Simulating Galaxies and the Universe

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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.

DARK MATTER + DARK ENERGY = DOUBLE DARK THEORY

Technical Name:

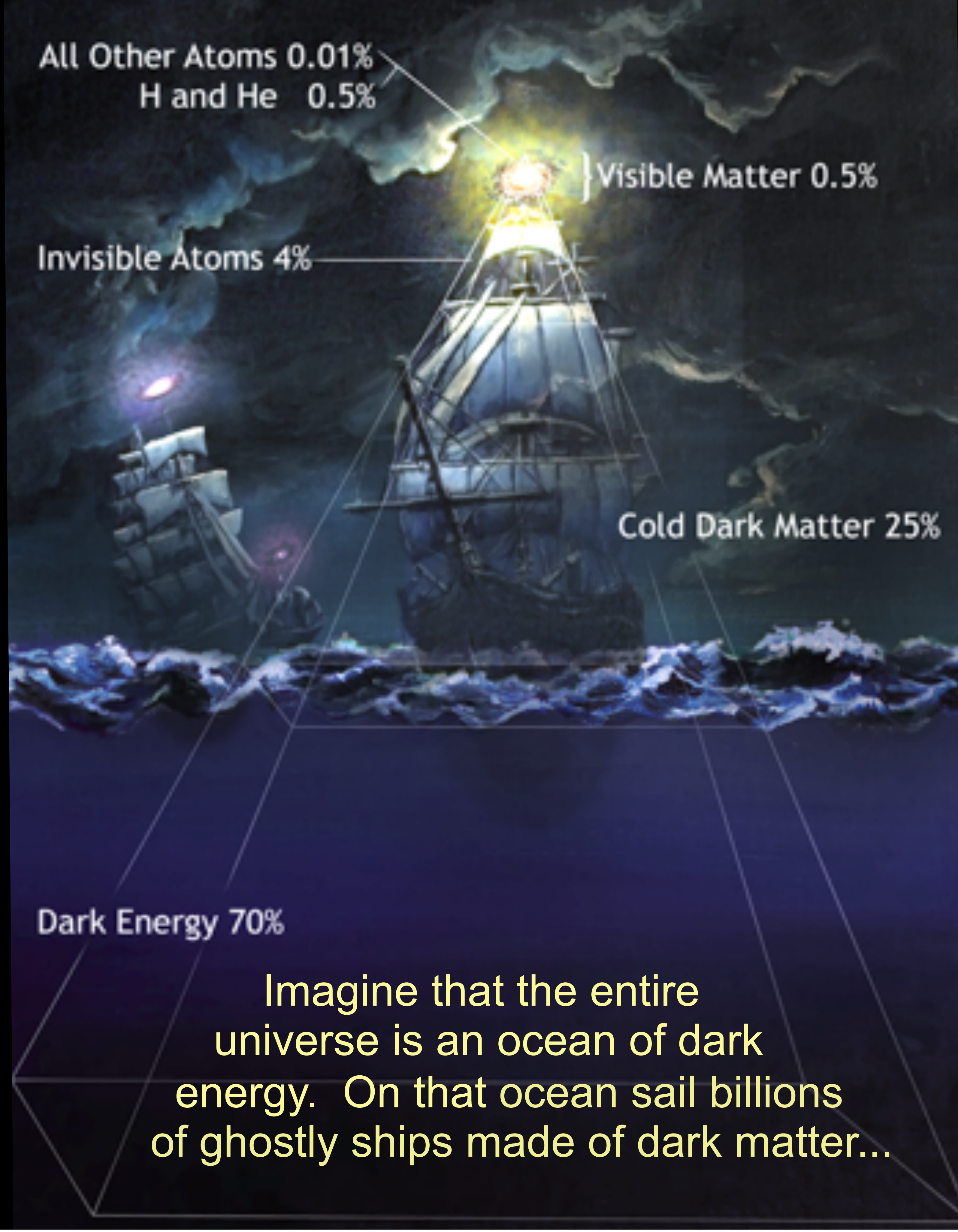
Lambda Cold Dark Matter (ΛCDM)

Matter and Energy Content of the Universe

Dark Matter Ships

on a

Dark Energy Ocean

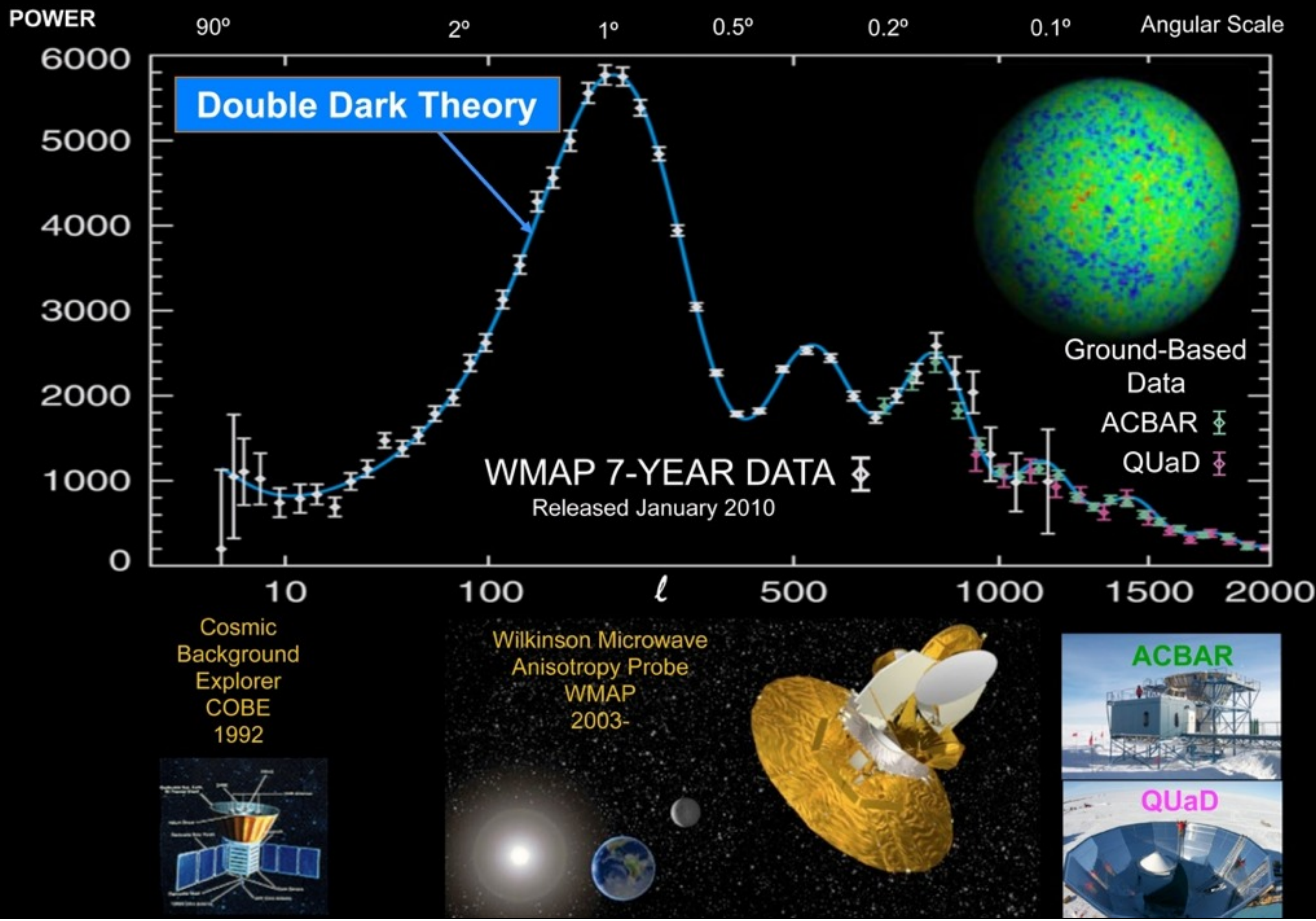


Matter and Energy Content of the Universe

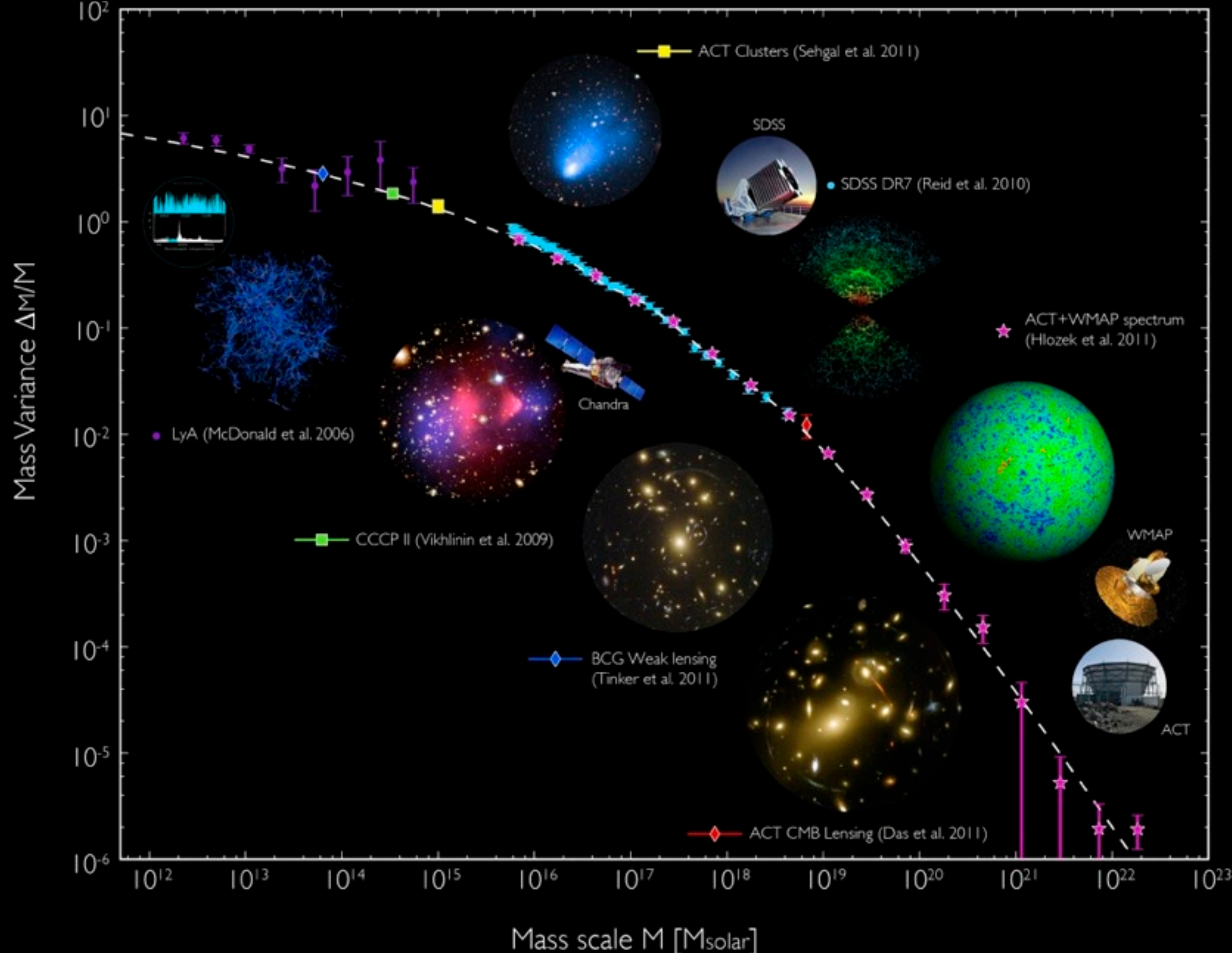
ΛCDM

Double Dark Theory

Big Bang Data Agree with Double Dark Theory



Distribution of Matter
Also Agrees with Double Dark Theory!



Because the ΛCDM **Dark Energy + Cold Dark Matter** **(Double Dark)** theory of structure formation is now so well confirmed by observations, we study the predictions of this theory for the formation of dark matter structure in the universe and use this to improve our understanding of the visible objects that we can see with our telescopes: galaxies, clusters, and the large-scale structure of the universe.

Cosmological Simulations

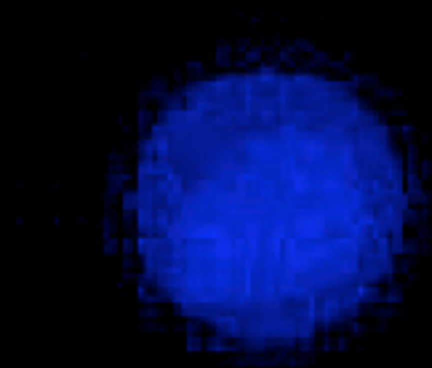
Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

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

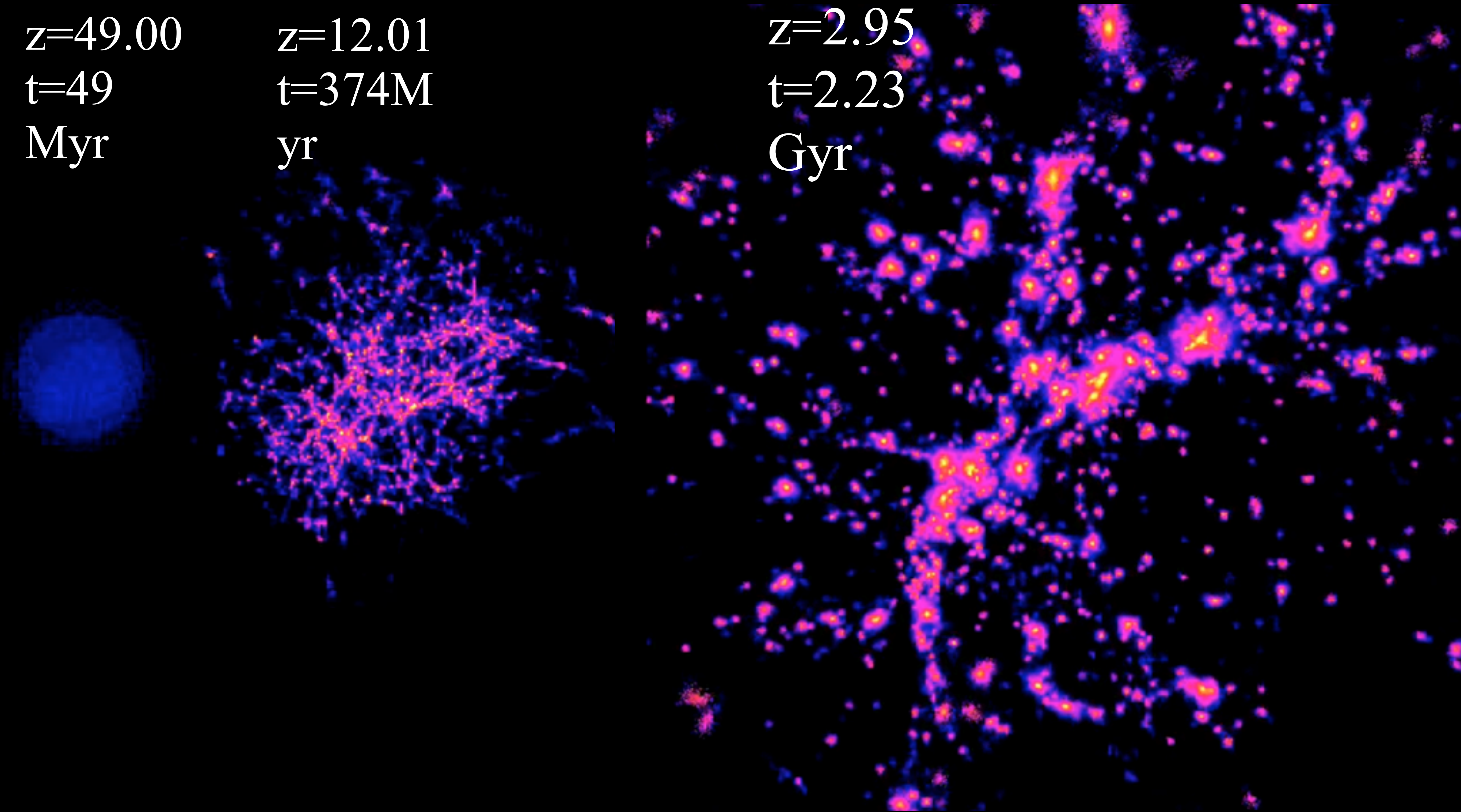
Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images in all wavebands including stellar evolution and dust

