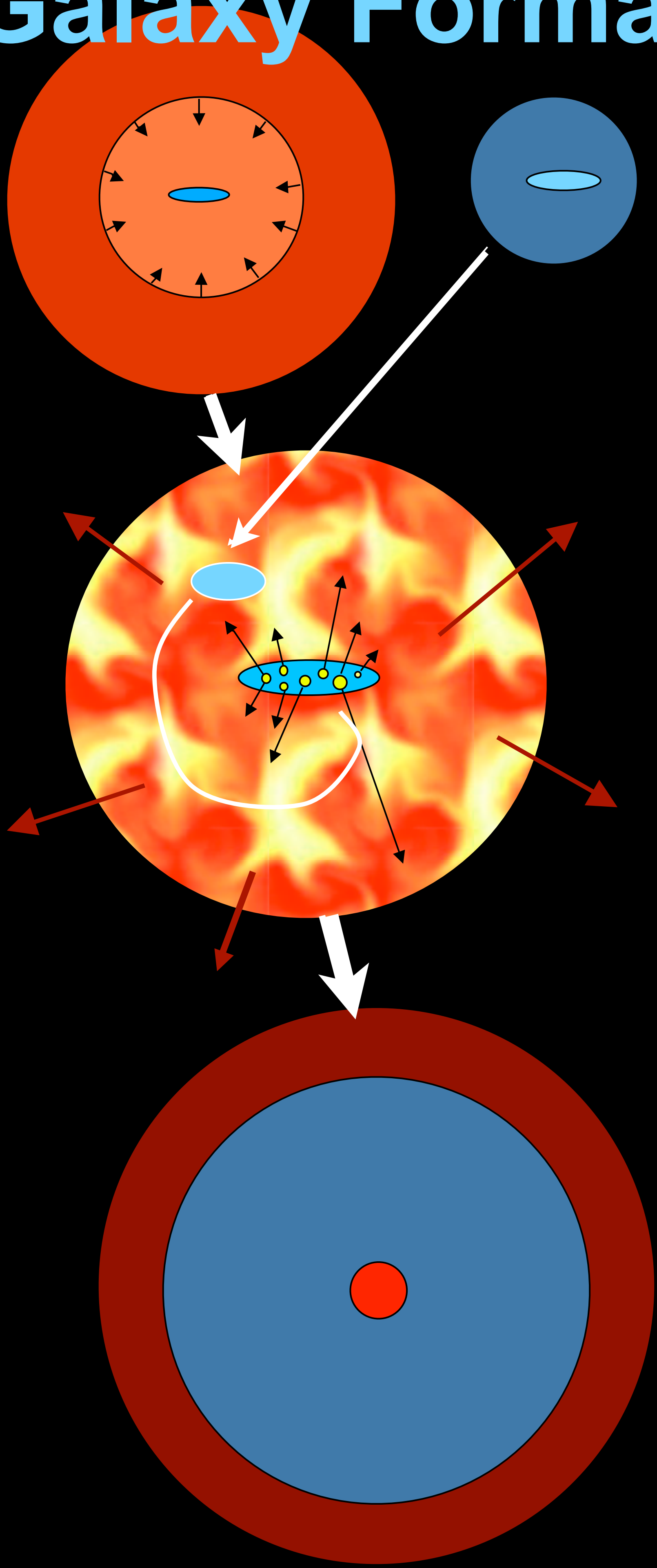
Statistics of MW bright satellites:
Sloan Digital Sky Survey data vs. Bolshoi simulation



Risa Wechsler

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

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?)
- 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
- **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.

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

SAM Predictions vs. SDSS Observations

Galaxy Age

Galaxy Metallicity

SAM

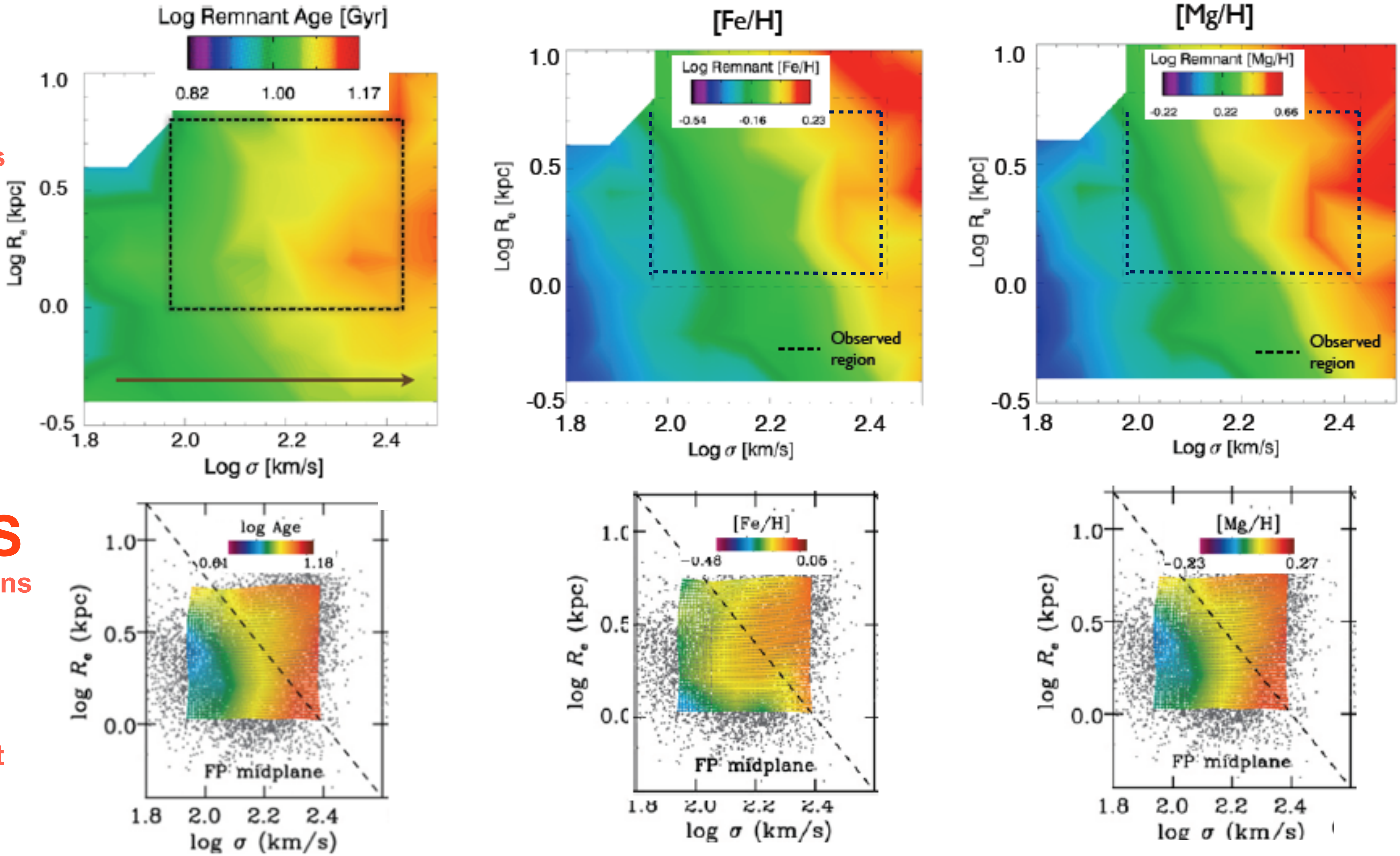
Predictions

Lauren Porter et al. 2013b

SDSS

Observations

Jenny Graves et al. 2009



Lauren Porter + 2013b

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.

