Supercomputing the Universe

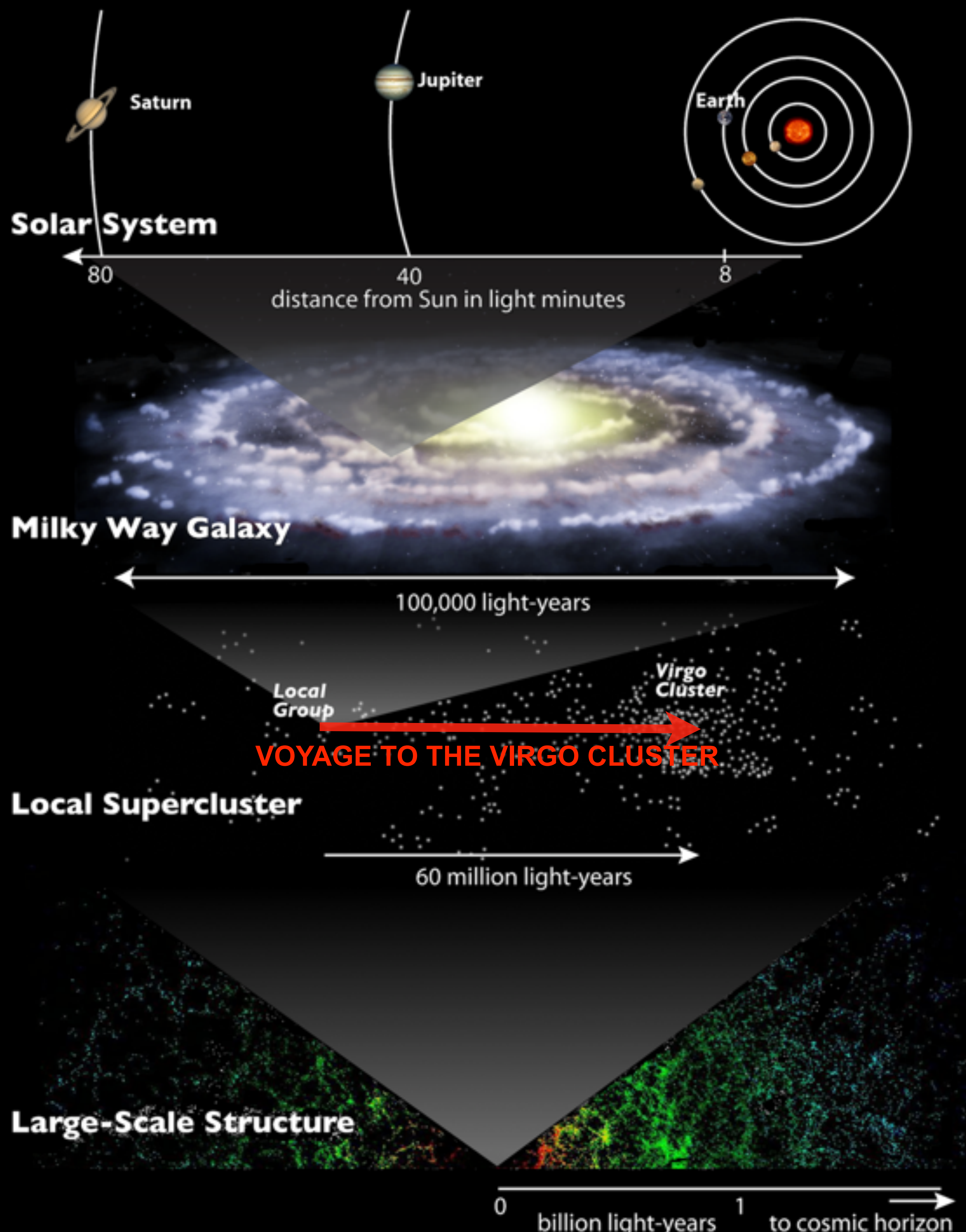
Joel R. Primack

Distinguished Professor of Physics, University of California, Santa Cruz

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

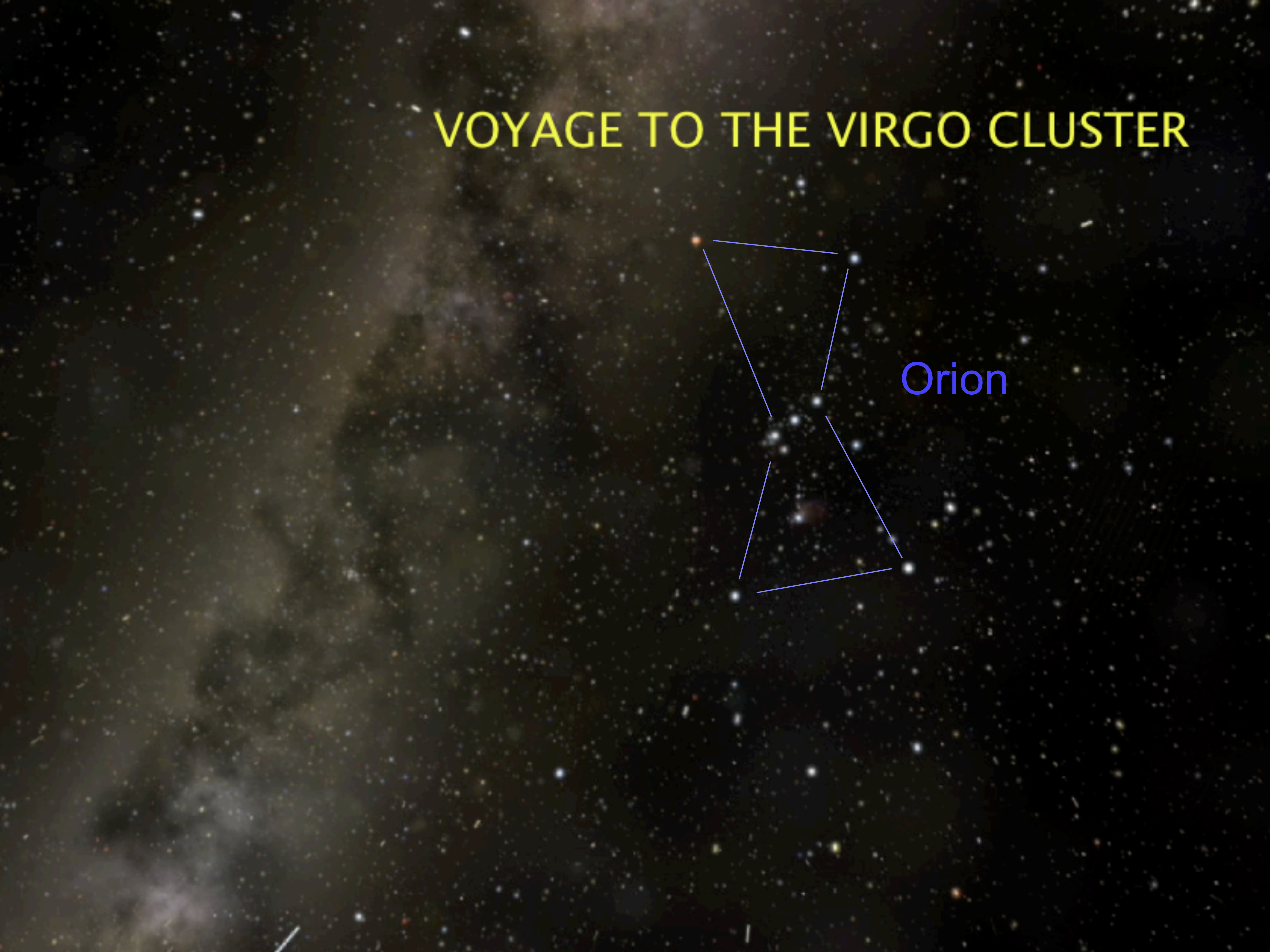
The Modern Scientific Cosmos

Our Cosmic Address



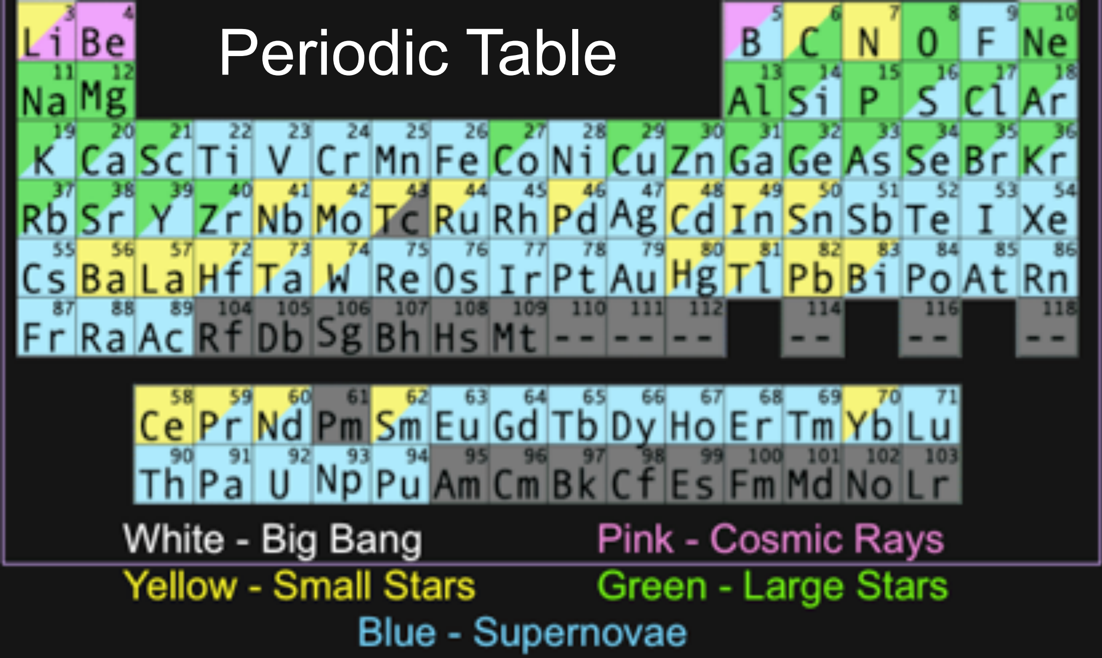
each dot is a big galaxy

Sloan Digital Sky Survey


VOYAGE TO THE VIRGO CLUSTER
Orion


VOYAGE TO THE VIRGO CLUSTER

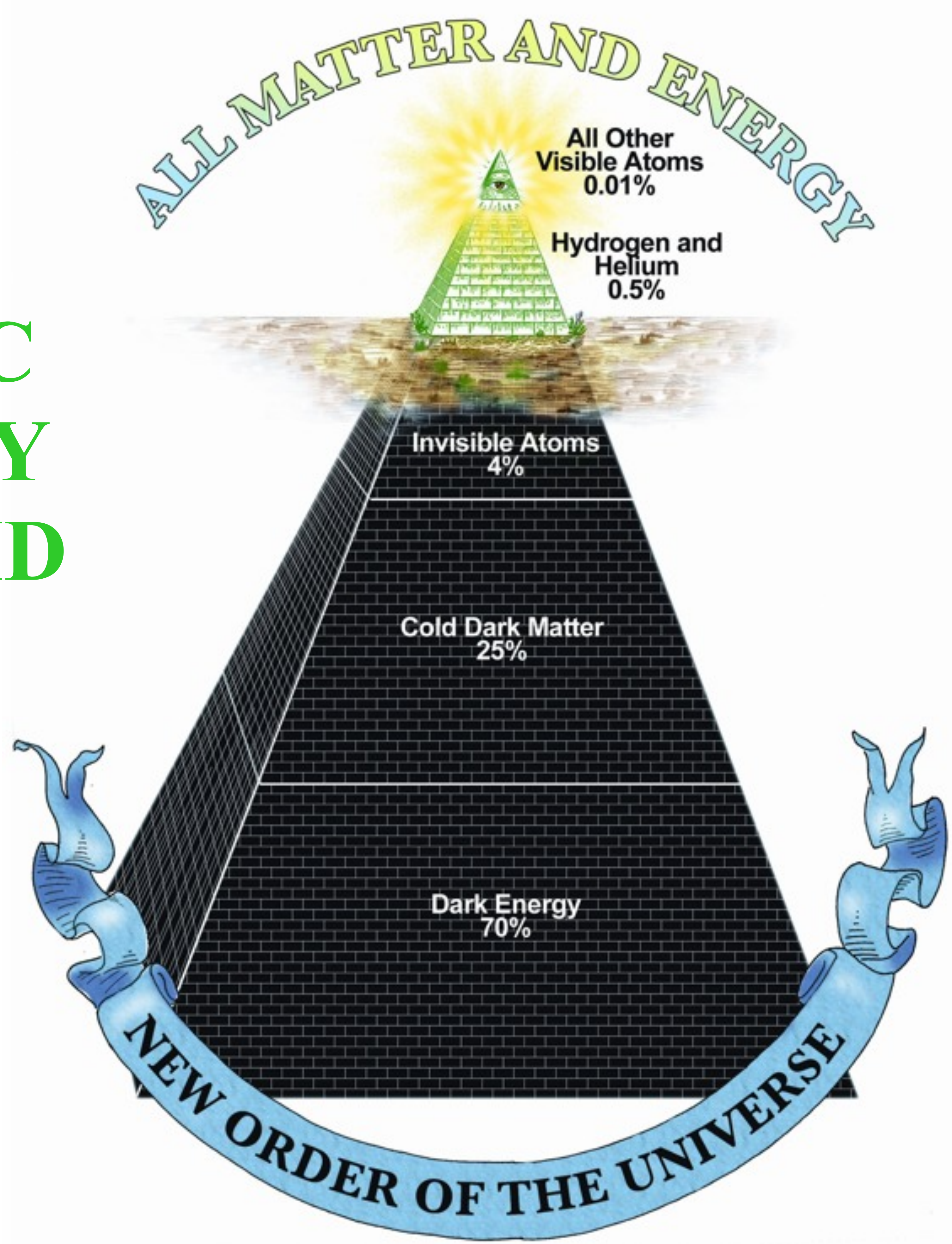

Hubble Space Telescope Ultra Deep Field - ACS
This picture is beautiful but misleading, since it only shows about 0.5% of the cosmic density.
The other 99.5% of the universe is invisible.



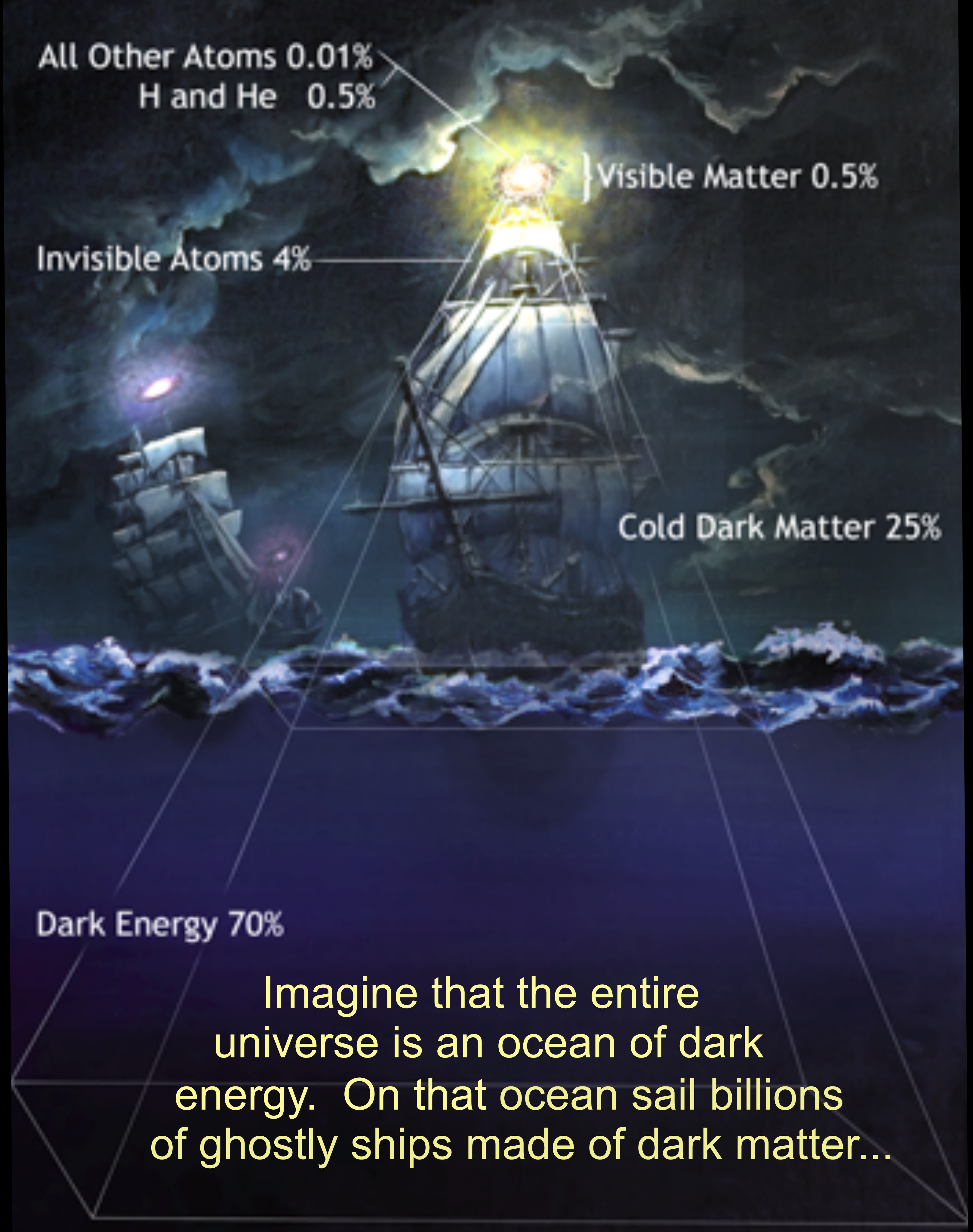
stardust

stars

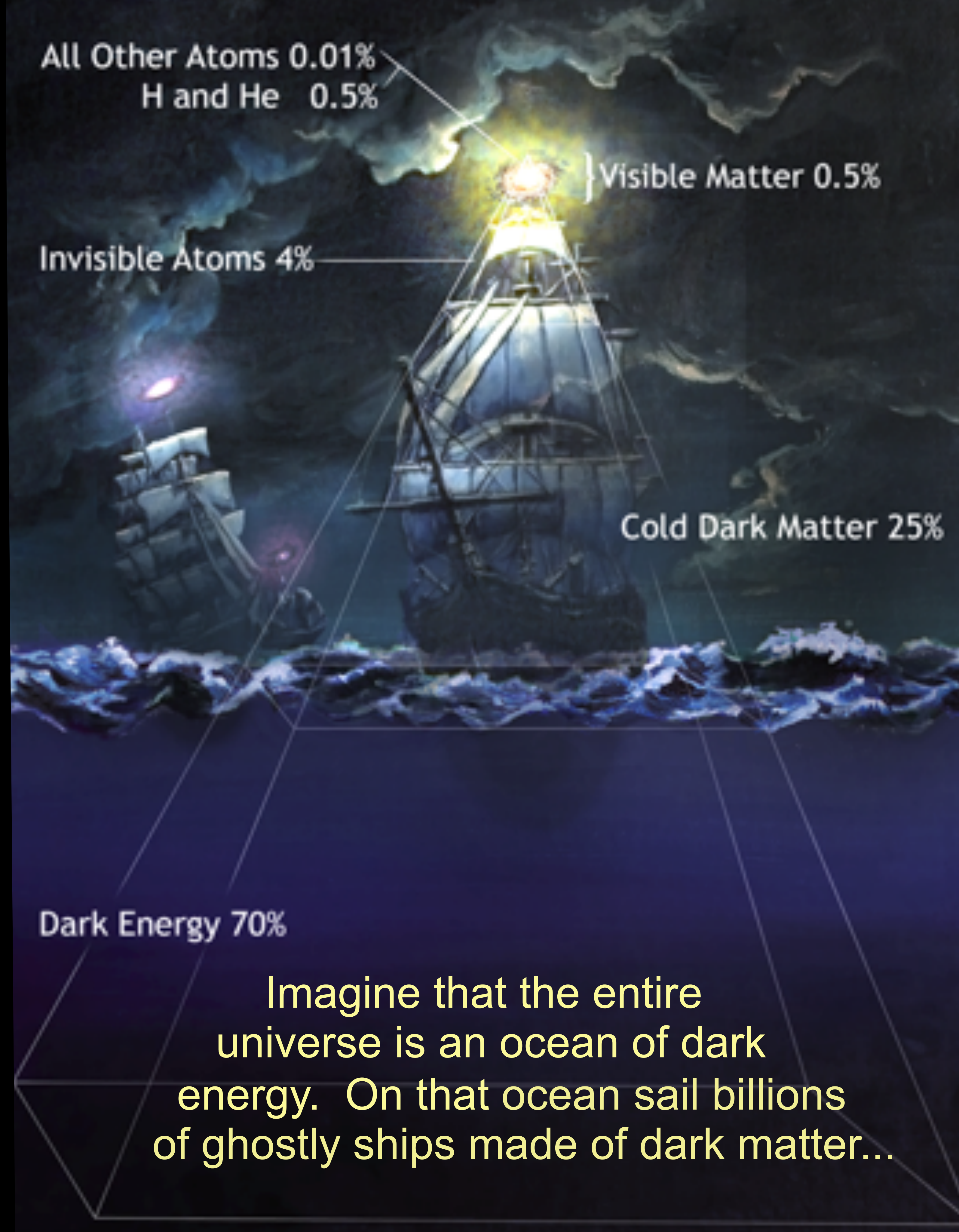
COSMIC DENSITY PYRAMID



Matter and Energy Content of the Universe



Dark Matter Ships on a Dark Energy Ocean

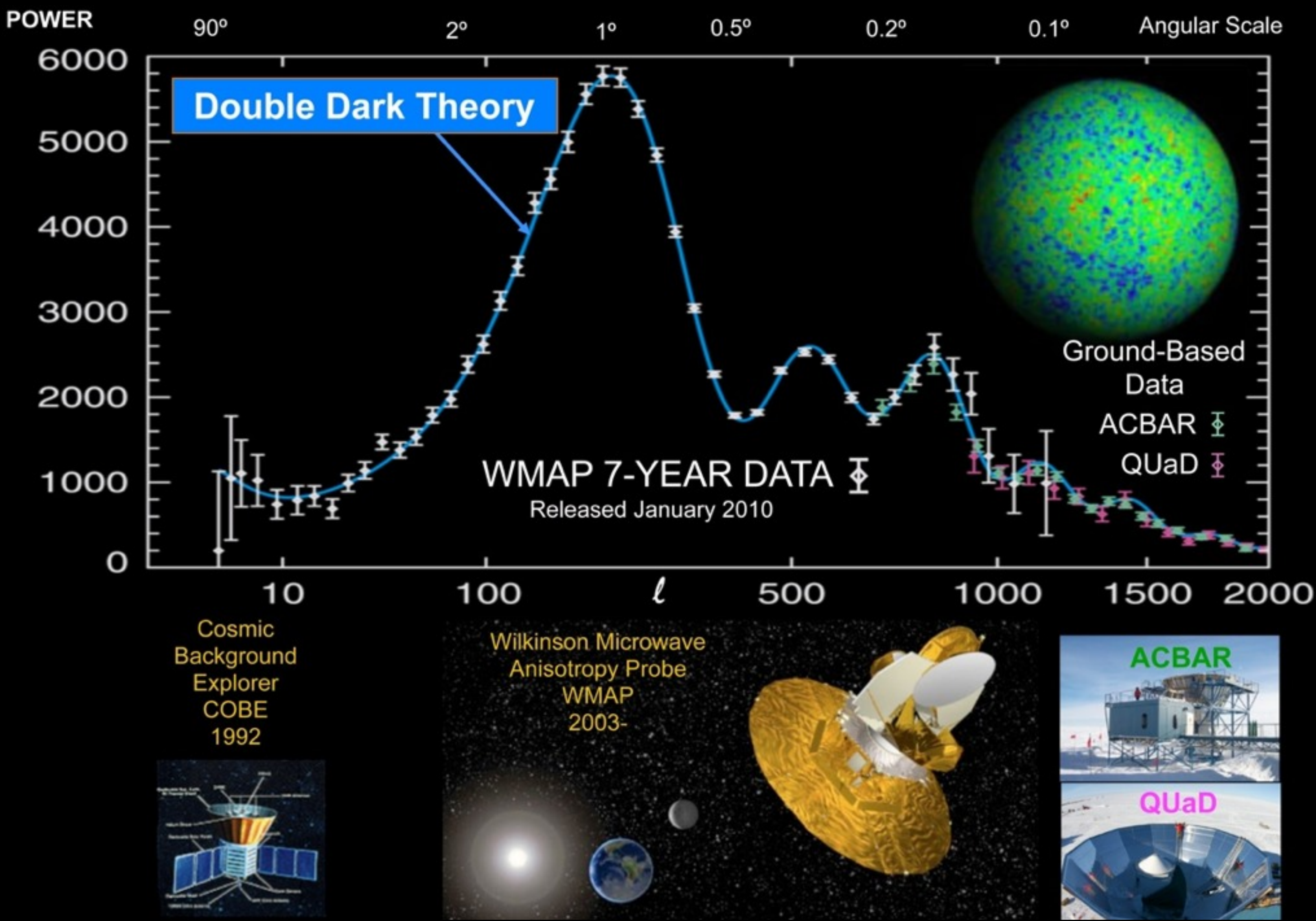


Matter and Energy Content of the Universe

ΛCDM

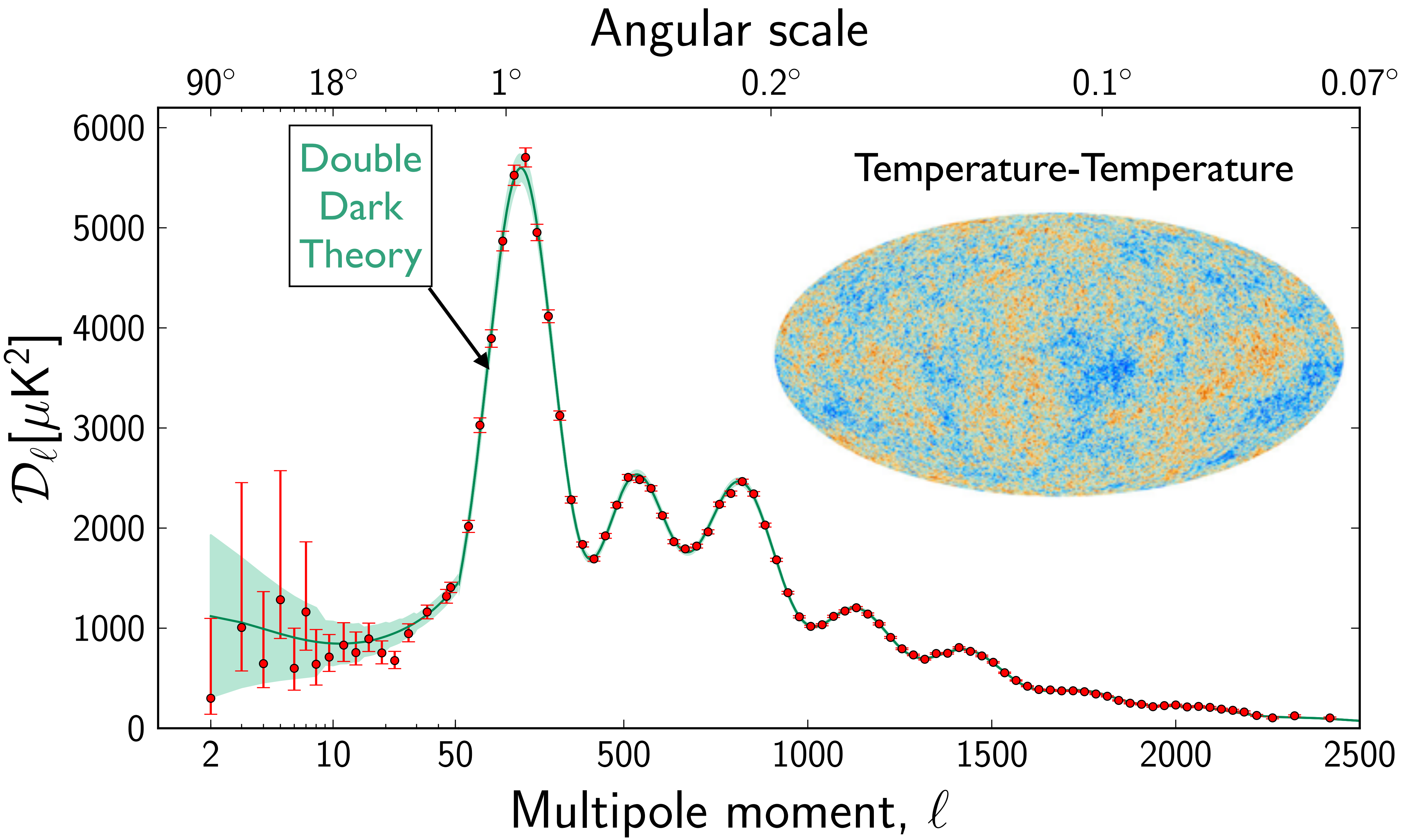
Double Dark Theory

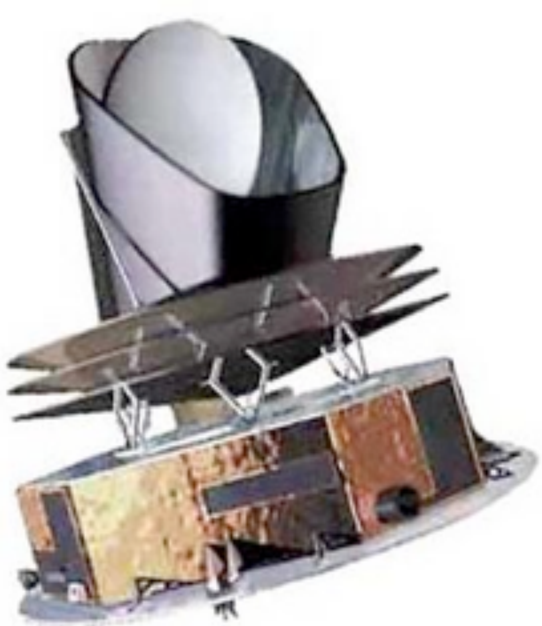
Big Bang Data Agree with Double Dark Theory