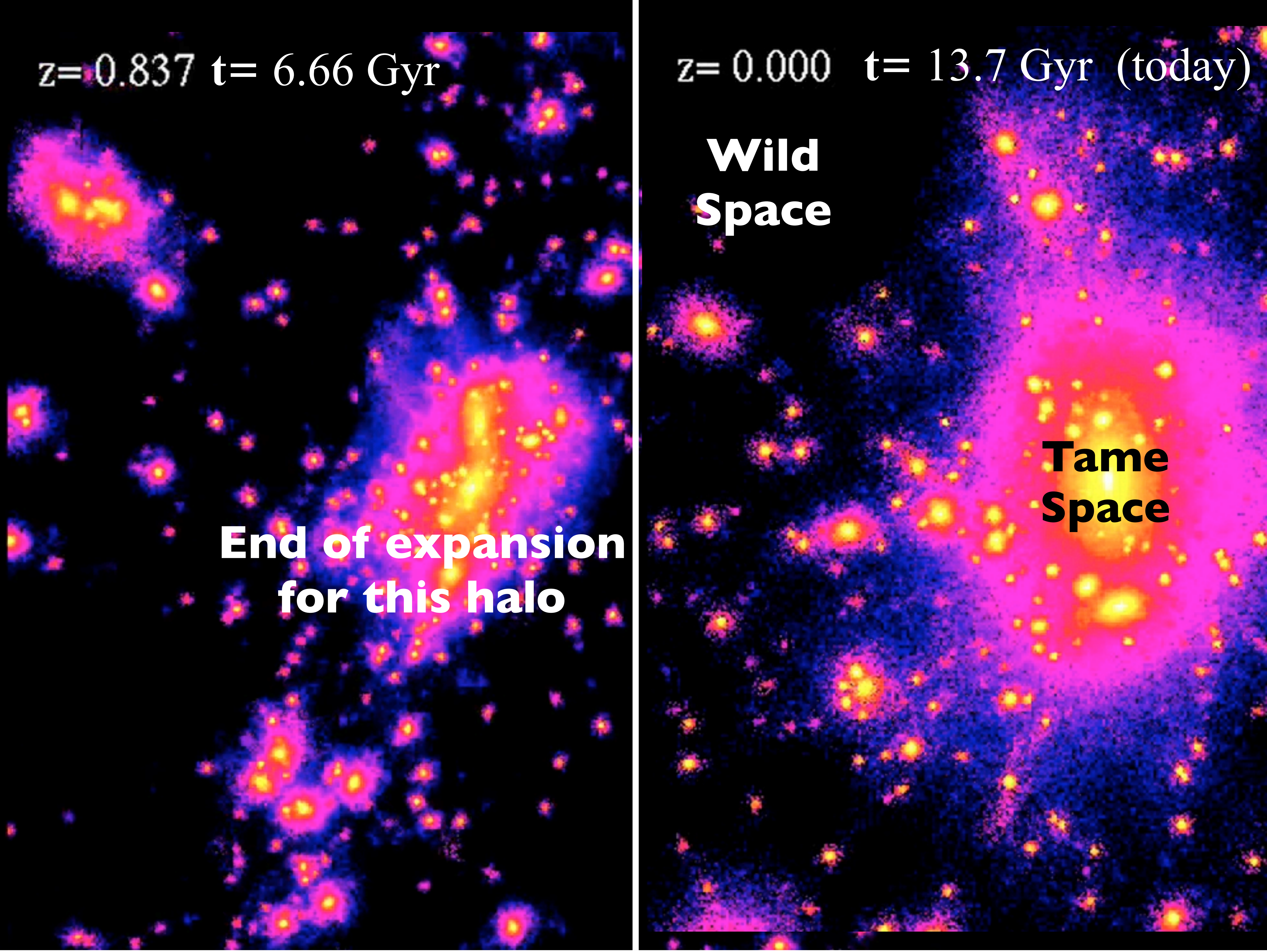

S. Harris
"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

Dark Matter Expanding

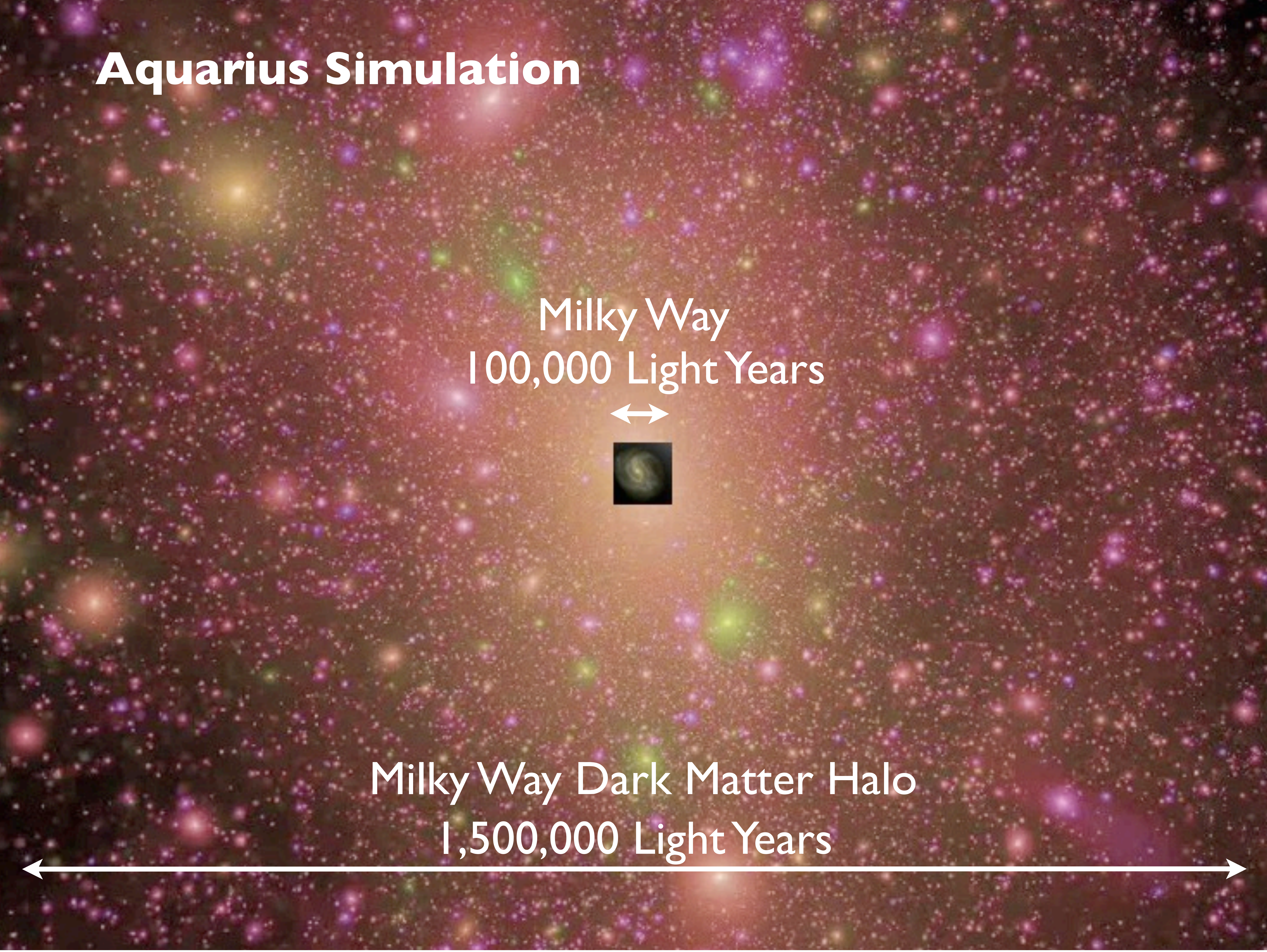


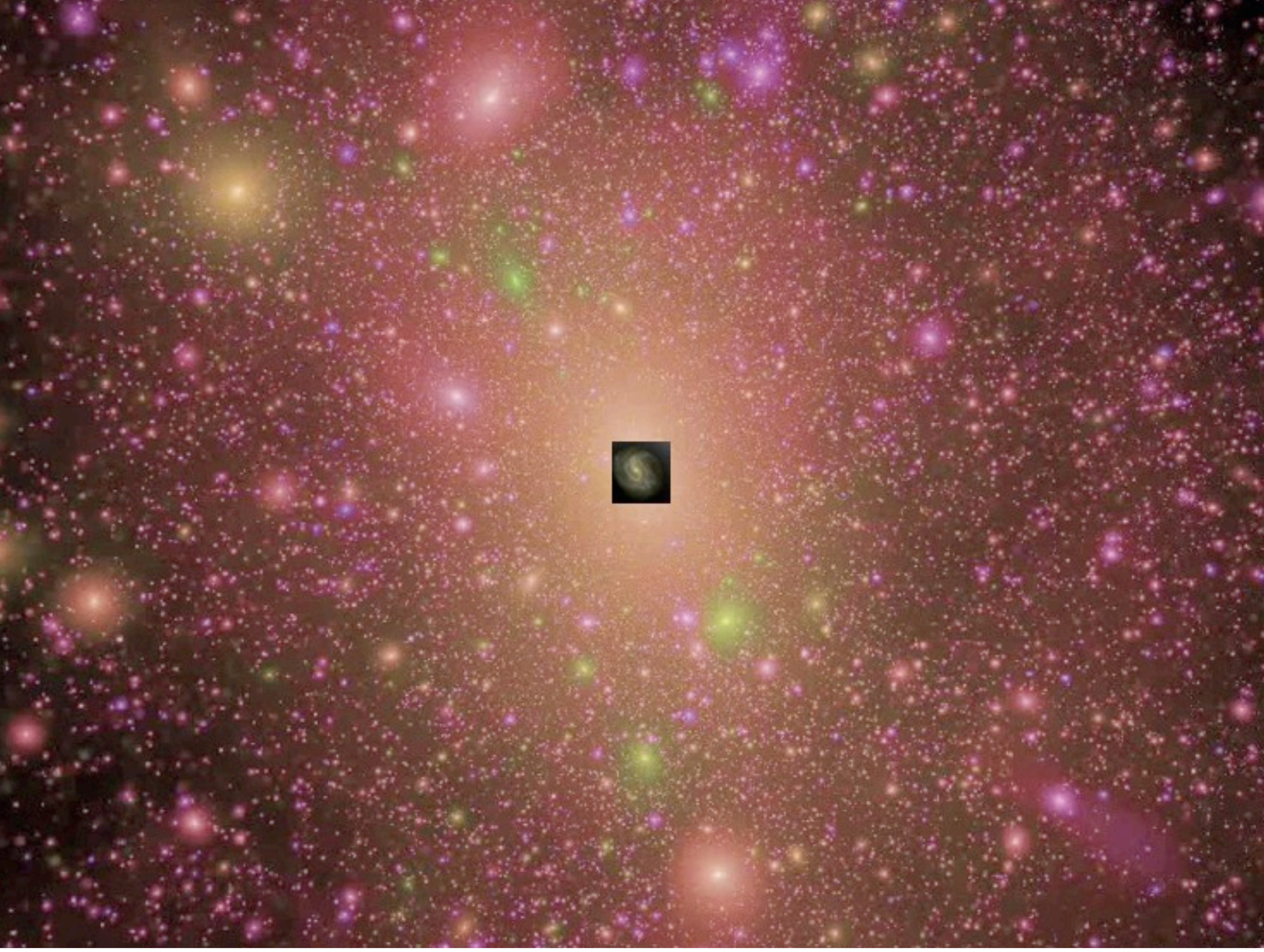
Expansion....

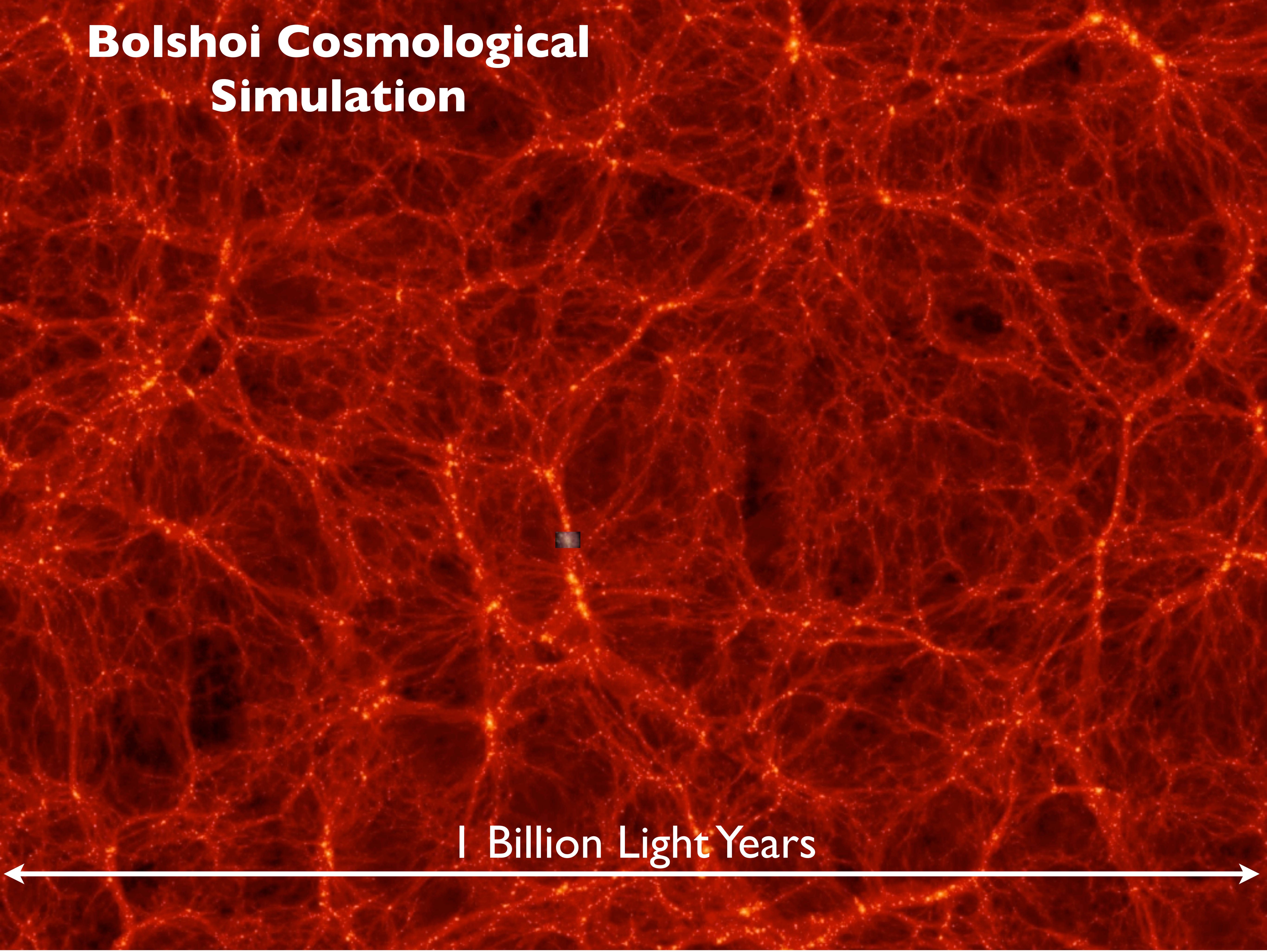


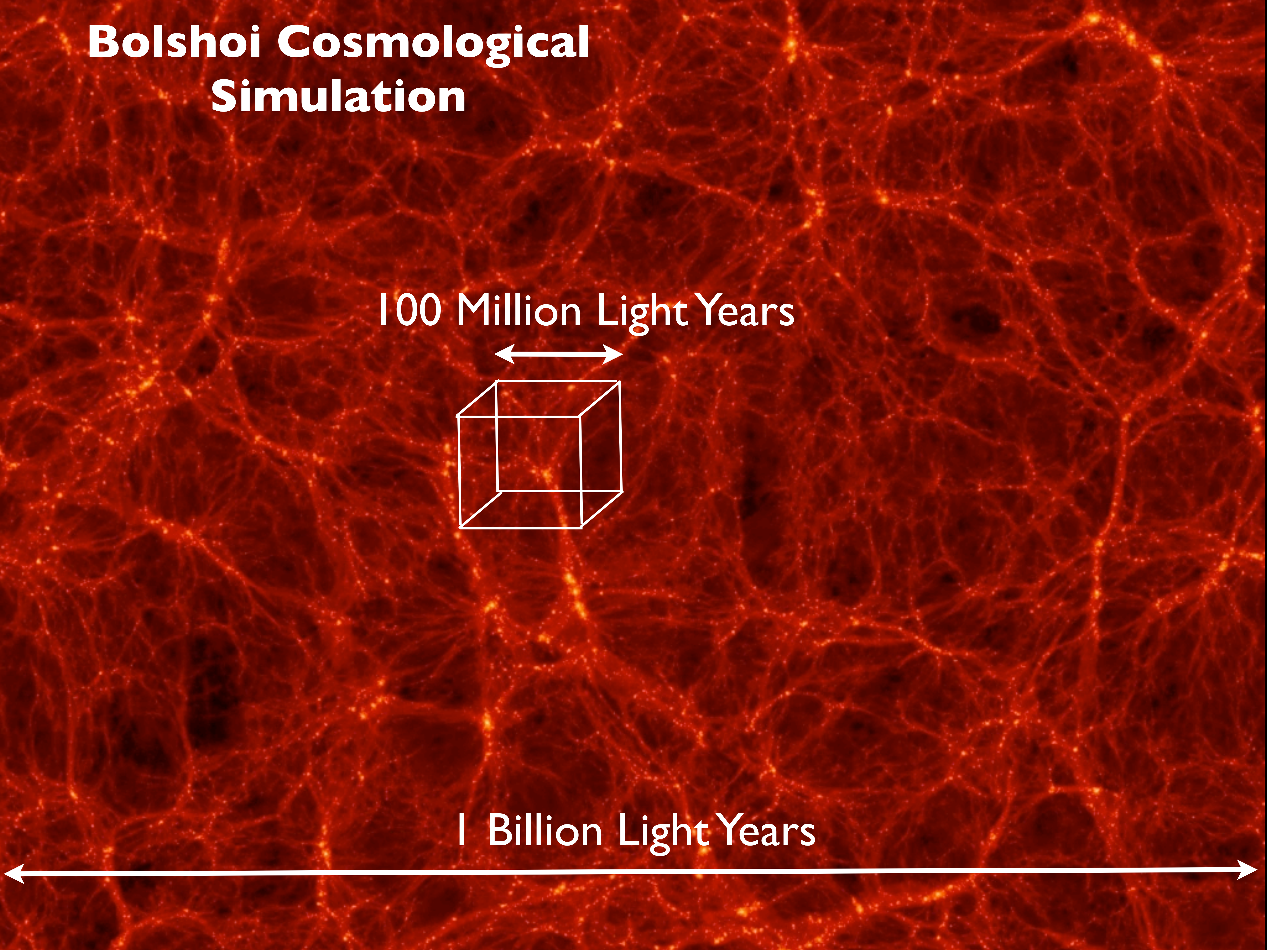

z= 0.837 t= 6.66 Gyr
End of expansion
for this halo
z= 0.000 t= 13.7 Gyr (today)
Wild
Space
Tame
Space