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

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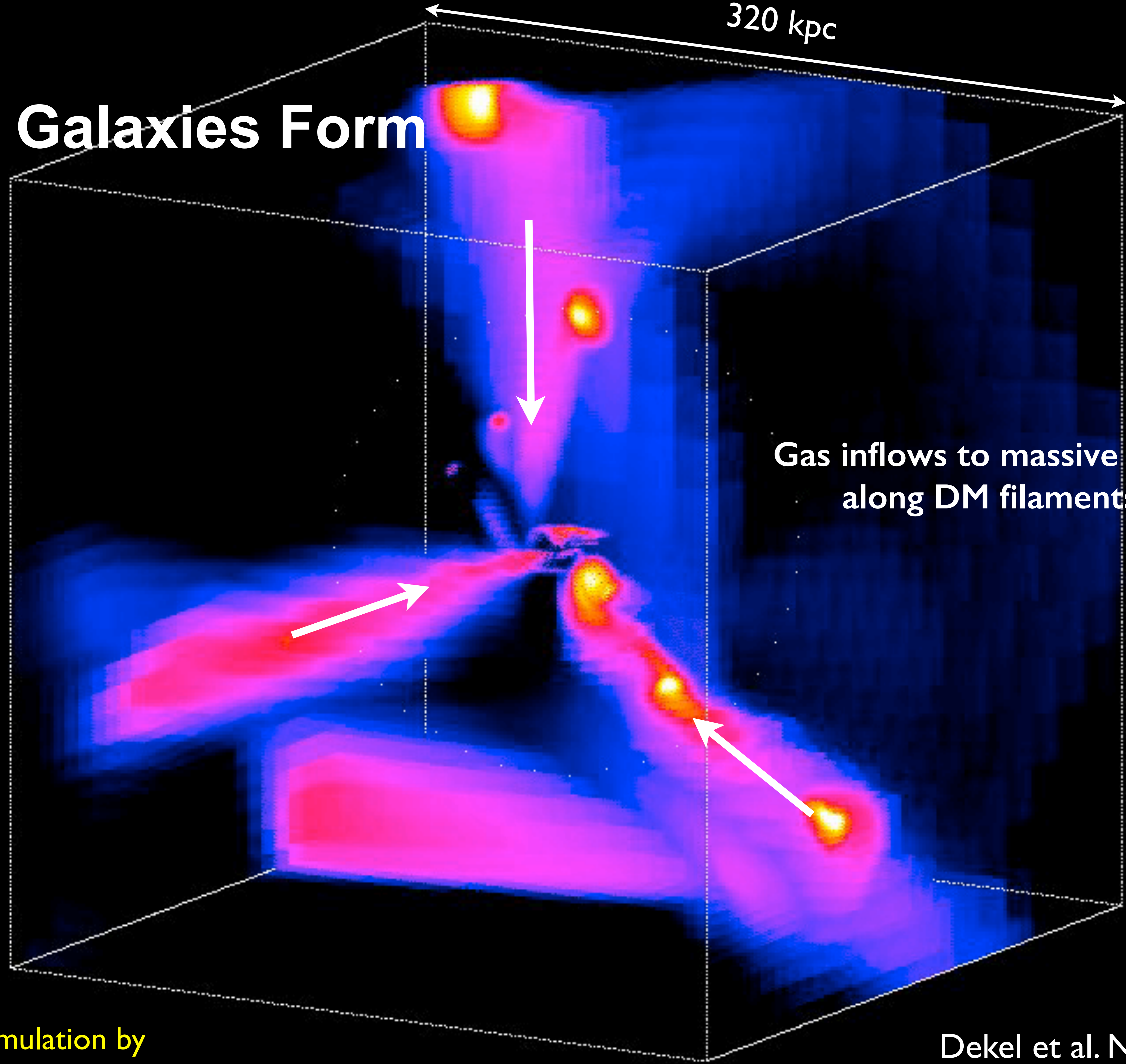
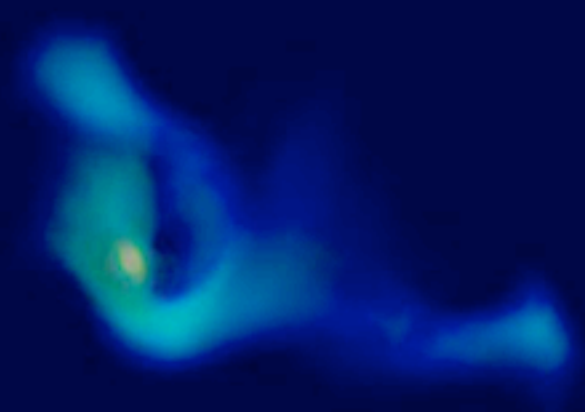
How Galaxies Form



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



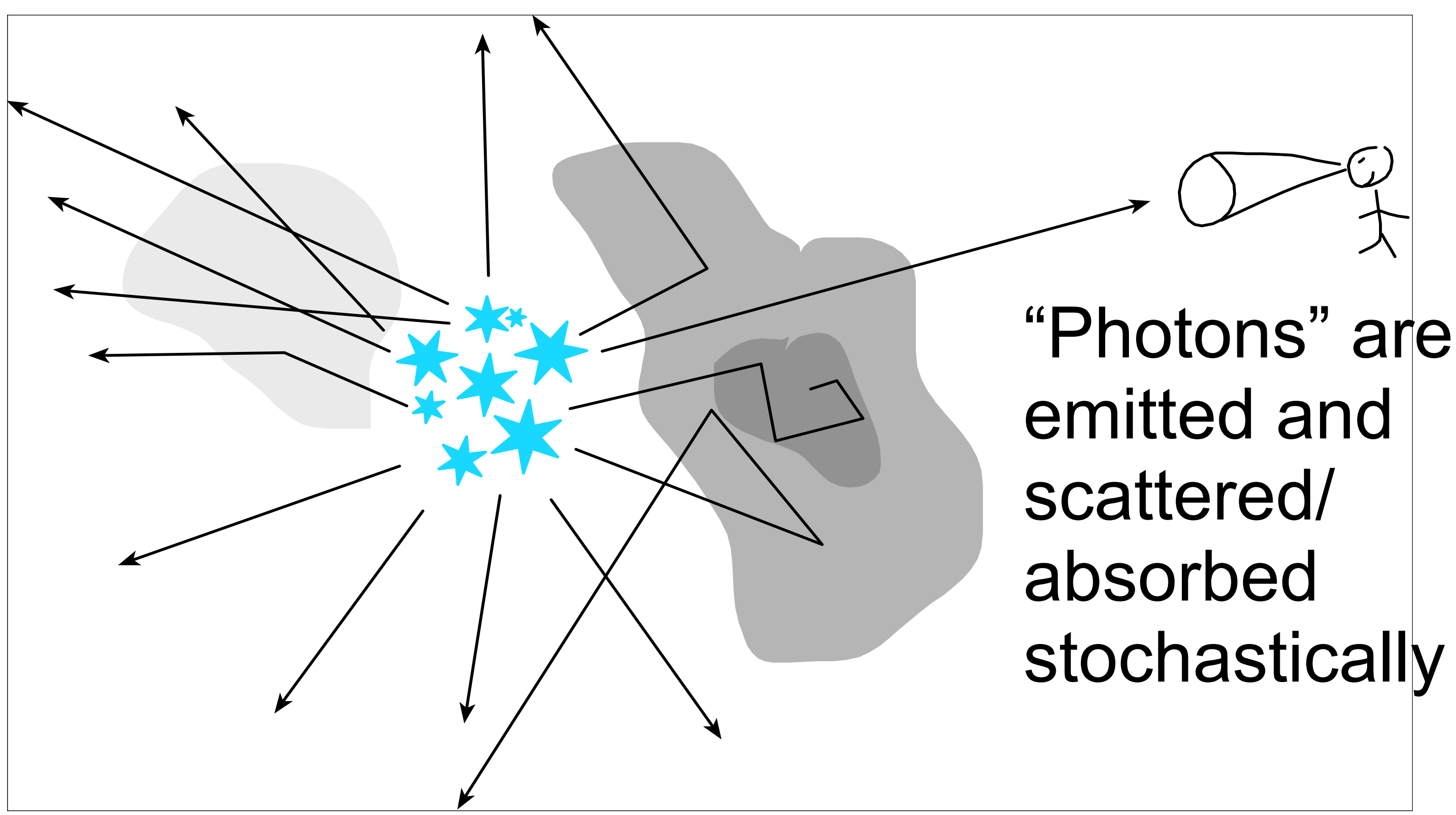
ART Simulation Daniel Ceverino;
Visualization: David Ellsworth