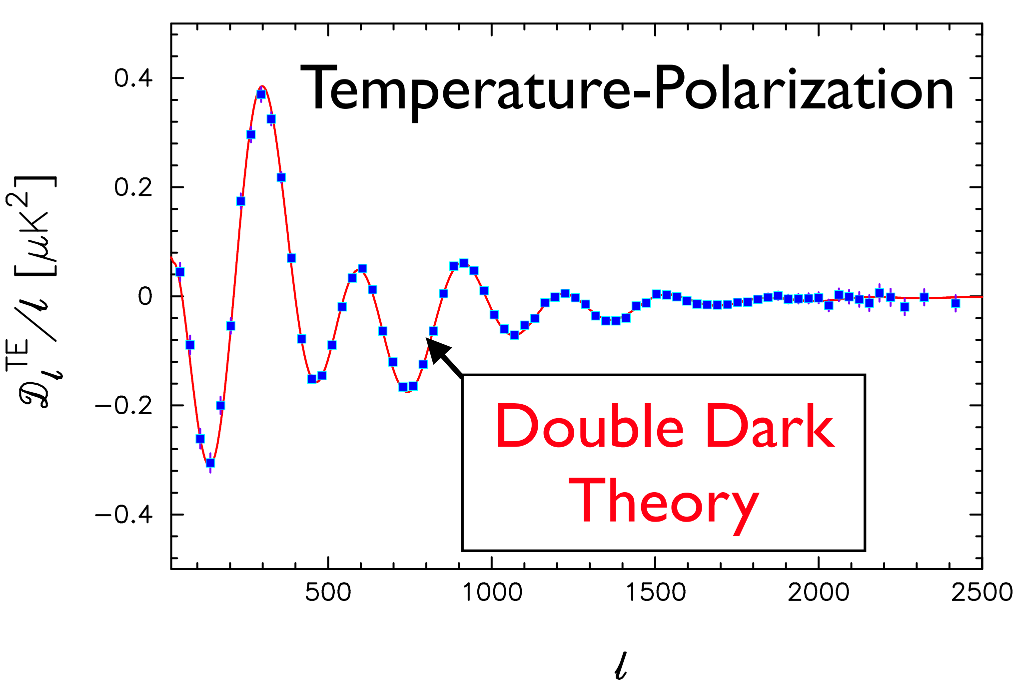


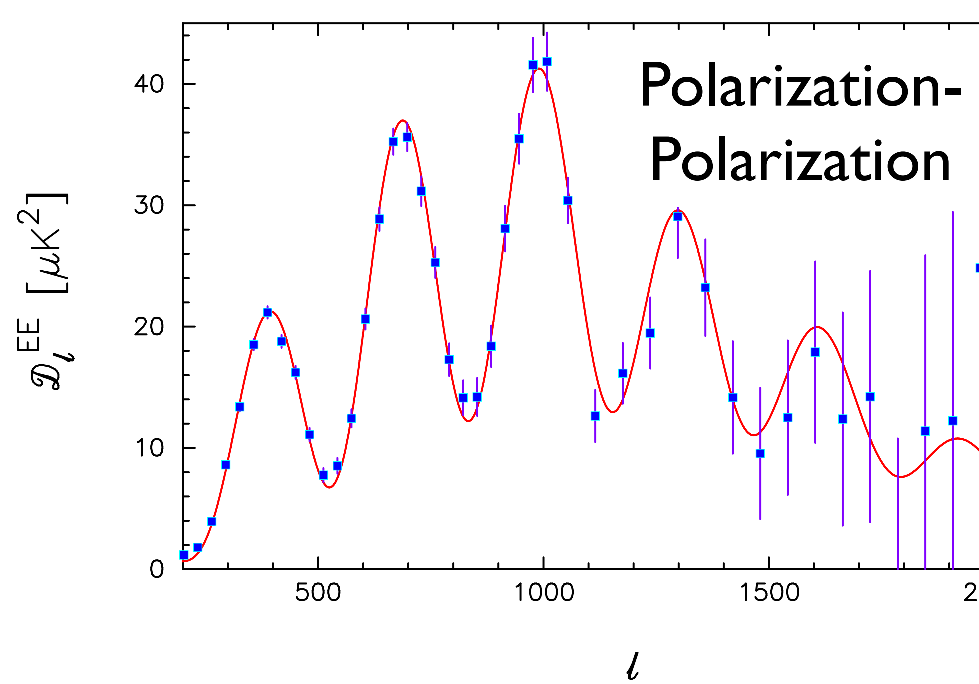
European Space Agency PLANCK Satellite Data

Released March 21, 2013









European Space Agency PLANCK Satellite Data

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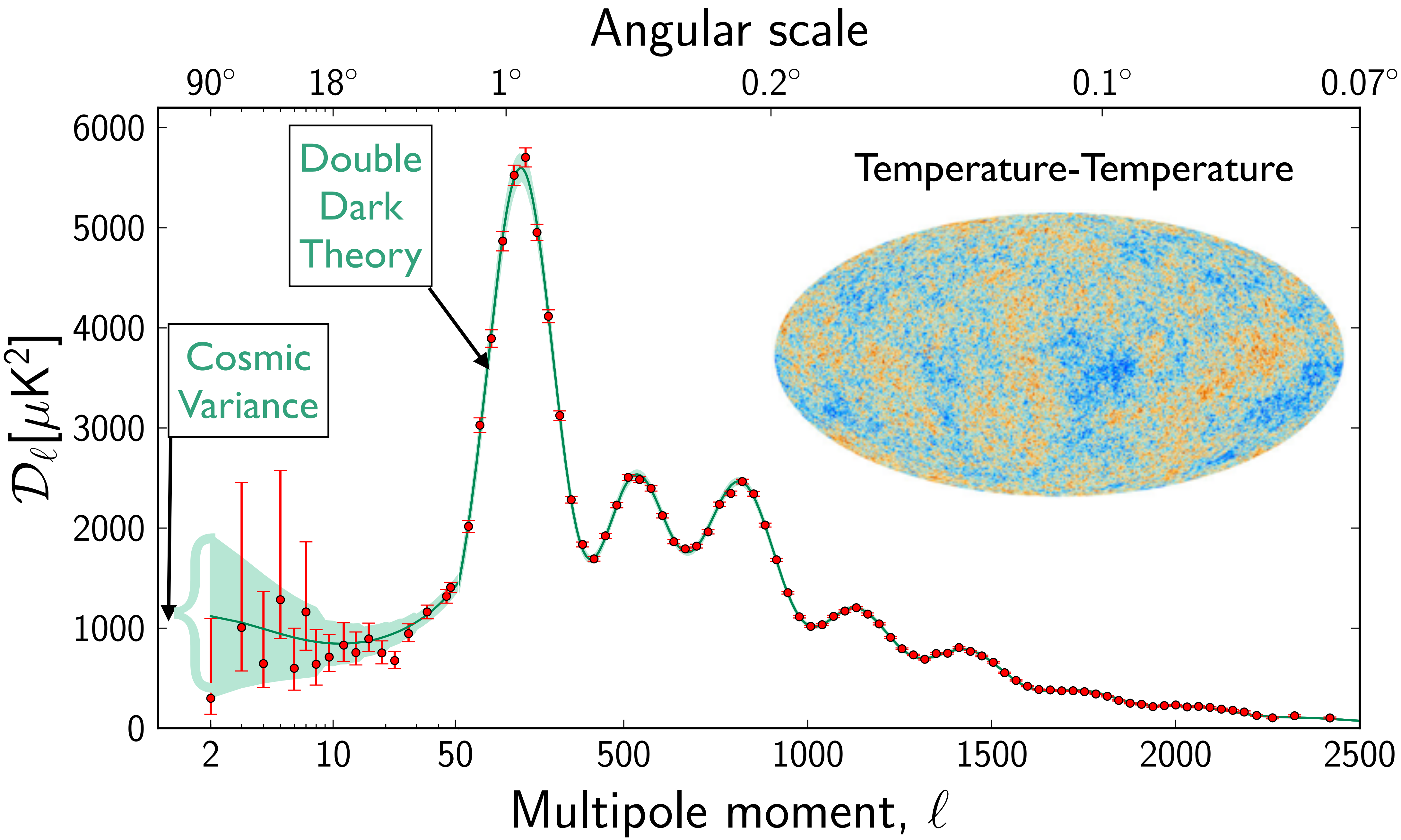
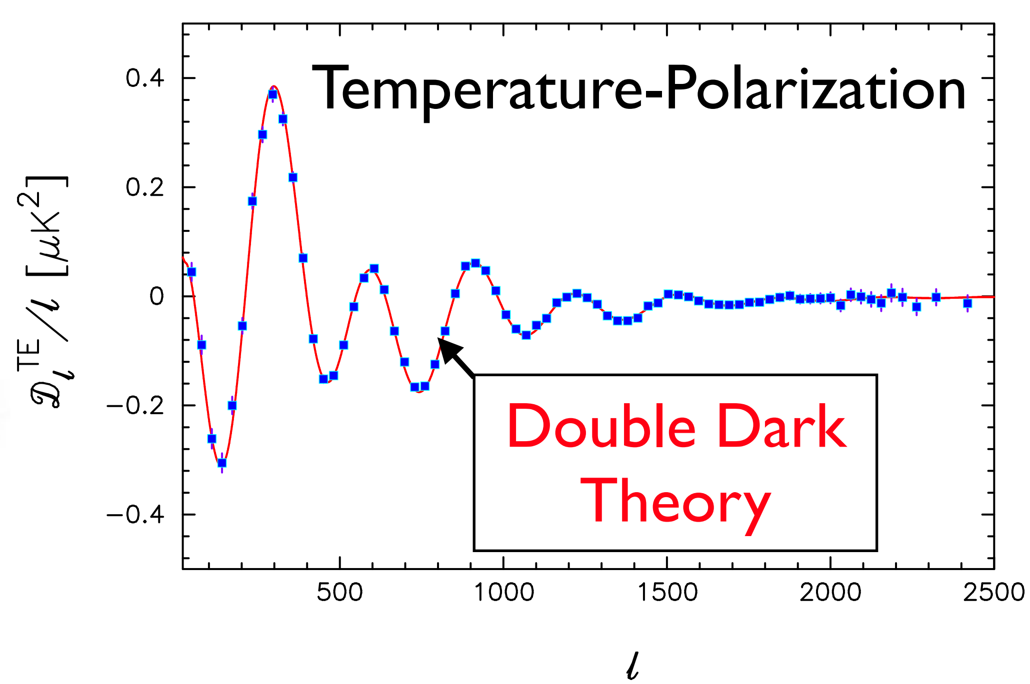
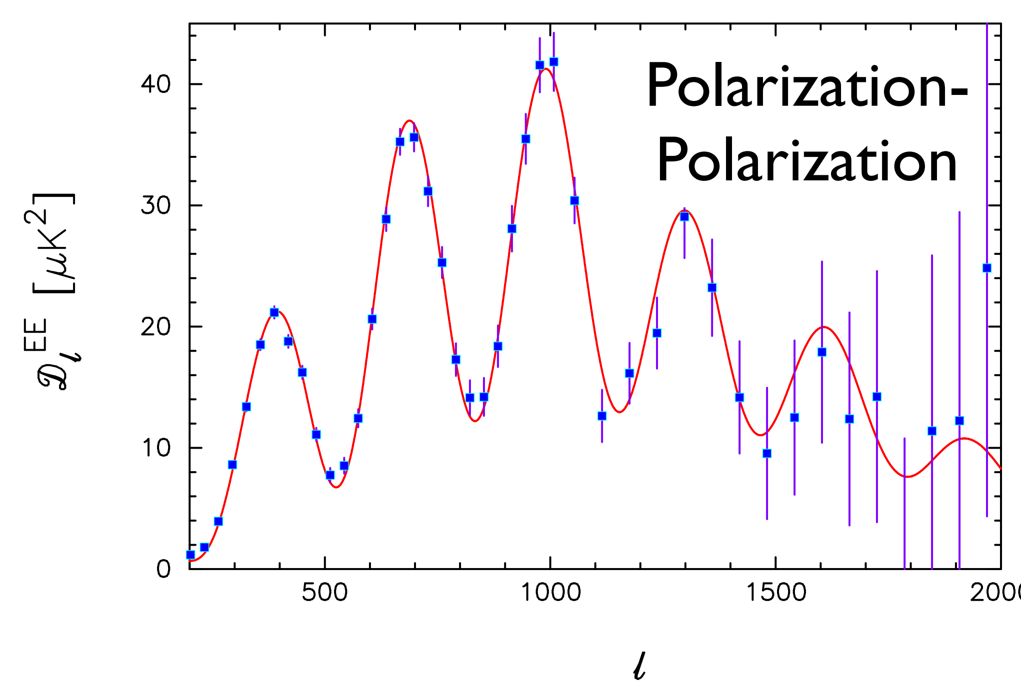
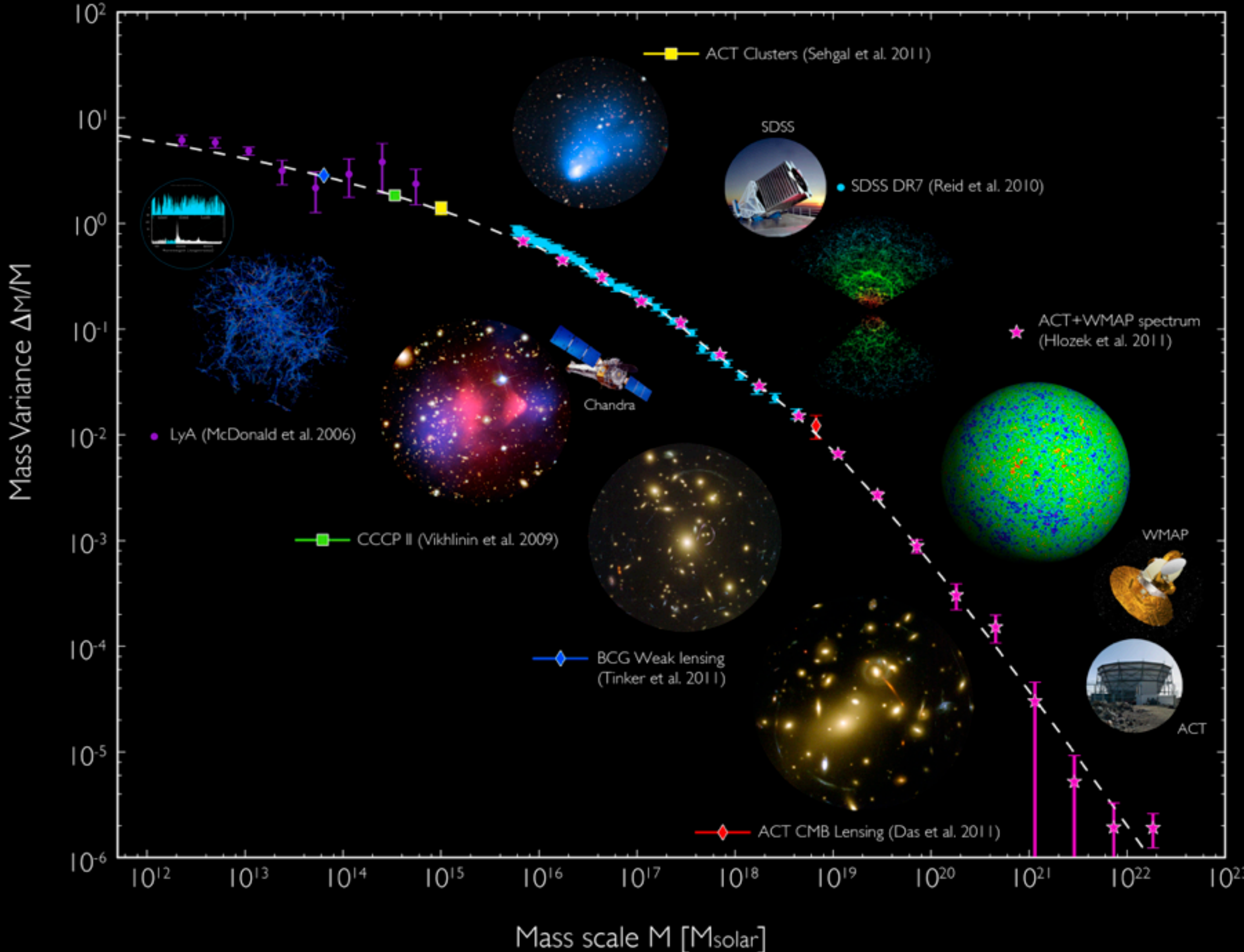






Matter Distribution Agrees with Double Dark Theory!



Cosmological Simulations

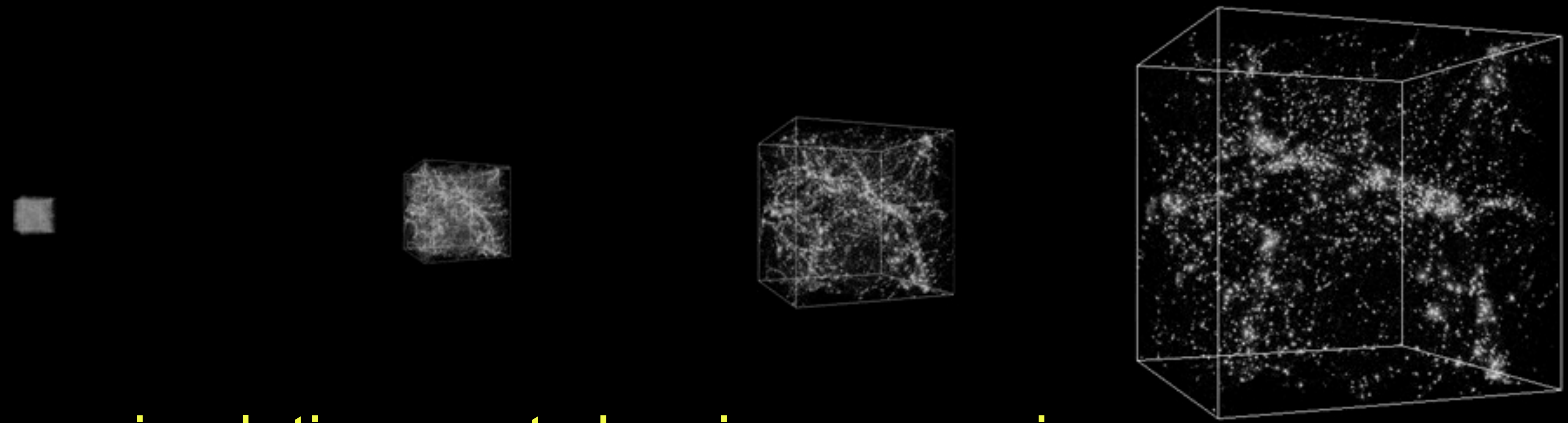
Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

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

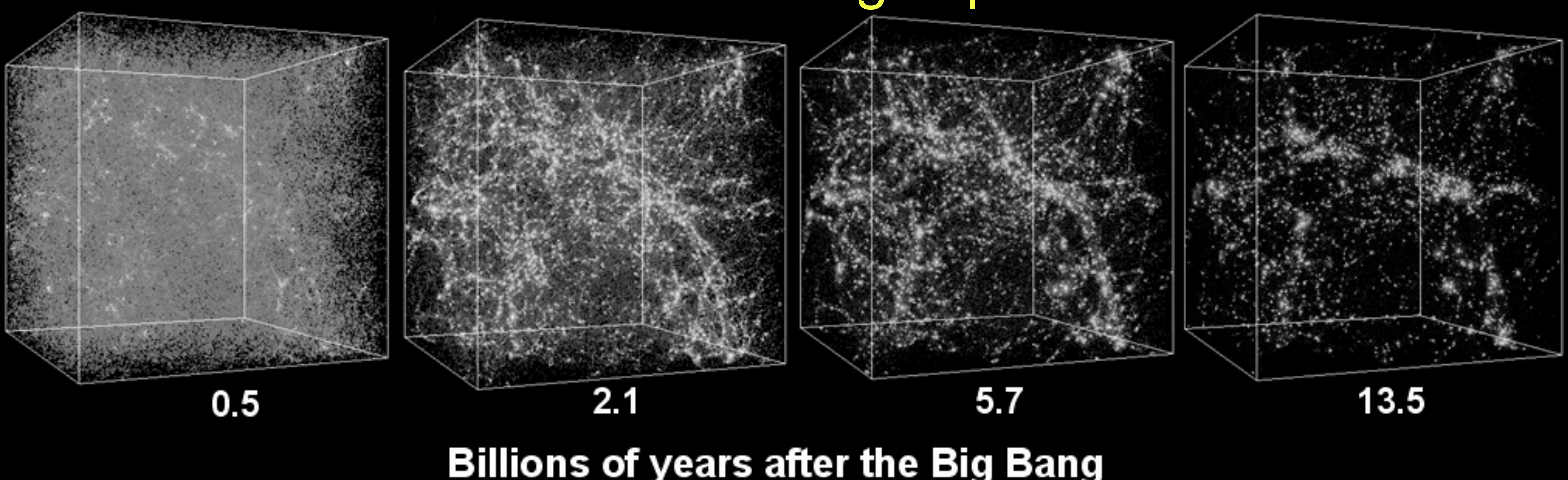
Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images in all wavebands including stellar evolution and dust