Aquarius Simulation






Bolshoi Cosmological Simulation
1 Billion Light Years


Bolshoi Cosmological
Simulation
100 Million Light Years
1 Billion Light Years

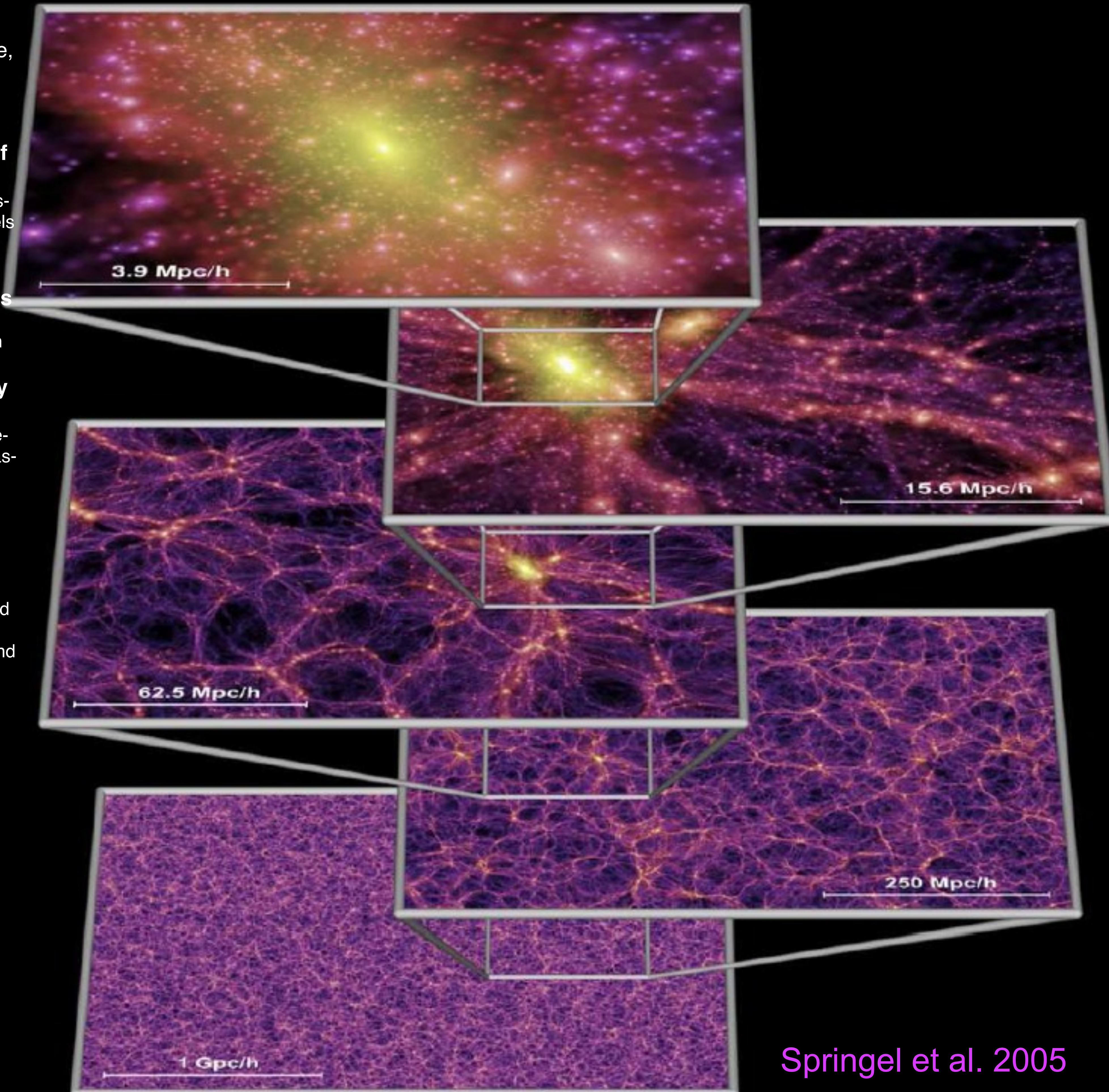
Bolshoi Cosmological Simulation

100 Million Light Years

Bjork "Dark Matter"
Biophilia

The Millennium Run

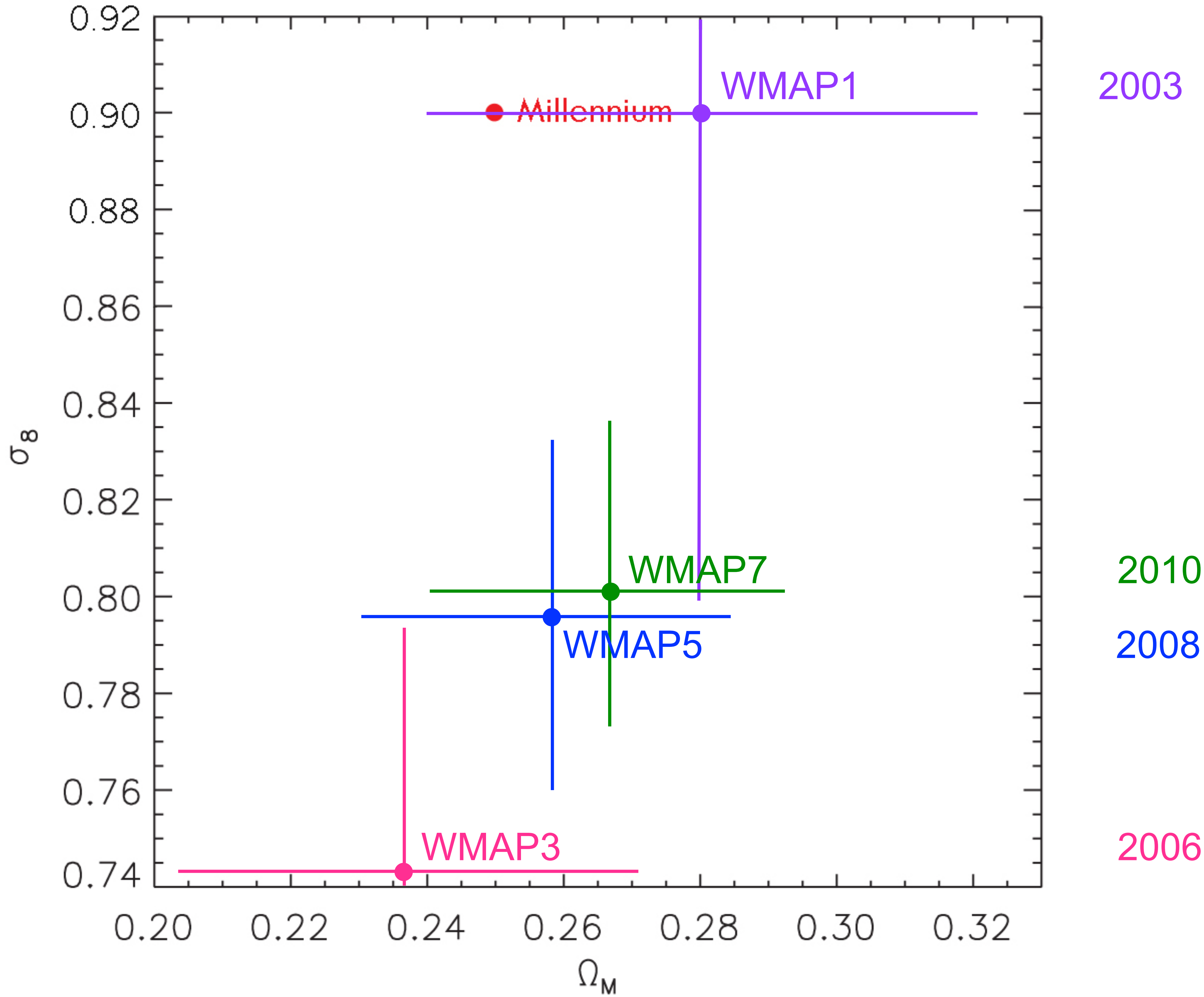
- **properties of halos** (radial profile, concentration, shapes)
- **evolution of the number density of halos**, essential for normalization of Press-Schechter- type models
- **evolution of the distribution and clustering of halos** in real and redshift space, for comparison with observations
- **accretion history of halos**, assembly bias (variation of large-scale clustering with assembly history), and correlation with halo properties including angular momenta and shapes
- **halo statistics** including the mass and velocity functions, angular momentum and shapes, subhalo numbers and distribution, and correlation with environment



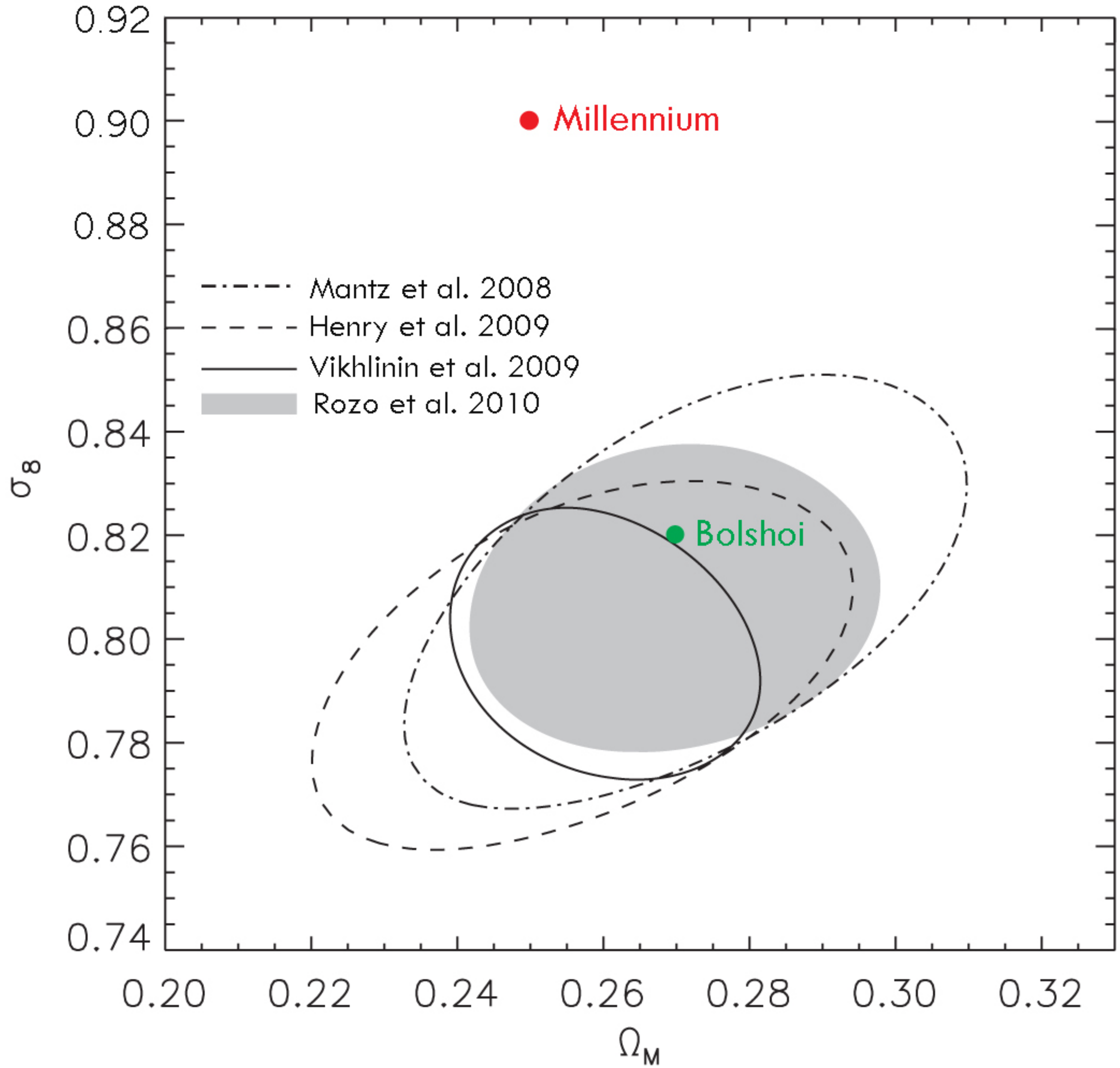
- **void statistics**, including sizes and shapes and their evolution, and the orientation of halo spins around voids
- quantitative descriptions of the evolving **cosmic web**, including applications to weak gravitational lensing
- preparation of **mock catalogs**, essential for analyzing SDSS and other survey data, and for preparing for new large surveys for dark energy etc.
- **merger trees**, essential for **semi-analytic modeling** of the evolving galaxy population, including models for the galaxy merger rate, the history of star formation and galaxy colors and morphology, the evolving AGN luminosity function, stellar and AGN feedback, recycling of gas and metals, etc.

Springel et al. 2005

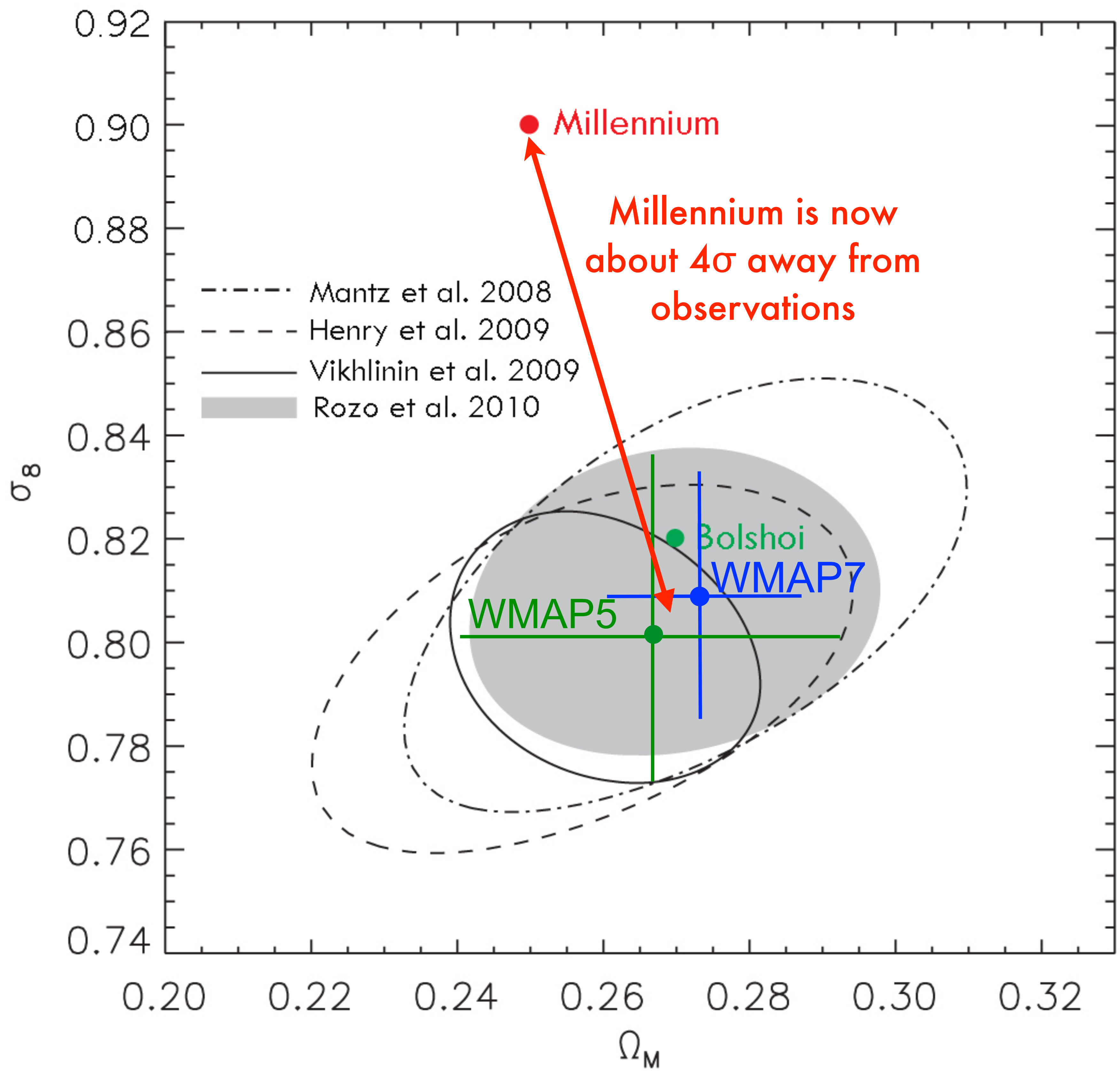
WMAP-only Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



WMAP+SN+Clusters Determination of σ_8 and Ω_M



The Bolshoi simulation

ART code

250Mpc/h Box
LCDM
σ_8 = 0.82
h = 0.70
8G particles
1kpc/h force resolution
1e8 Msun/h mass res

dynamical range 262,000
time-steps = 400,000

NASA AMES
supercomputing center
Pleiades computer
13824 cores
12TB RAM
75TB disk storage
6M cpu hrs
18 days wall-clock time

Cosmological parameters are consistent with the latest observations

Force and Mass Resolution are nearly an order of magnitude better than Millennium-I

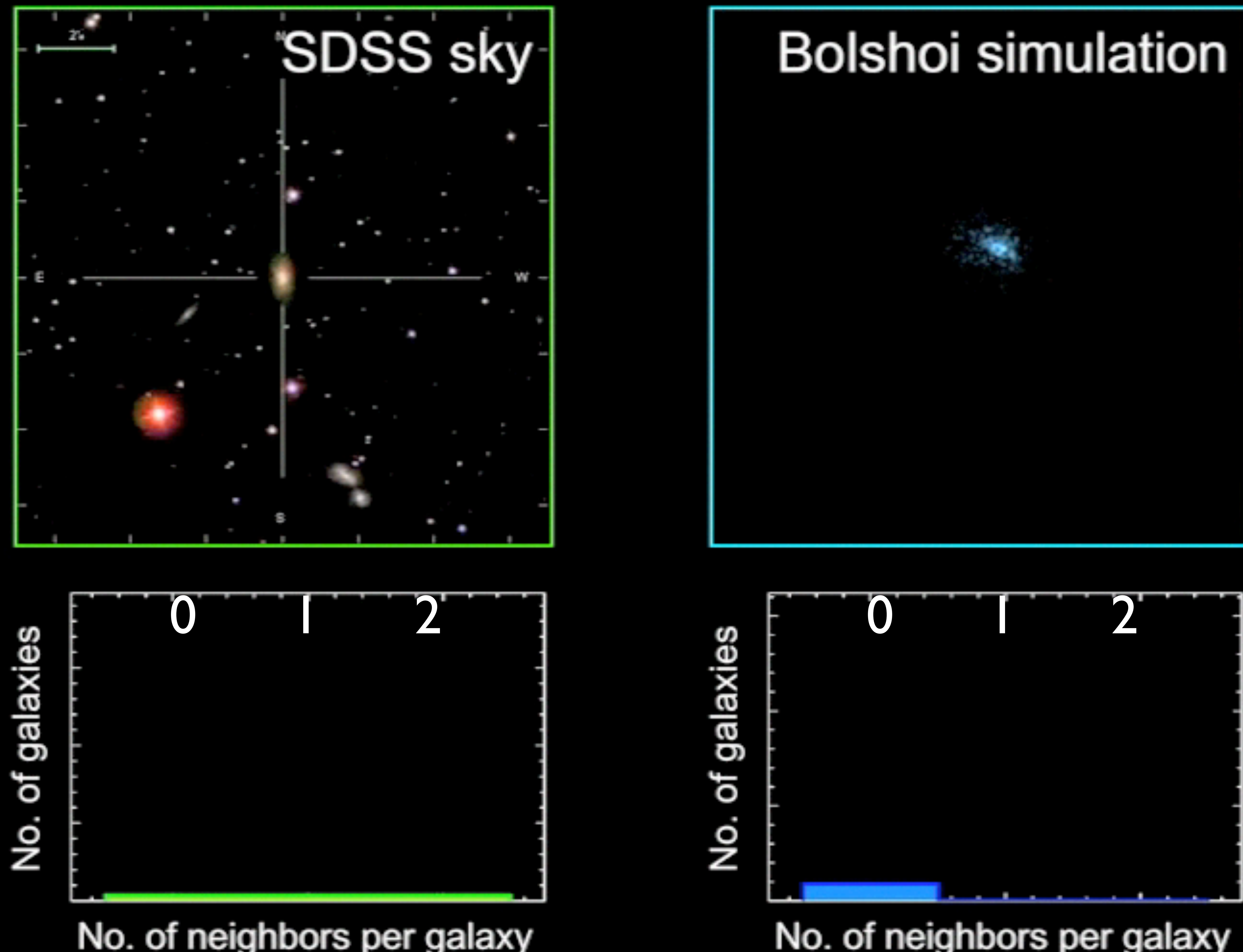
Force resolution is the same as Millennium-II, in a volume 16x larger

Halo finding is complete to V_{circ} > 50 km/s, using both BDM and ROCKSTAR halo finders

Bolshoi and MultiDark halo catalogs were released in September 2011 at Astro Inst Potsdam; Merger Trees will soon be available