Sunrise Radiative Transfer Code

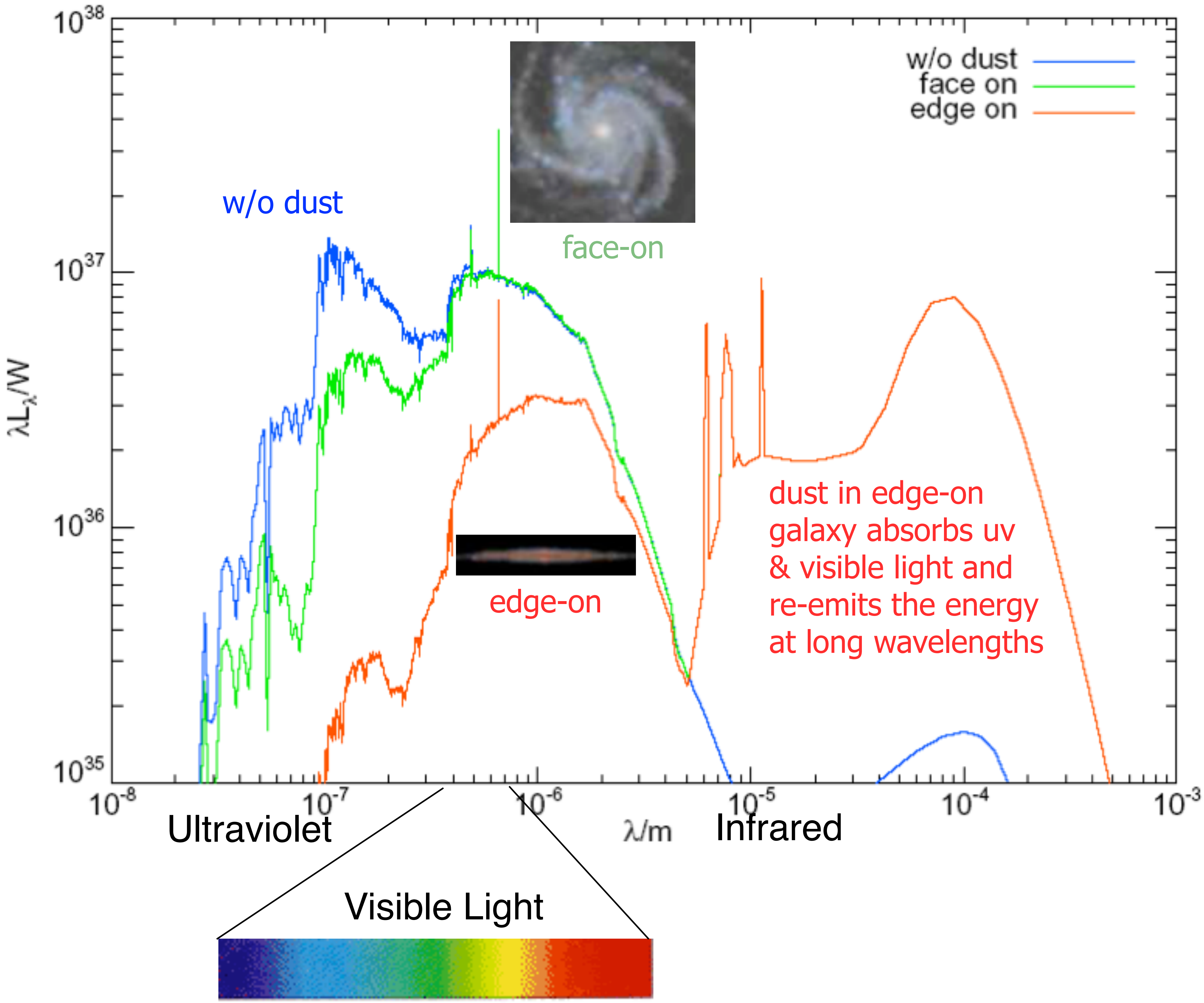
Patrik Jonsson
& Joel Primack

For every simulation snapshot:

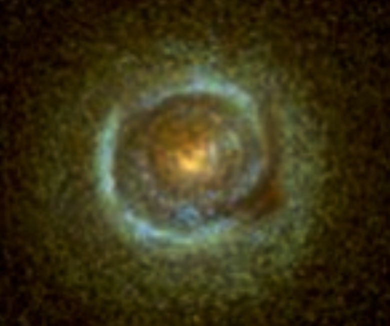
- Evolving stellar spectra calculation
- Adaptive grid construction
- Monte Carlo radiative transfer
- "Polychromatic" rays save 100x CPU time
- Graphic Processor Units give 10x speedup



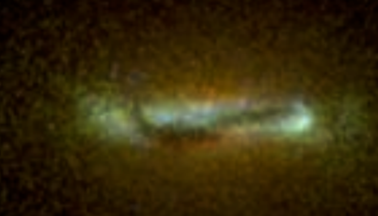
Spectral Energy Distribution



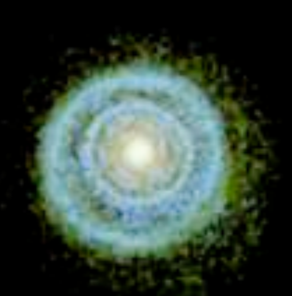
What's the effect of including dust?



with
dust



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



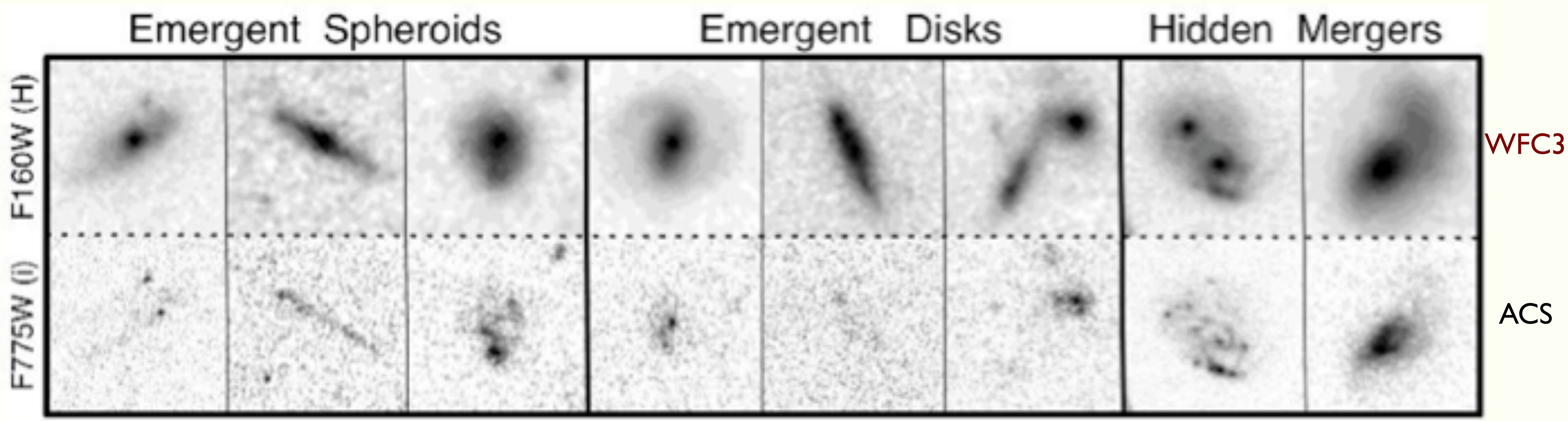
stars
only

face-on

edge-on

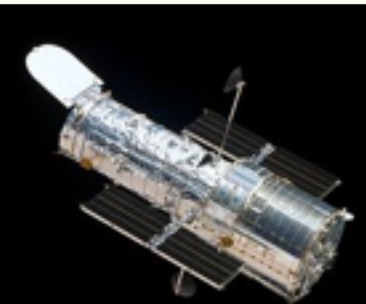
The CANDELS Survey with new near-ir camera WFC3