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

dark matter simulation - expanding with the universe

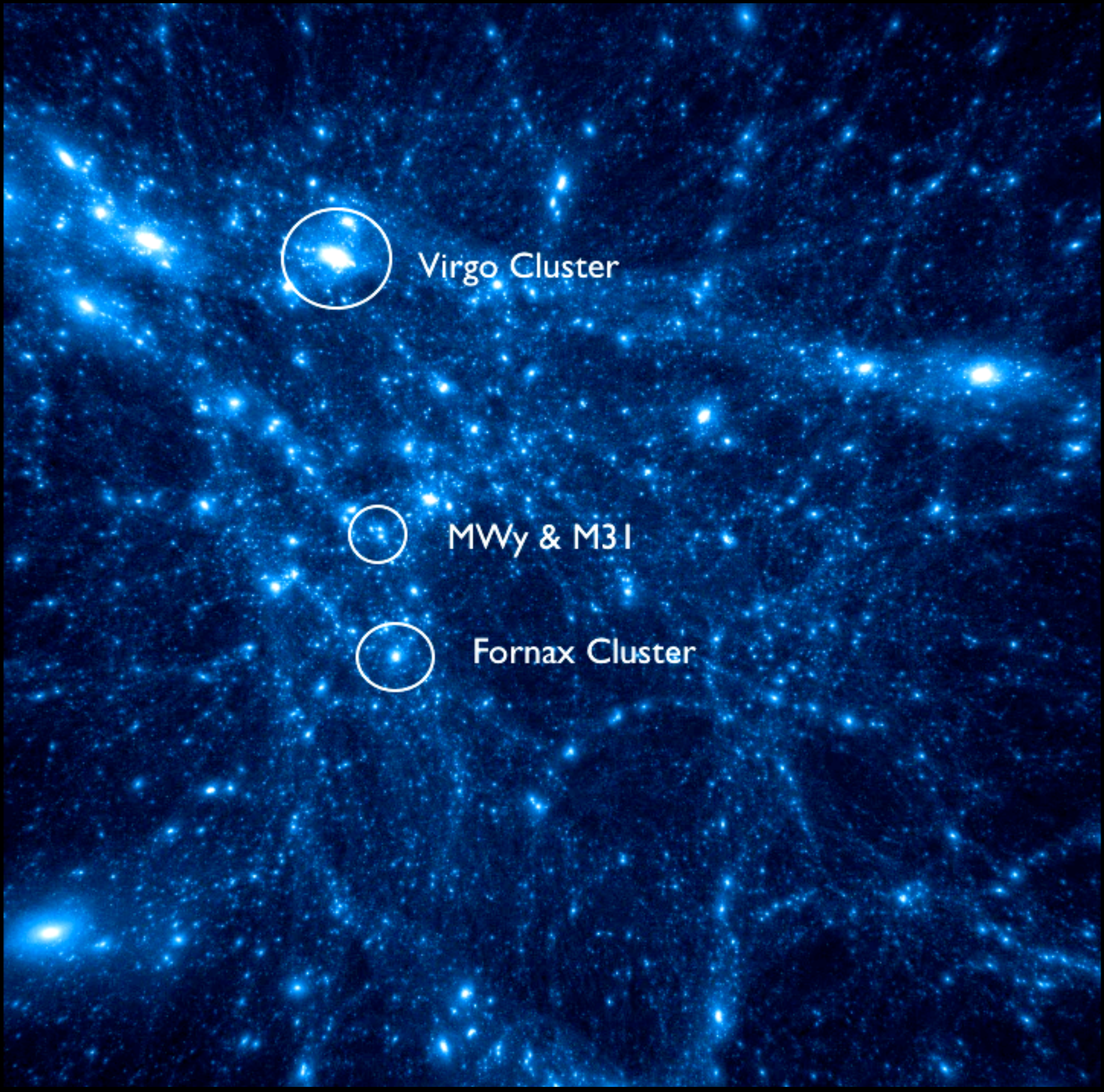


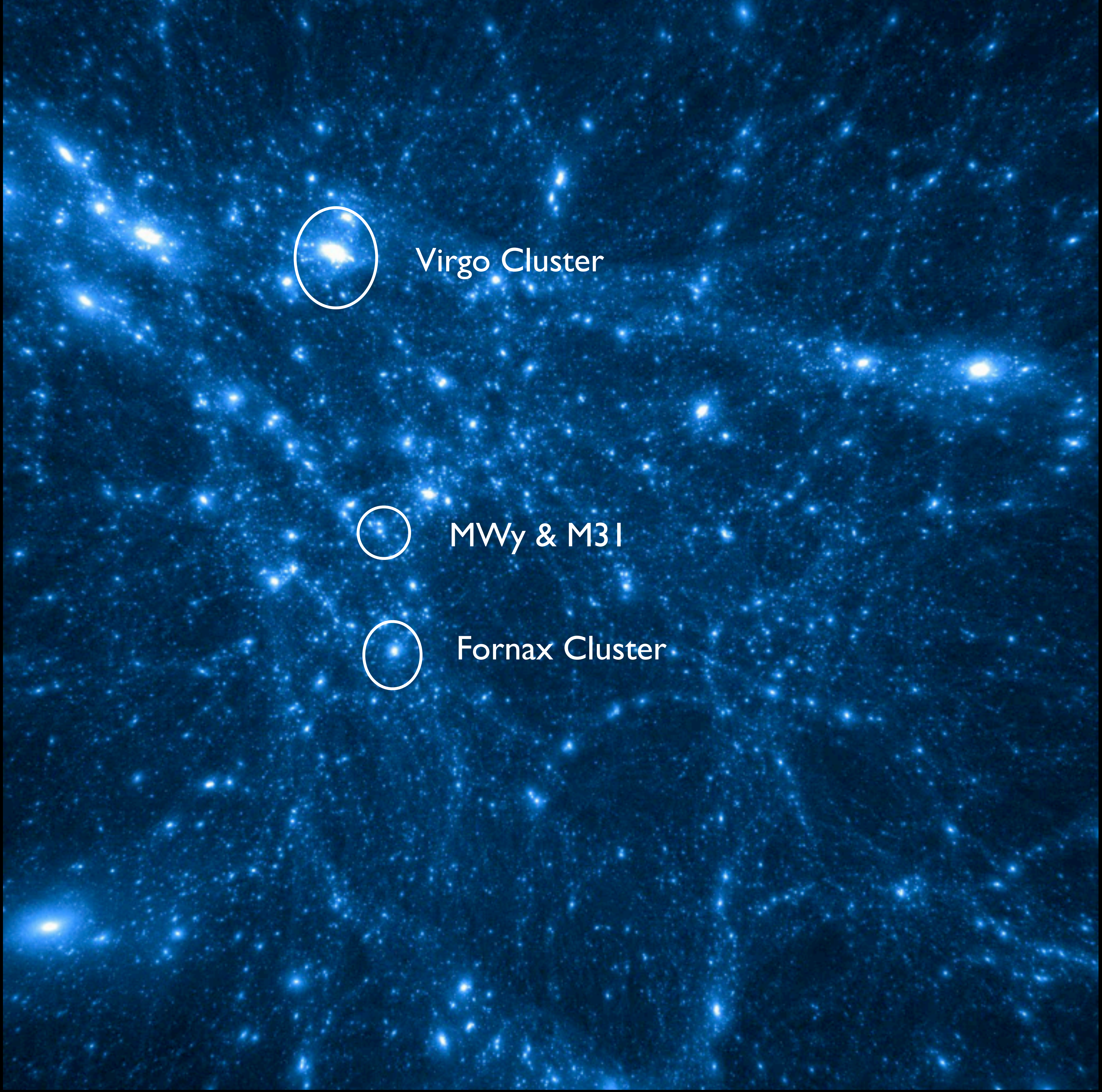
same simulation - not showing expansion



Andrey Kravtsov

CONSTRAINED LOCAL UNIVERSE SIMULATION


Virgo Cluster
MWy & M31
Fornax Cluster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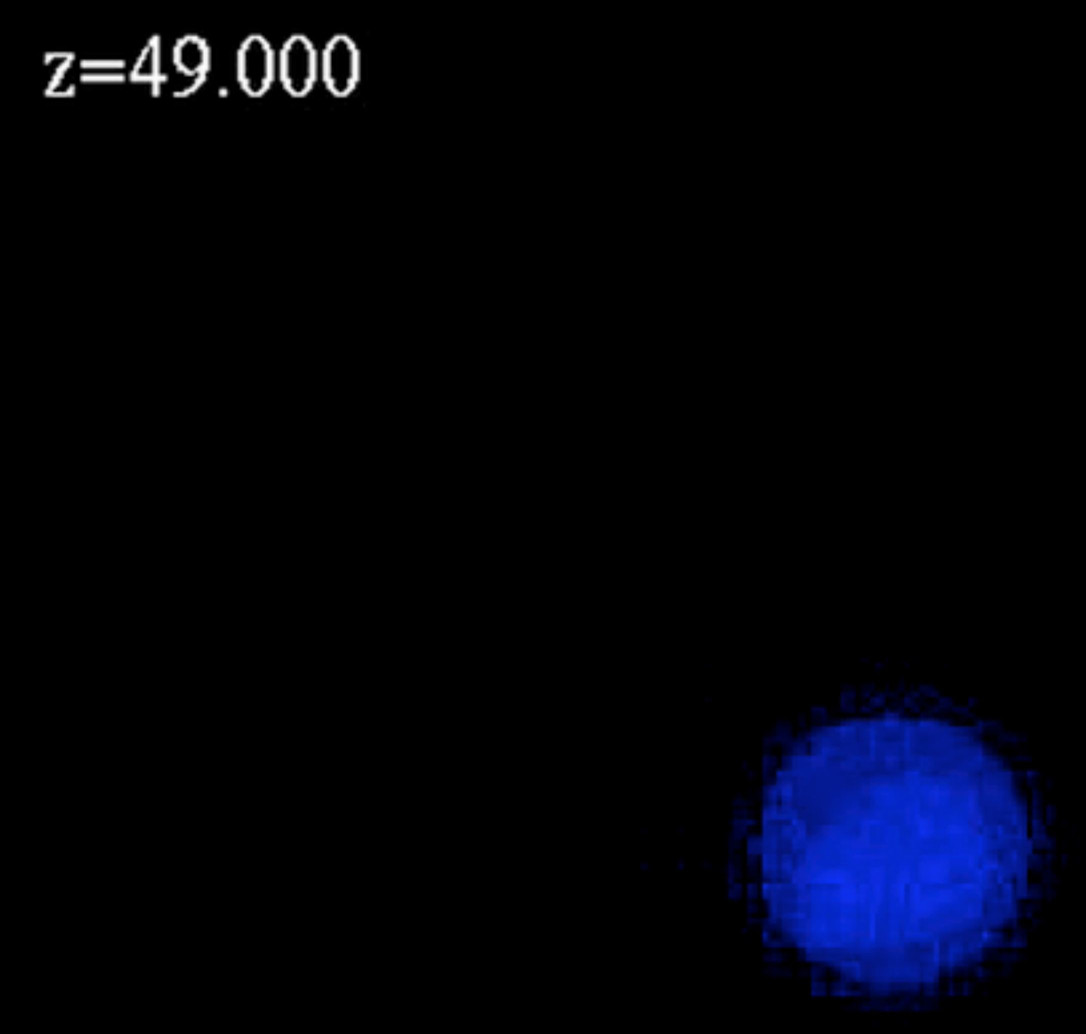
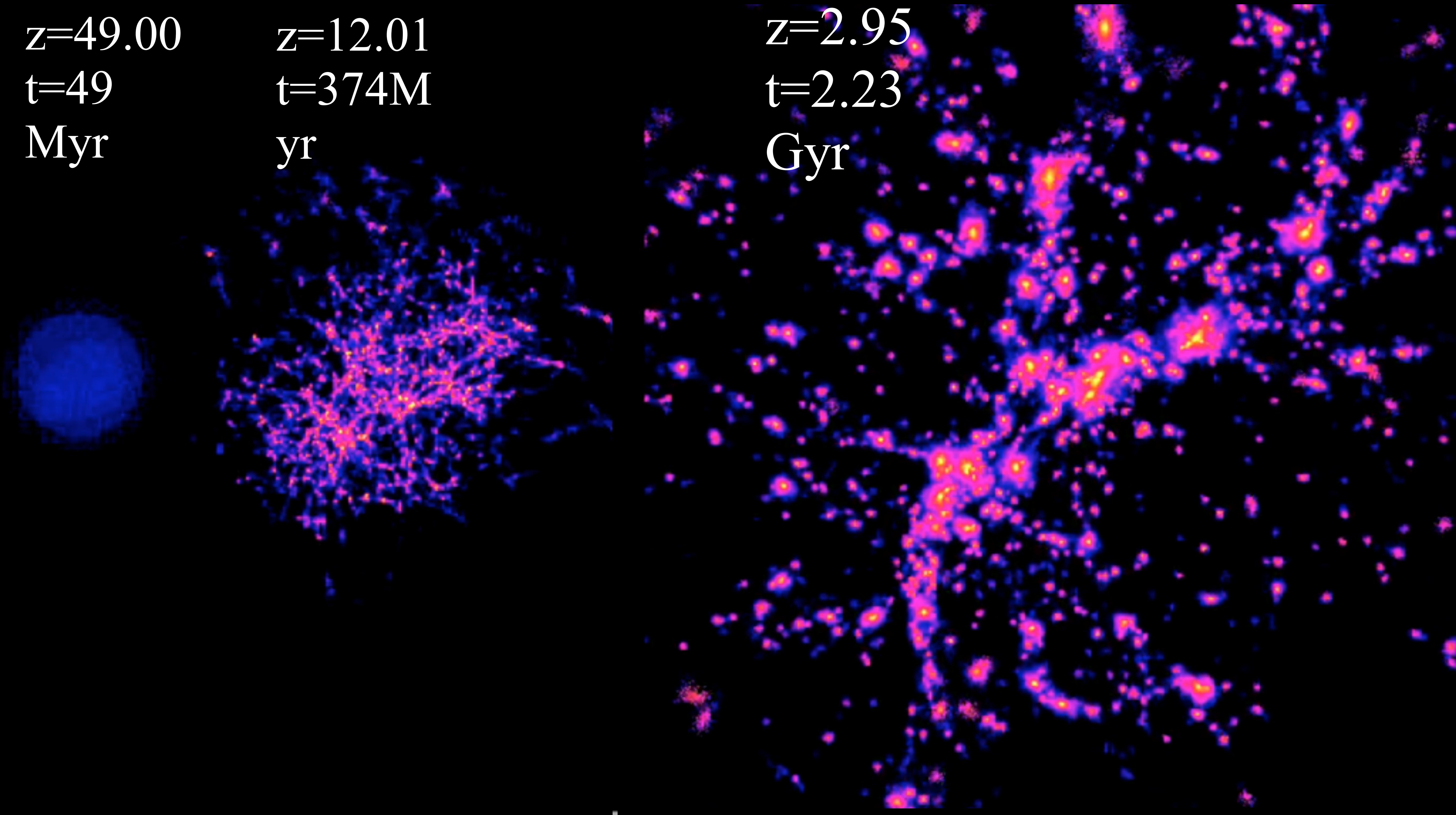
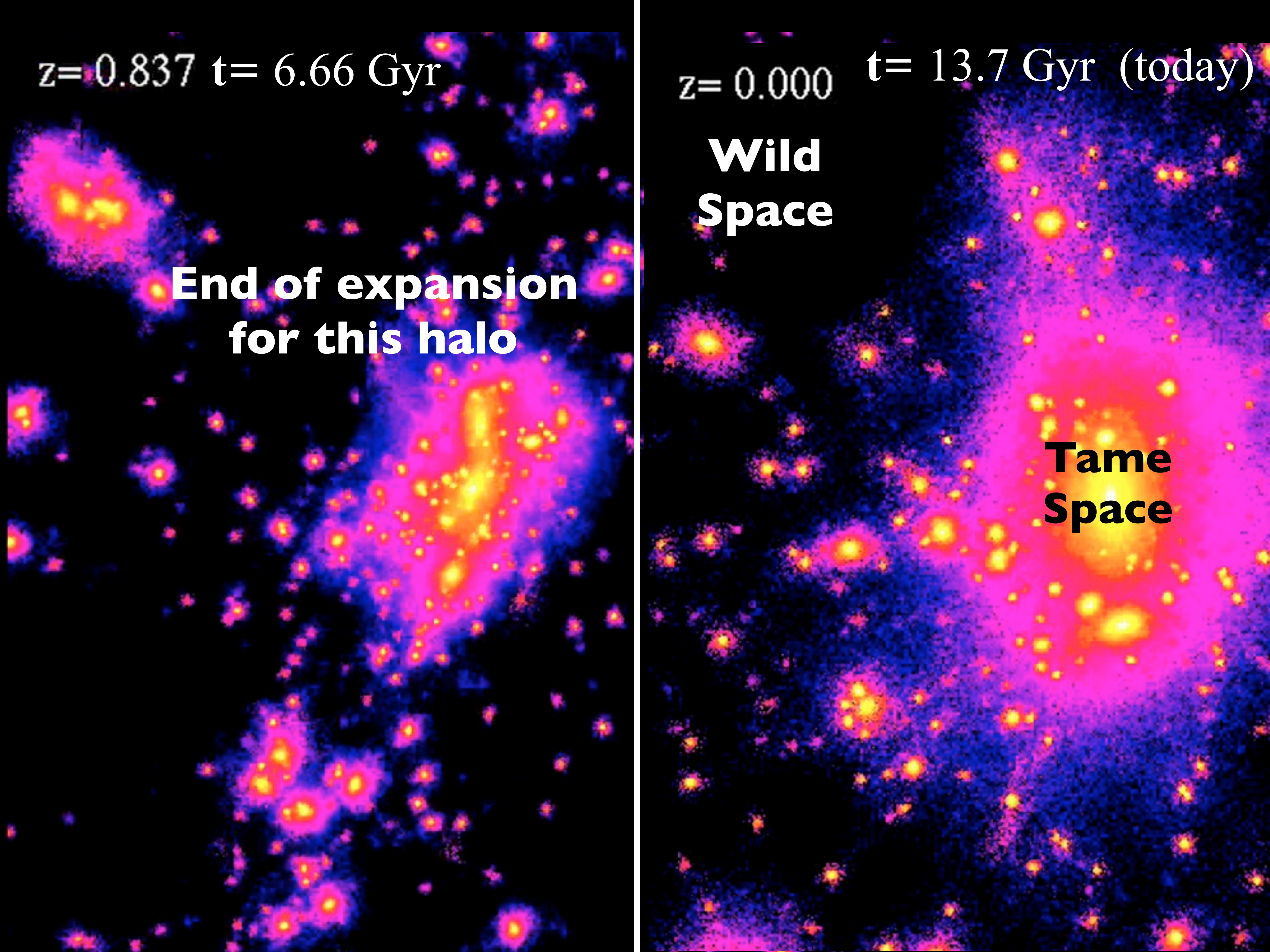
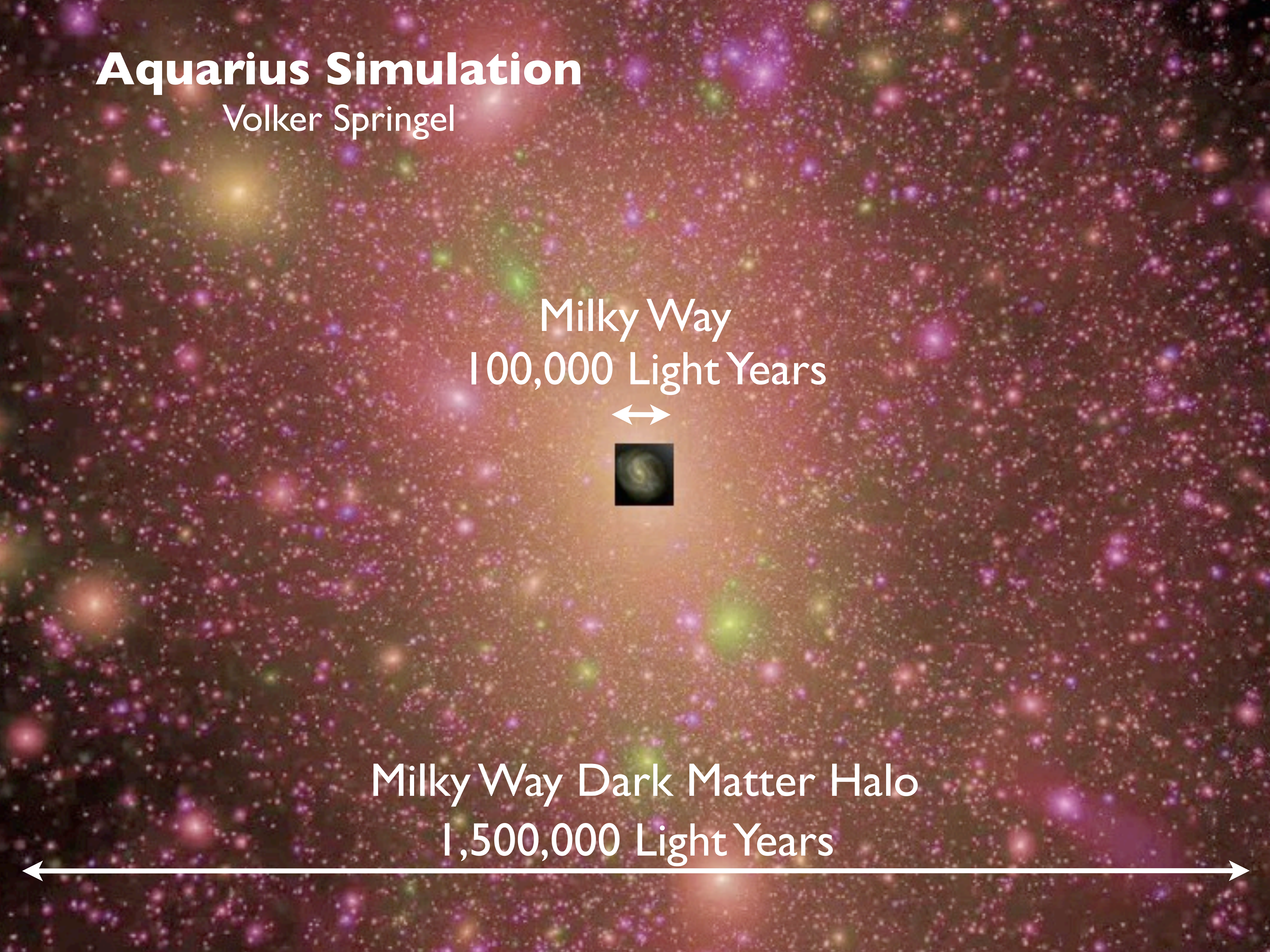


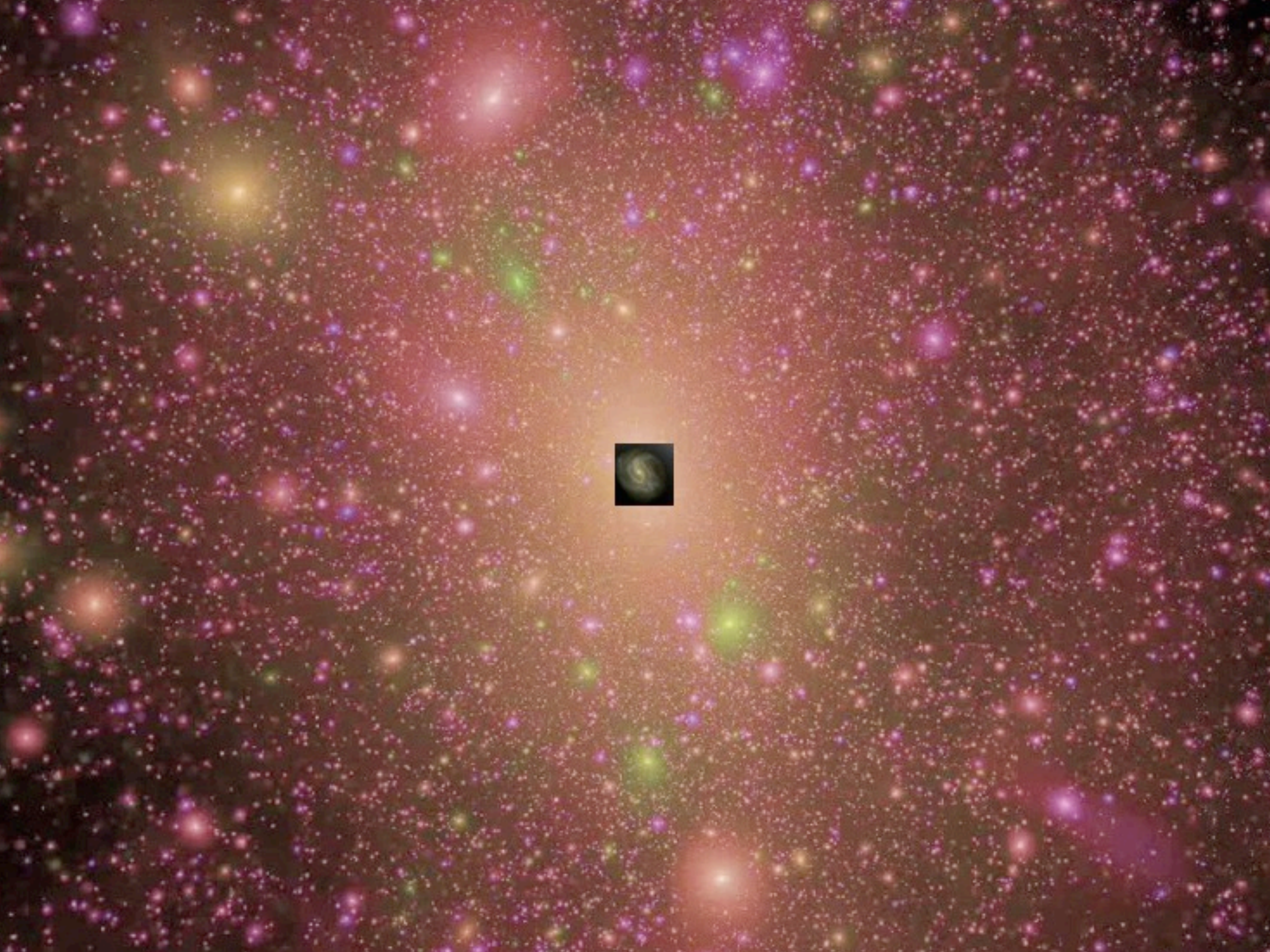
Expanding Simulation - Ben Moore et al.
Music: L. Subramanian & Stephane Grapelli
“French Resolution” album *Conversations*

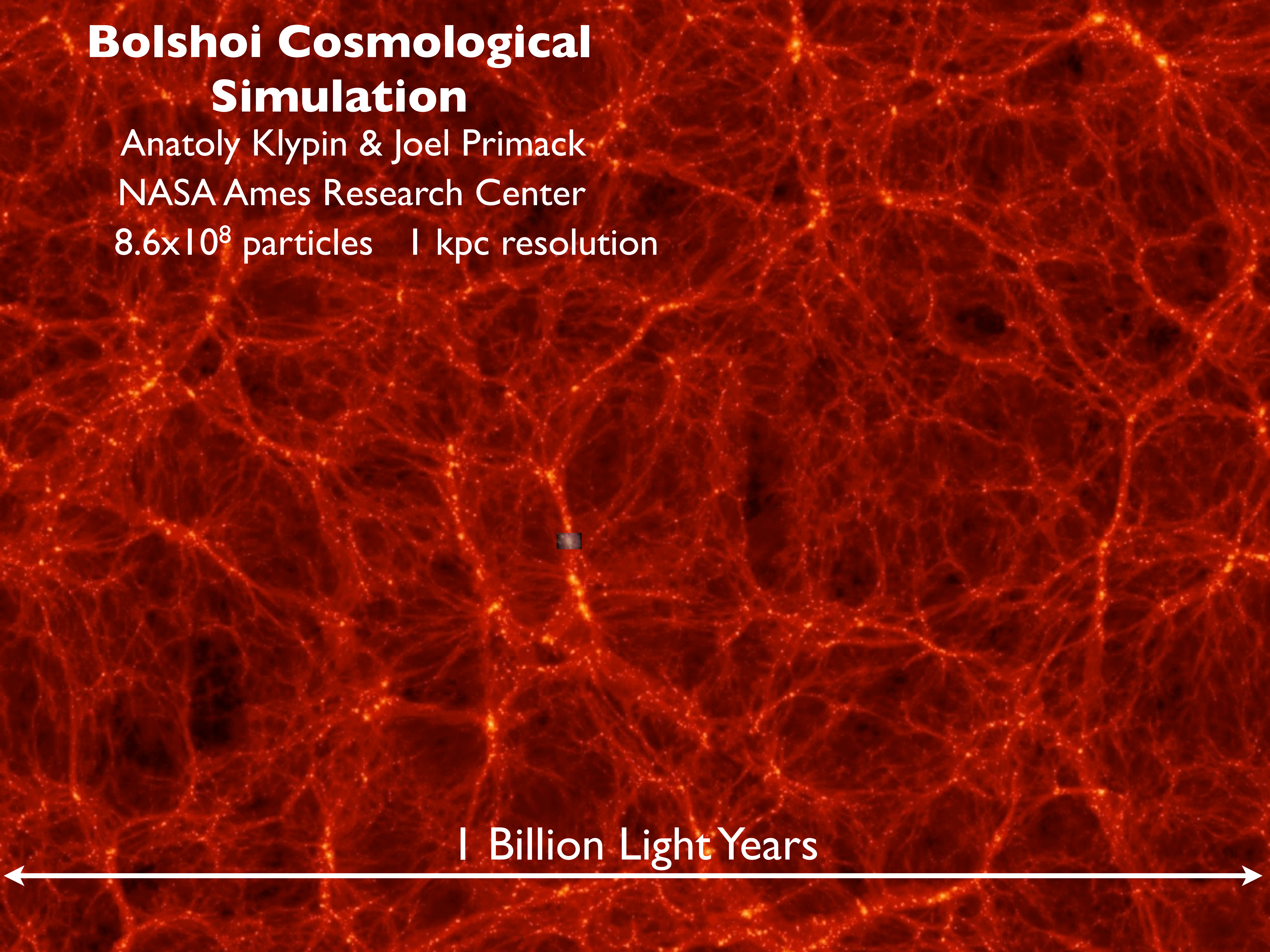
Expansion....