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

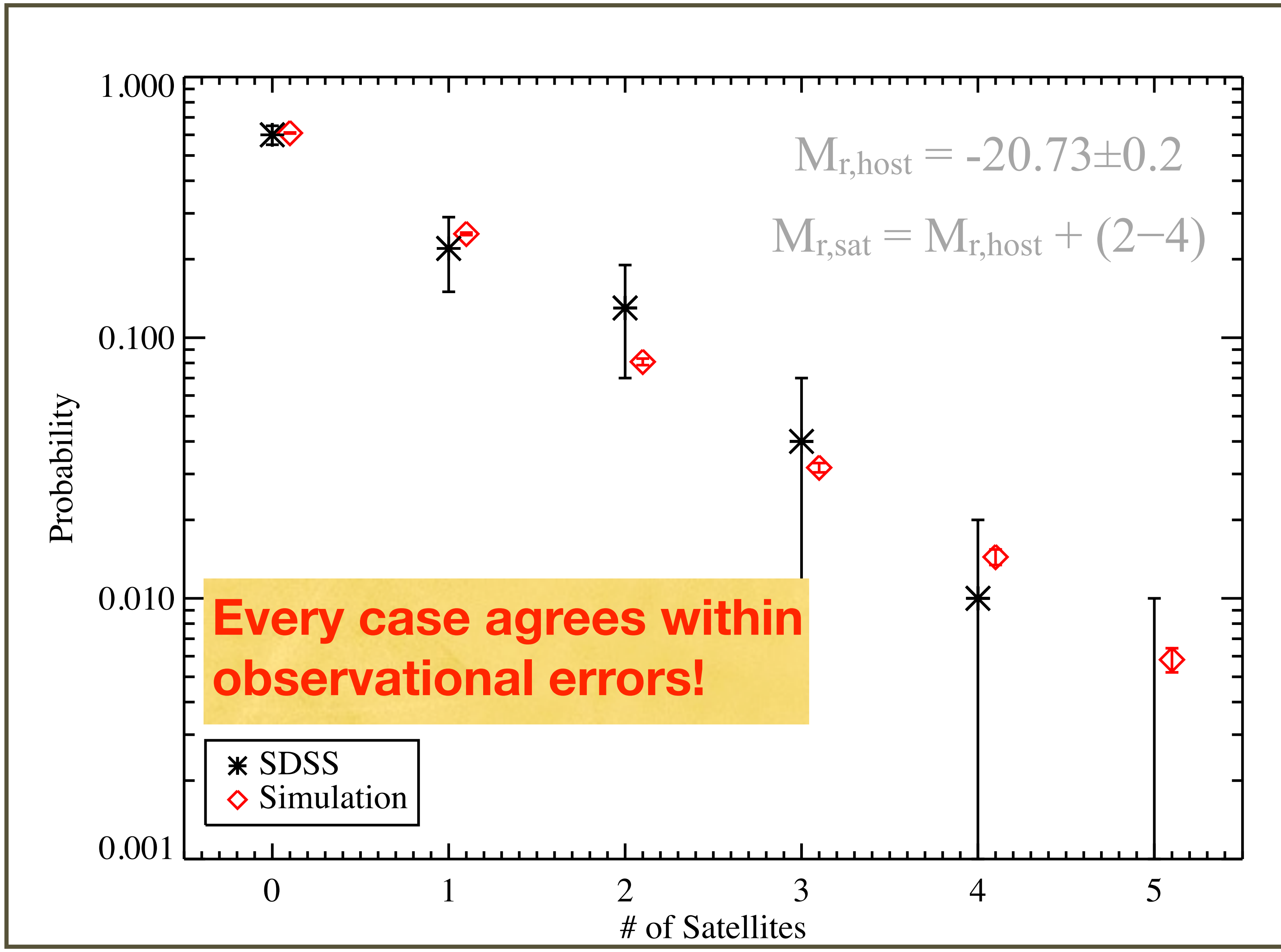
The Bolshoi simulation + halo abundance matching predicts the likelihood of this


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

- Apply the same absolute magnitude and isolation cuts to Bolshoi+SHAM galaxies as to SDSS:
  - Identify all objects with absolute ${}^{0.1}M_r$ = -20.73±0.2 and observed $m_r < 17.6$
  - Probe out to z = 0.15, a volume of roughly 500 (Mpc/h)^3
  - leaves us with 3,200 objects.
- Comparison of Bolshoi with SDSS observations is in close agreement, well within observed statistical error bars.

# of Subs	Prob (obs)	Prob (sim)
0	60%	61%
1	22%	25%
2	13%	8.1%
3	4%	3.2%
4	1%	1.4%
5	0%	0.58%

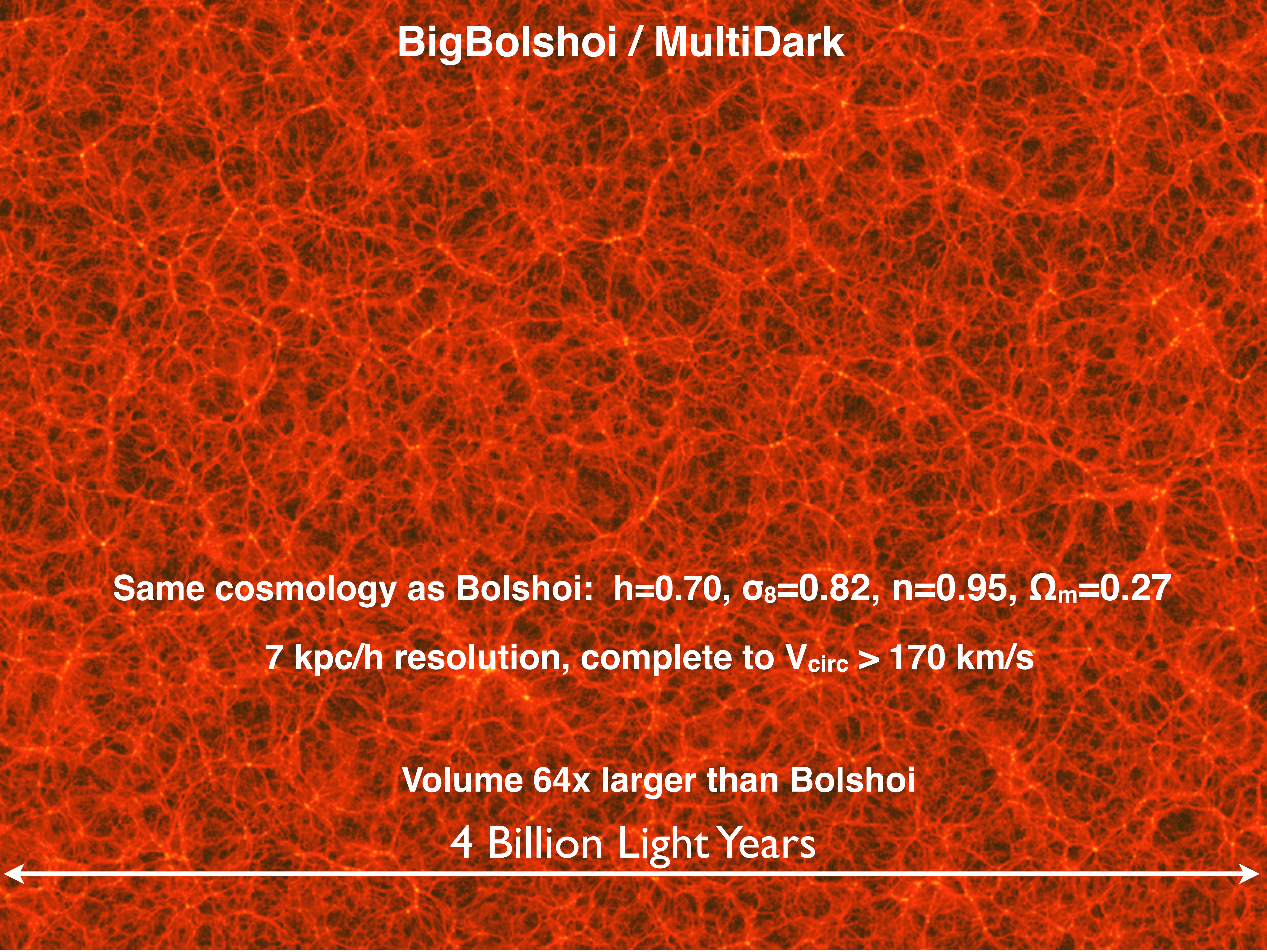
Statistics of MW bright satellites: SDSS data vs. Bolshoi simulation



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

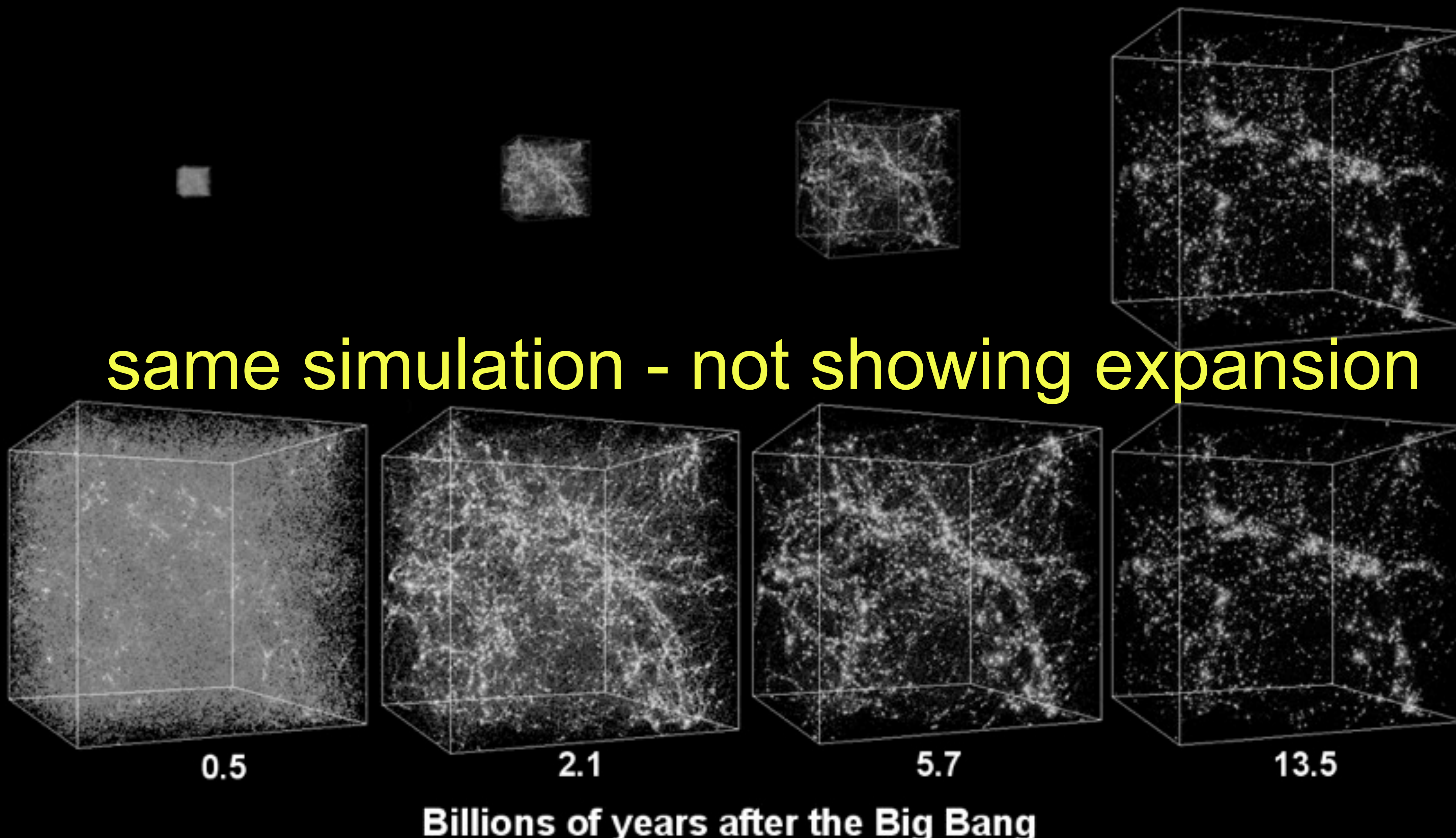
Risa Wechsler

Similarly good agreement with SDSS for brighter satellites with spectroscopic redshifts compared with Millennium-II using abundance matching -- Tollerud, Boylan-Kolchin, et al. 2011 ApJ


BigBolshoi / MultiDark
Same cosmology as Bolshoi: $h=0.70$, $\sigma_8=0.82$, $n=0.95$, $\Omega_m=0.27$
7 kpc/h resolution, complete to $V_{circ} > 170$ km/s
Volume 64x larger than Bolshoi
4 Billion Light Years

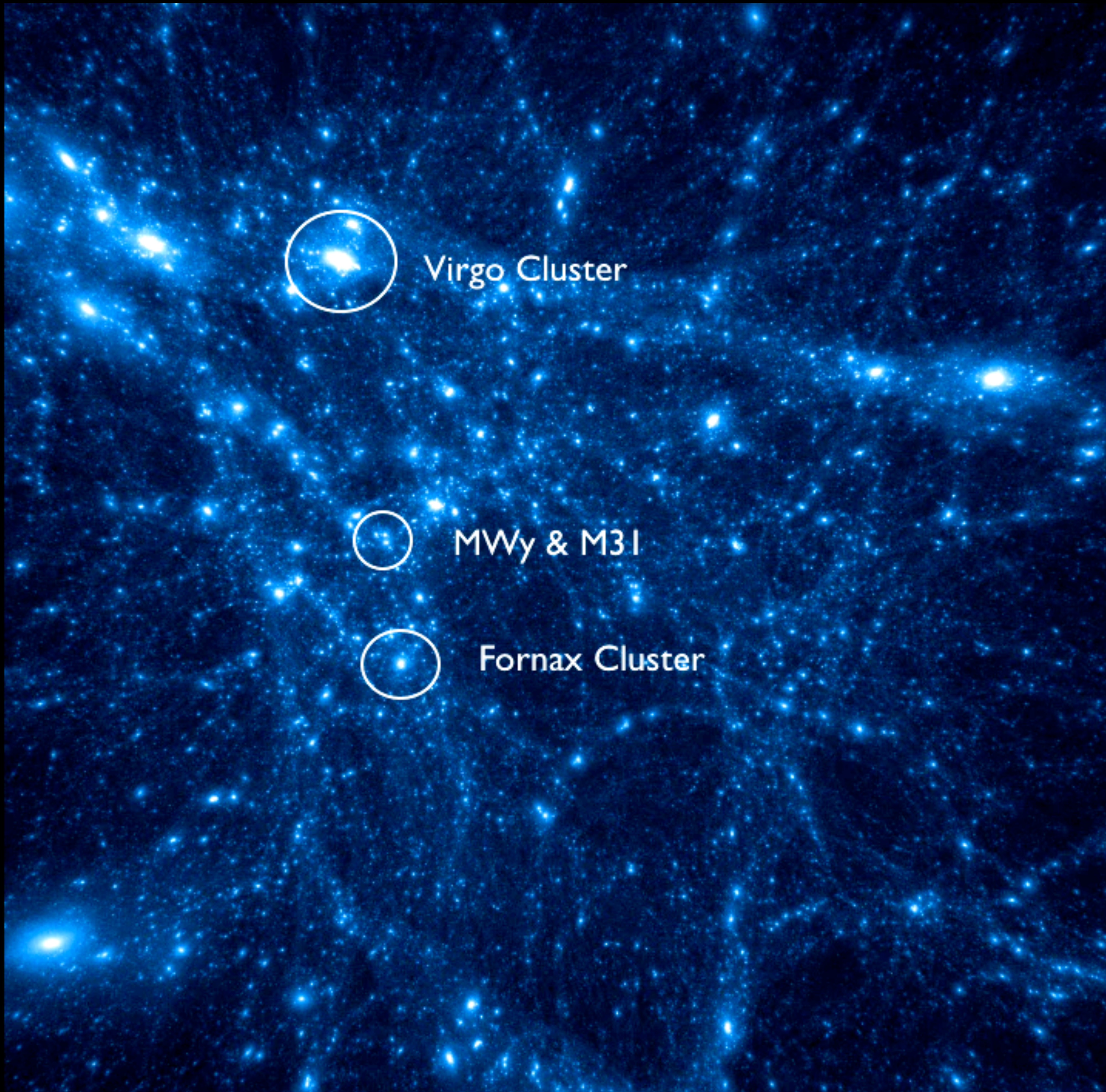
dark matter simulation - expanding with the universe

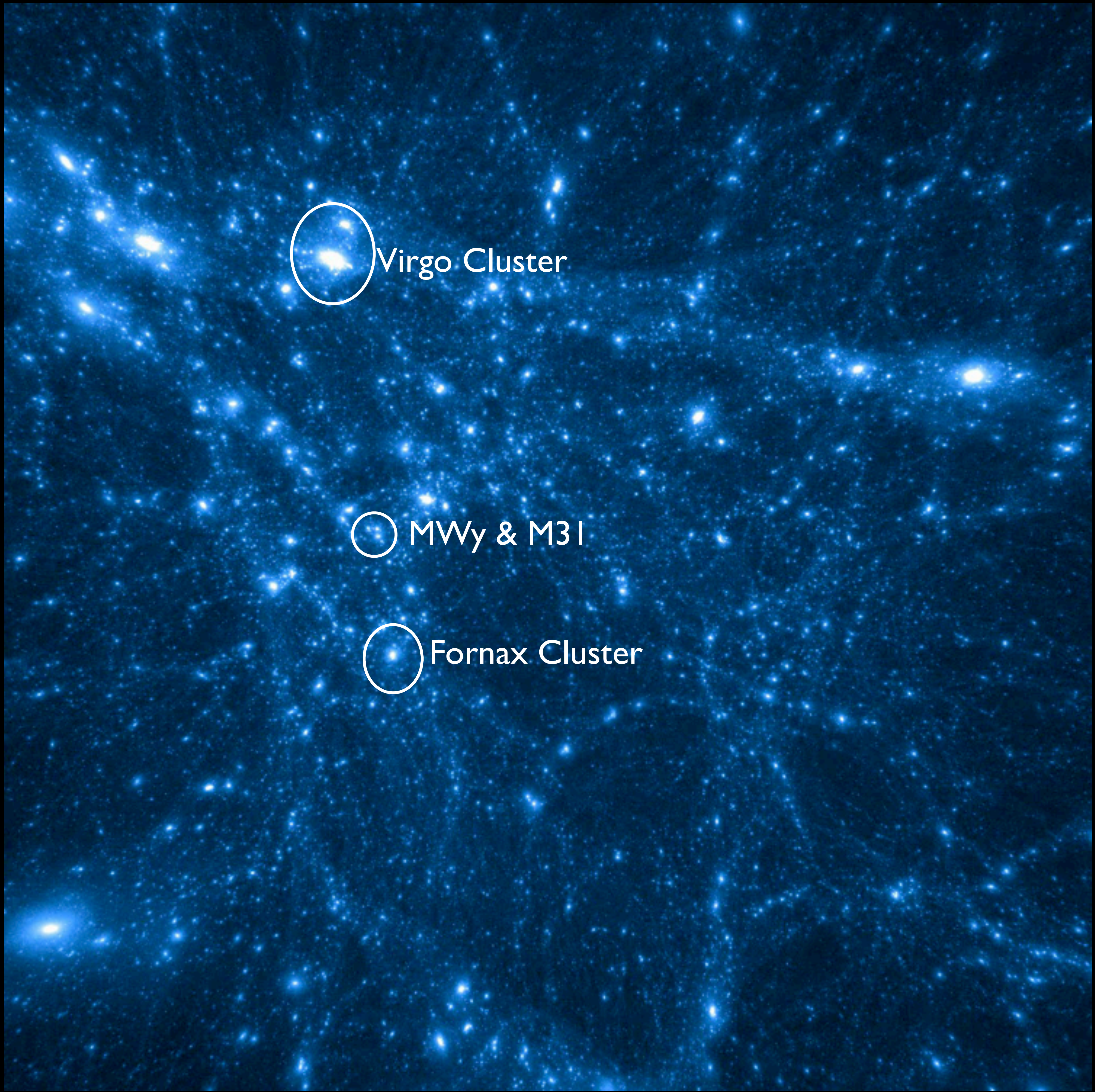
same simulation - not showing expansion



CONSTRAINED LOCAL UNIVERSE SIMULATION

300 Million Light Years


Virgo Cluster
MWy & M31
Fornax Cluster


Virgo Cluster
MWy & M31
Fornax Cluster

Bolshoi Merger Tree for the Formation of a Big Cluster Halo

Peter Behroozi

Formation of galaxies and large-scale structure with cold dark matter

Blumenthal, Feber, Primack, & Rees -- Nature 311, 517 (1984)