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

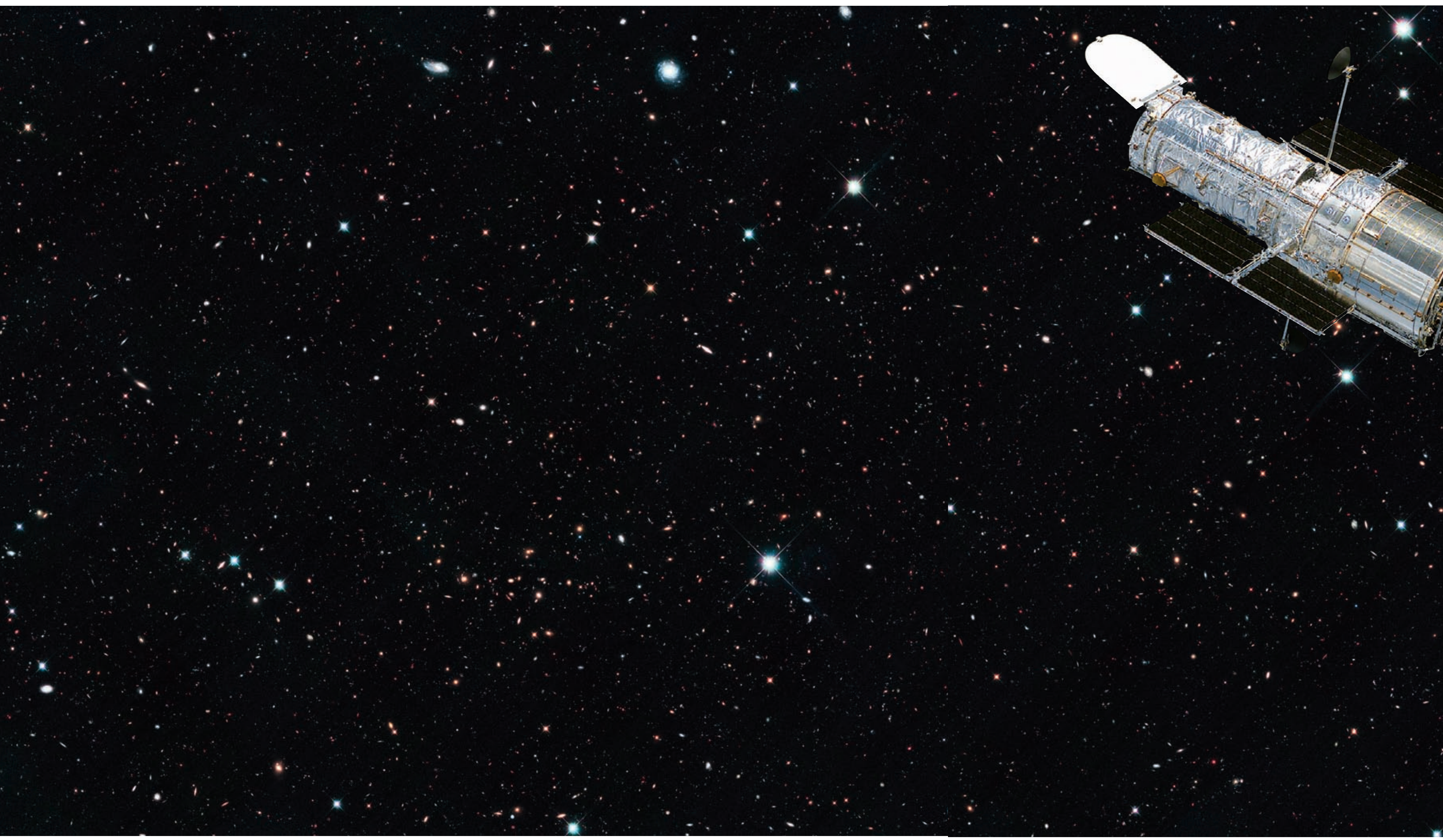
CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

- 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.

Article to appear in the June 2014 *Sky & Telescope* magazine

Staring Back to Cosmic Dawn

Hubble's single largest observing program is detecting the earliest galaxies, finding the most distant supernovae, and revealing the fireworks-like peak of star formation at cosmic high noon.



NASA / ESA / A. VAN DER WEL / H. FERGUSON / A. KOEKEMOER / CANDELS TEAM

COSMIC SURVEY As part of the CANDELS survey, the Hubble Space Telescope scanned a small patch of Cetus for a total of 61 hours. The 61 hours were divided among 352 separate exposures spread across a mosaic of 44 different telescope pointings. The picture reveals a few foreground stars in our galaxy, and thousands of galaxies ranging from the local universe to a time when the universe was less than 1 billion years old.

Sandra M. Faber, Henry C. Ferguson,
David C. Koo, Joel R. Primack
& Trudy E. Bell

The Hubble Space Telescope is a time machine, staring not only billions of light-years into the depths of space but also billions of years back in time. With its extraordinarily sensitive detectors above Earth's shrouding and blurring atmosphere, HST can witness the peak of star formation at cosmic high noon, which ended about 5 billion years after the Big Bang. And at the outer limits of its capabilities, we wondered if it could detect the faintest candles of creation: the earliest galaxies made of the earliest stars at cosmic dawn, when the universe was less than a billion years old.

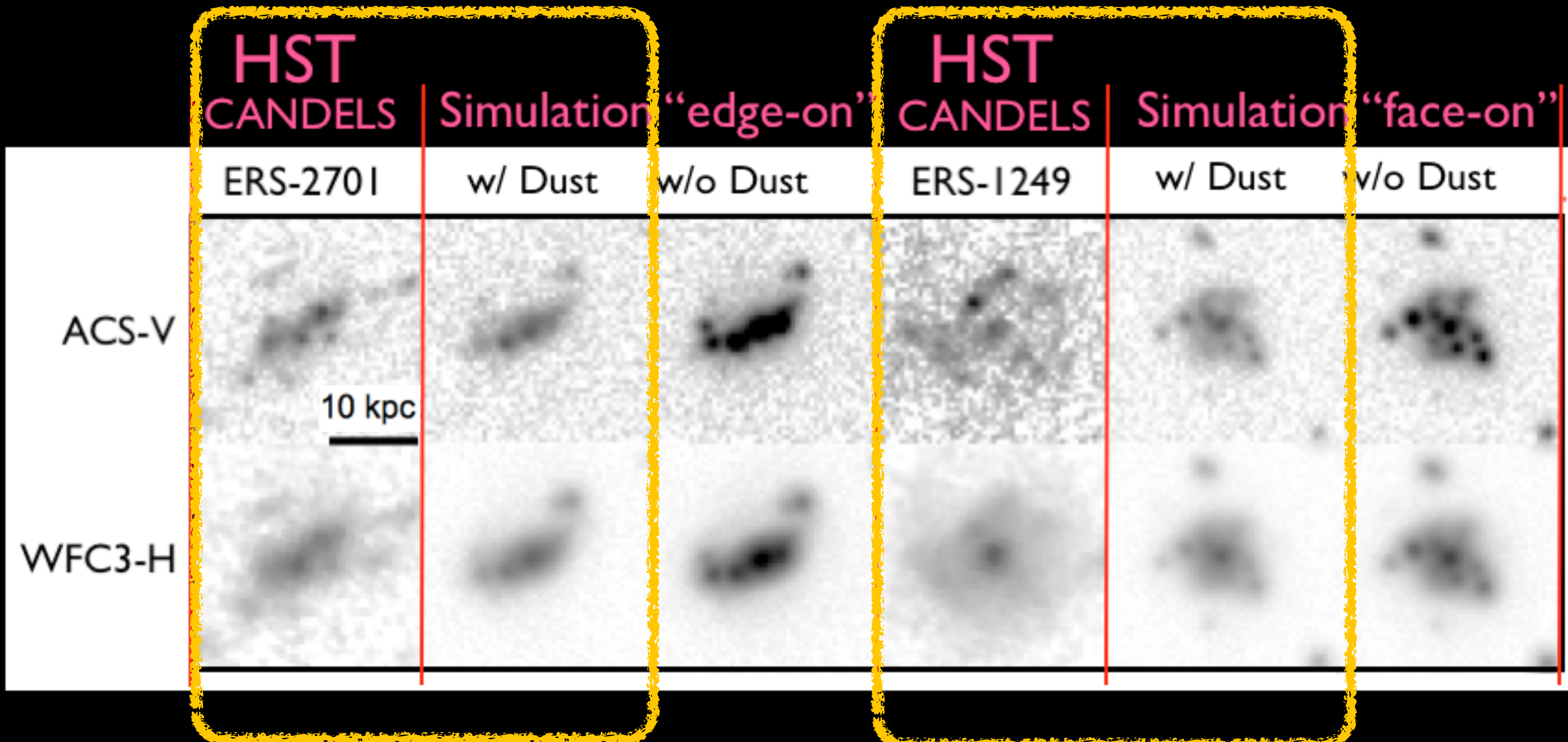
Those were the hopes of two of us authors (Faber and Ferguson) after NASA astronauts installed HST's Wide-Field Camera 3 (WFC3) in 2009, which enabled Hubble to survey the infrared sky about 30 times faster than before. Within a few months, Hubble pointed the new camera at the Hubble Ultra-Deep Field (HUDF) — a tiny region in Fornax only a tenth the diameter of the full Moon — and took exposures totaling about three days. Those deep HUDF images revealed some of the most distant galaxies ever found, which look very different than nearby galaxies. But the HUDF represented just a pinprick poke at the universe.