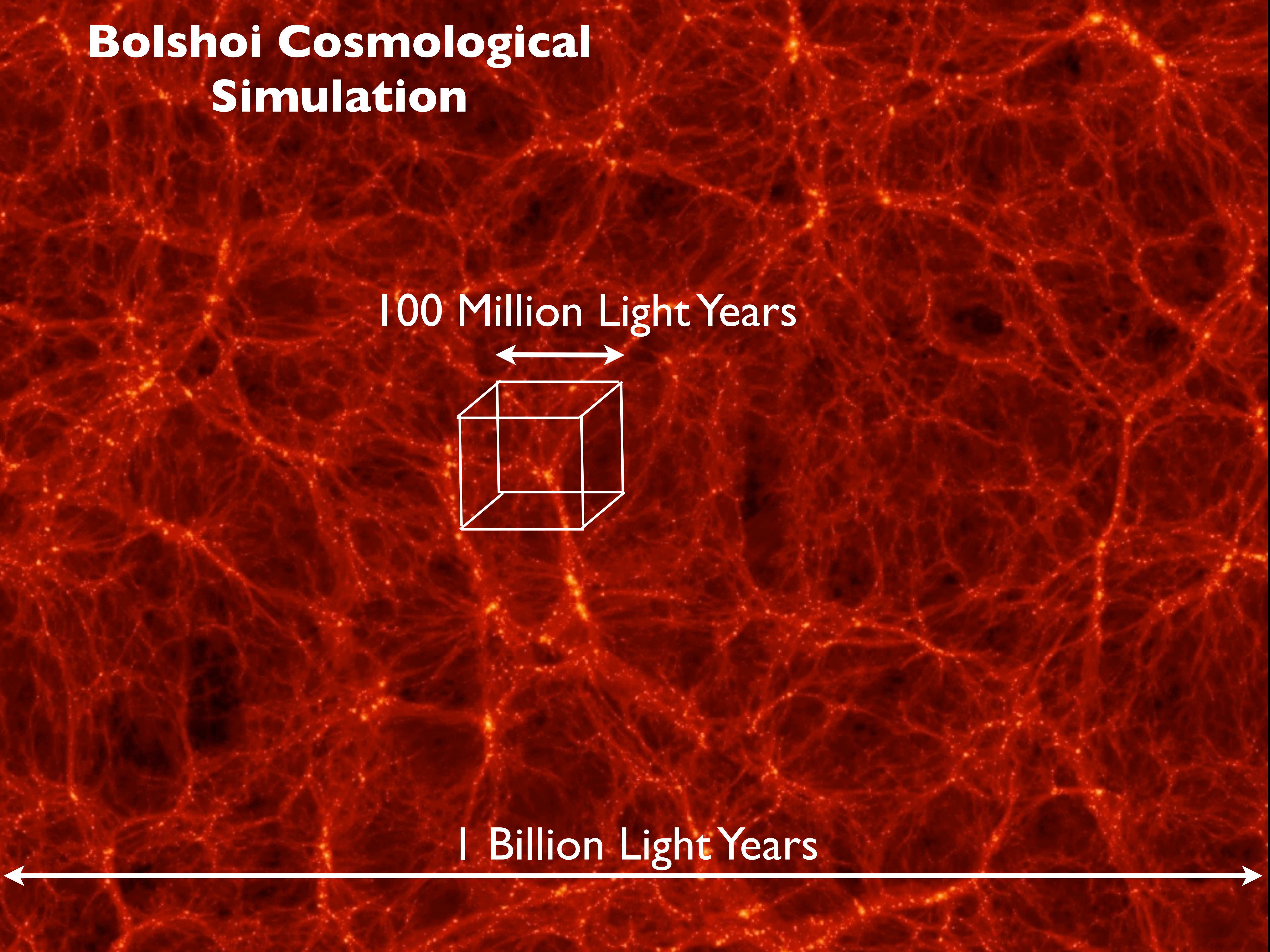



z= 0.837 t= 6.66 Gyr
End of expansion
for this halo
z= 0.000
t= 13.7 Gyr (today)
Wild
Space
Tame
Space


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
8.6×10^8 particles 1 kpc resolution
1 Billion Light Years

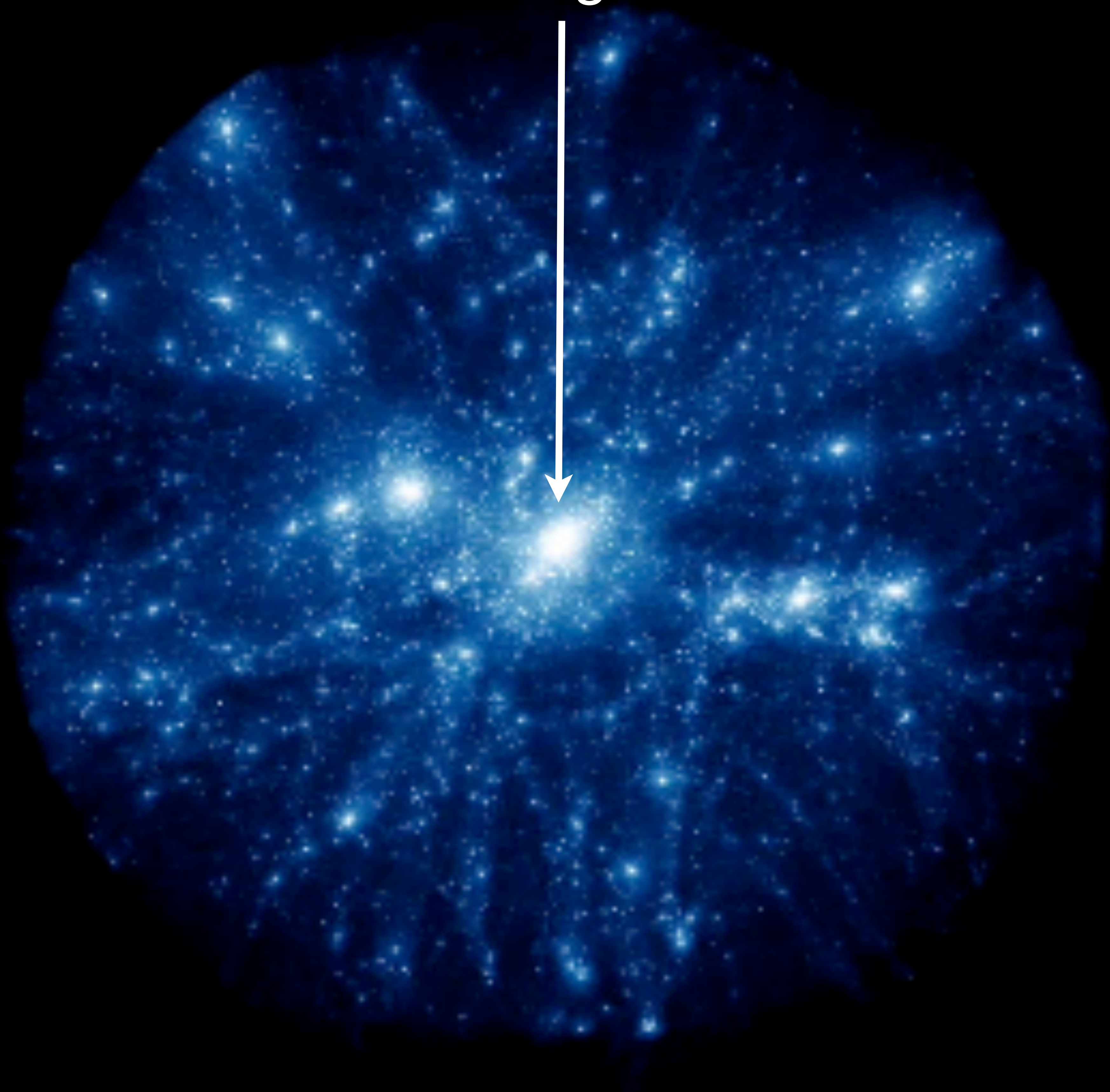

Bolshoi Cosmological Simulation
100 Million Light Years
1 Billion Light Years

Bolshoi Cosmological Simulation

100 Million Light Years

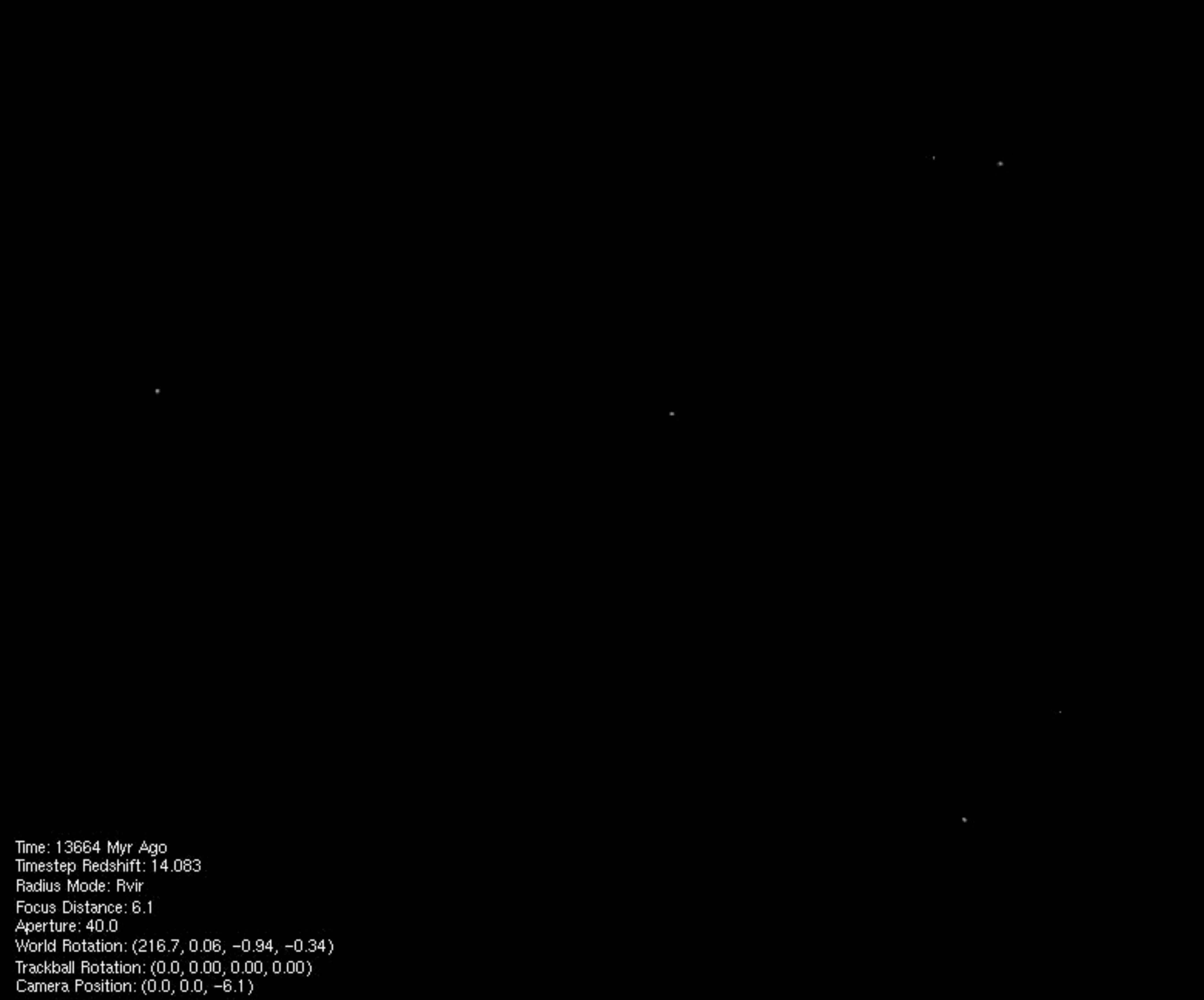
Bolshoi Simulation - Anatoly Klypin & Joel Primack
Visualization: Christopher Henze, NASA
Music: Ray Lynch "Her Knees Deep in My Mind"
album *Nothing Above My Head But the Evening*

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 Fallen in by Today



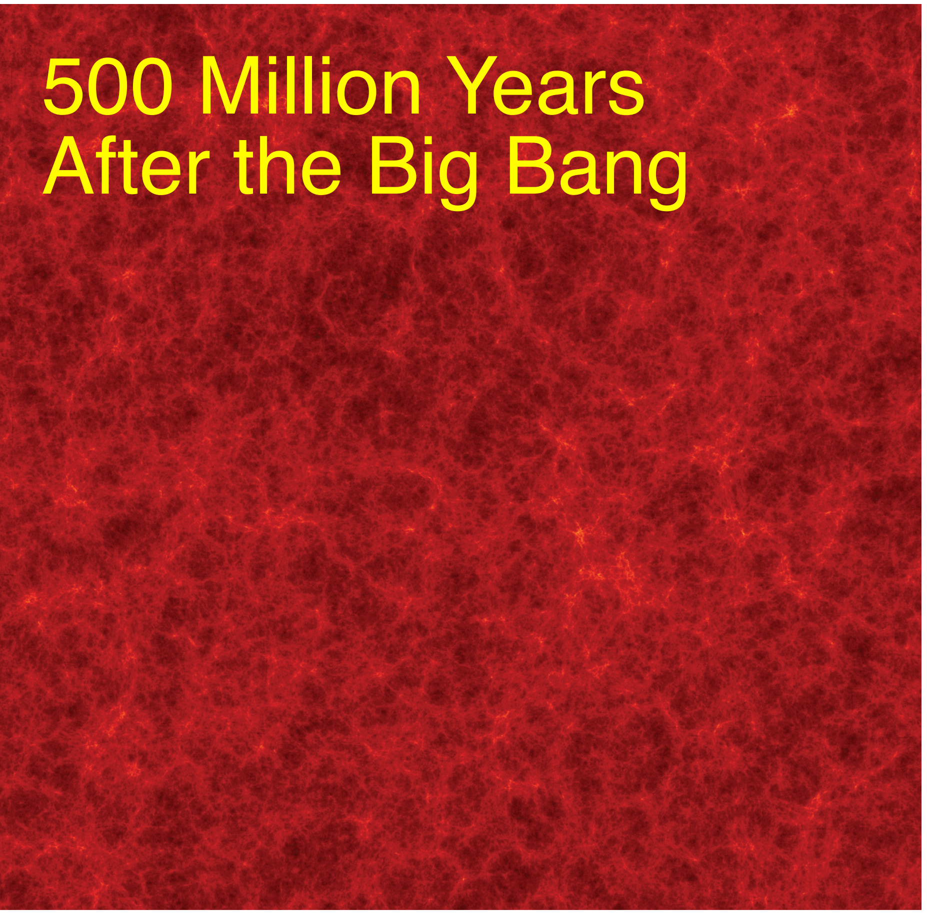
Peter Behroozi

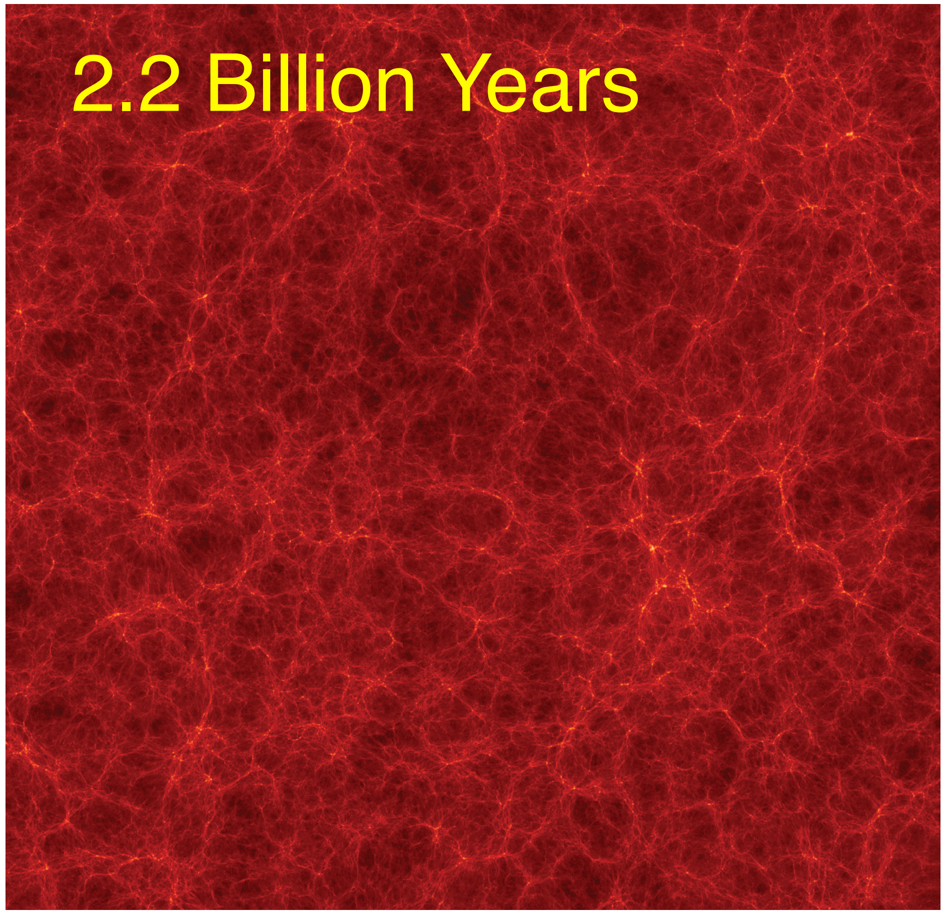
Bjork "Dark Matter"

Biophilia


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

IEEE Spectrum - October 2012

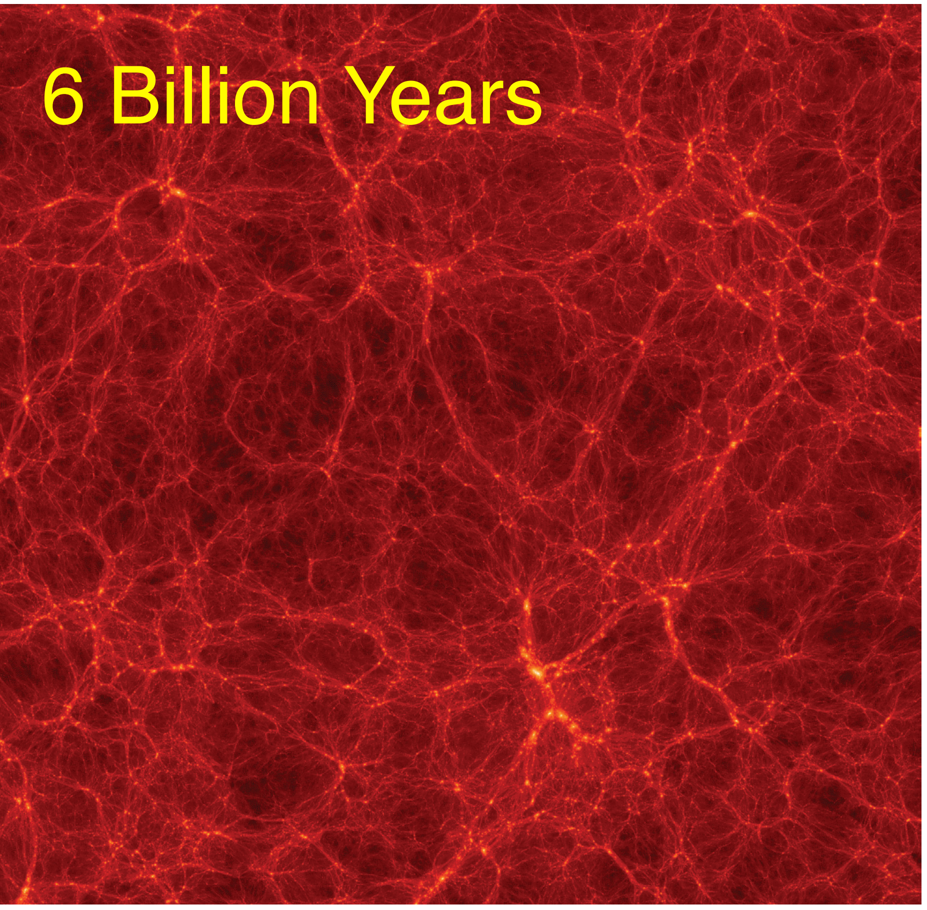


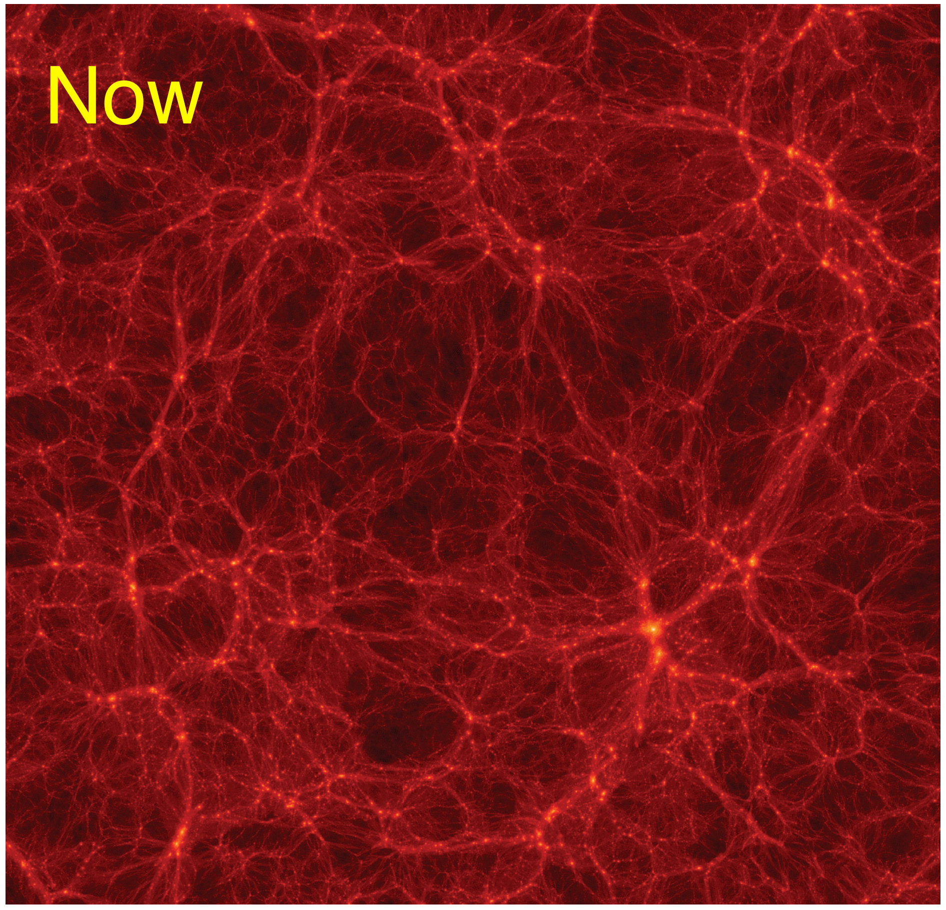


COSMIC WEB: The Bolshoi simulation models the evolution of dark matter, which is responsible for the large-scale structure of the universe. Here, snapshots from the simulation show the dark matter distribution at 500 million and 2.2 billion years [top] and 6 billion and 13.7 billion years [bottom] after 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

THE UNIVERSE IN A SUPERCOMPUTER





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

By Joel R. Primack

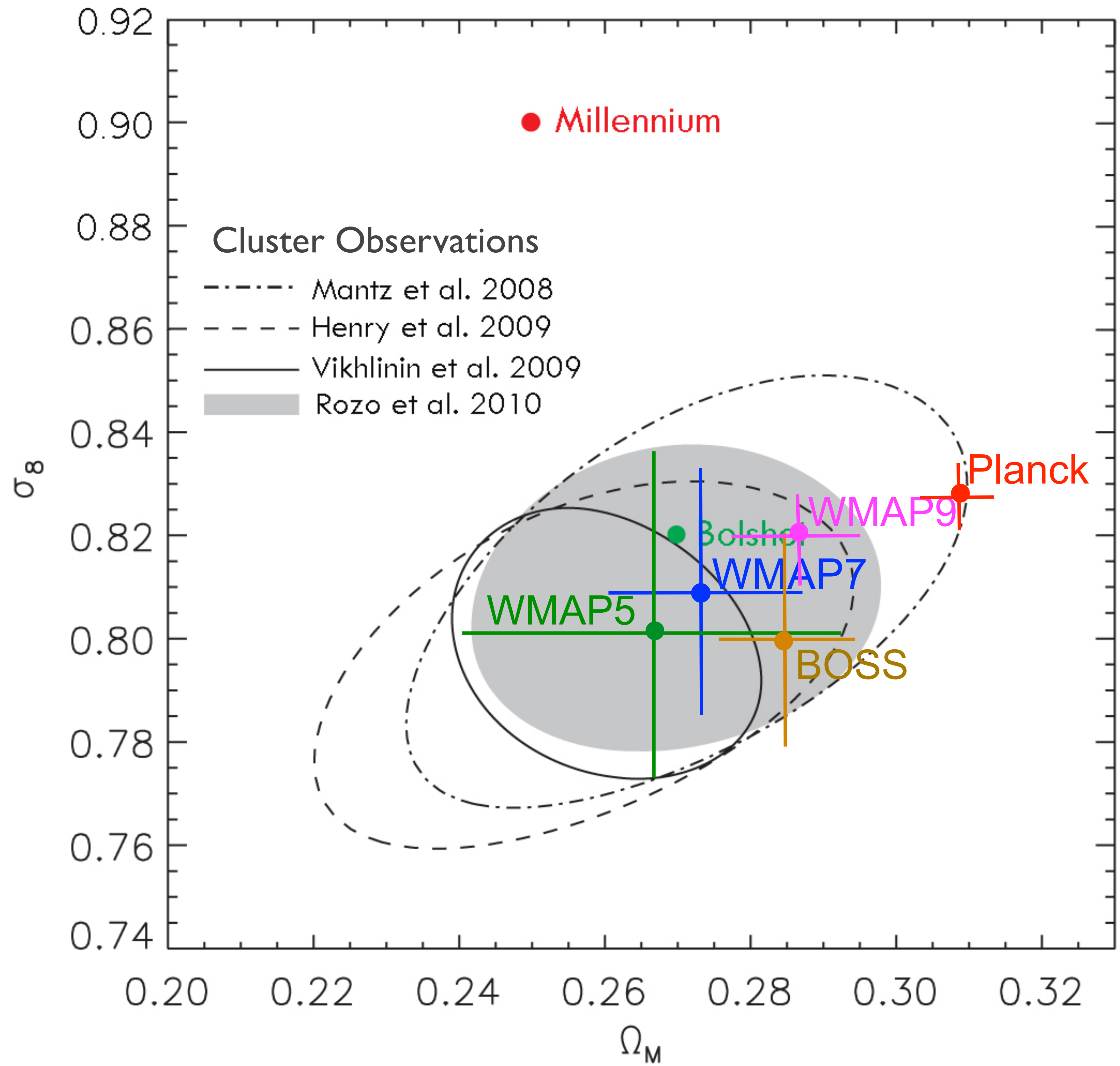
WHEN IT COMES TO RECONSTRUCTING THE PAST, you might think that astrophysicists have it easy. After all, the sky is awash with evidence. For most of the universe's history, space has been largely transparent, so much so that light emitted by distant galaxies can travel for billions of years before finally 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.