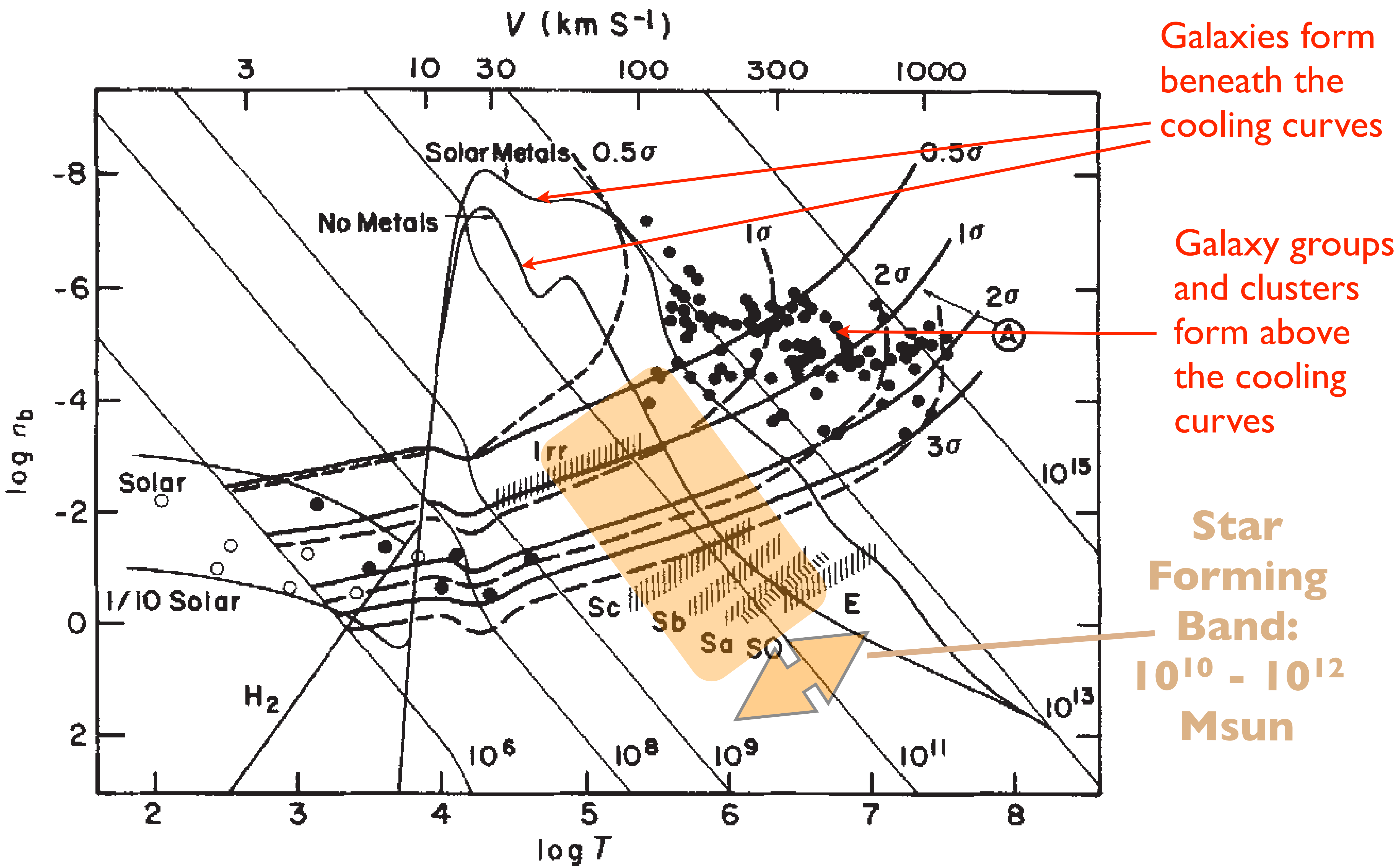
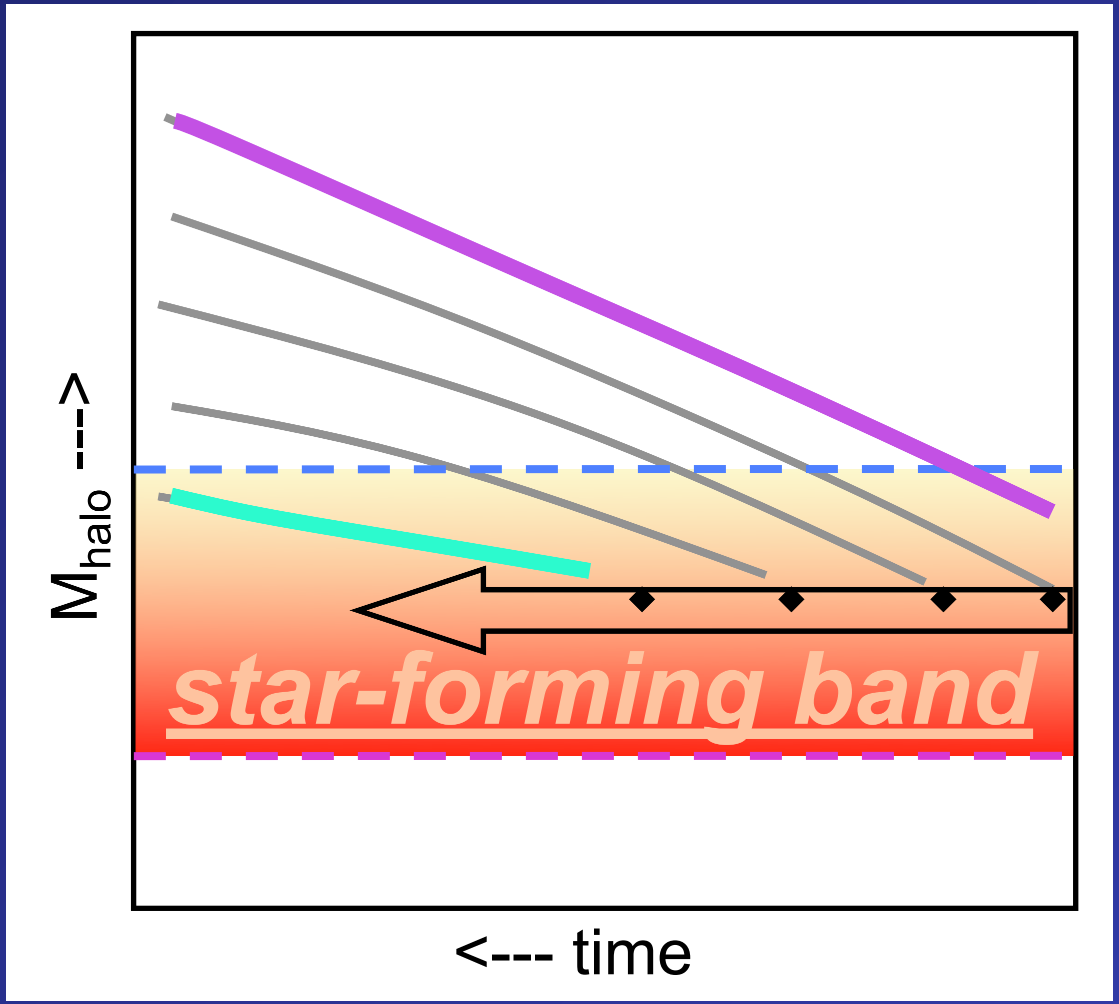


Fig. 3 Baryon density n_b versus three-dimensional, r.m.s. velocity dispersion V and virial temperature T for structures of various size in the Universe. The quantity T is $\mu V^2/3k$, where μ is mean molecular weight ($\approx$0.6 for ionized, primordial H+He) and k is Boltzmann's constant.

Implications and Predictions of the Model



Massive galaxies:

- Started forming stars early.
- Shut down early.
- Are red today.
- Populate dark halos that are much more massive than their stellar mass.

Small galaxies:

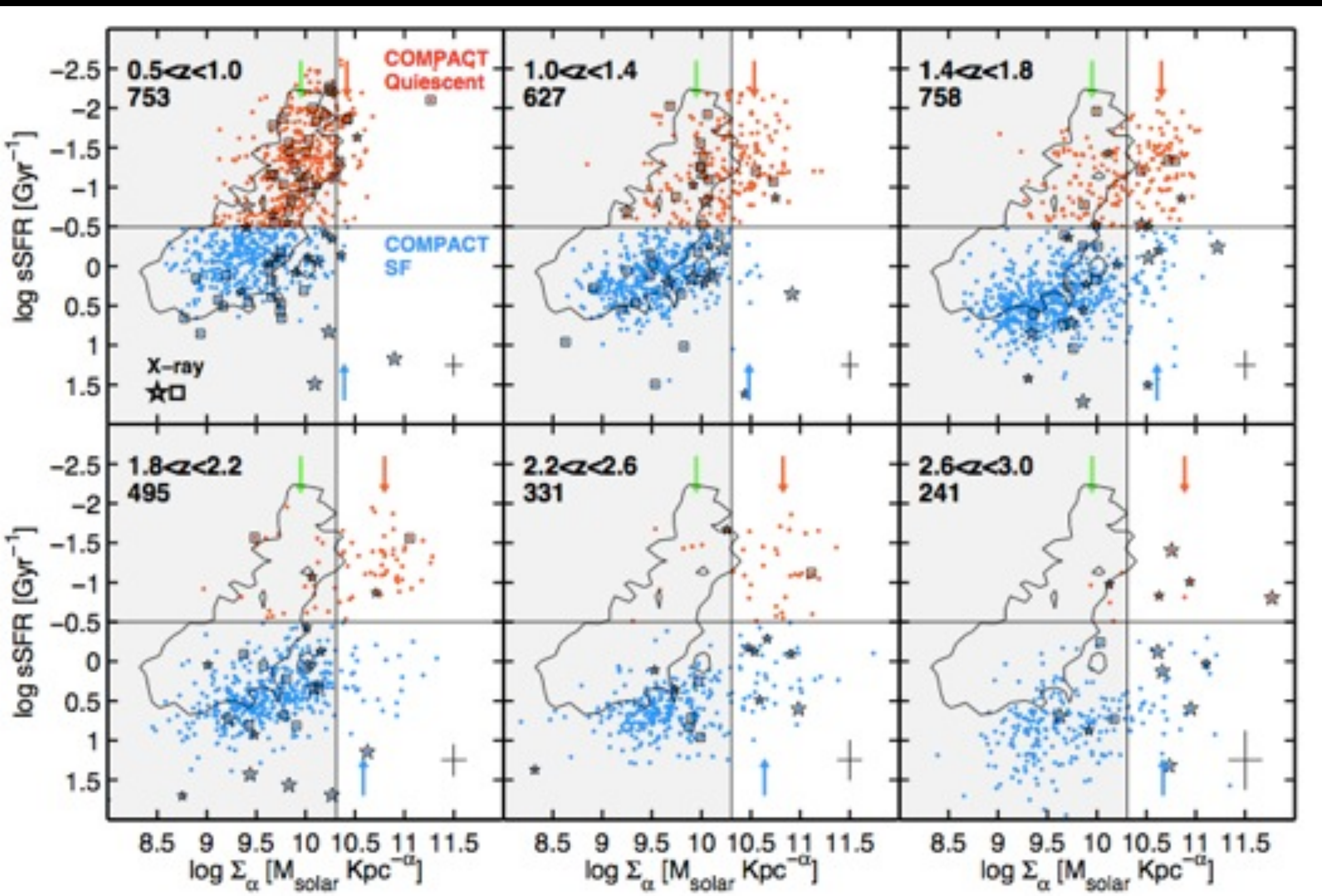
- Started forming stars late.
- Are still making stars today.
- Are blue today.
- Populate dark halos that match their stellar mass.

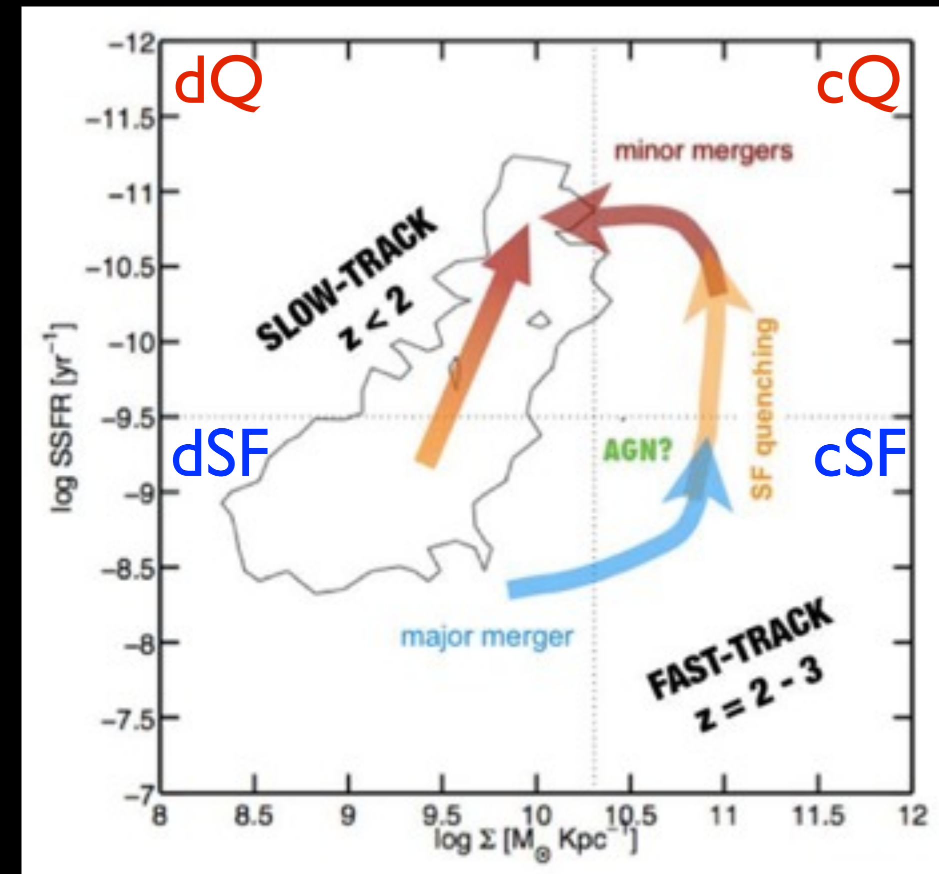
"Downsizing"

Star formation is a wave that started in the largest galaxies and swept down to smaller masses later (Cowie et al. 1996).

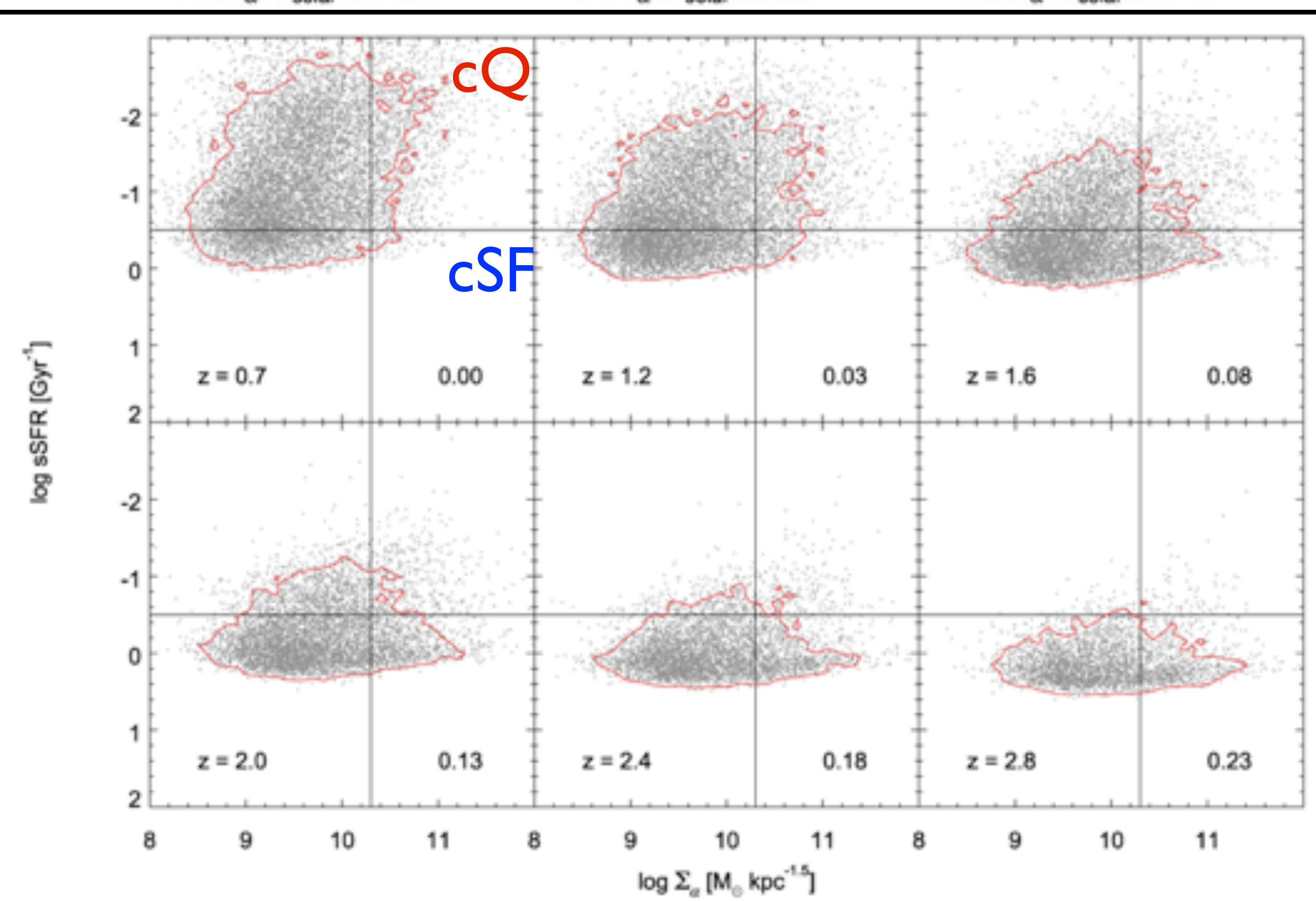
Sandy Faber

Evolution of Galaxies: Observations vs. Theory

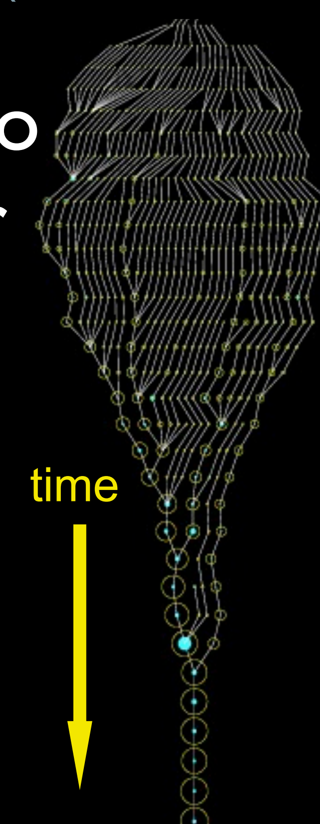




Barro et al. (2012 - Hubble Observations)