So we began an ambitious program at visible and near-infrared wavelengths as a natural successor to HUDF: the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS), pronounced "candles." We designed CANDELS primarily to document the first one-third of galaxy evolution. The program also would enable astronomers to search for the most distant Type Ia supernovae — exploding white dwarfs that are the best-known standard candles for measuring the universe's recent expansion rate. CANDELS could thus test whether Type Ia supernovae are also a valid yardstick for the early universe.

CANDELS became the largest observing program ever undertaken by Hubble. The telescope devoted 600 hours — fully 10% of its observing time — to CANDELS for three years, surveying an area of sky 60 times larger

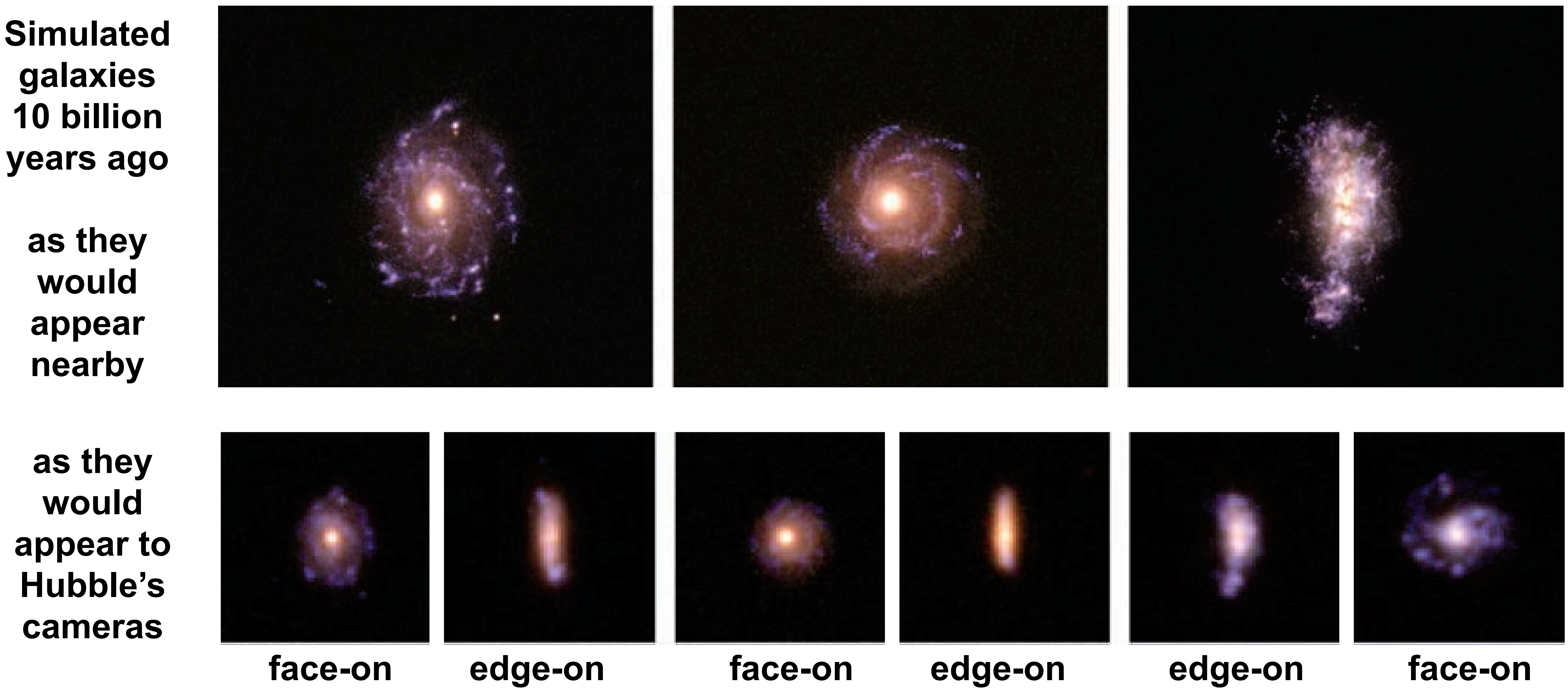
To view more images related to this article, visit skypub.com/CANDELS.

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.*)

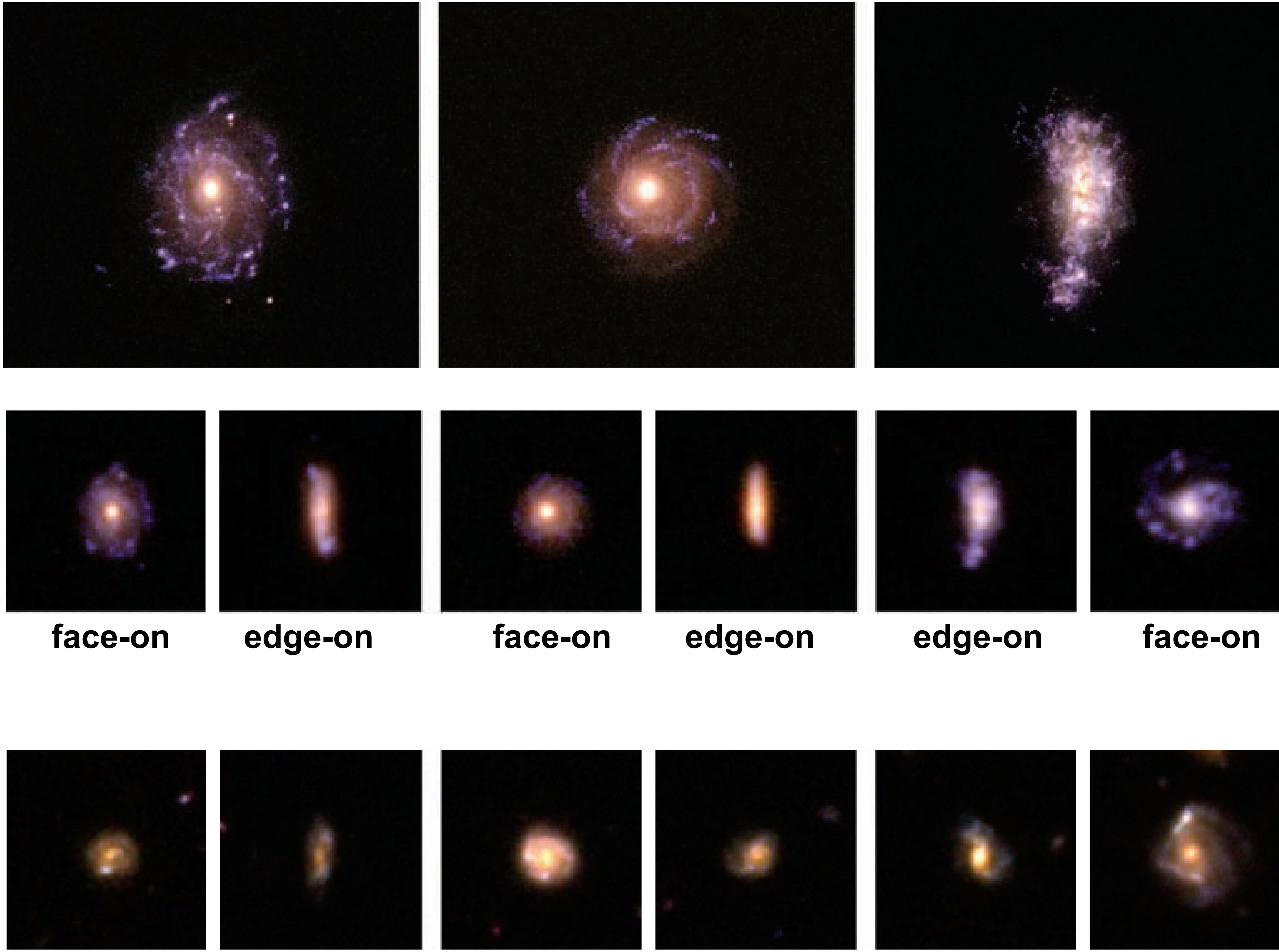

Simulated galaxies 10 billion years ago
as they would appear nearby
as they would appear to Hubble's cameras
face-on
edge-on
face-on
edge-on
edge-on
face-on