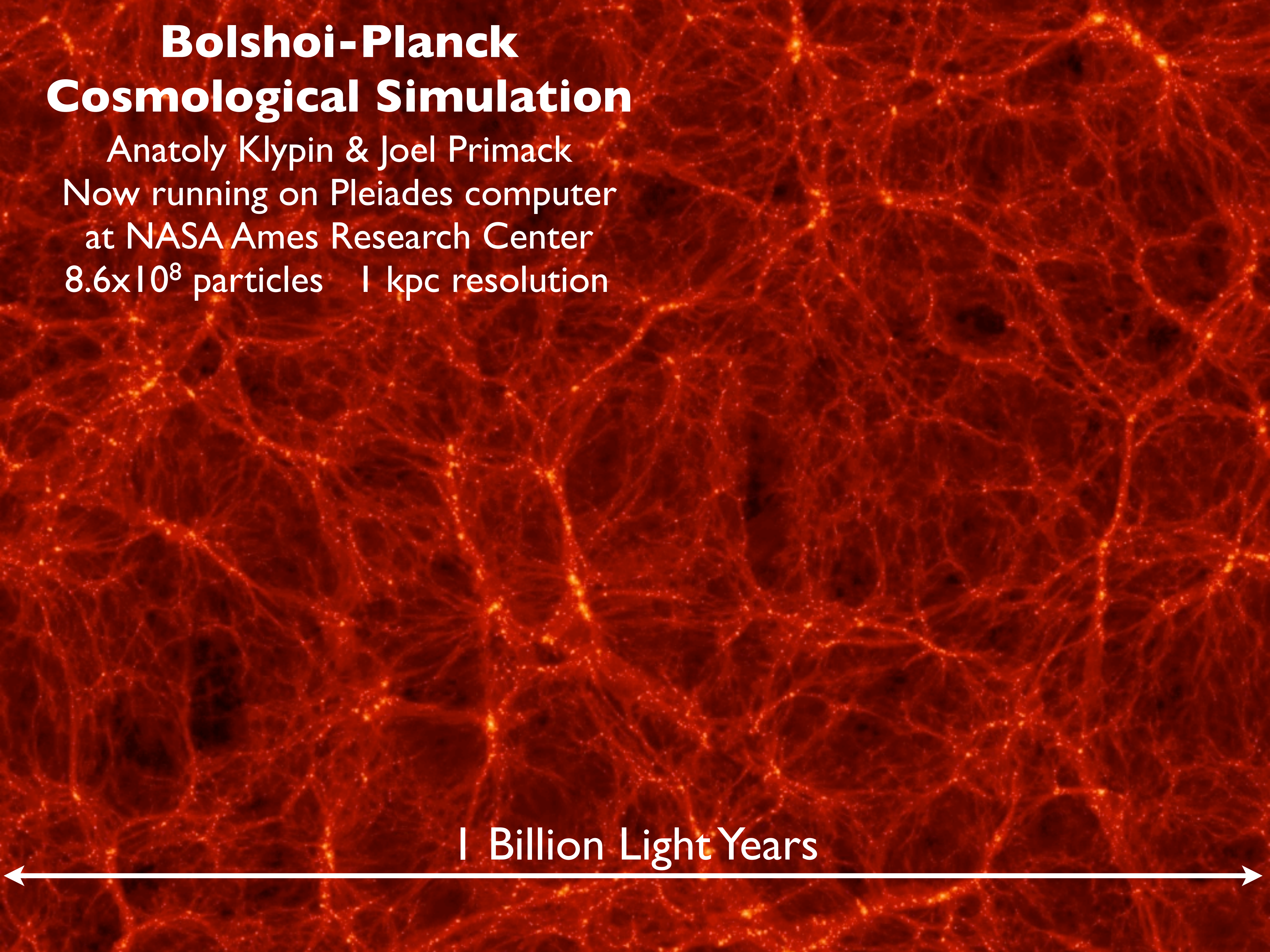
Actually, it's more complicated than that. Most of the ordinary matter in the universe—the stuff that makes up all the atoms, stars, and galaxies astronomers can see—is invisible, either sprinkled throughout intergalactic space in tenuous forms that emit and absorb little light or else swaddled inside 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

Determination of σ_8 and Ω_M from CMB+

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




Bolshoi-Planck
Cosmological Simulation
Anatoly Klypin & Joel Primack
Now running on Pleiades computer
at NASA Ames Research Center
8.6x10^8 particles 1 kpc resolution
1 Billion Light Years

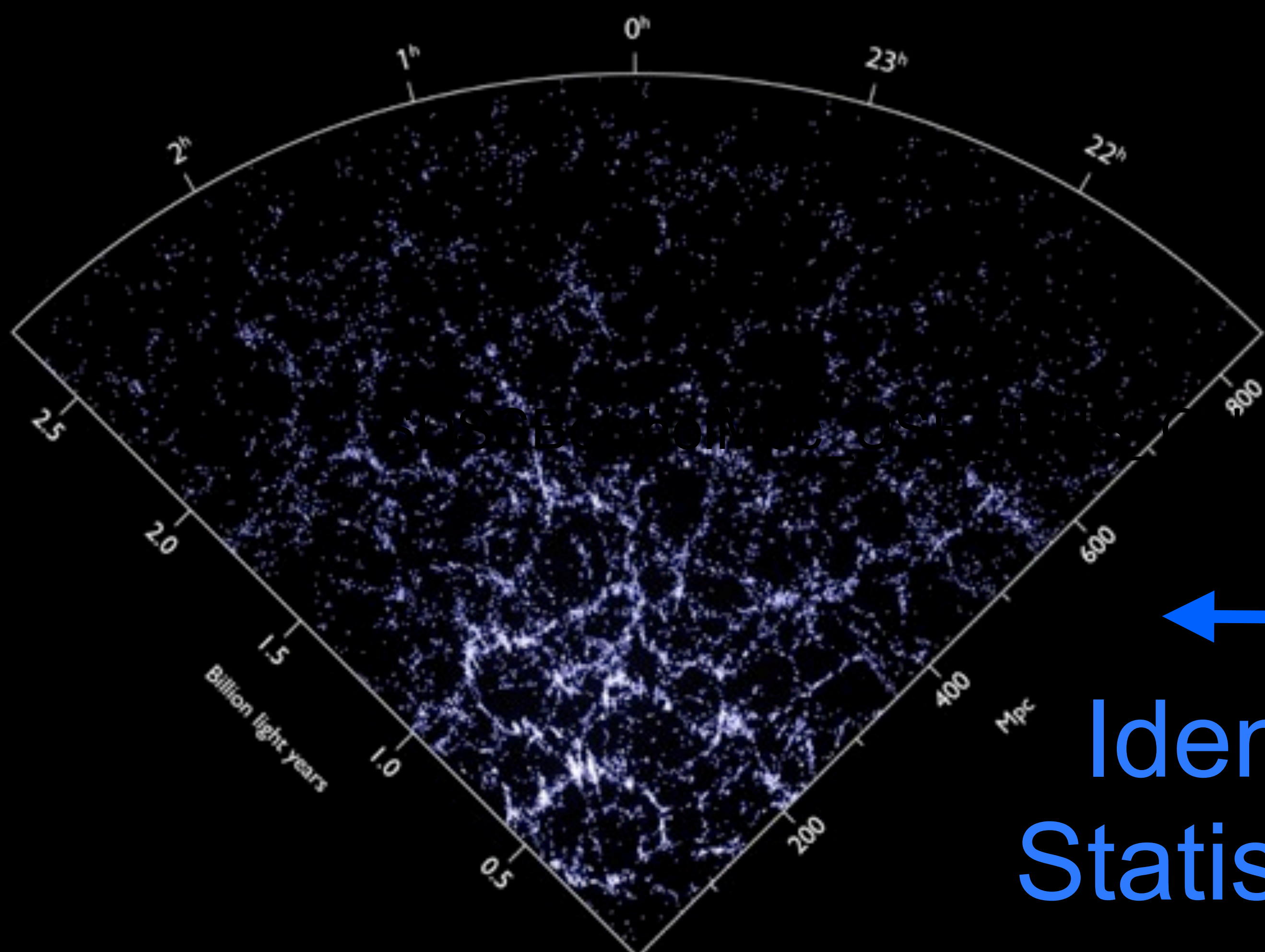
Observational Data

Sloan Digital Sky Survey

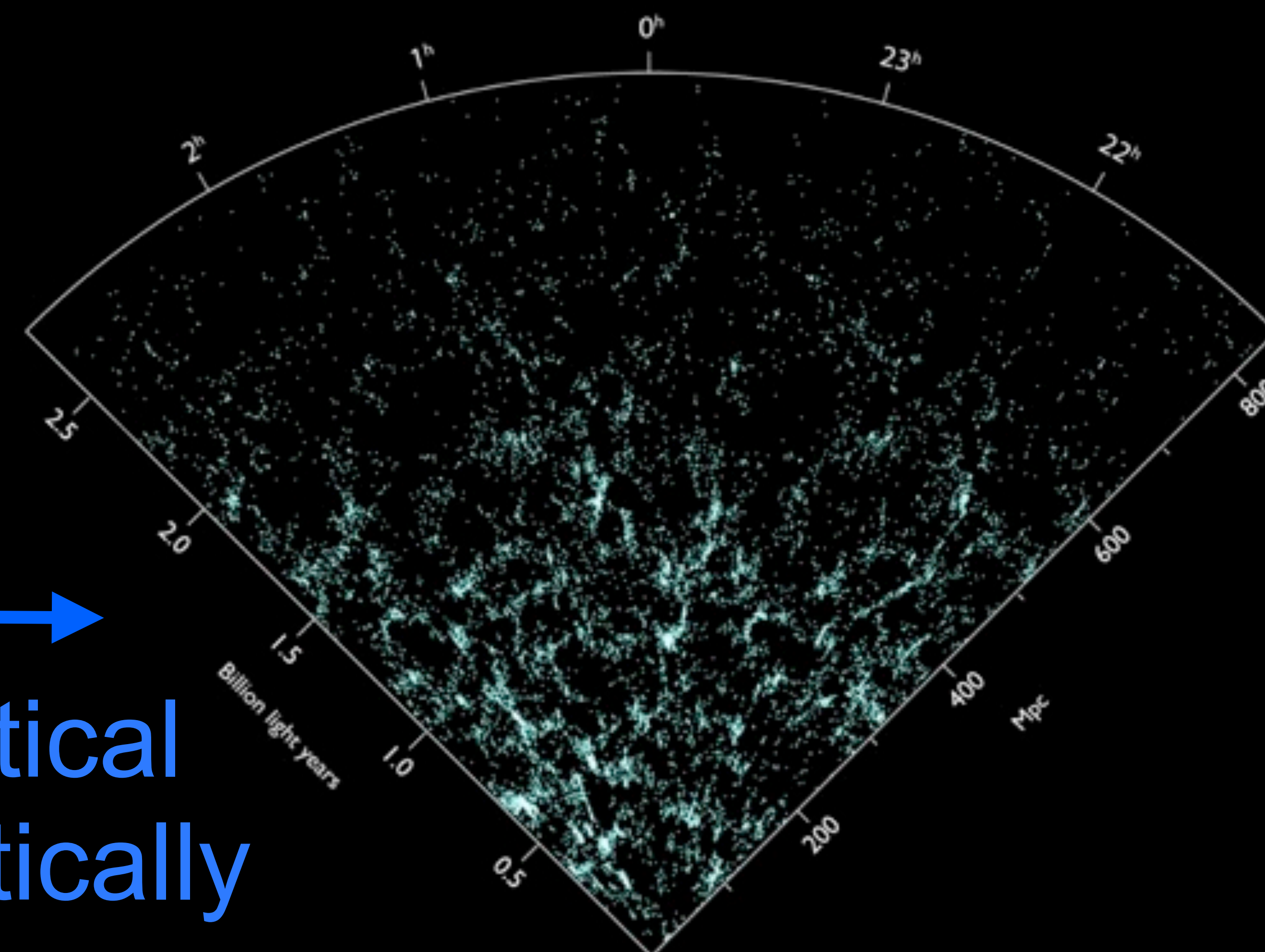
Cosmological Simulation

Risa Wechsler, Ralf Kahler, Nina McCurdy

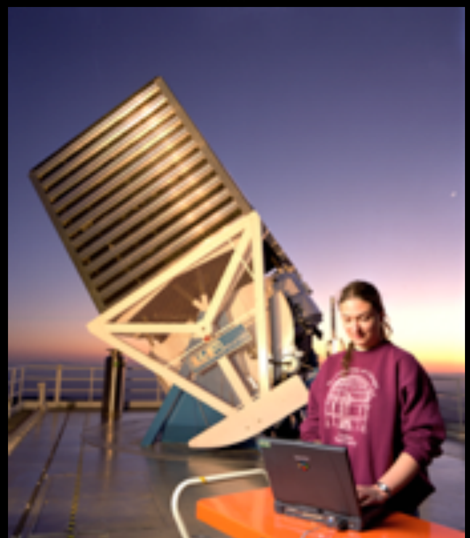
SDSS

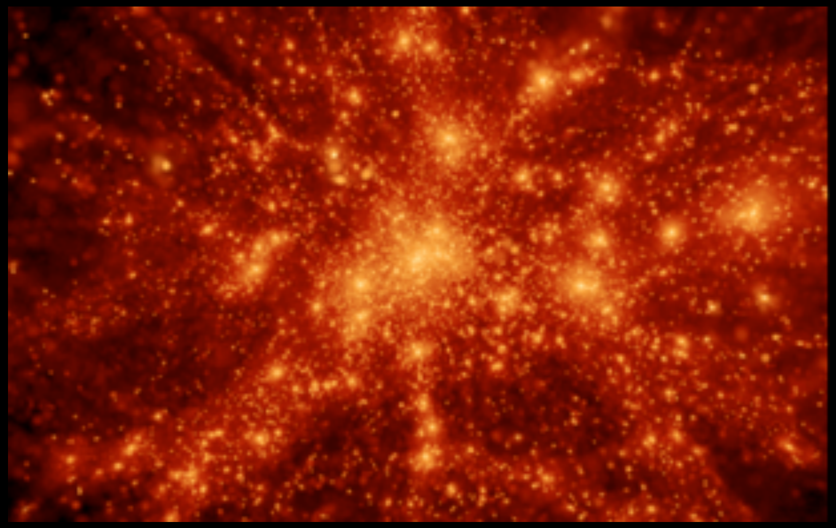


Bolshoi



Identical Statistically

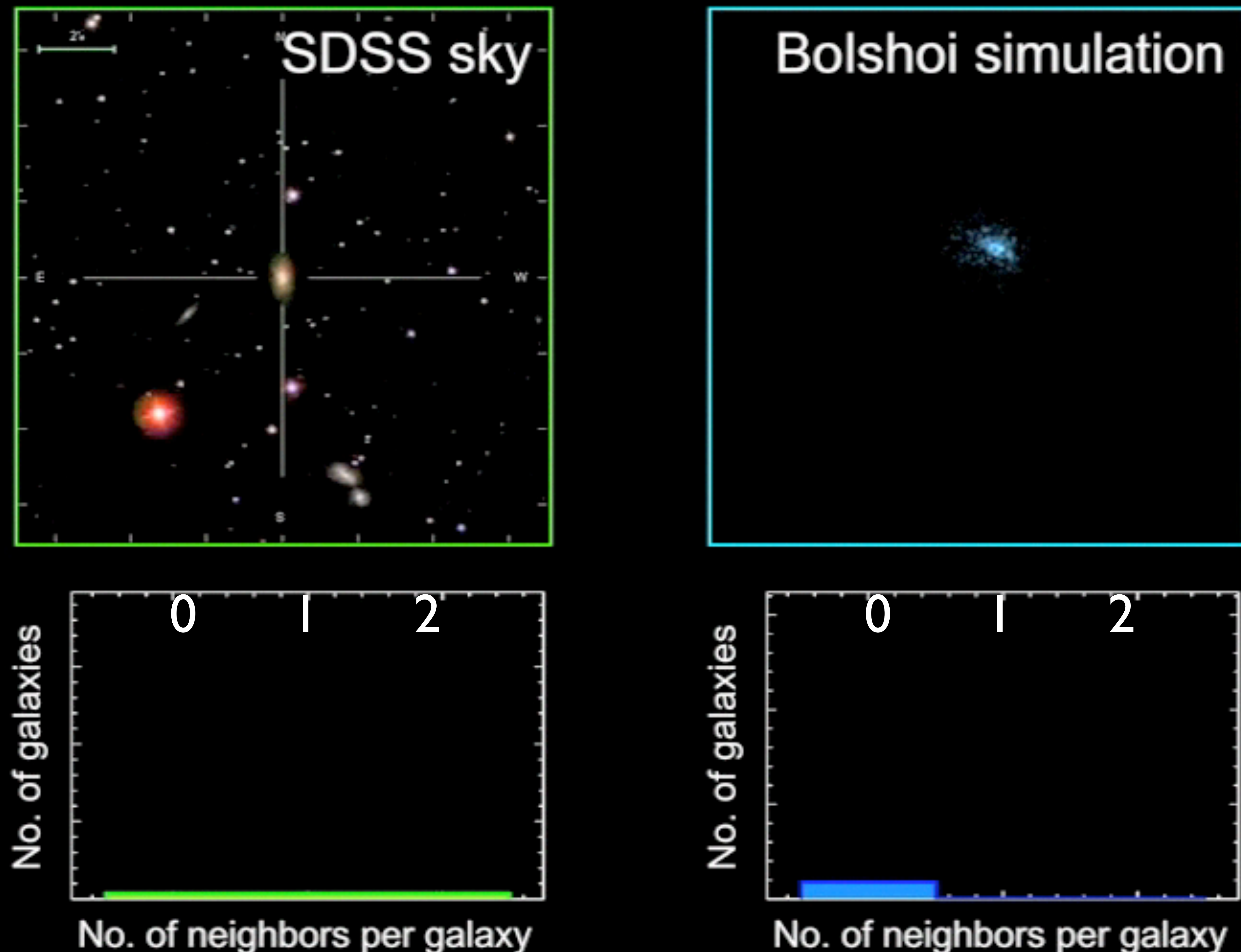




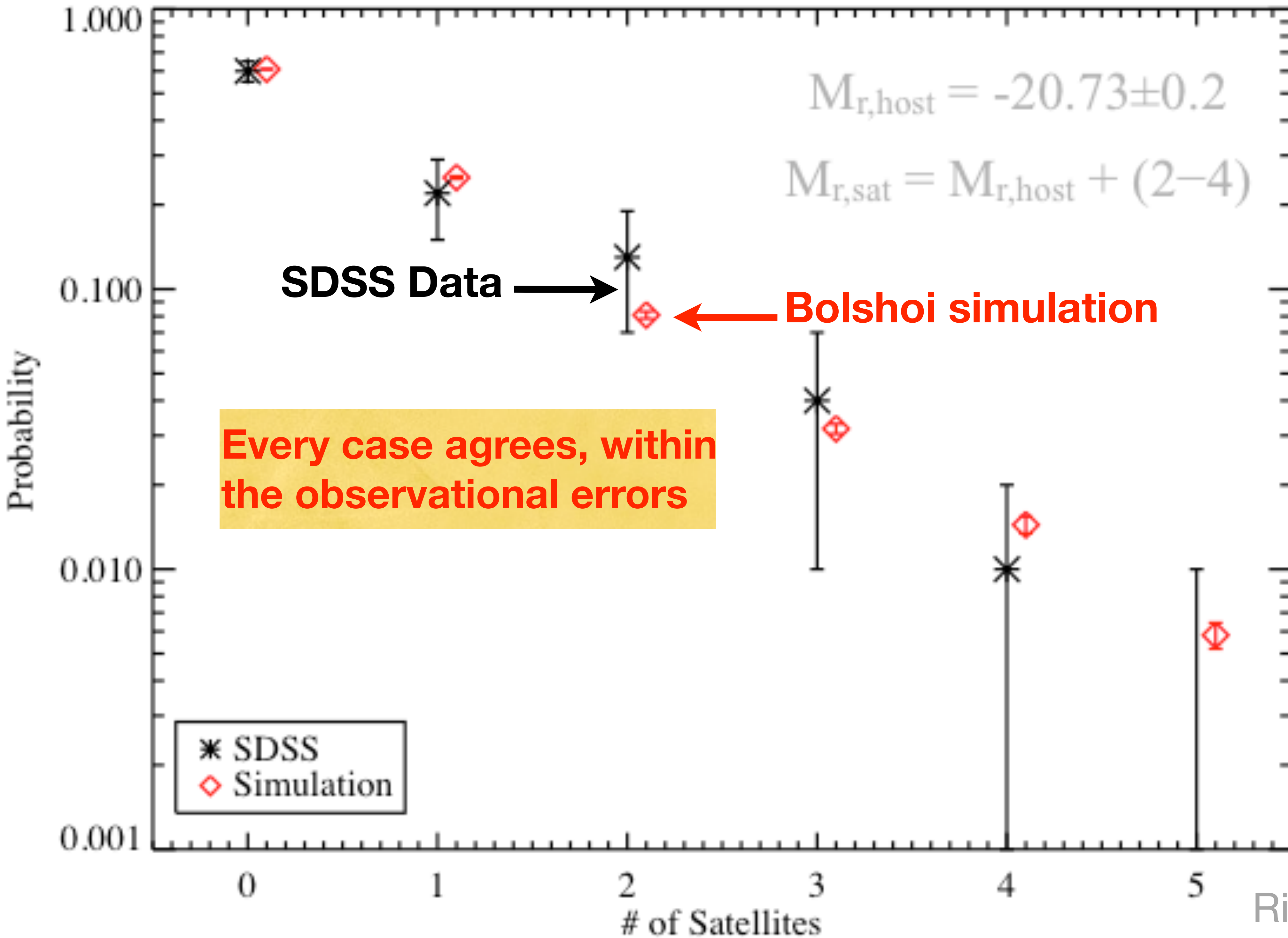
The Milky Way has two large satellite galaxies, the small and large Magellanic Clouds

How common is this?

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


SDSS sky
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

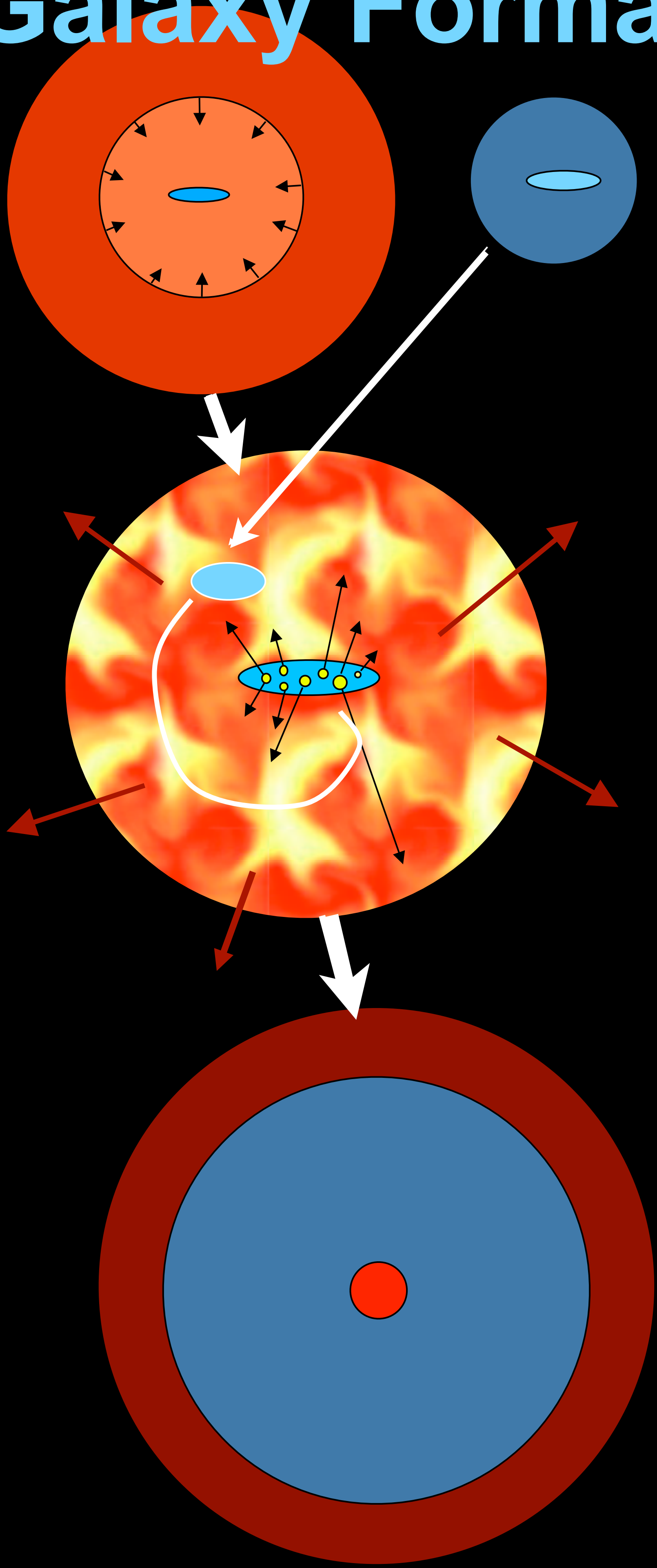
Statistics of MW bright satellites:
Sloan Digital Sky Survey data vs. Bolshoi simulation



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. The Bolhoi semi-analytic model correctly predicts this and the other relations of elliptical galaxies.
- Disk galaxies follow a relation between the speed they spin and their luminosity. The theory also correctly predict this.