DM Halo Merger Tree



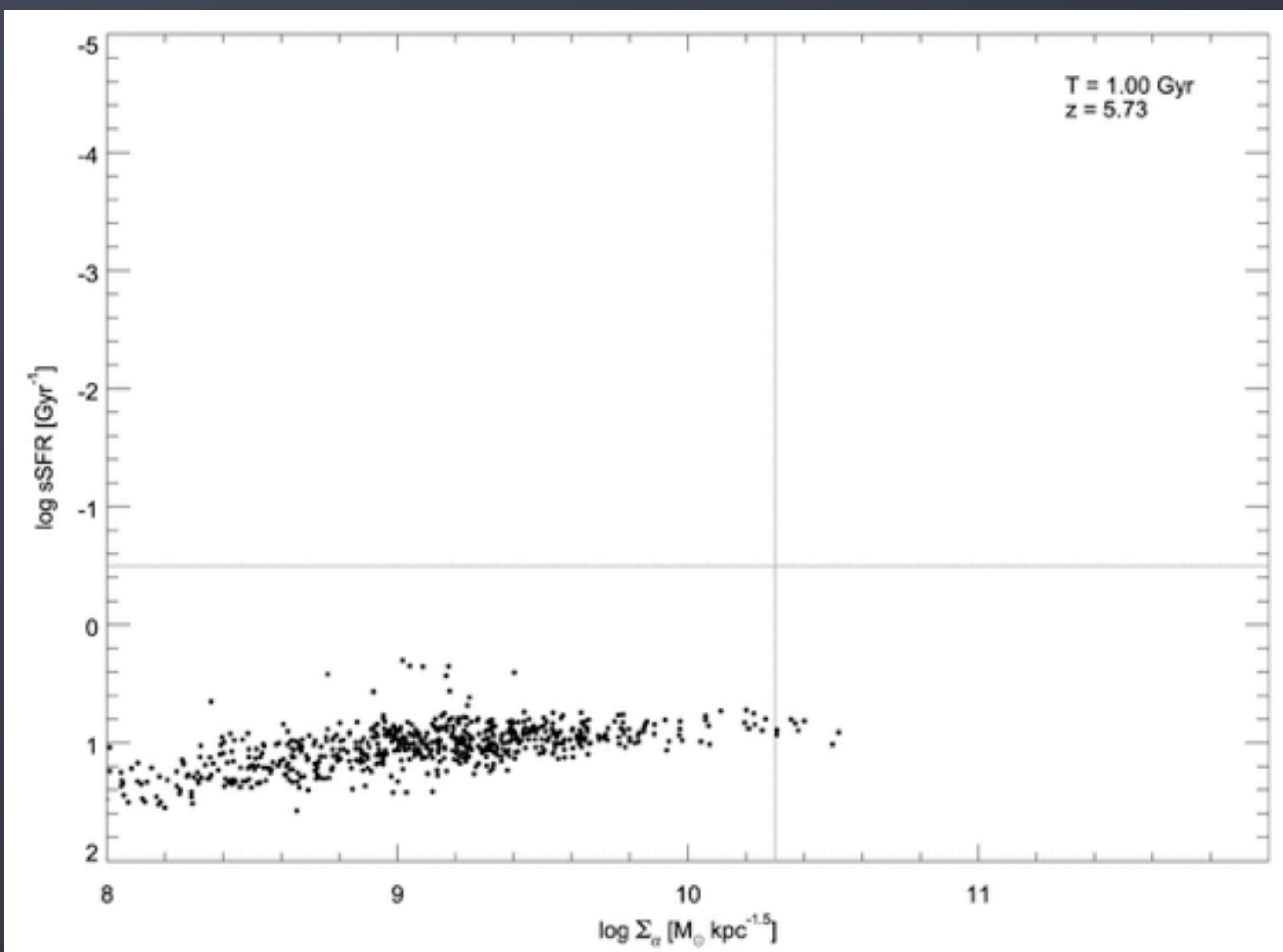
Astrophysical processes modeled:

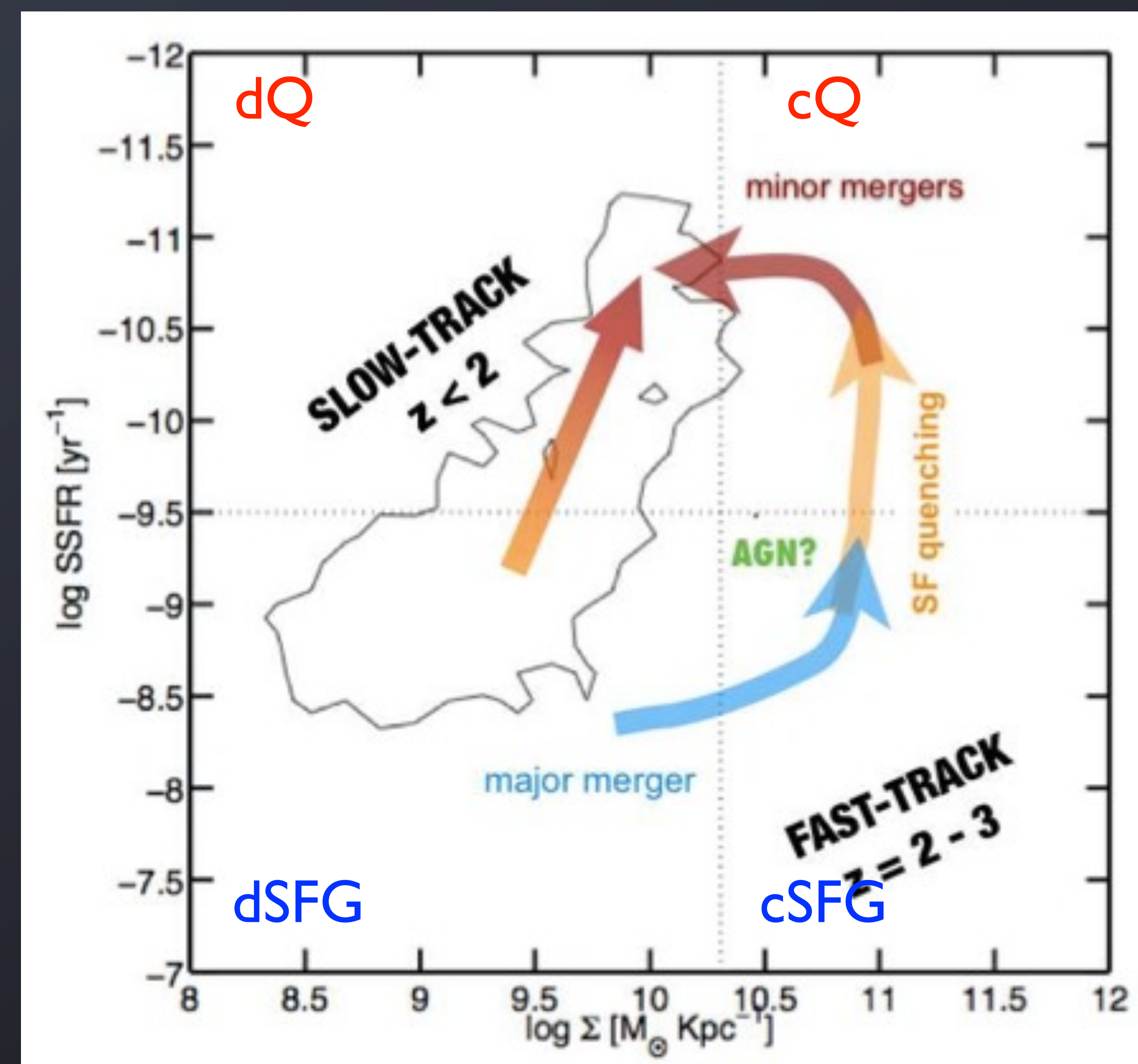
- shock heating & radiative cooling
- photoionization squelching
- merging
- star formation (quiescent & burst)
- SN heating & SN-driven winds
- AGN accretion and feedback
- chemical evolution
- stellar populations & dust

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

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

Observed Evolution of Galaxies from Latest Hubble Telescope Data





Gas-rich merger in past Gyr

Gas-poor merger in past Gyr

cSFG at z = 2.4

Barro et al. (2012 - Hubble Observations)

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

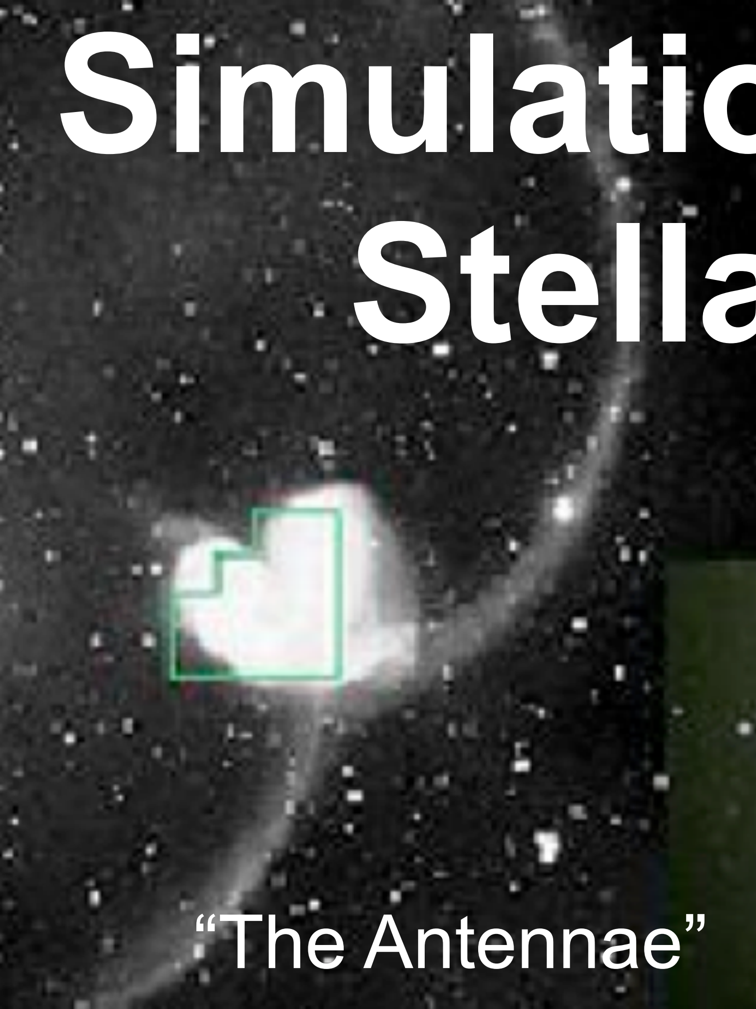
Cosmological Simulations

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.

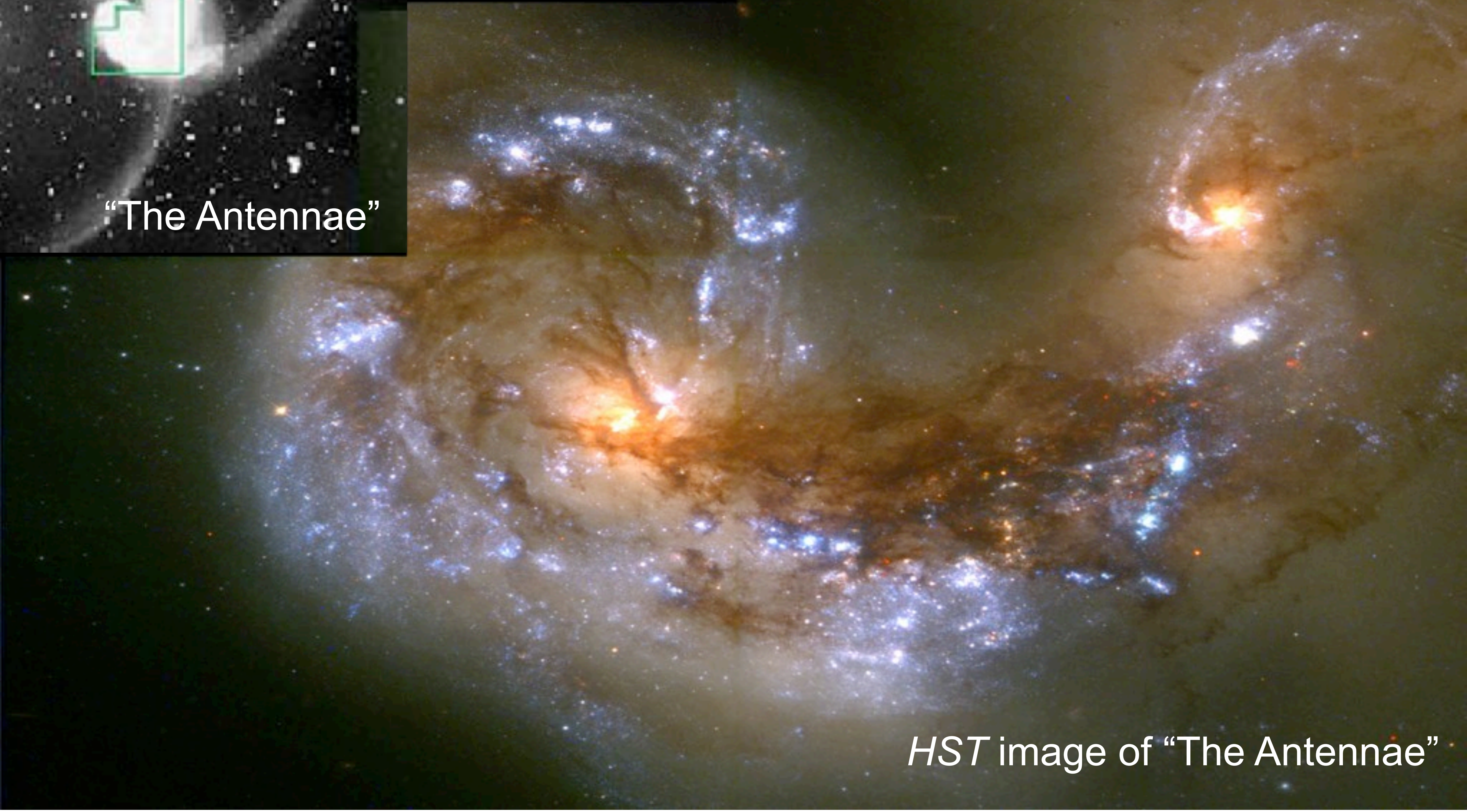
Cosmological dark matter simulations show large scale structure, growth of structure, and dark matter halo properties

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

Simulations of Galaxies Including Stellar Evolution and Dust



“The Antennae”

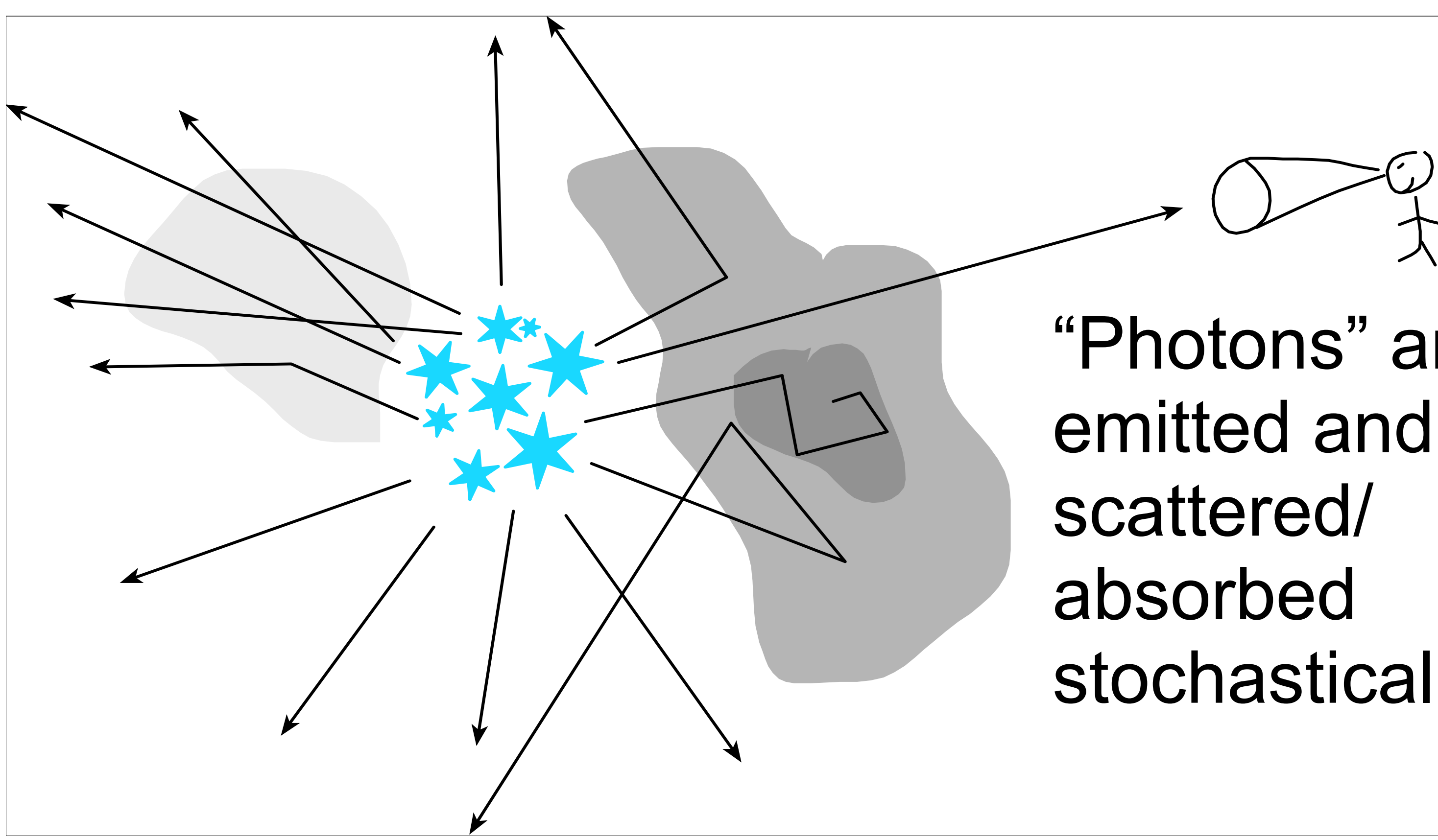


HST image of “The Antennae”

Sunrise Radiative Transfer Code

For every simulation snapshot:

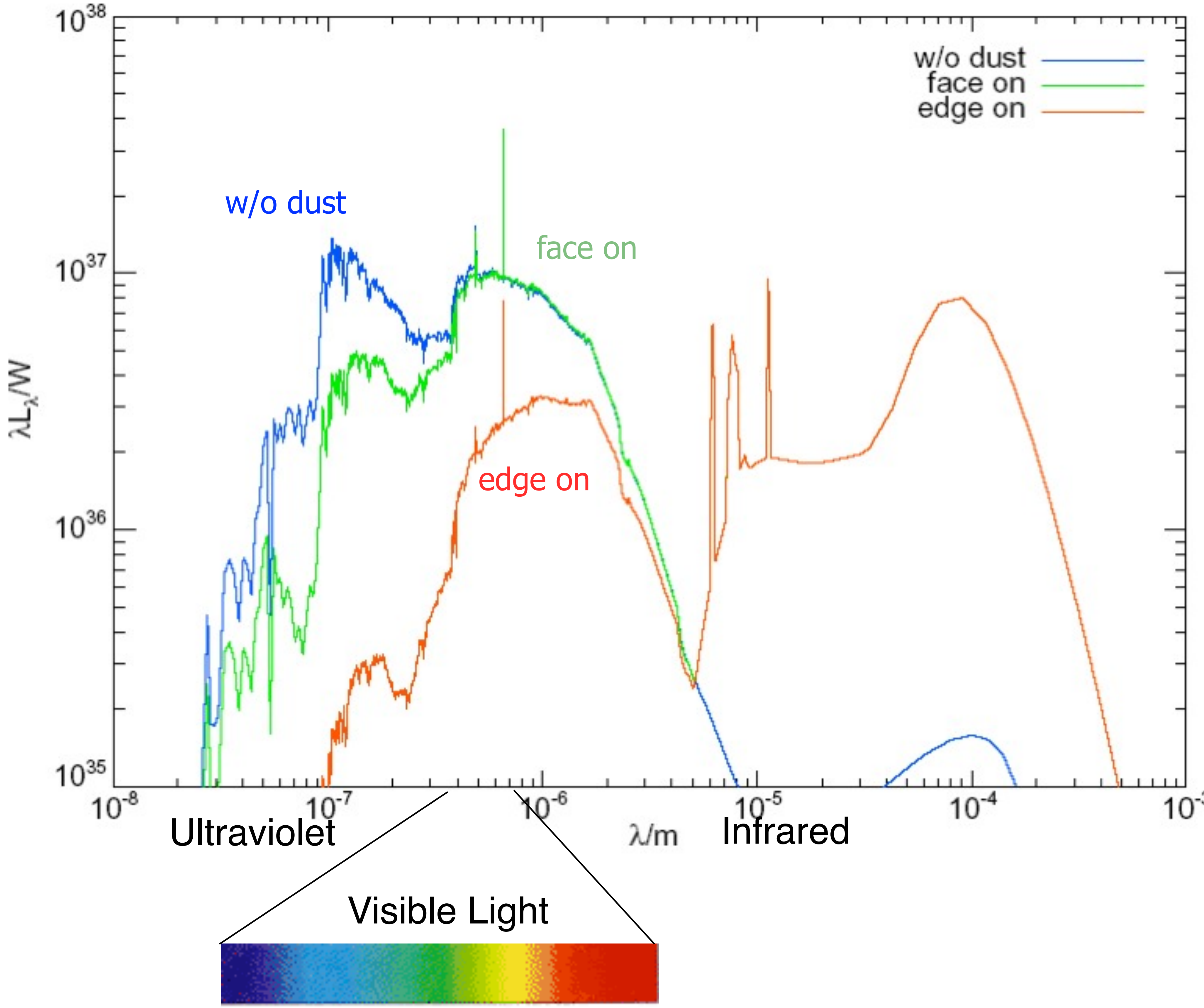
- Evolving stellar spectra calculation
- Adaptive grid construction
- Monte Carlo radiative transfer
- “Polychromatic” rays save 100x CPU time
- Graphic Processor Units give 10x speedup



“Photons” are emitted and scattered/ absorbed stochastically

Patrik Jonsson

Spectral Energy Distribution



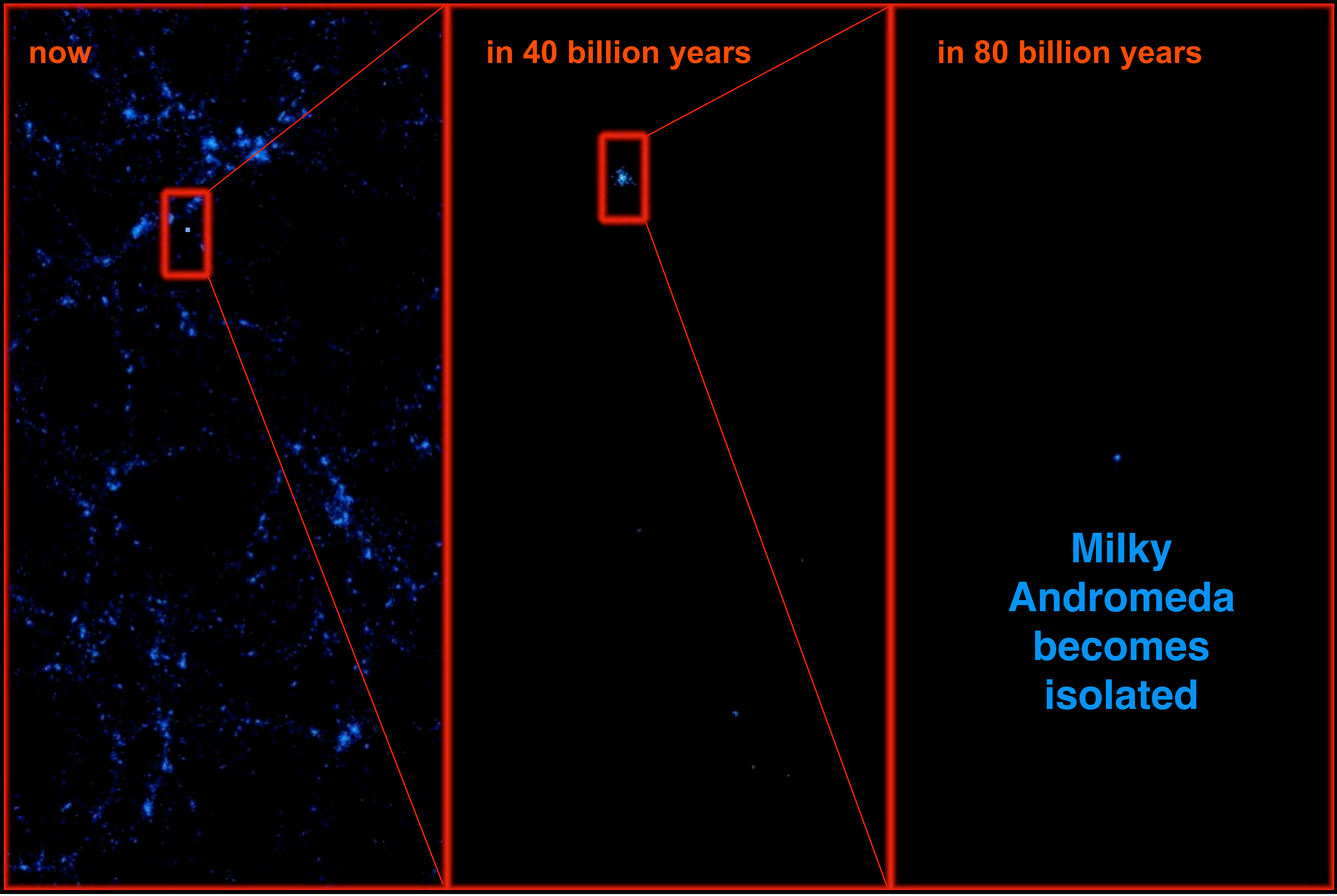
Galaxy Merger Simulation

A merger between galaxies like the Milky Way and the Andromeda galaxy. Galaxy mergers like this one trigger gigantic "starbursts" forming many millions of new stars (which look blue in these images). But dust (orange in the video) absorbs ~90% of the light, and reradiates the energy in invisible long wavelengths.

When the universe is twice its present age, the distant galaxies will have disappeared over the cosmic horizon.

Milky Andromeda will eventually become all that’s visible.

The Double Dark Future of the Universe



Accelerating Dust Temperature Calculations with Graphics Processing Units

Patrik Jonsson, Joel R. Primack

New Astronomy **15**, 509 (2010) (arXiv:0907.3768)

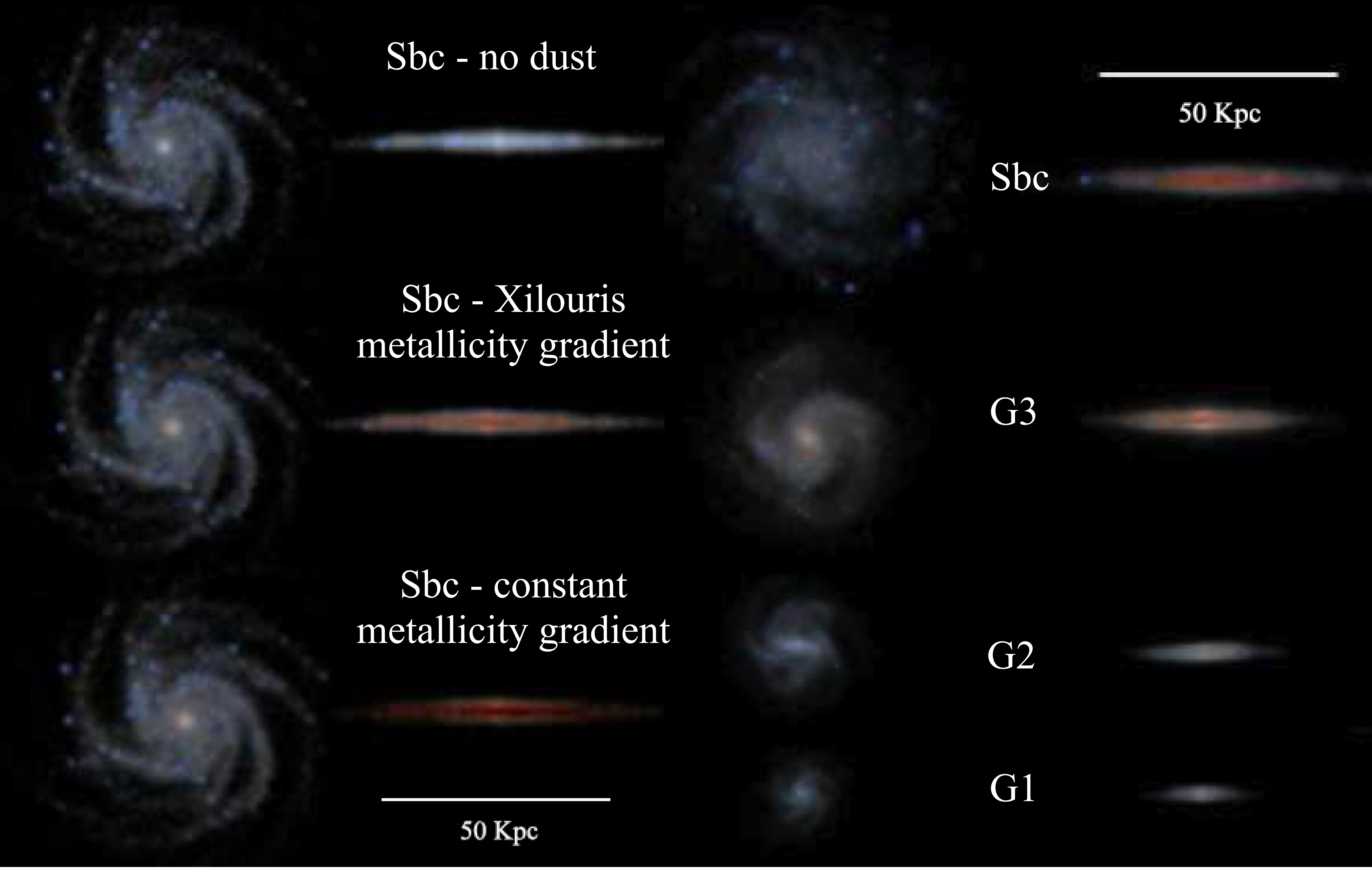
When calculating the infrared spectral energy distributions (SEDs) of galaxies in radiation-transfer models, the calculation of dust grain temperatures is generally the most time-consuming part of the calculation. Because of its highly parallel nature, this calculation is perfectly suited for massively parallel general-purpose Graphics Processing Units (GPUs). This paper presents an implementation of the calculation of dust grain equilibrium temperatures on GPUs in the Monte-Carlo radiation transfer code Sunrise, using the CUDA API. The Nvidia Tesla GPU can perform this calculation 55 times faster than the 8 CPU cores, showing great potential for accelerating calculations of galaxy SEDs.

On 64 special NAS Pleiades nodes with 2 Westmere chips (12 cores) and an Nvidia 2090 GPU, using the GPU makes the calculation run 12x faster.

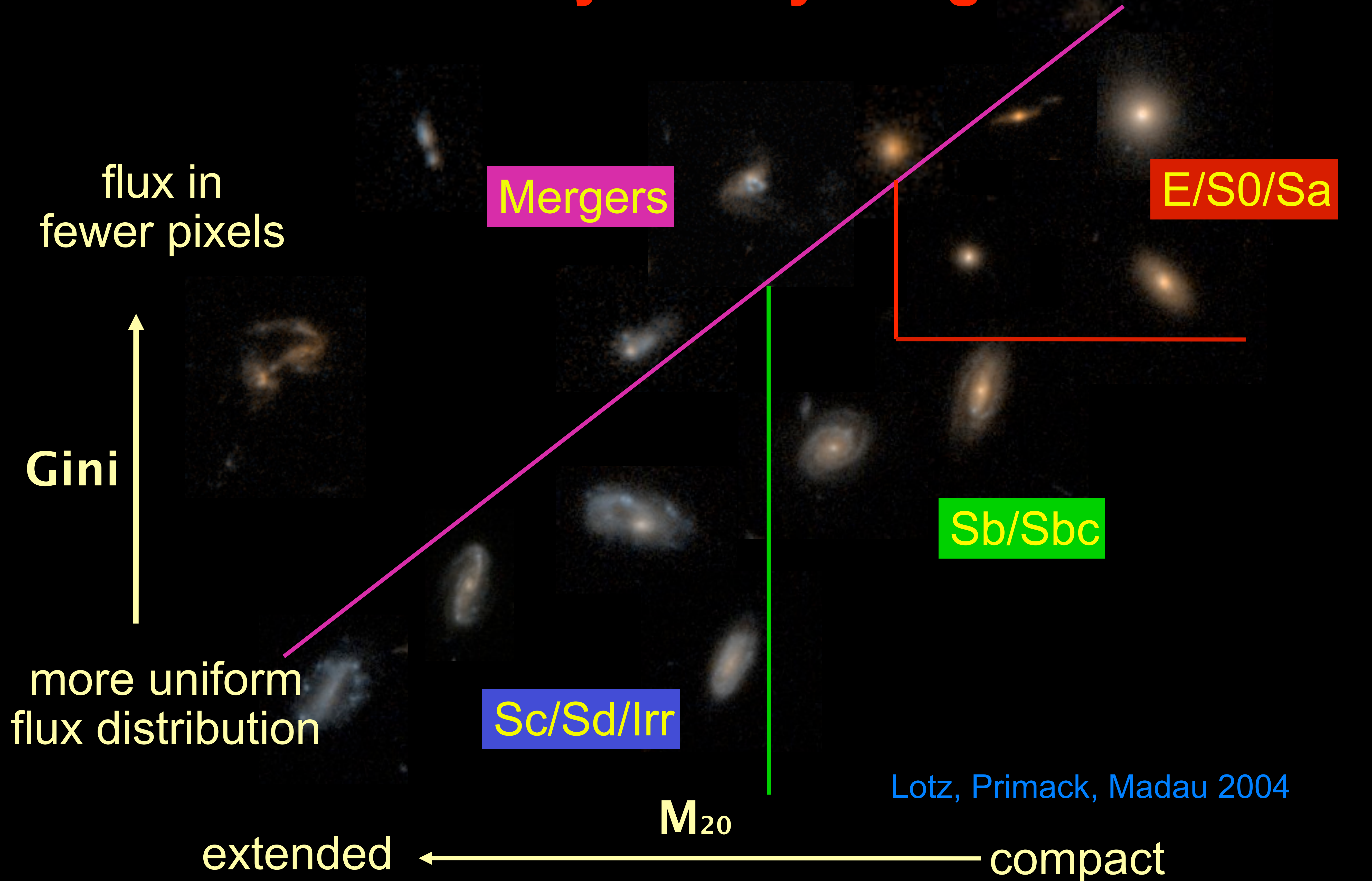
Dust Attenuation in Hydrodynamic Simulations of Spiral Galaxies

Rocha, Jonsson, Primack, & Cox 2008 MN

Right hand side:
Xilouris et al. 1999
metallicity gradient



G-M_{20} Nonparametric Morphology Measures Can Identify Galaxy Mergers

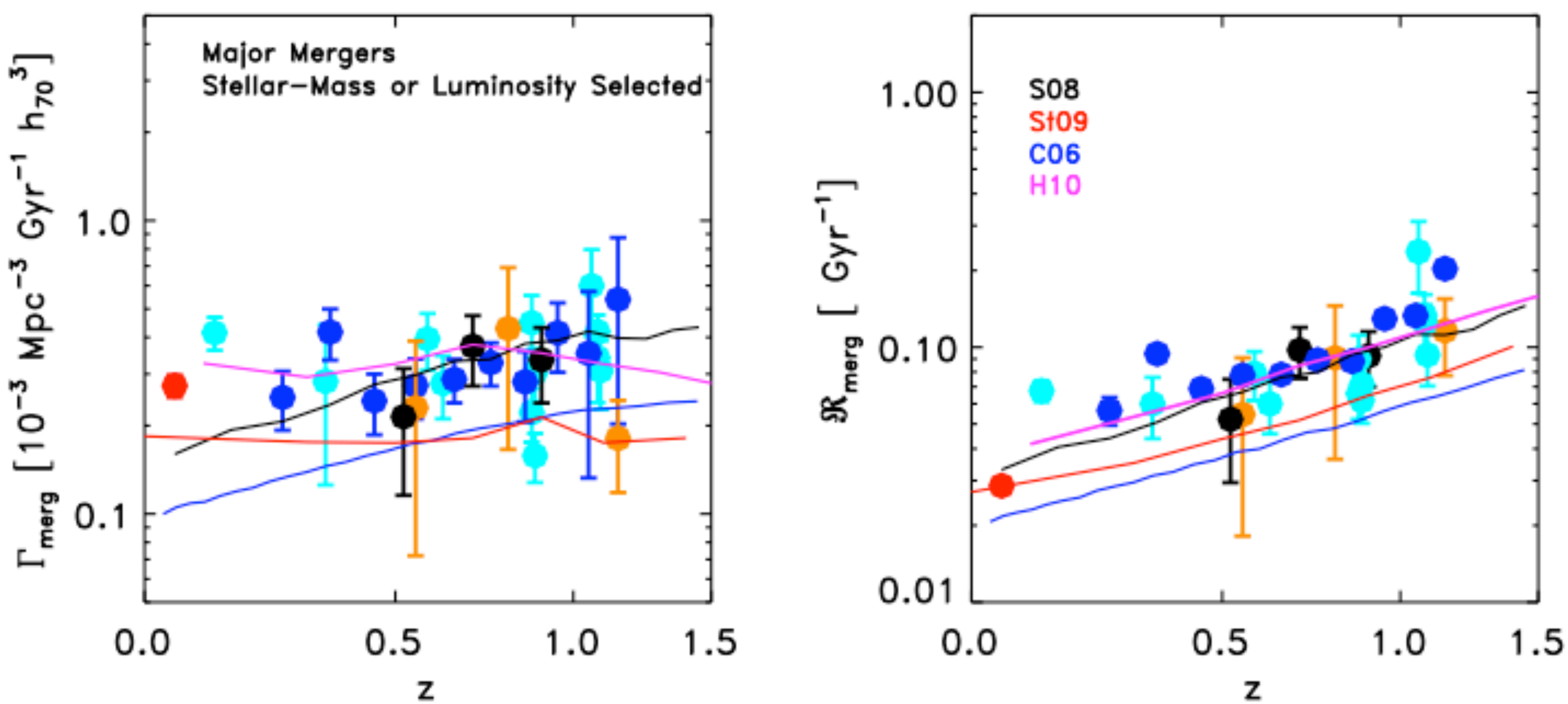


THE MAJOR AND MINOR GALAXY MERGER RATES AT Z < 1.5

Jennifer M. Lotz, Patrik Jonsson, T.J. Cox, Darren Croton, Joel R. Primack, Rachel S. Somerville, and Kyle Stewart