Simulated galaxies 10 billion years ago

as they would appear nearby

as they would appear to Hubble's cameras

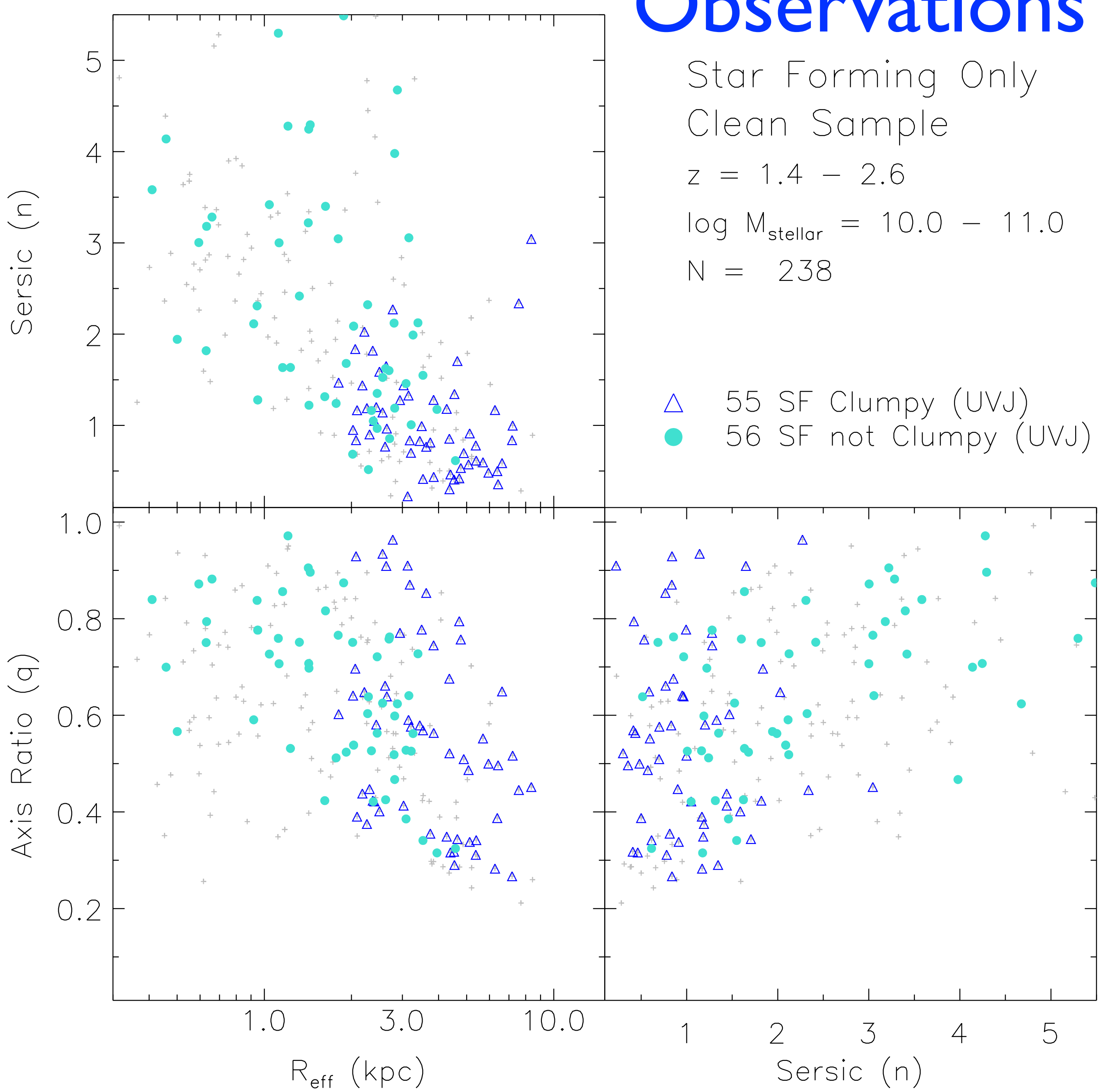
similar galaxy images from Hubble Space Telescope



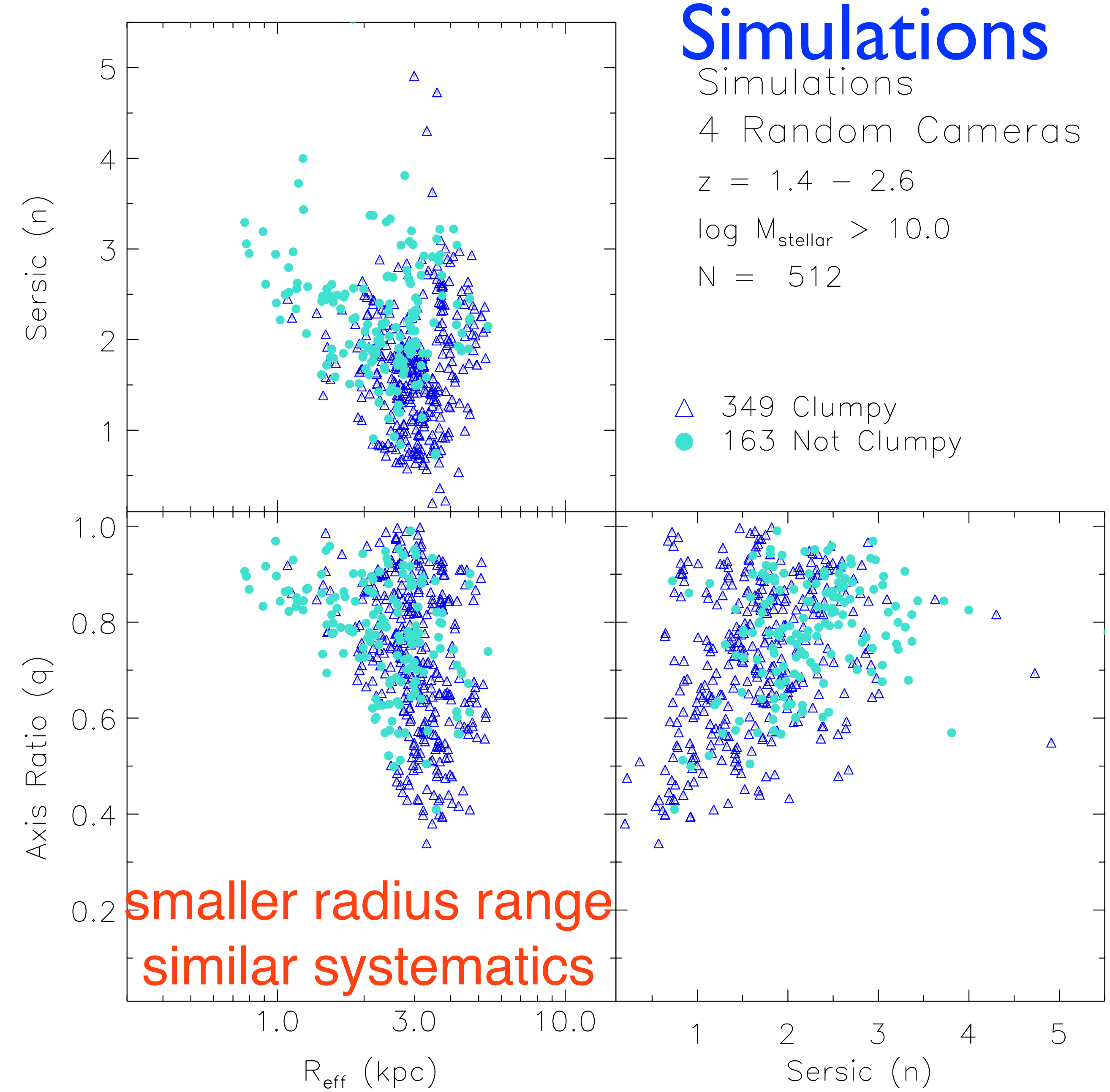
From article to appear in the June 2014 *Sky & Telescope* magazine

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

Observations



Simulations



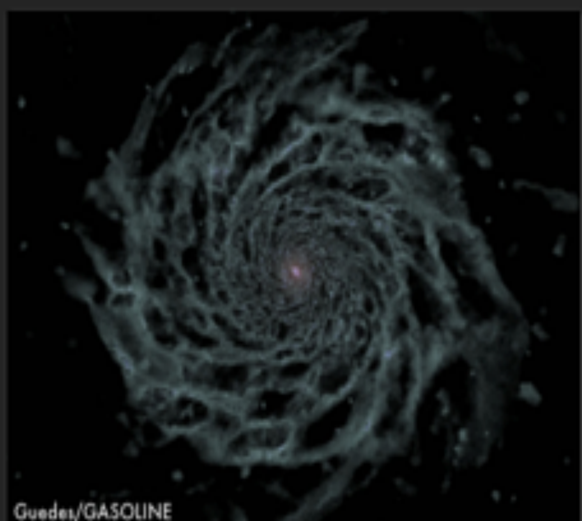
Mark Mozena (in prep)