- Finally, the theory correctly predicts the numbers of Disk Galaxies and Elliptical Galaxies of all masses

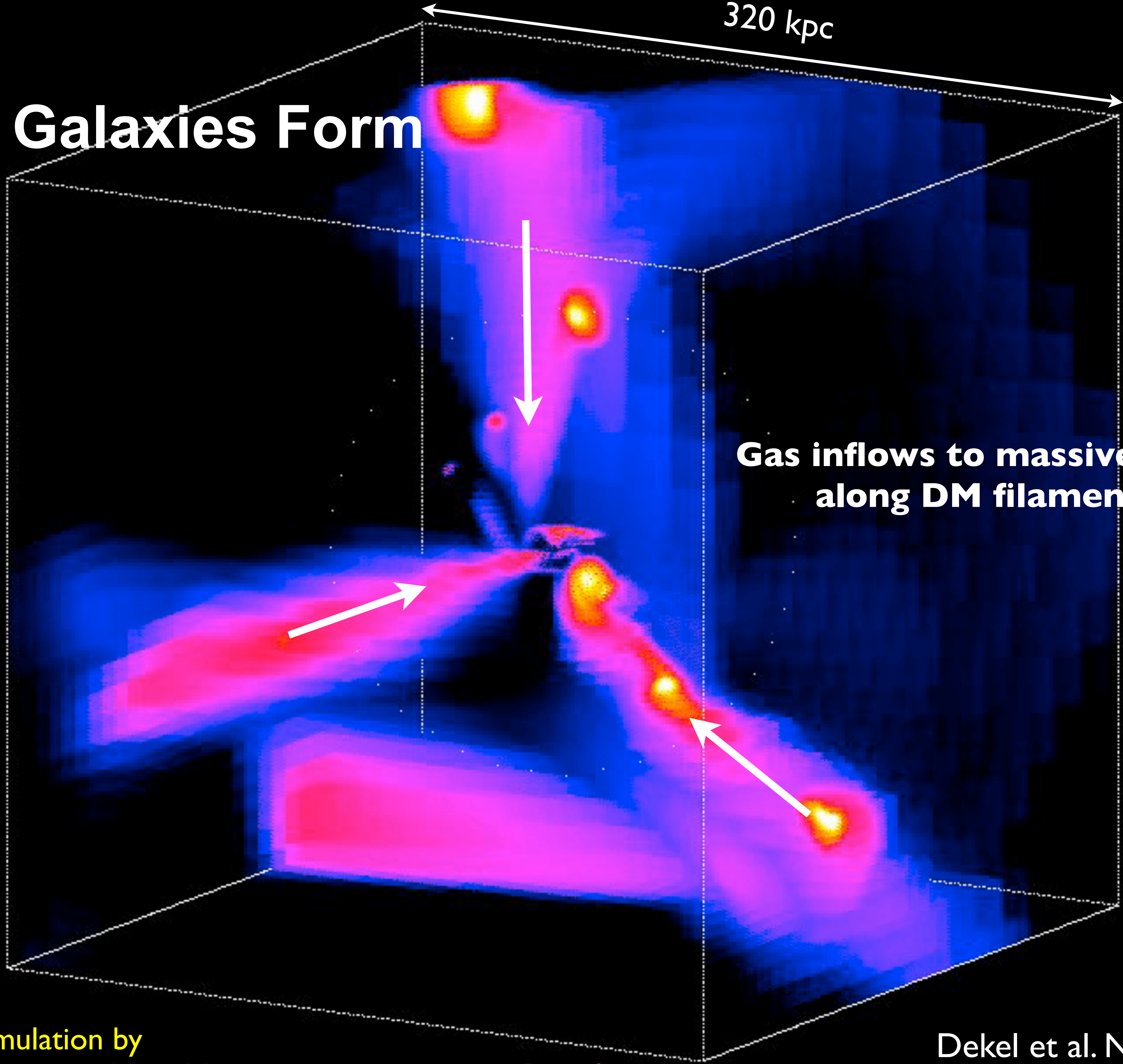
Cosmological Simulations

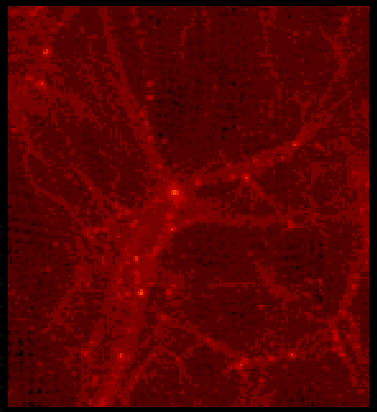
Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

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

How Galaxies Form

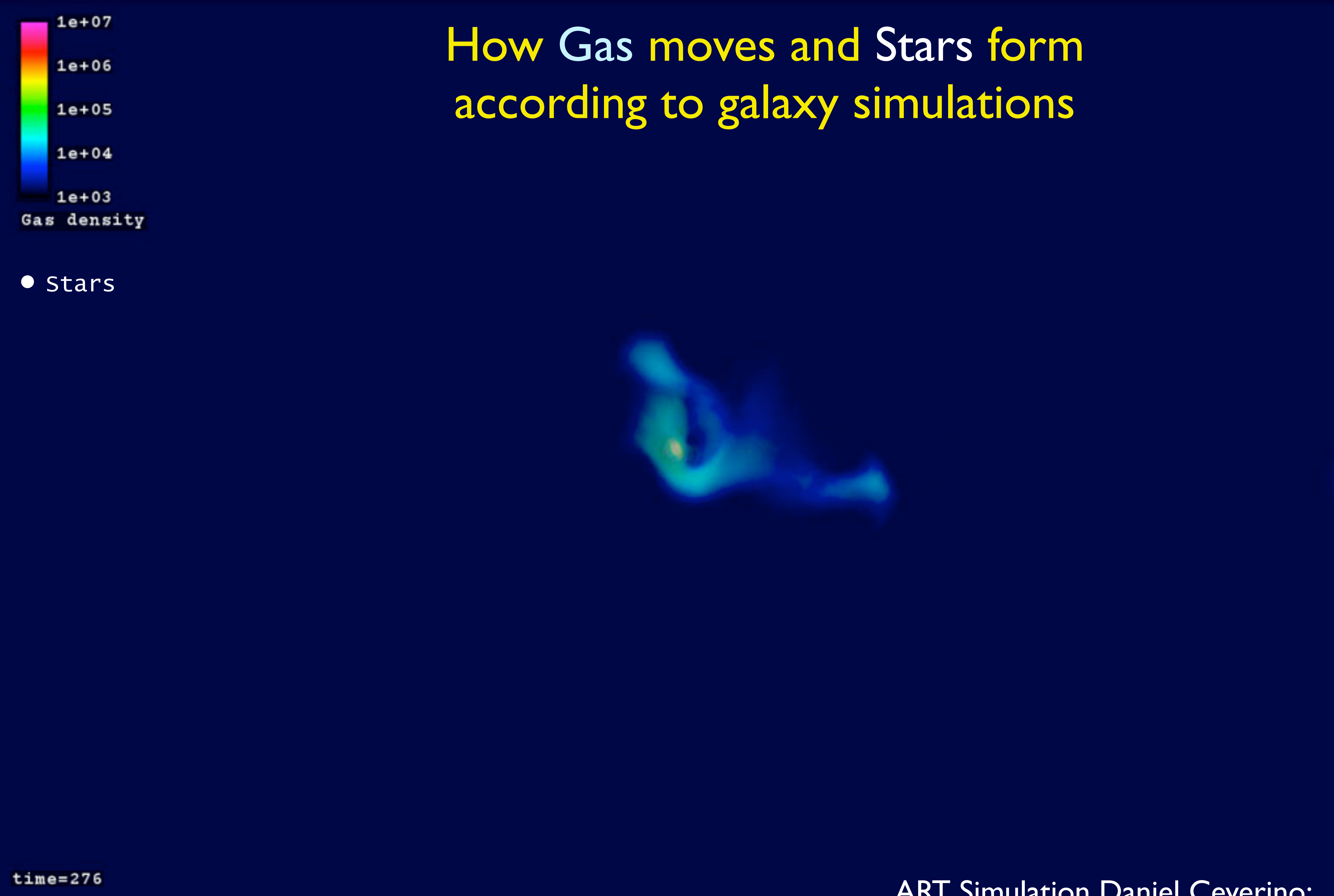




RAMSES simulation by
Romain Teyssier on Mare Nostrum supercomputer, Barcelona

Dekel et al. Nature 2009

How Gas moves and Stars form according to galaxy simulations

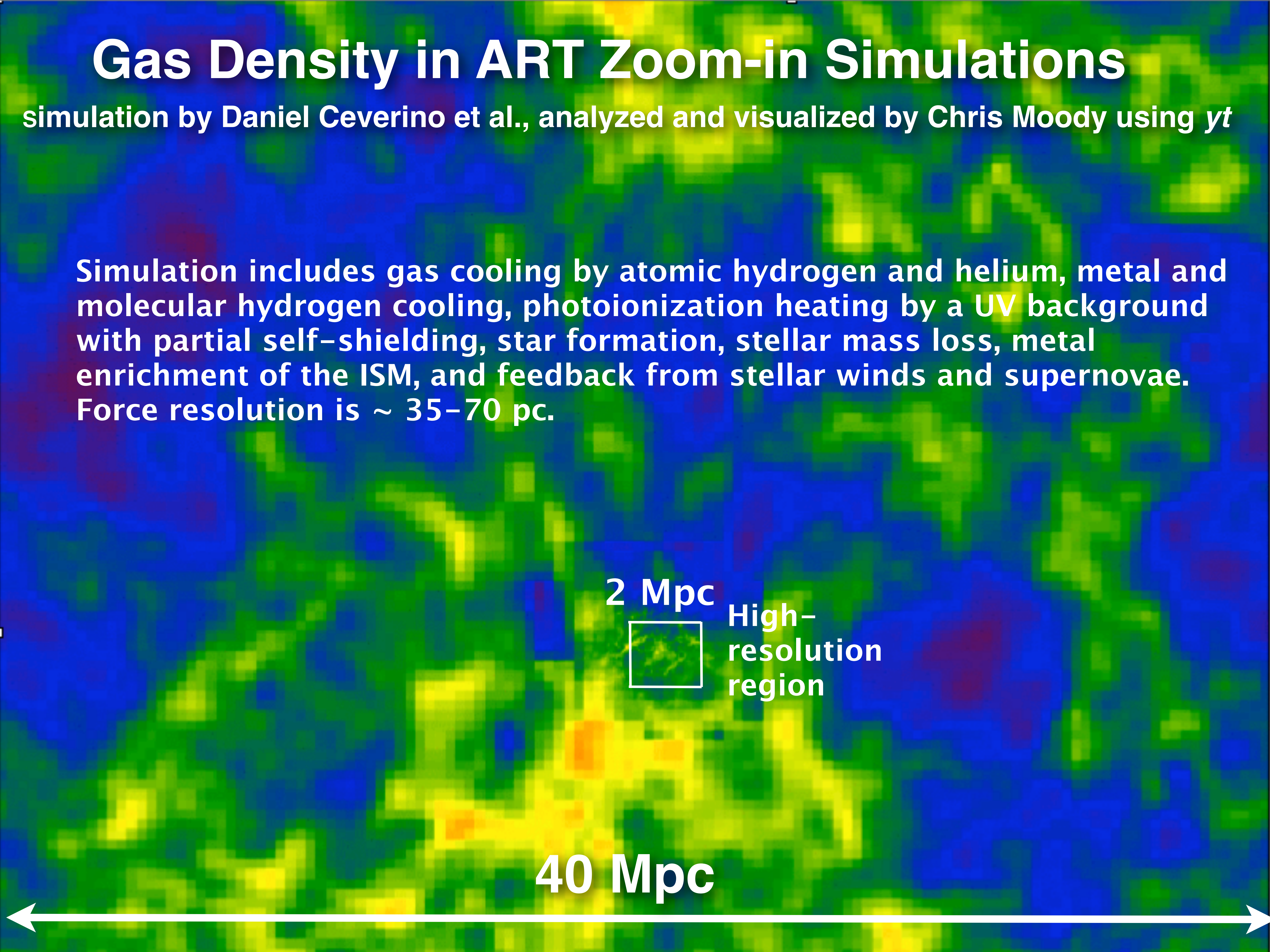


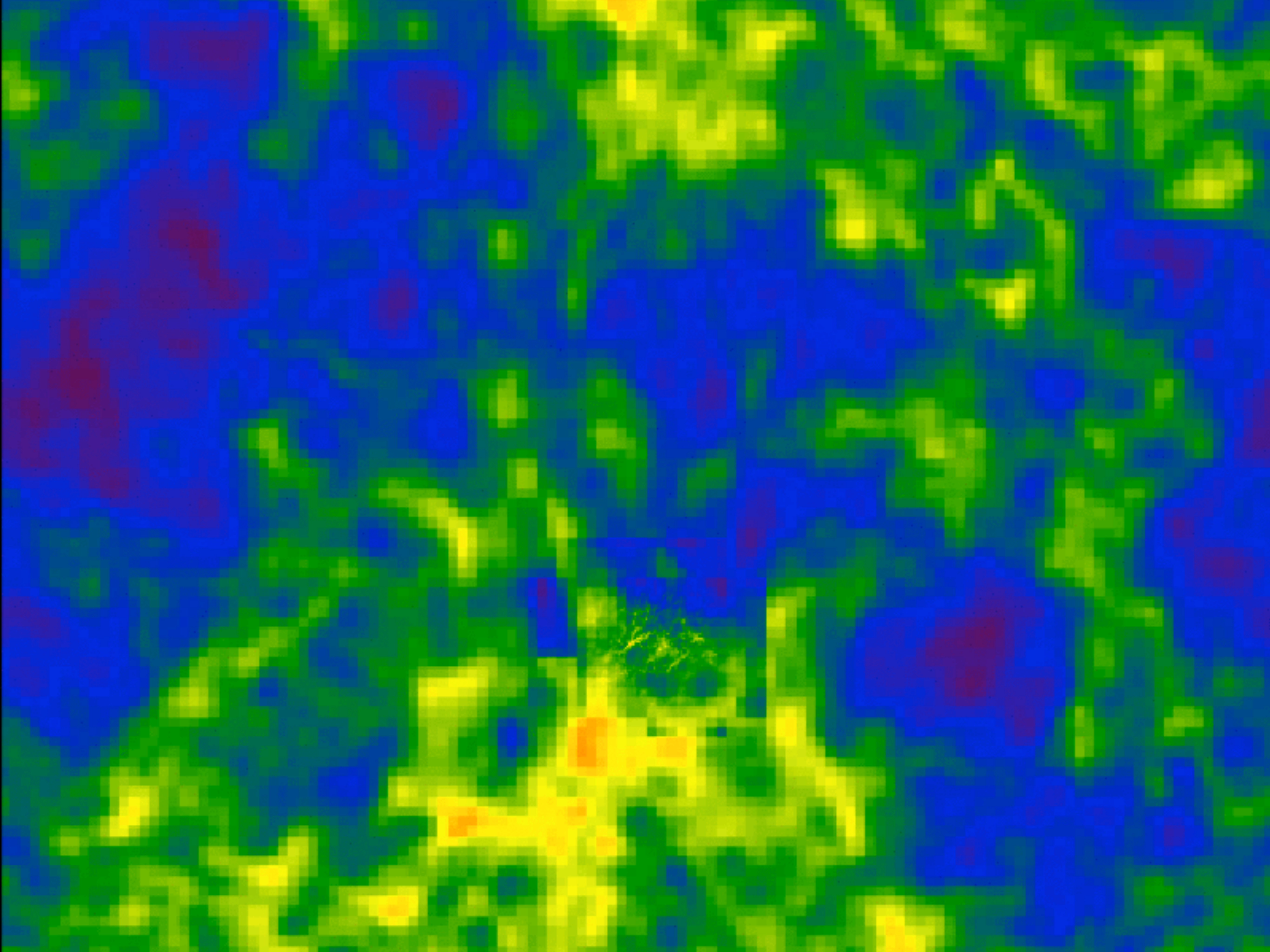
ART Simulation Daniel Ceverino;
Visualization: David Ellsworth

Gas Density in ART Zoom-in Simulations

simulation by Daniel Ceverino et al., analyzed and visualized by Chris Moody using *yt*

Simulation includes gas cooling by atomic hydrogen and helium, metal and molecular hydrogen cooling, photoionization heating by a UV background with partial self-shielding, star formation, stellar mass loss, metal enrichment of the ISM, and feedback from stellar winds and supernovae. Force resolution is ~ 35-70 pc.



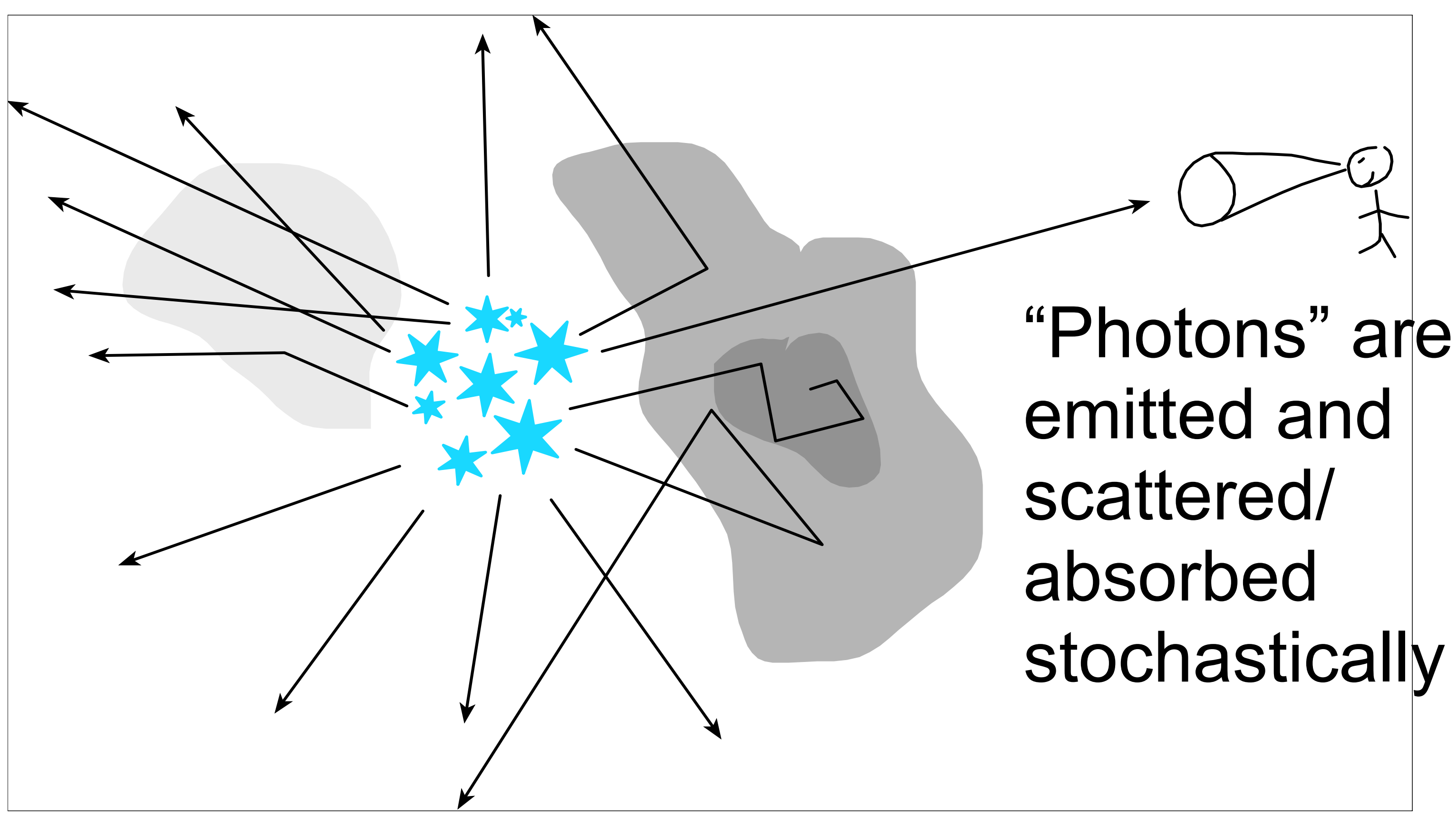


Sunrise Radiative Transfer Code

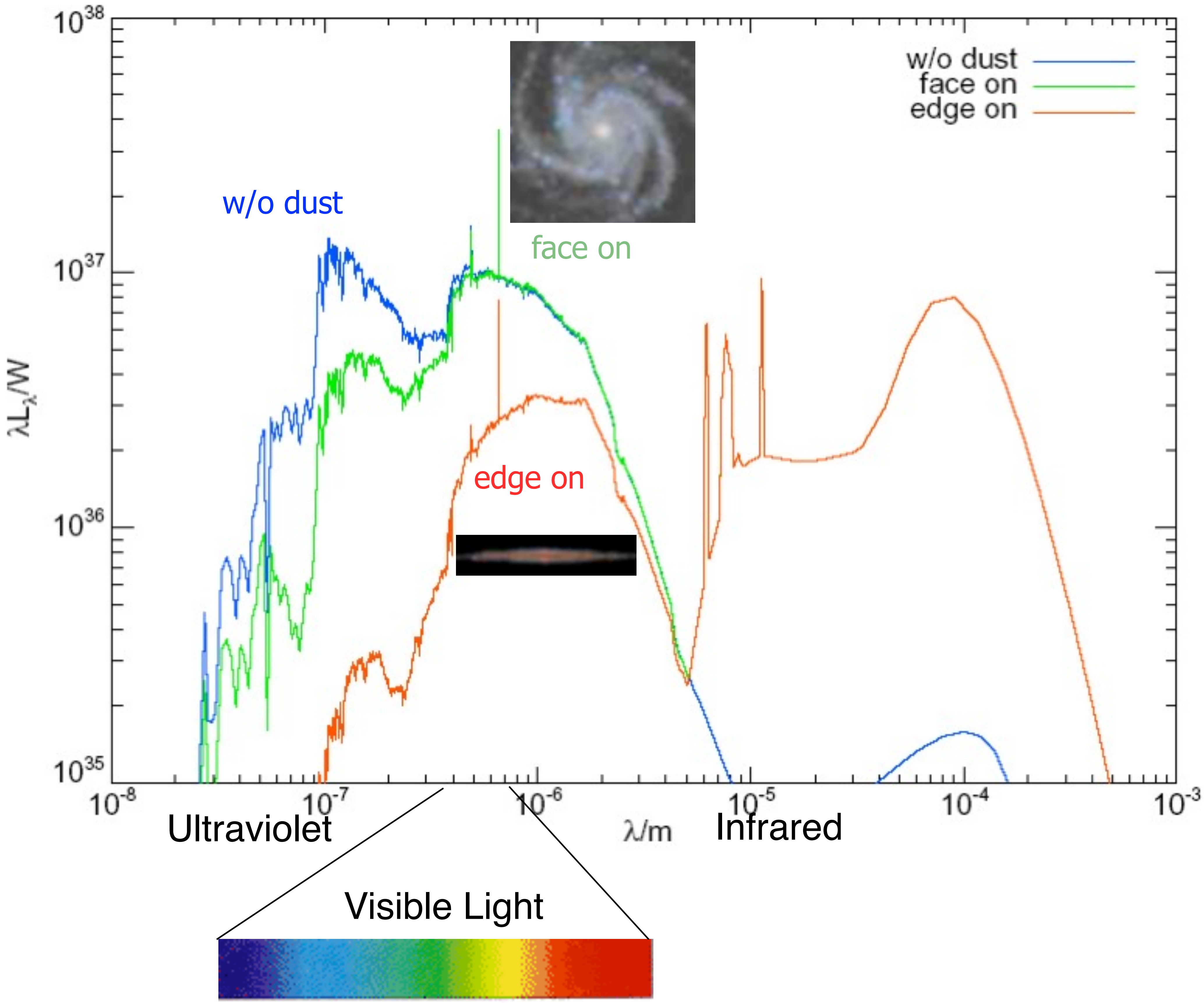
Patrik Jonsson
& Joel Primack

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

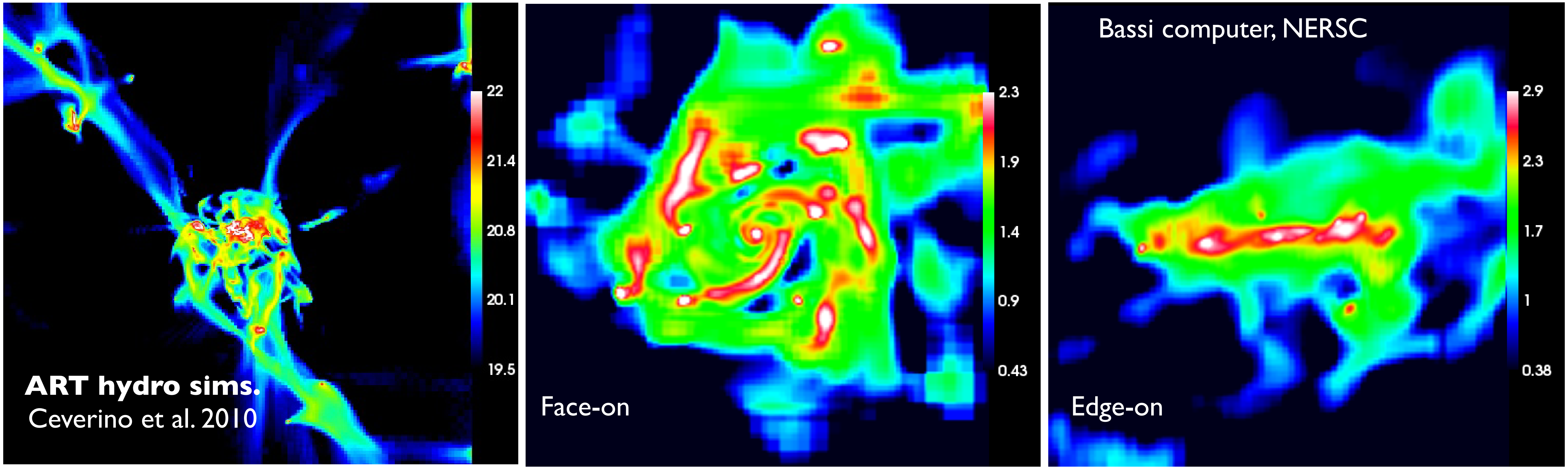


Spectral Energy Distribution

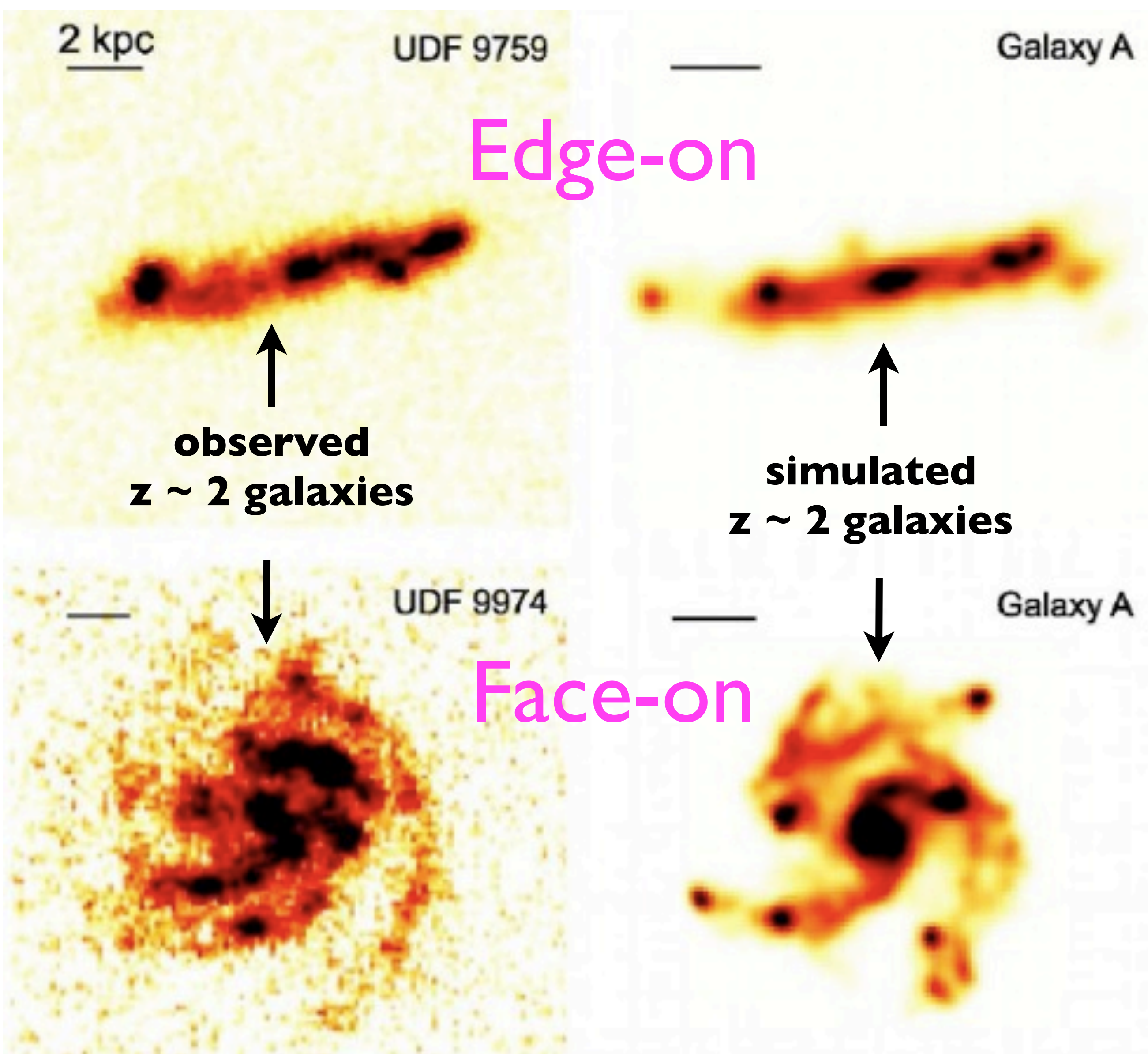


In about 5 billion years, our Milky Way Galaxy will collide and merge with our neighboring giant galaxy, Andromeda.

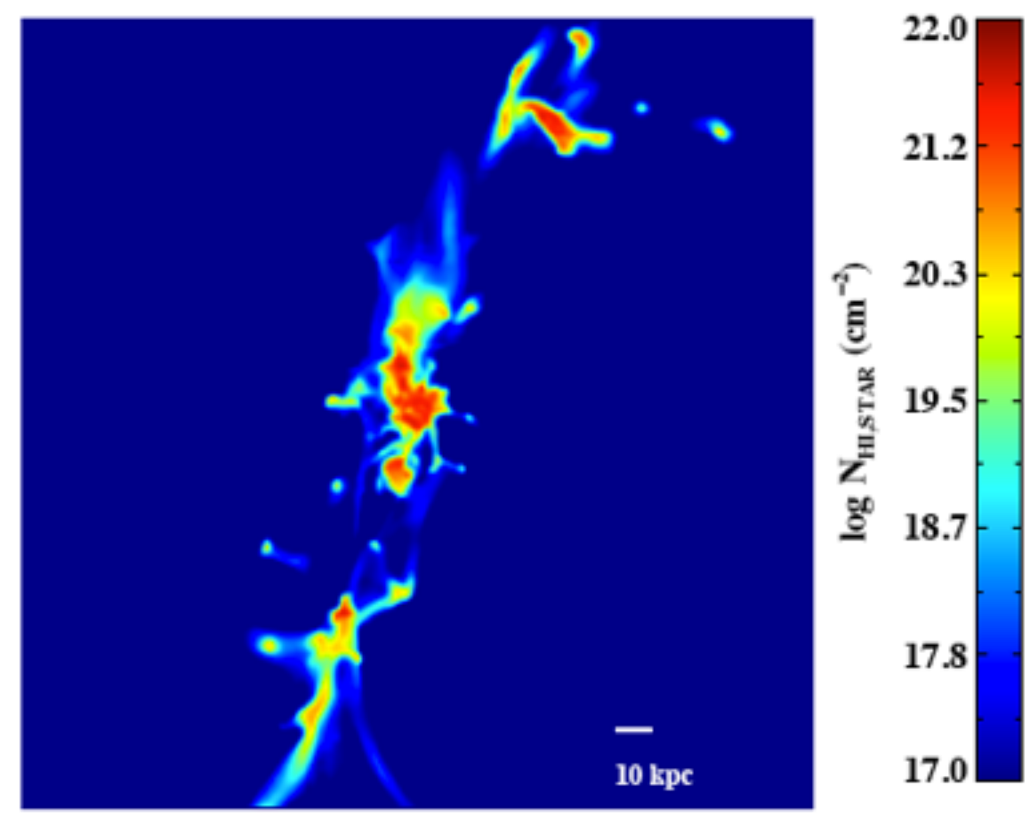
Spiral Galaxy Merger Simulation - Patrik Jonsson, Greg Novak, Joel Primack
Music: Nancy Abrams "All's Well that Ends Well" from album *Alien Wisdom*



now running on NERSC Hopper-II
and NASA Ames Pleiades supercomputers

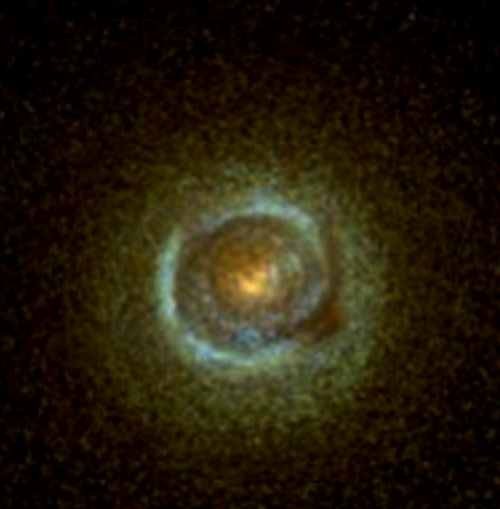


Ly alpha blobs from same simulation



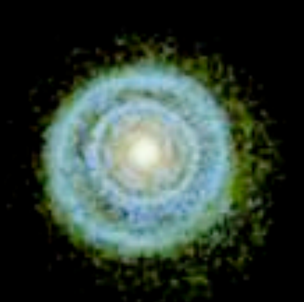
Fumagalli, Prochaska, Kasen, Dekel, Ceverino, & Primack 2011

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

Ceverino+ VL6 Cosmological Zoom-in Simulation

Face-On

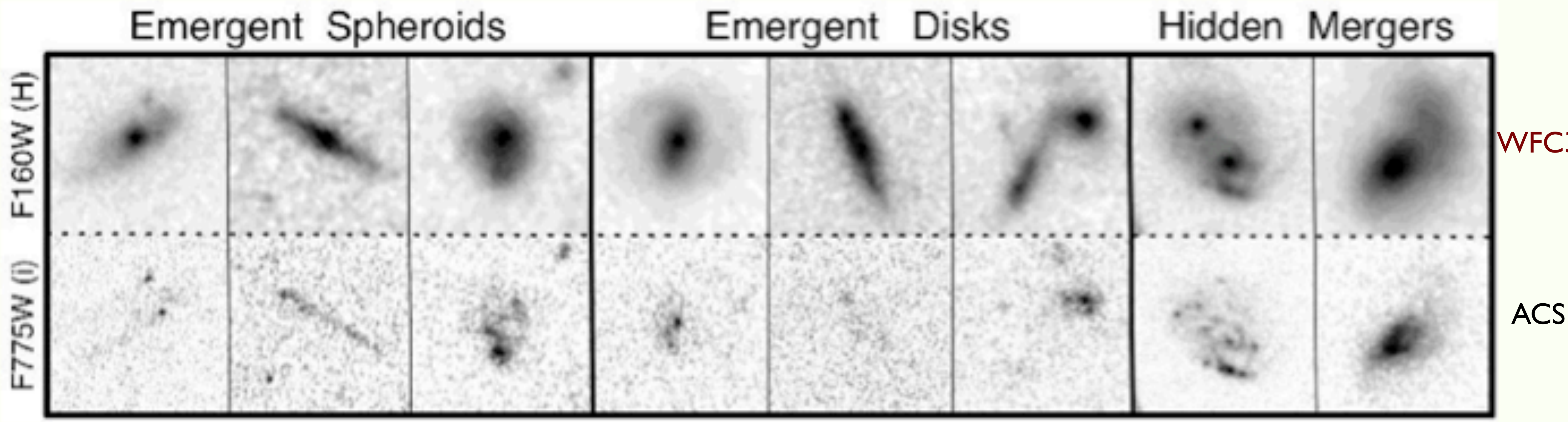
Edge-On

$z = 8.1$

Chris Moody

The CANDELS Survey with new near-ir camera WFC3

GALAXIES ~10 BILLION YEARS AGO

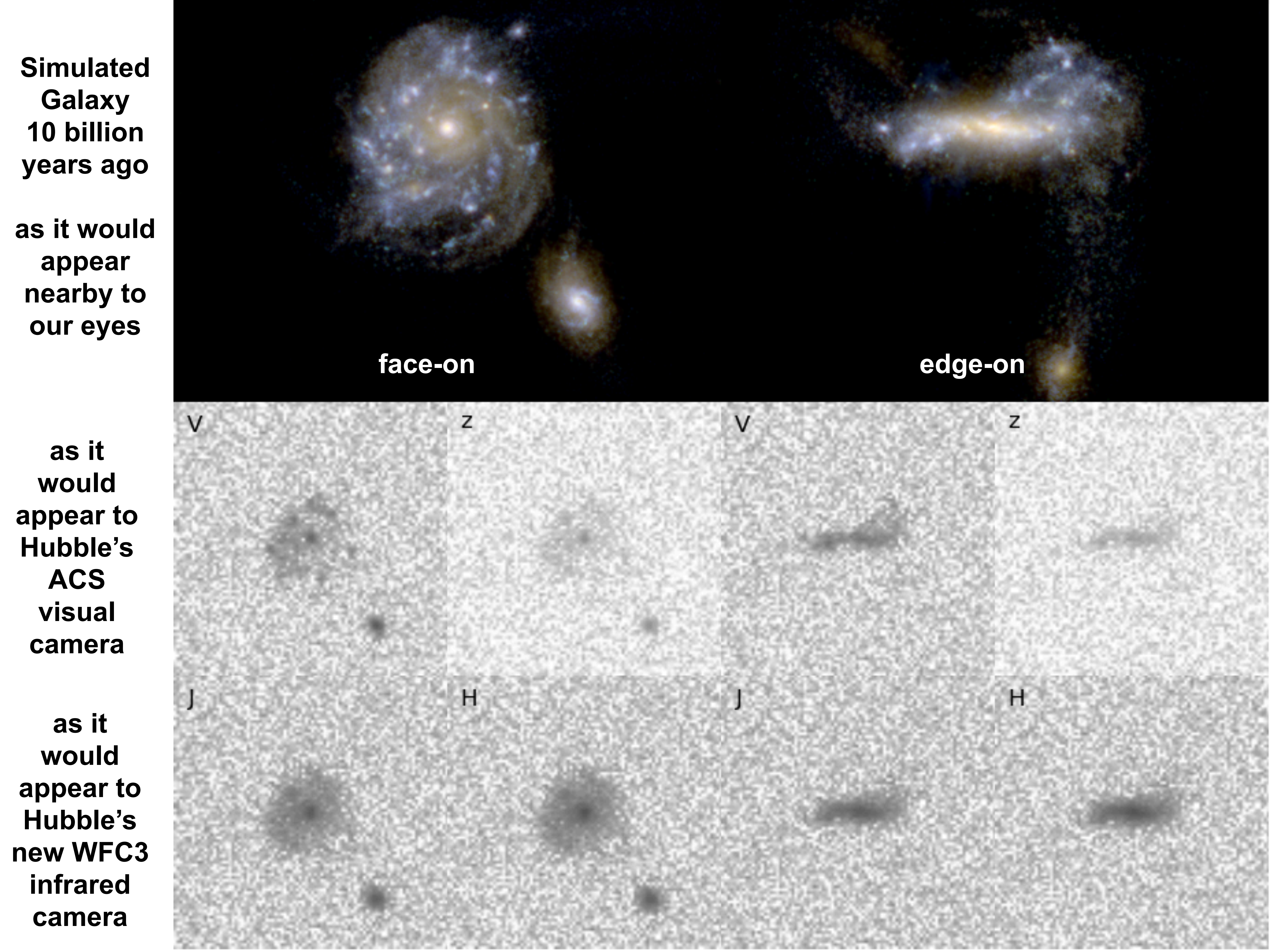


CANDELS makes use of the near-infrared WFC3 camera (top row) and the visible-light ACS camera (bottom row). Using these two cameras, CANDELS will reveal new details of the distant Universe and test the reality of cosmic dark energy.

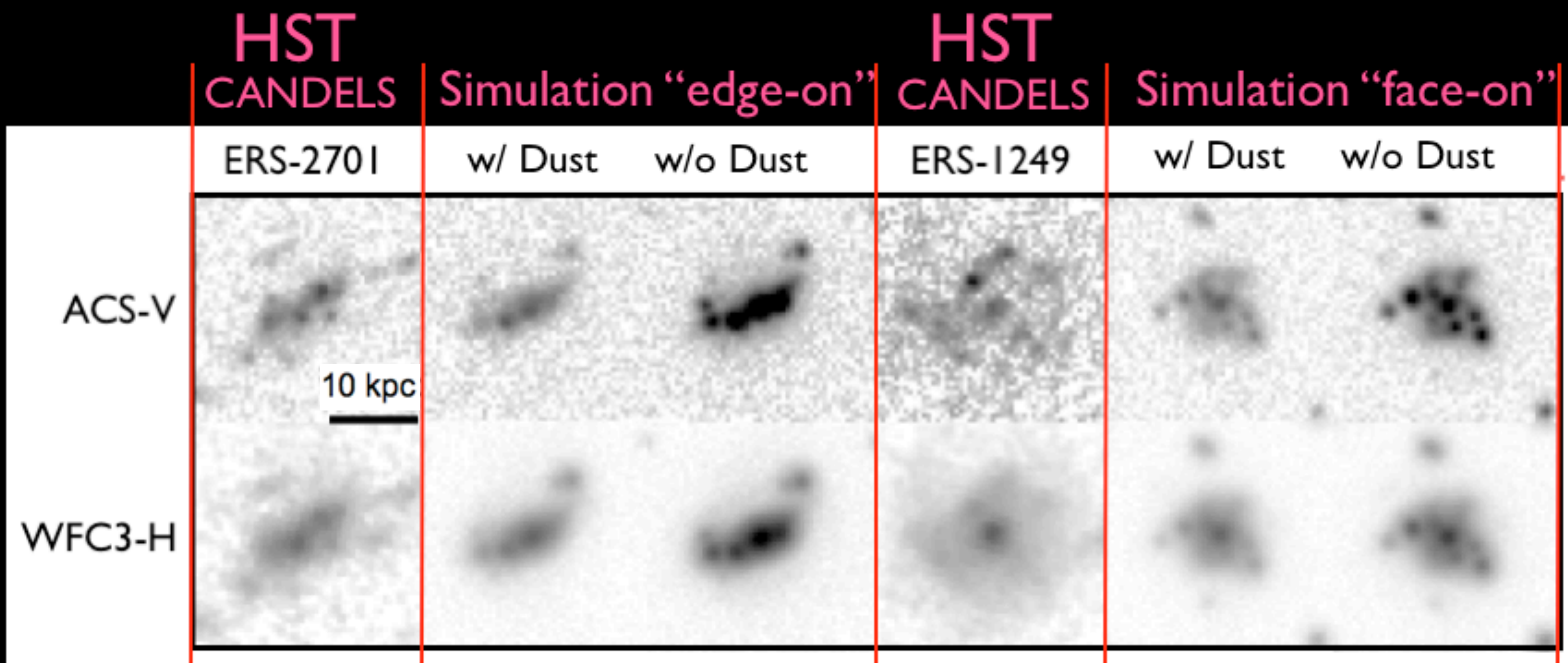
http://candels.ucolick.org

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

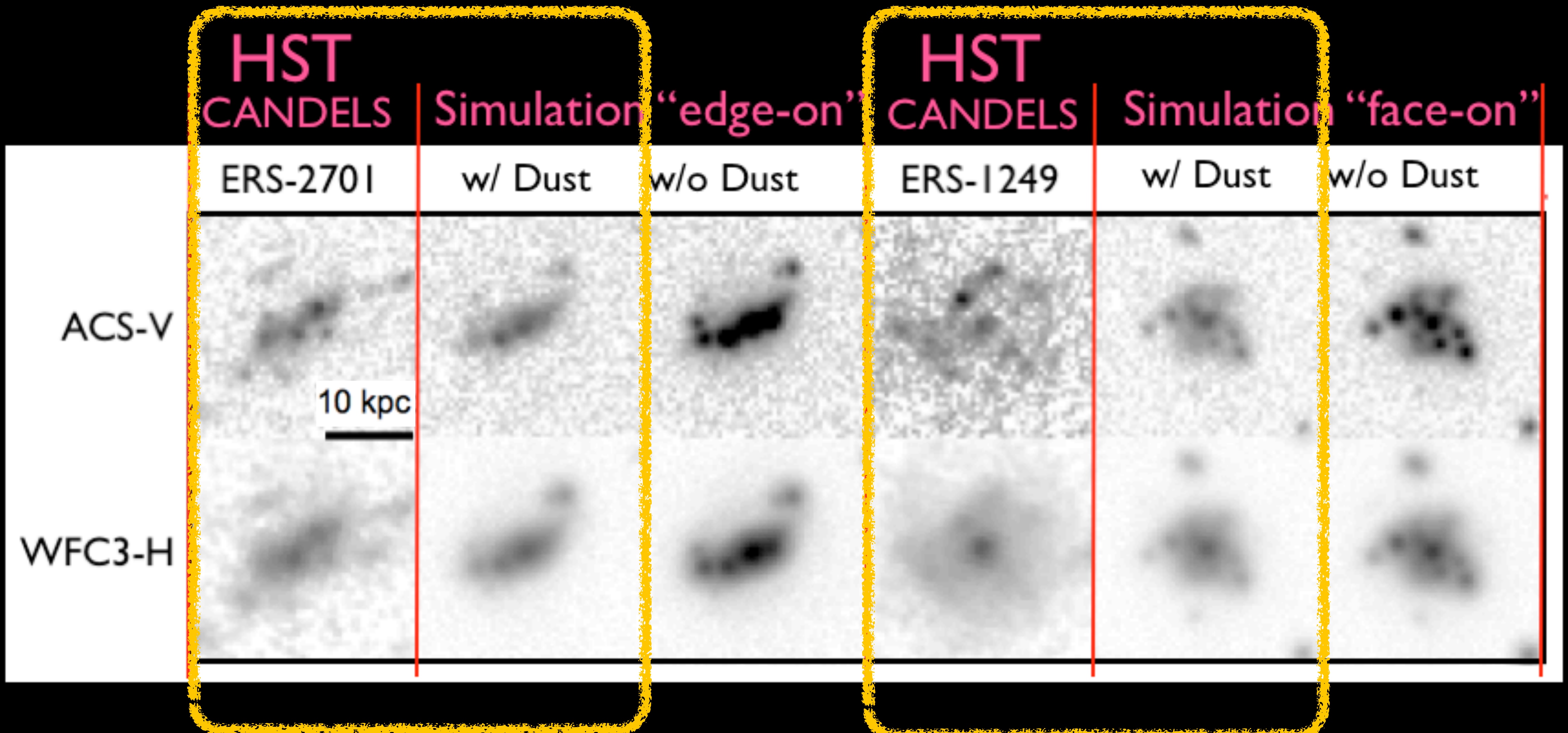
- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared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


Simulated Galaxy 10 billion years ago
as it would appear nearby to our eyes
face-on
edge-on
as it would appear to Hubble's ACS visual camera
V
z
V
z
as it would appear to Hubble's new WFC3 infrared camera
J
H
J
H

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



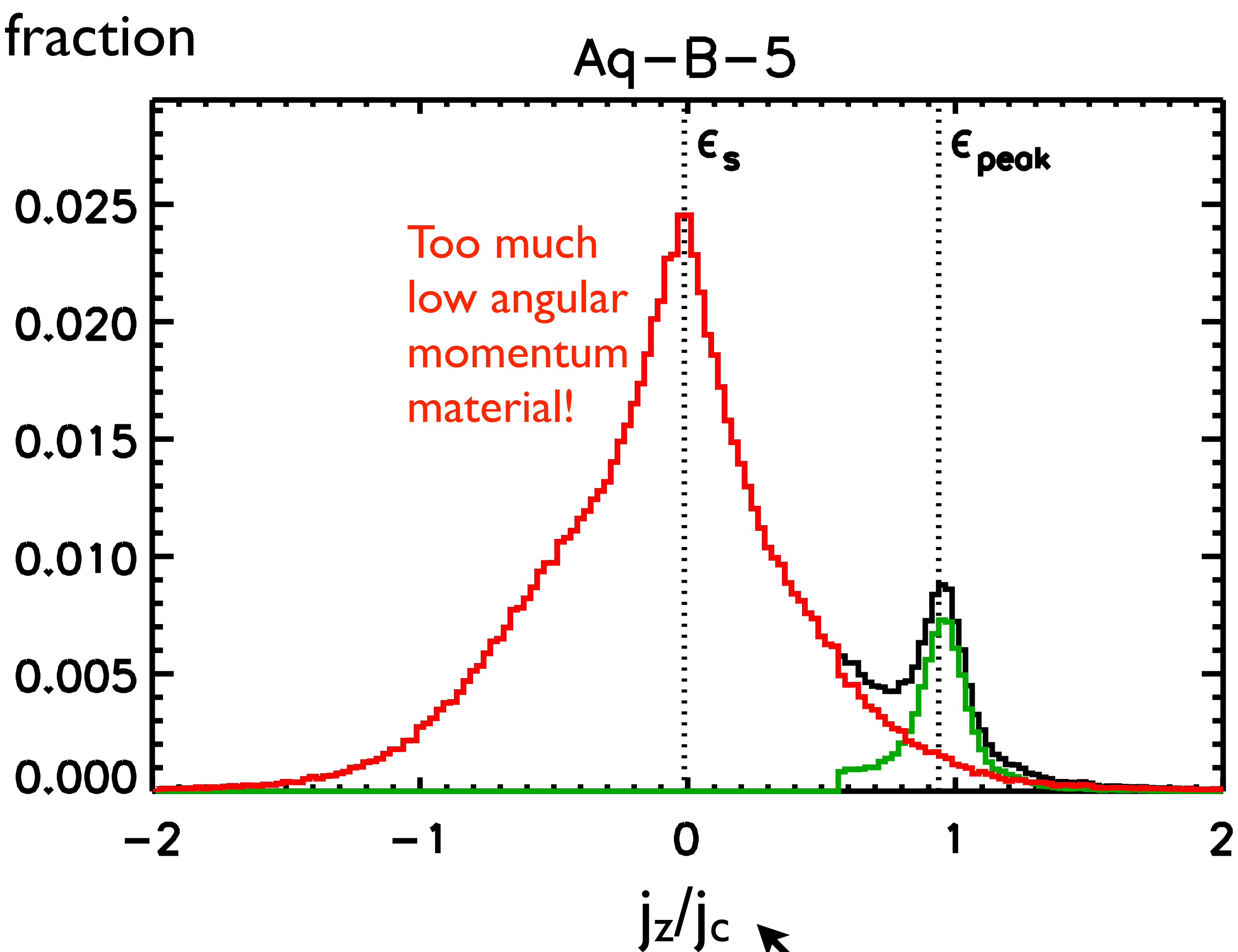
Our Simulations w/ Dust look a lot like galaxies from 10 billion years ago that we see with Hubble Space Telescope



We are now systematically comparing simulated and observed galaxy images

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.



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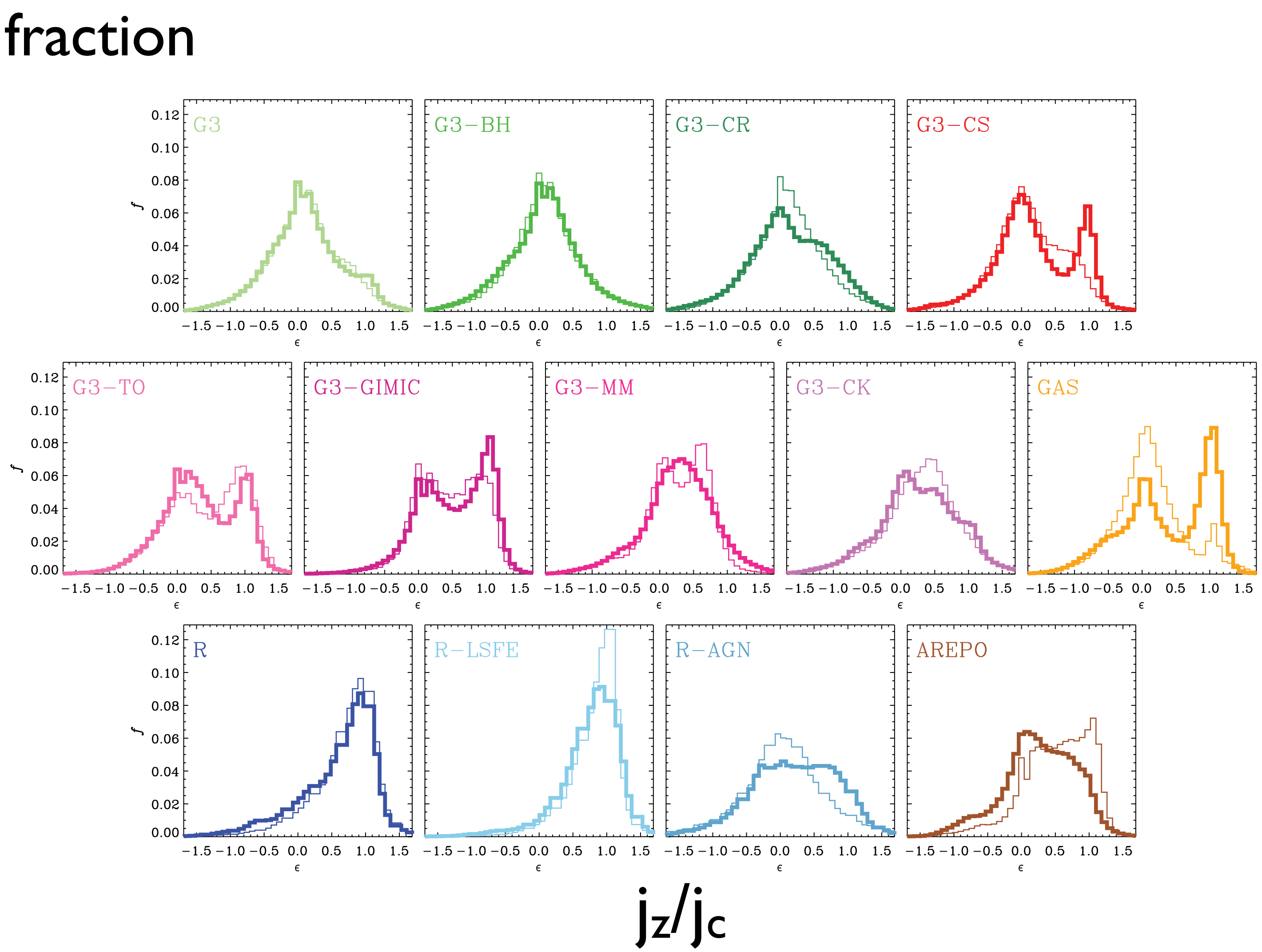
Scannapieco et al. 2009

angular momentum / ang mom needed for rotation

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.



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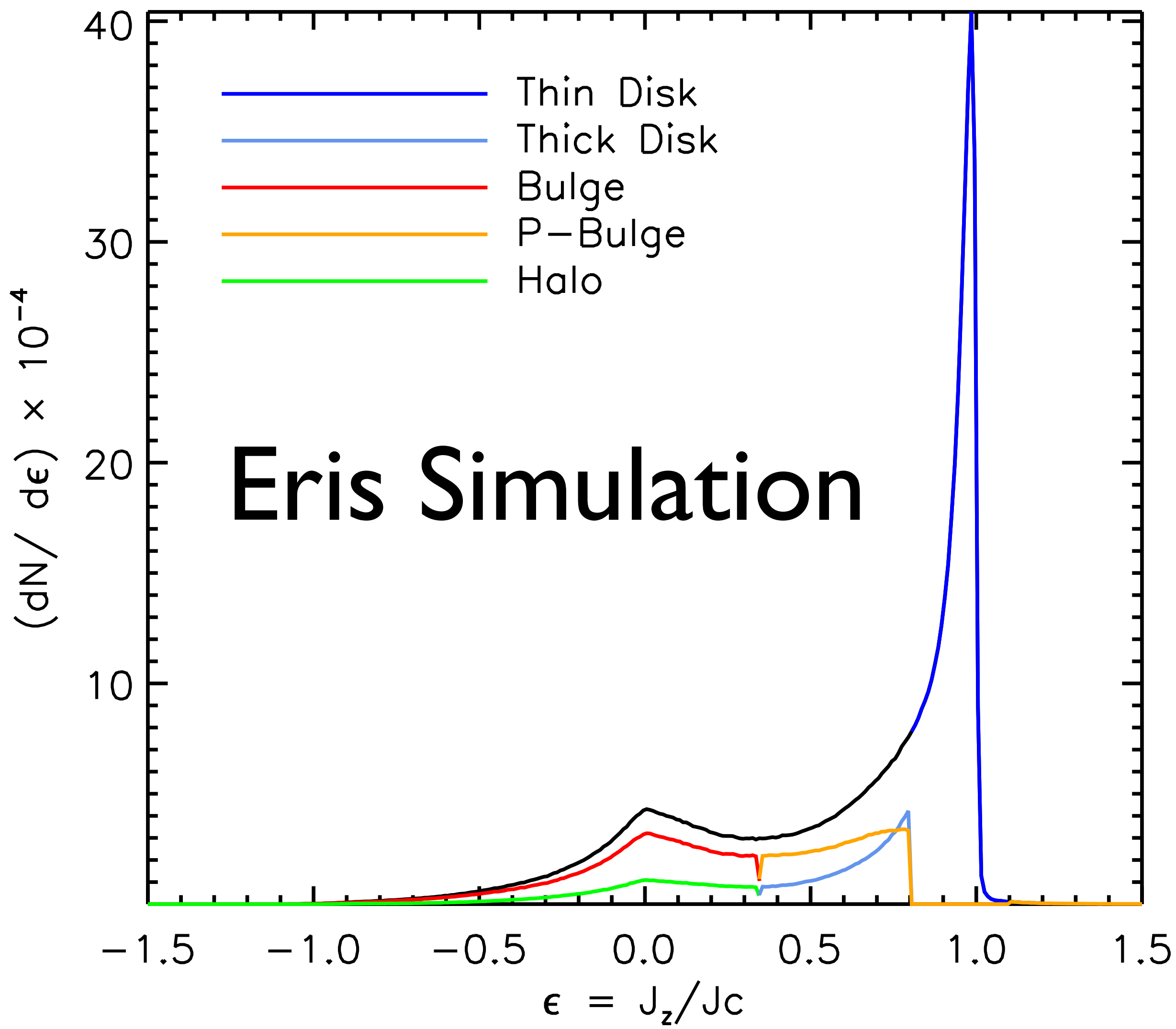
Scannapieco et al., Aquila Galaxy Simulation Comparison, 2012

The Angular Momentum ~~Catastrophe~~

Eris, the first high-resolution simulation of a ~10^{12} $M_\odot$ halo, 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)

~90 astrophysicists using 9 codes have joined AGORA
Next meeting: after UCSC Galaxy Workshop Aug 16-19, 2013

www.AGORAsimulations.org

AGORA High-Resolution Simulation Comparison

Initial Conditions for Simulations

MUSIC galaxy masses at $z\sim0$: $\sim10^{10}, 10^{11}, 10^{12}, 10^{13}\ M_\odot$

with both quiet and busy merging trees

isolation criteria agreed for Lagrangian regions

Isolated Spiral Galaxy at $z\sim1$: $\sim10^{12}\ M_\odot$

Astrophysics that all groups will include

UV background (Haardt-Madau 2012)

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
S10	Lyα Absorption and Emission	prediction of Lyα maps for simulated galaxies and their environments including effects of radiative transfer

AGORA High-Resolution Galaxy Simulation Comparison Project: Calendar

AGORA Kickoff Meeting: August 17-18-19, 2012, at UCSC

Roughly every four months: AGORA SeeVogh web conference
First web conf. Nov. 16, 2012; next April 26, 2013; ...

yt Developers Workshop: UCSC March 6-8

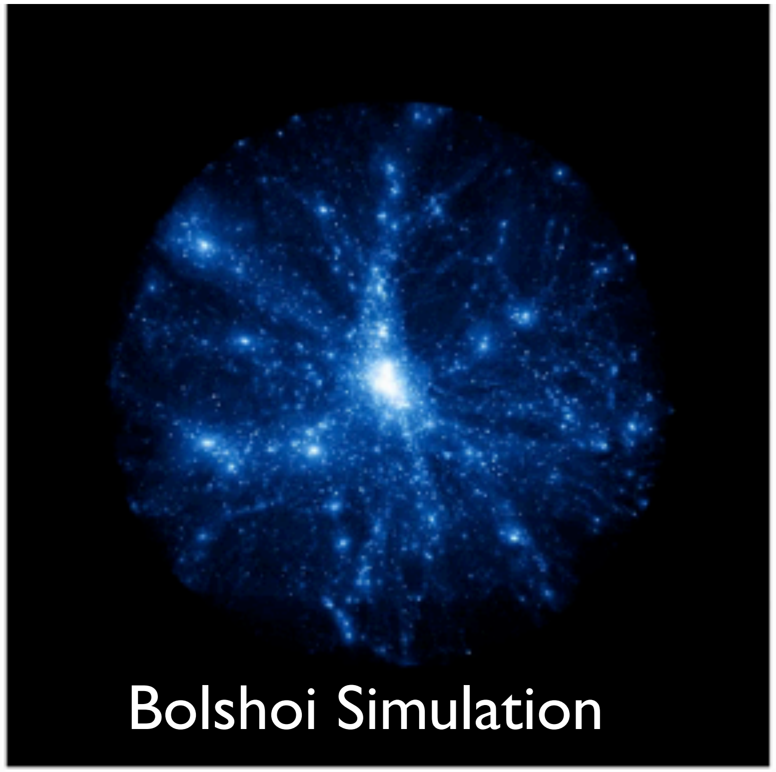
AGORA Flagship Paper to be submitted: June 30

Summer 2013:
UC-HiPACC Summer School on Star and Planet Formation
July 22 - August 9, at UCSC, directed by Mark Krumholz
Santa Cruz Galaxy Workshop - August 12-16 (by invitation - contact Avishai Dekel or Joel Primack)

AGORA Conference August 16-19 at UCSC

Cosmic 3D Questions

Milky Way Meets Andromeda
Our galactic future?