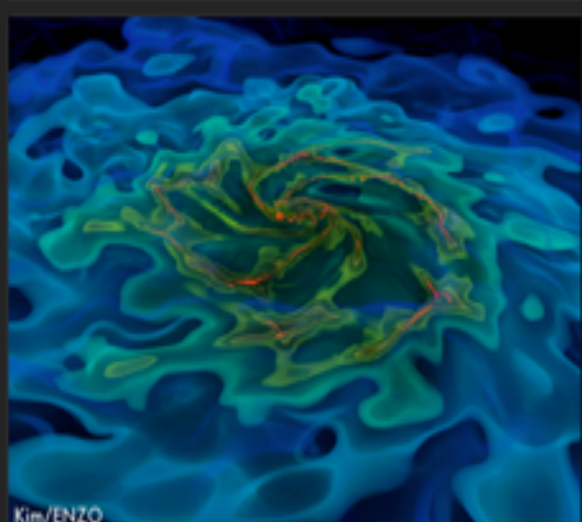
AGORA Assembling Galaxies of Resolved Anatomy

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

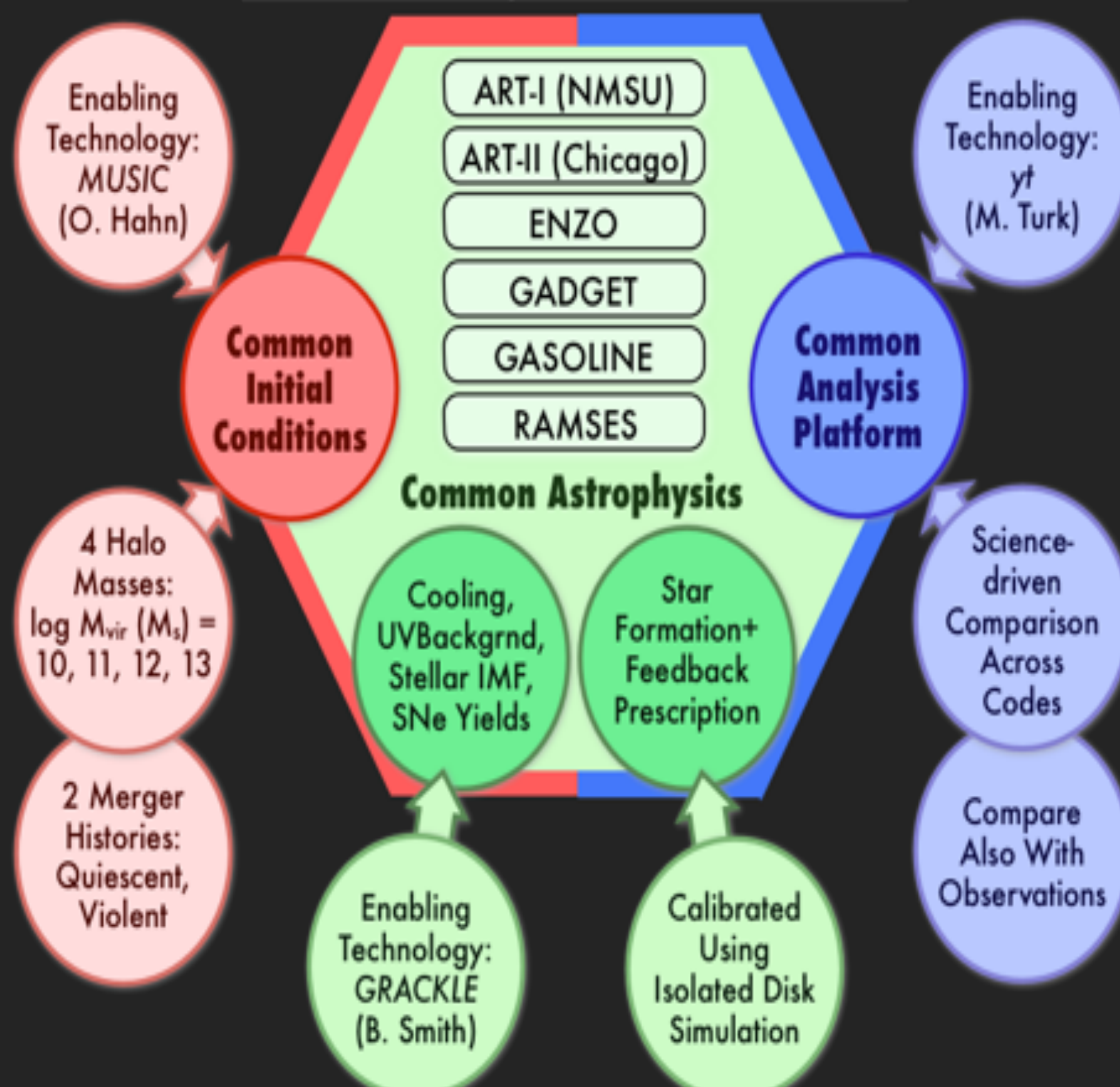
Steering Committee: Piero Madau & Joel Primack (UCSC), co-chairs; Tom Abel (Stanford), Nick Gnedin (Chicago), Romain Teyssier and Lucio Mayer (Zurich), James Wadsley (McMaster)

High-res Galaxy Simulations





AGORA Comparison Infrastructure



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, 94 participants from 47 institutions as of 2nd Workshop, Aug. 2013
- 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:

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

Big Data in Astronomy

Exponential growth in computing power and detectors and falling cost of data storage has enabled vast increases in

- Ambitious surveys, with massive storage for archives
- Simulation realism - virtual experiments on the universe

Astronomy is becoming dominated by surveys and simulations

- How can we understand such huge amounts of data?
  We have to analyze outputs as the supercomputers run

- Users will send questions (algorithms) to where the data is stored and get back answers including visualizations (not raw data) - We're doing this for the AGORA collaboration

- Citizen Scientists are helping us deal with vast data sets

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) 2014

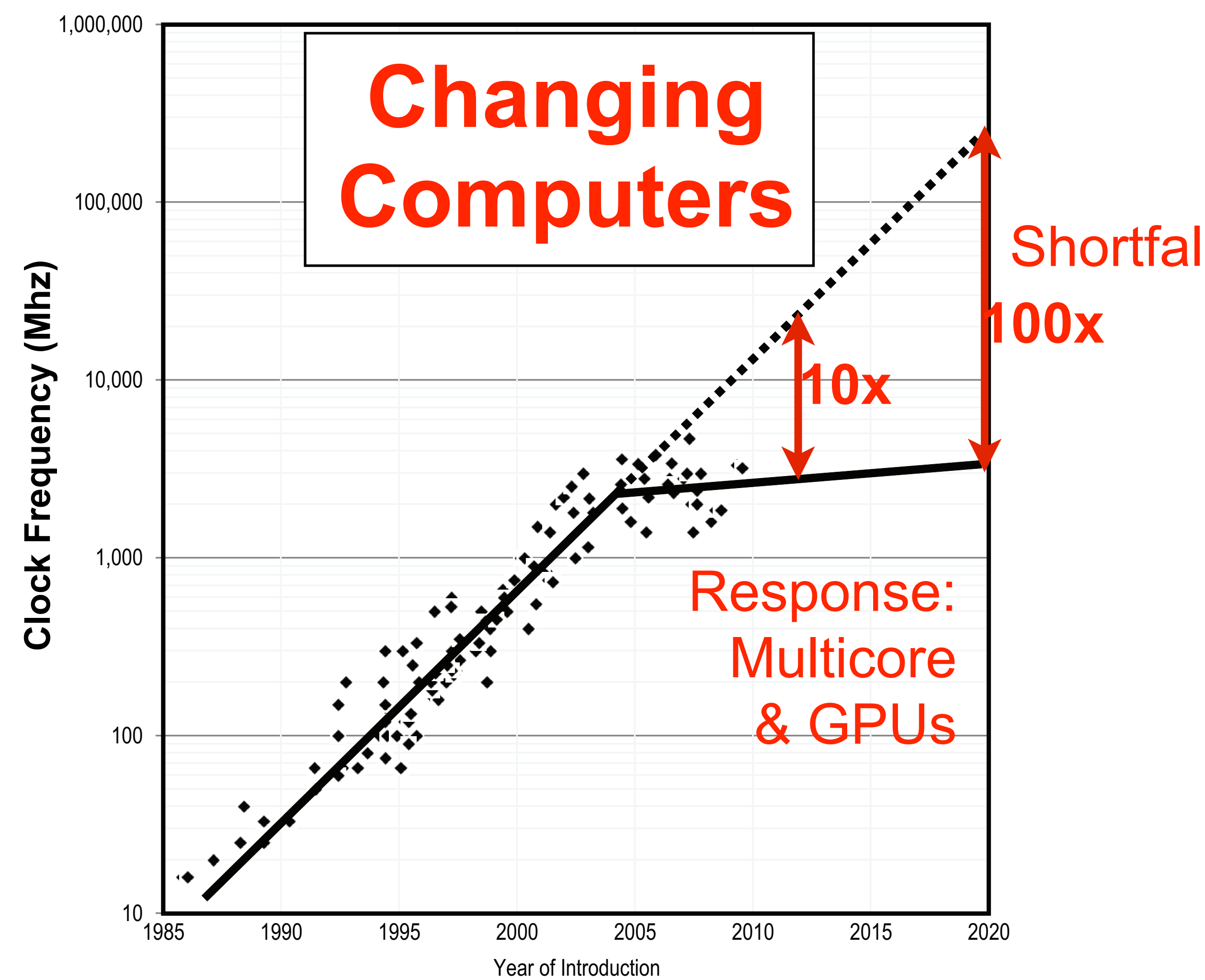
185 TB of images
25 TB/year ingest rate
>100 TB/year retrieval rate

Large Synoptic Survey Telescope (LSST) 2019

20 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

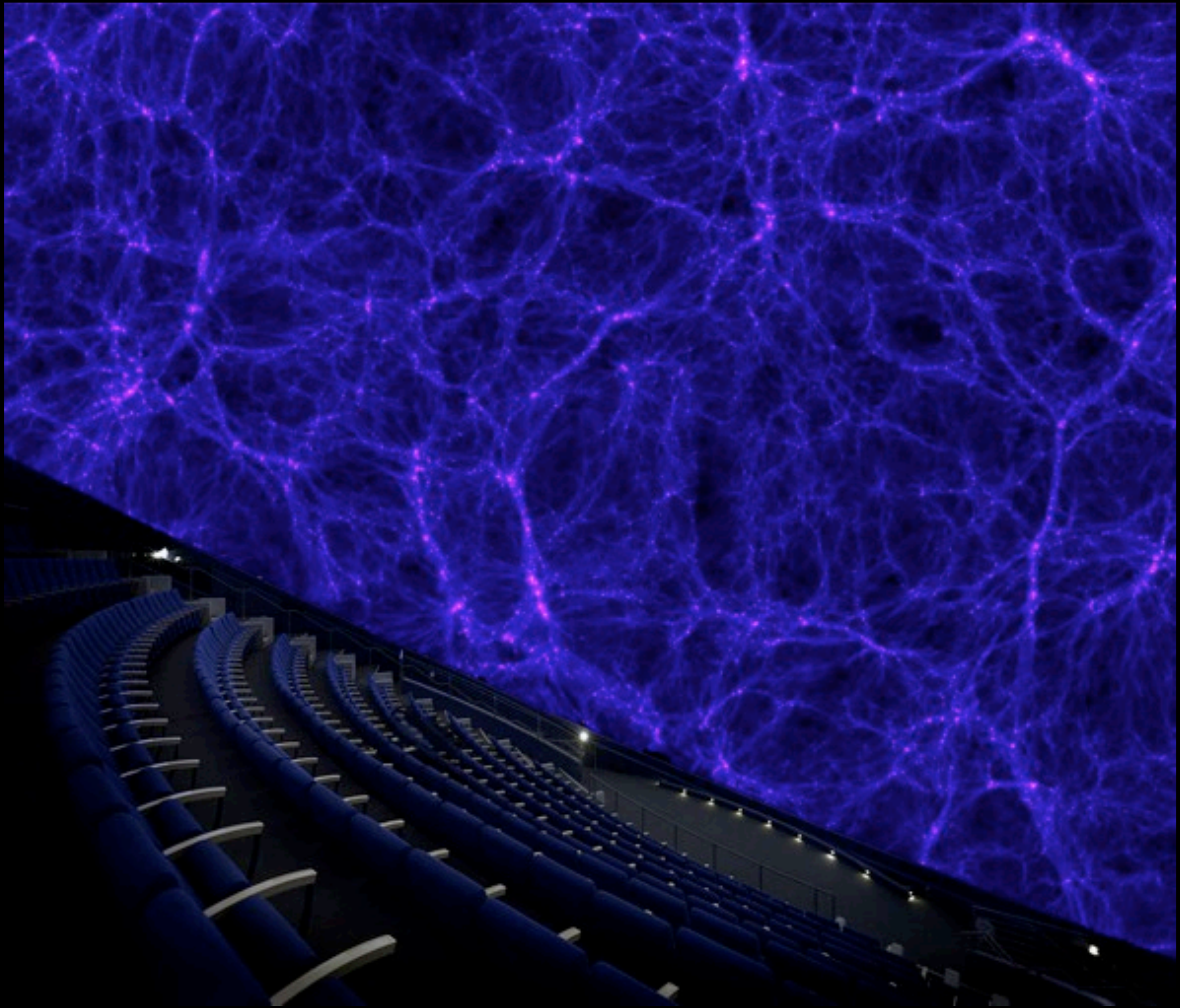


Increasingly inhomogeneous computers are harder to program! We need computational scientists and engineers and new compilers that generate code for nodes with cores+accelerators with automatic load balancing and fault tolerance.

Astro-Computation Visualization and Outreach

Project lead: Prof. Joel Primack, Director, UC High-Performance AstroComputing Center
UC-HIPACC Visualization and Outreach Specialist: Nina McCurdy

http://hipacc.ucsc.edu



HIPACC is working with the Morrison Planetarium at the California Academy of Sciences (pictured here) to show how dark matter shapes the universe. We helped prepare their show *LIFE: a Cosmic Story* that opened in fall 2010, and also a major planetarium show that opened the new Adler Planetarium Grainger Sky Theater July 8, 2011.

Thanks!

Supercomputing the Universe

Joel R. Primack, UCSC

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

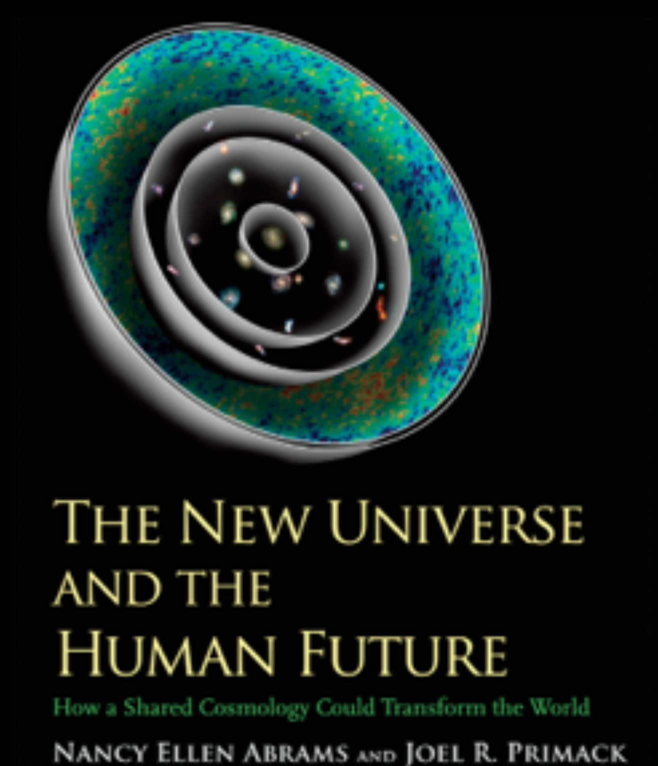
Websites related to this talk:

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

Abrams & Primack Book Websites with images and videos:

ViewfromtheCenter.com

New-Universe.org



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