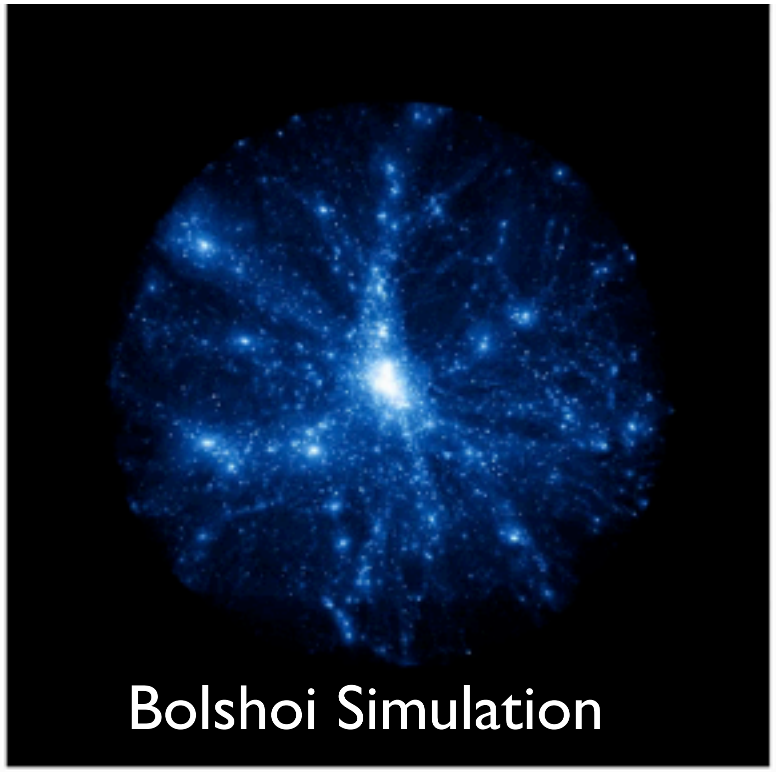
Halo Shape and Orientation
Do observations agree?

Milky Way's Universe
Special Environment ?

Satellite Galaxies
Do they fit in subhalos ?

Ways of Showing 3D

Milky Way Meets Andromeda
Extreme Perspective



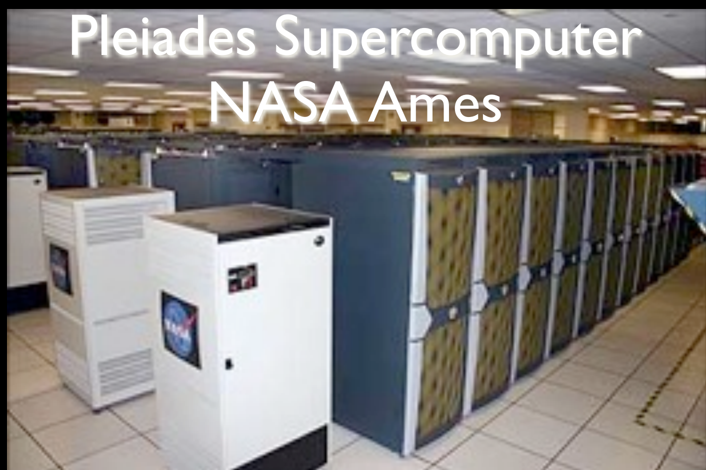
The Cosmic Web
Rotation & Zoom-in

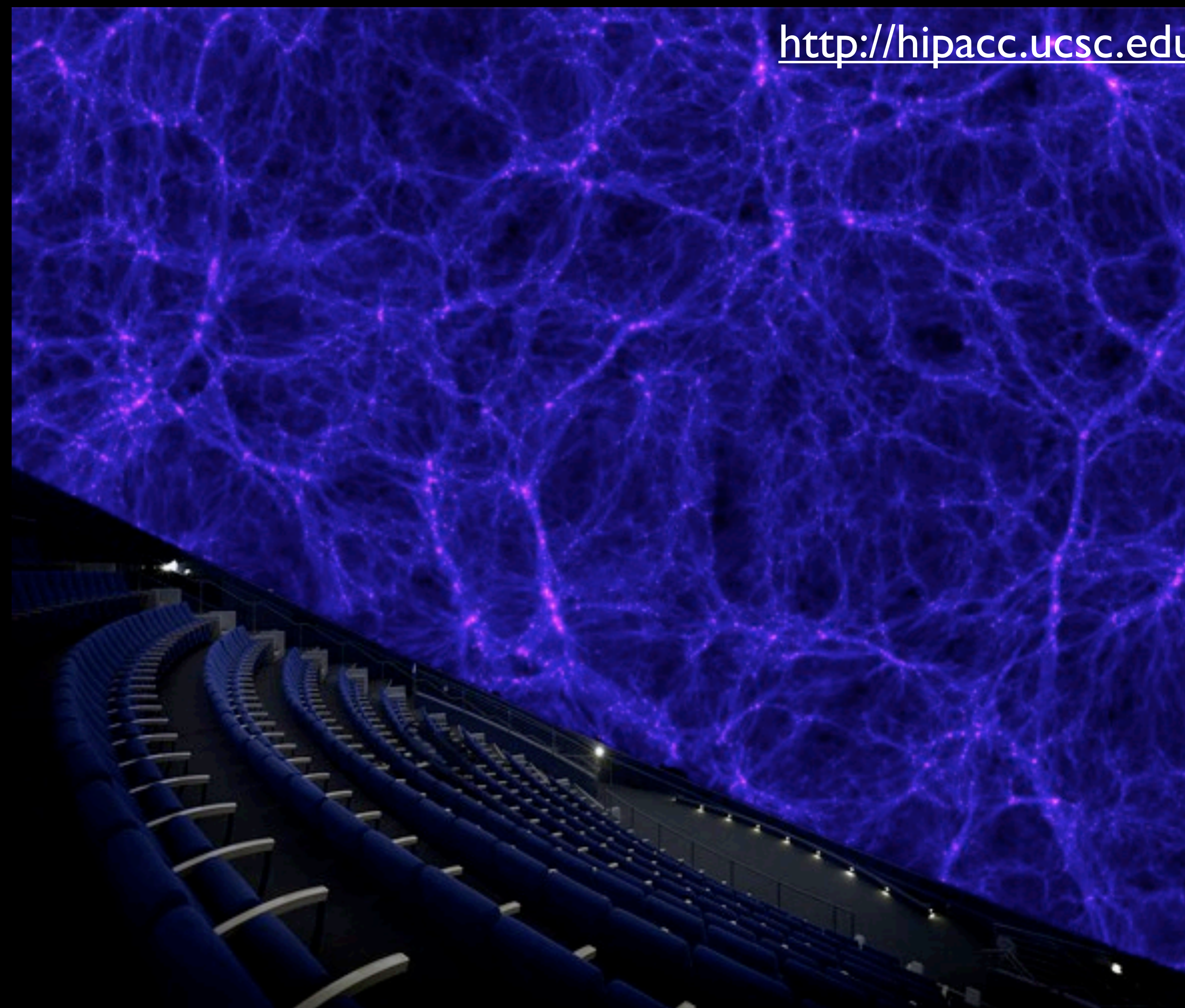
Milky Way's Universe
Comoving Evolution, Fly-through

Satellite Galaxies
Accretion History

Astro-Computation Visualization and Outreach

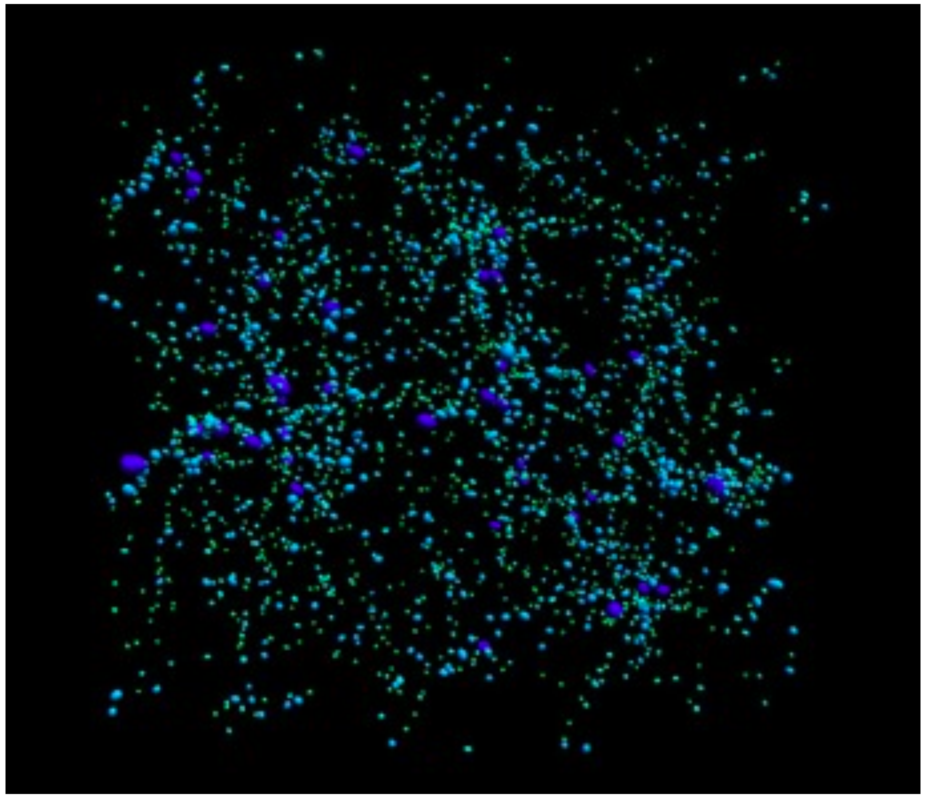
Project lead: Prof. Joel Primack, Director, UC High-Performance AstroComputing Center
UC-HIPACC Visualization and Outreach Specialist: Nina McCurdy



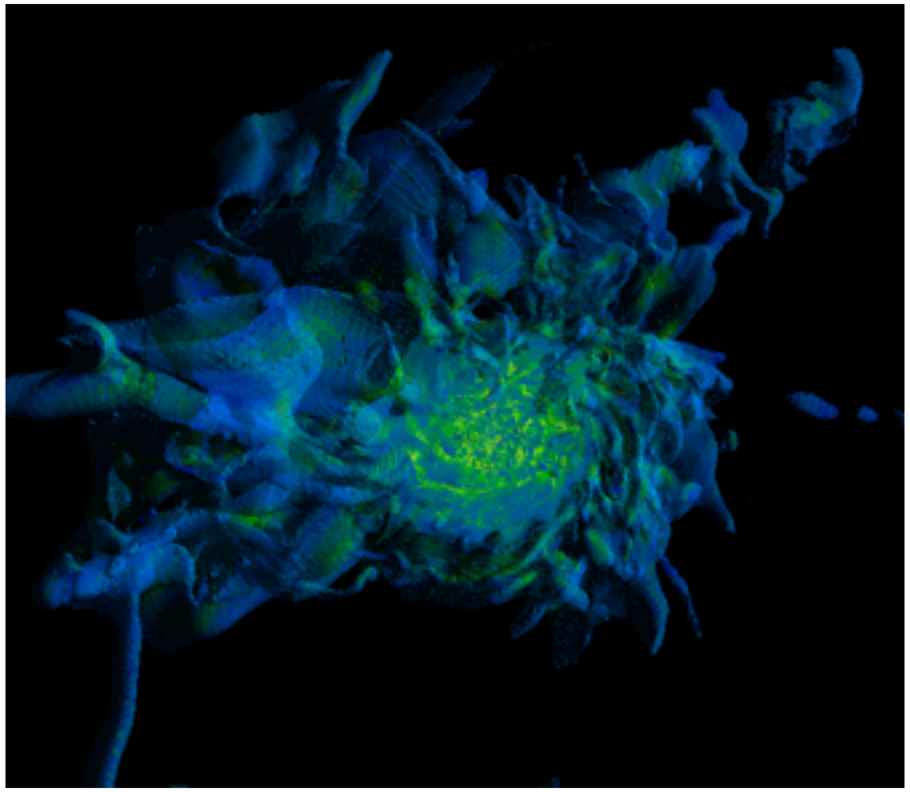


HIPACC is working with the Morrison Planetarium at the California Academy of Sciences (pictured here) to show how dark matter shapes the universe. We helped prepare their show *LIFE: a Cosmic Story* that opened in fall 2010, and also a major planetarium show that opened the new 8000 pixel across Adler Planetarium Grainger Sky Theater in July 2011.

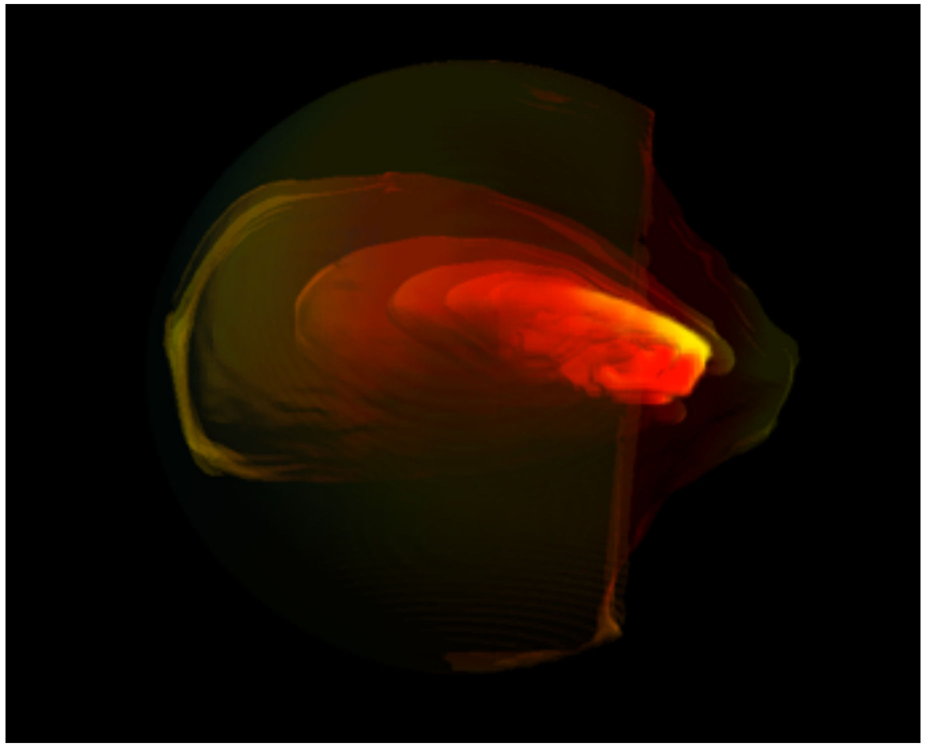
Current zSpace Projects



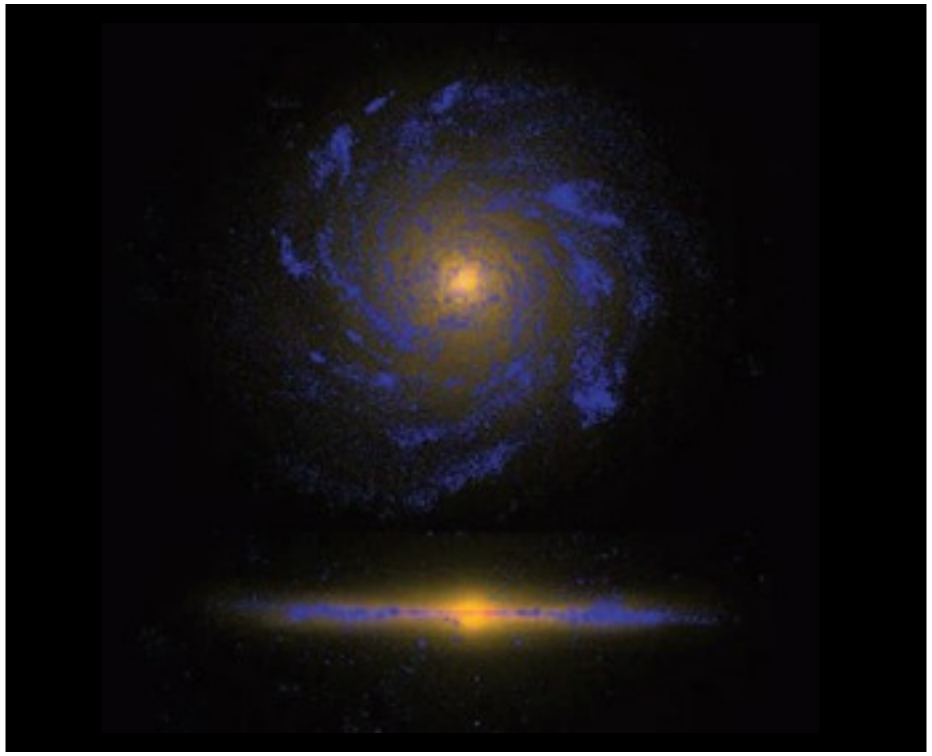
Dark Matter Halos in the Cosmic Web



Galaxy Formation & Evolution



Dwarf Galaxies & Gas Collection



The Epicyclic Motion of Galactic Stars

AstroComputing is Prototypical Scientific Computing

Astronomy has several advantages:

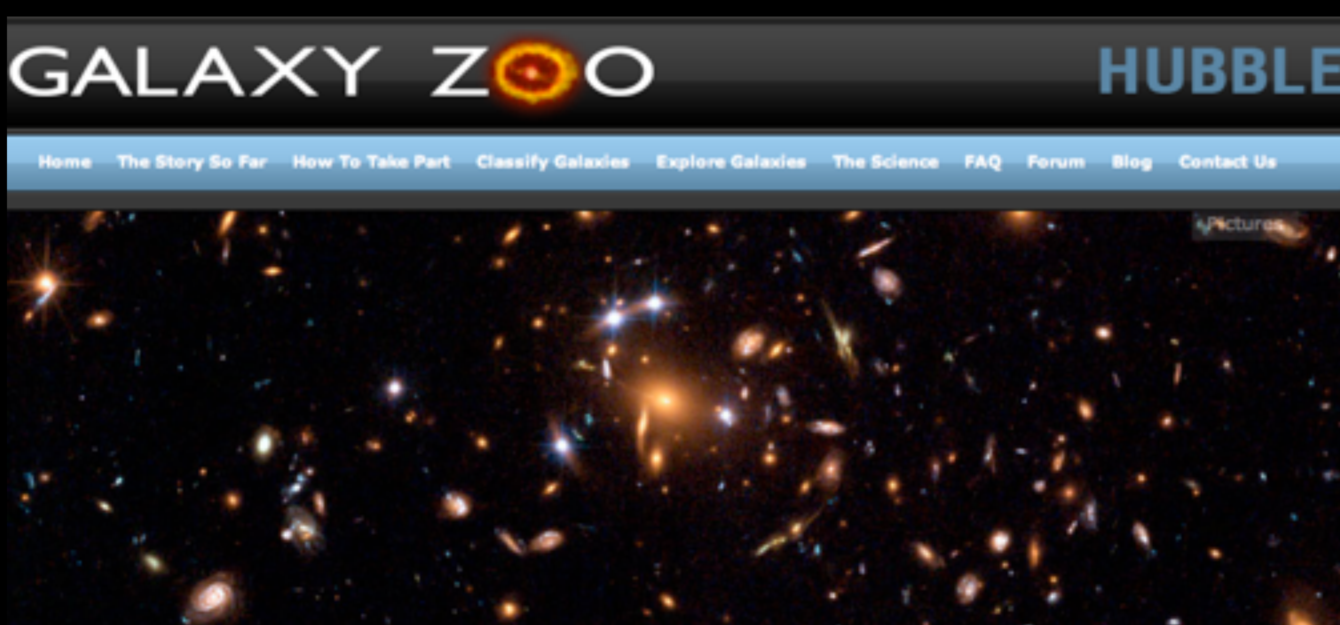
The data tends to be pretty **clean**

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

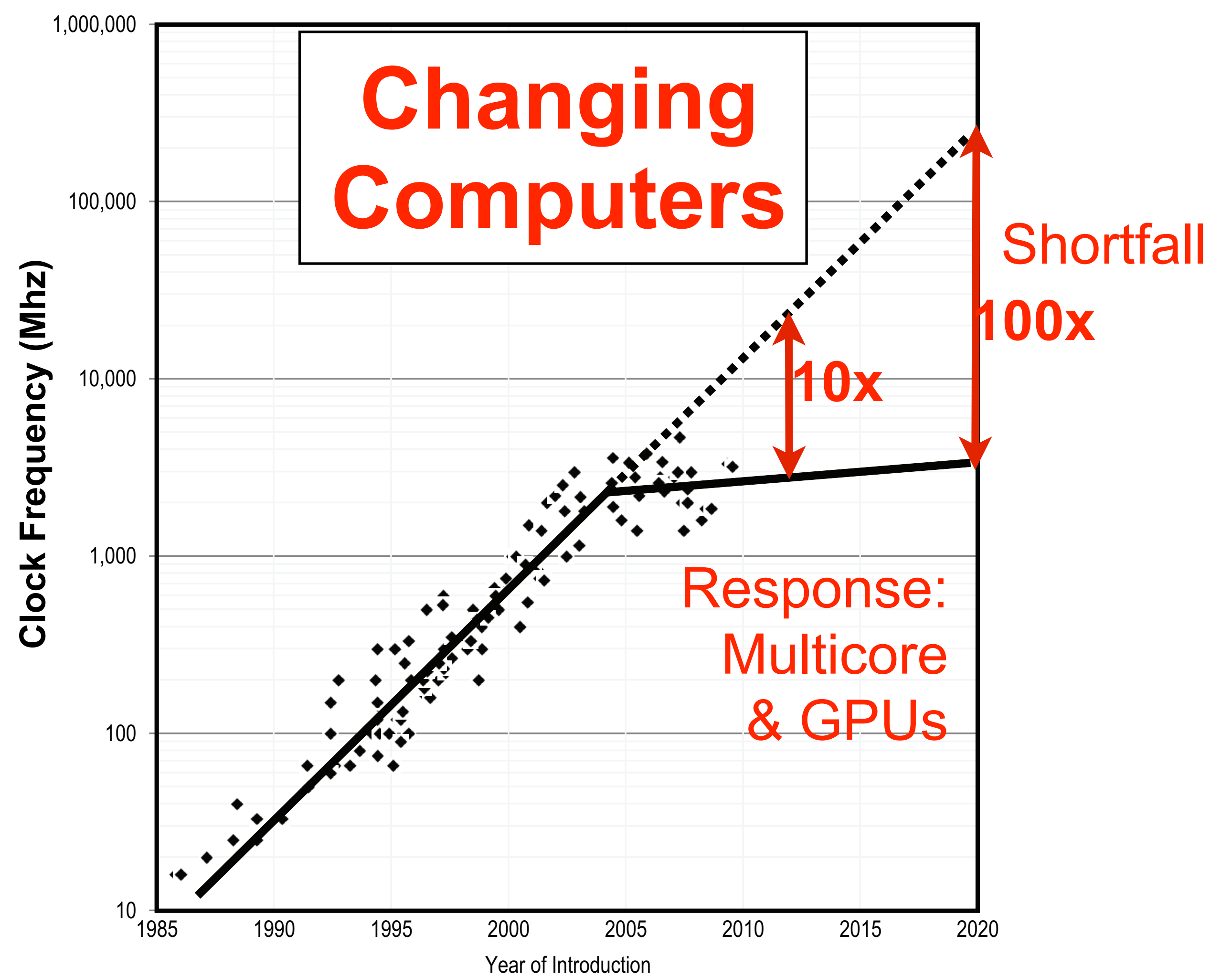
Big Data

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.

The Big Data Future 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 need data microscopes and telescopes!

- We have to analyze outputs as the supercomputers run
  Users will send questions (algorithms) to where the data is stored and get back answers (not raw data)

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 architectures, including fault tolerance and automatic load balancing
- New ways to visualize and analyze big data remotely
- Train new generations of scientific 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!

Supercomputing, Petabyte-scale storage, and constantly improving visualization technologies have made modern astrophysics research possible, and we expect to benefit greatly from continuing rapid improvements.

Thanks!

(questions?)

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
http://new-universe.org Beautiful visualizations: images and videos