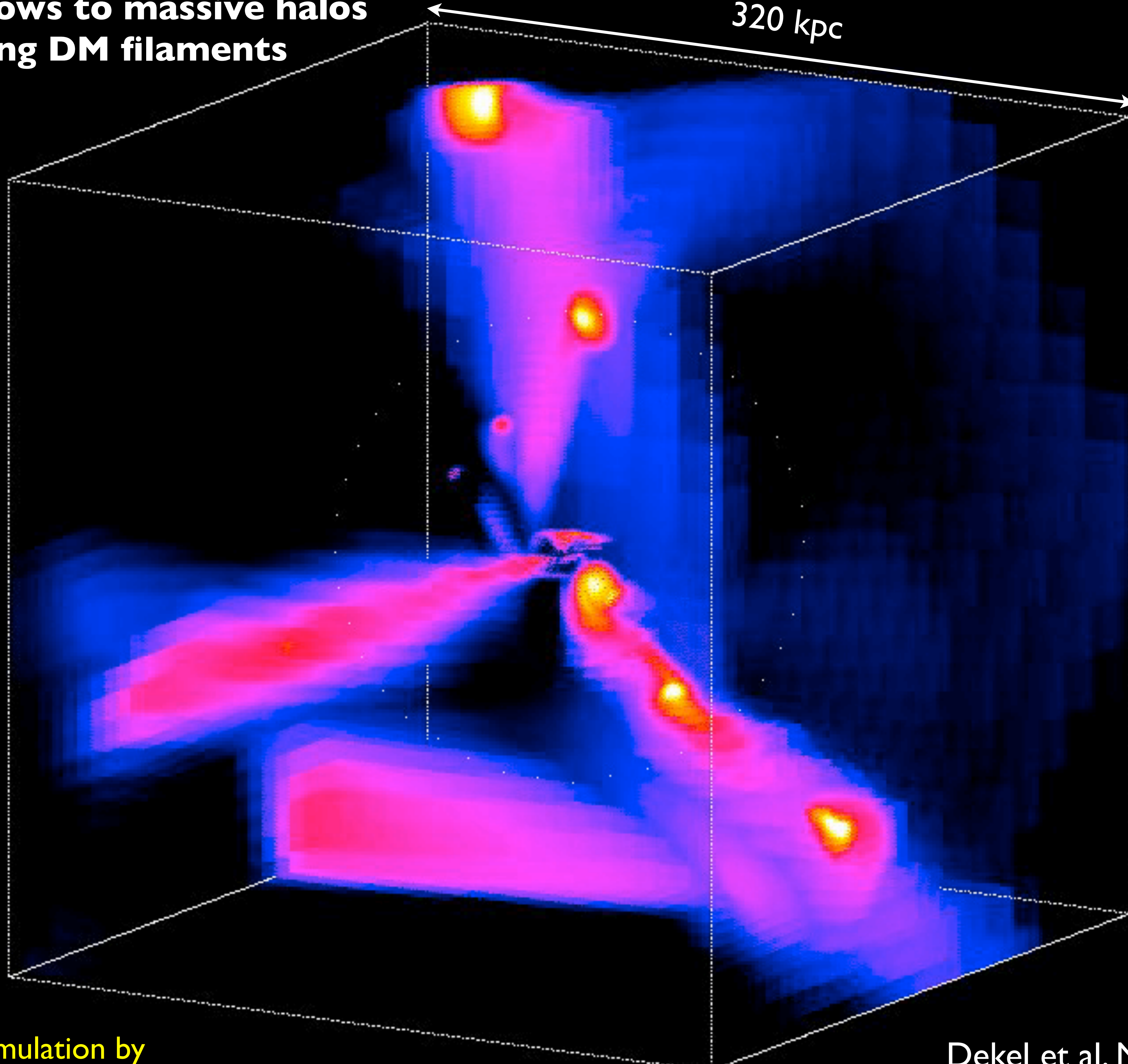
Astrophysical Journal December 2011

Calculating the galaxy merger rate requires both a census of galaxies identified as merger candidates, and a cosmologically-averaged 'observability' timescale $\langle T_{obs}(z) \rangle$ for identifying galaxy mergers. While many have counted galaxy mergers using a variety of techniques, $\langle T_{obs}(z) \rangle$ for these techniques have been poorly constrained. We address this problem by calibrating three merger rate estimators with a suite of hydrodynamic merger simulations and three galaxy formation models. When our physically-motivated timescales are adopted, the observed galaxy merger rates become largely consistent.



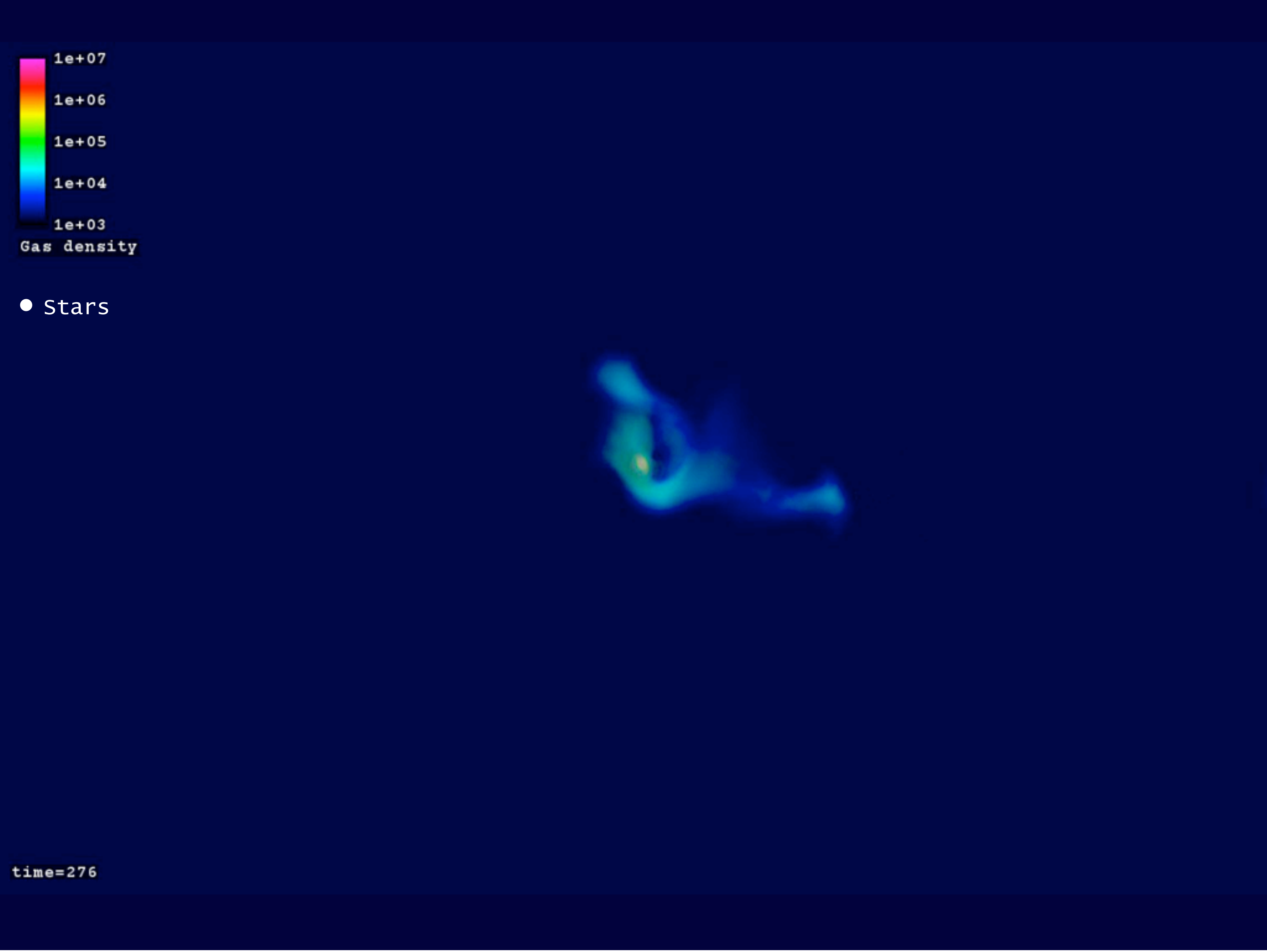
Observed Galaxy Merger Rates v. Theoretical Predictions. The volume-averaged (left) and fractional major merger (right) rates given by stellar-mass and luminosity-selected close pairs are compared to the major merger rates given by the S08 (black lines), St09 (red lines), C06 (blue line), and Hopkins et al. 2010b (magenta lines) models for 1:1 - 1:4 stellar mass ratio mergers and galaxies with $M_{star} > 10^{10}$ $M_{\odot}$. The theoretical predictions are in good agreement with the observed major merger rates.

Gas inflows to massive halos along DM filaments

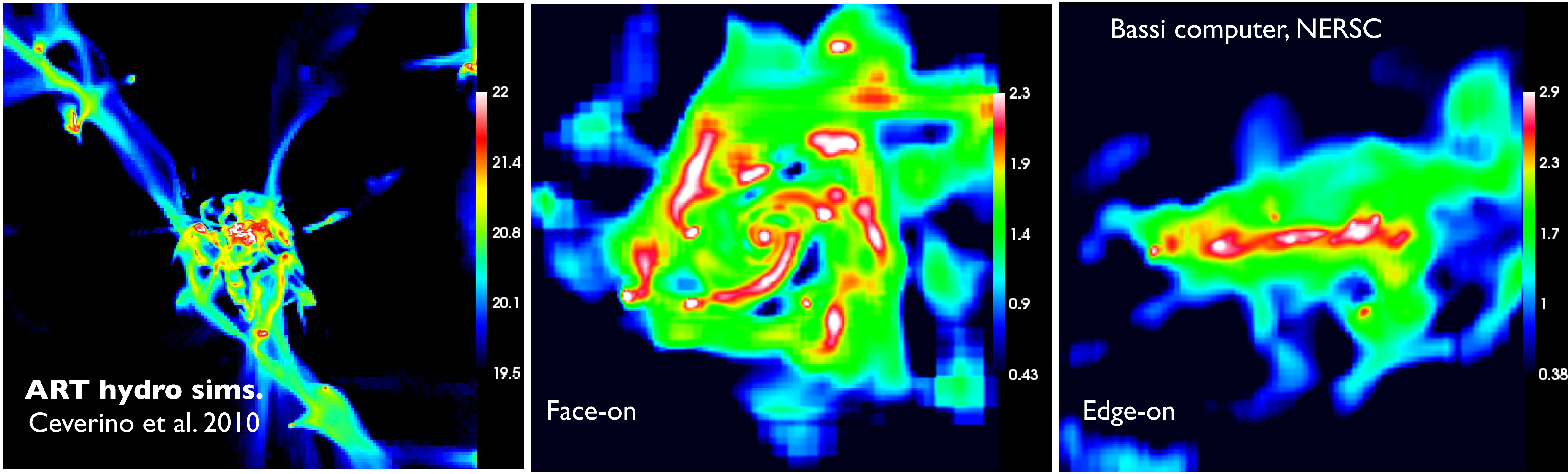


RAMSES simulation by
Romain Teyssier on Mare Nostrum supercomputer, Barcelona

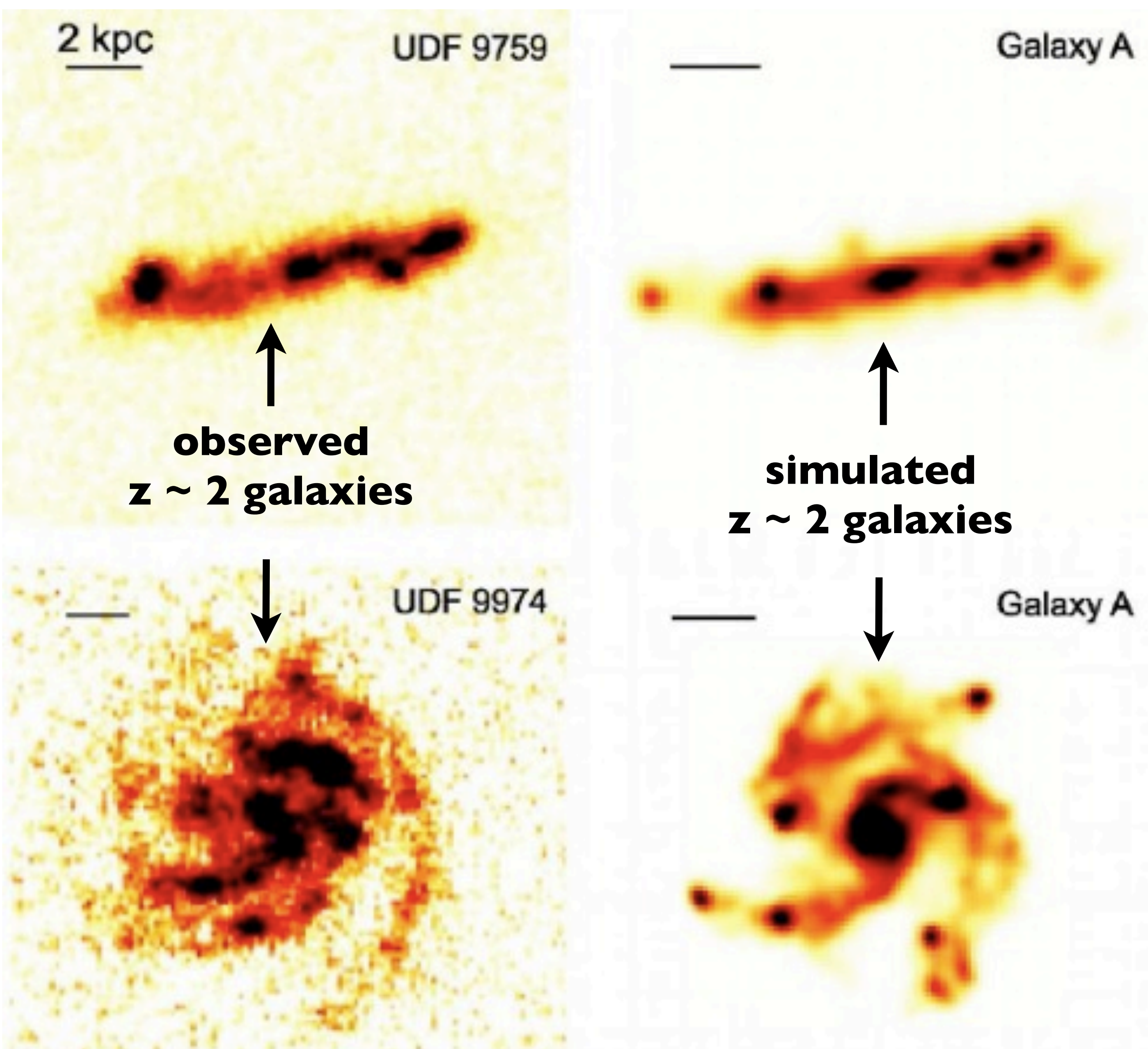
Dekel et al. Nature 2009


1e+07
1e+06
1e+05
1e+04
1e+03
Gas density
Stars
time=276

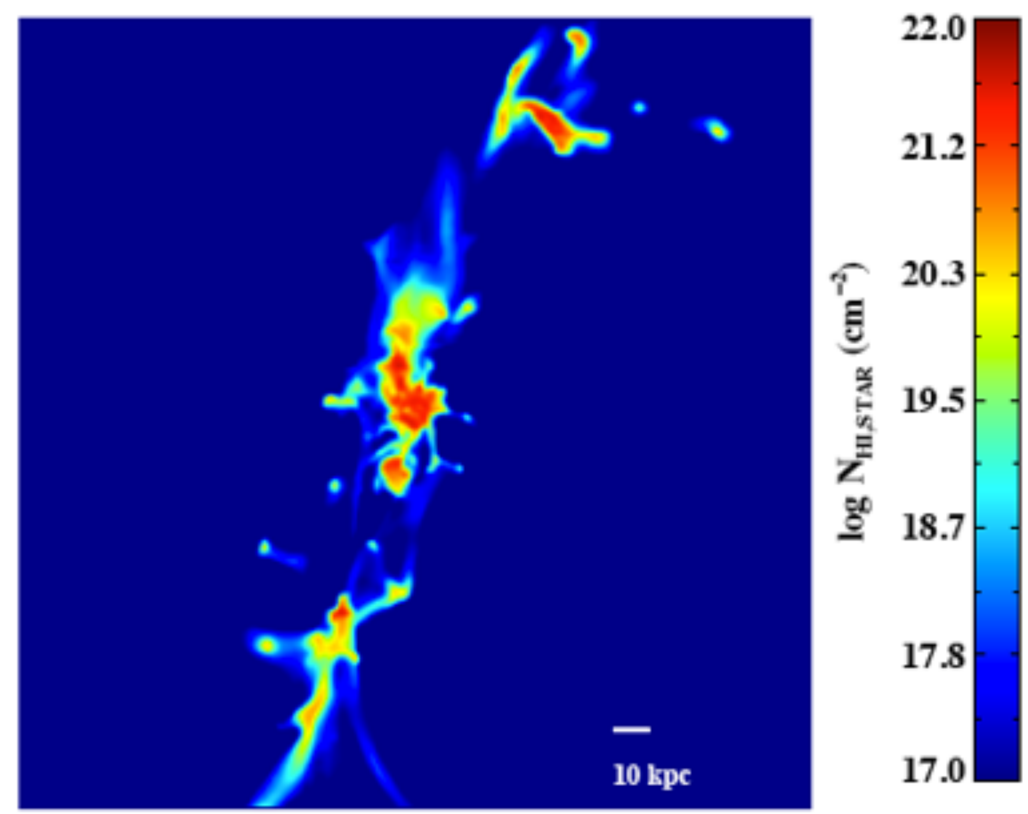
Simulated Evolution of an Elliptical Galaxy
U-V-J Images Every ~100 Million Years



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

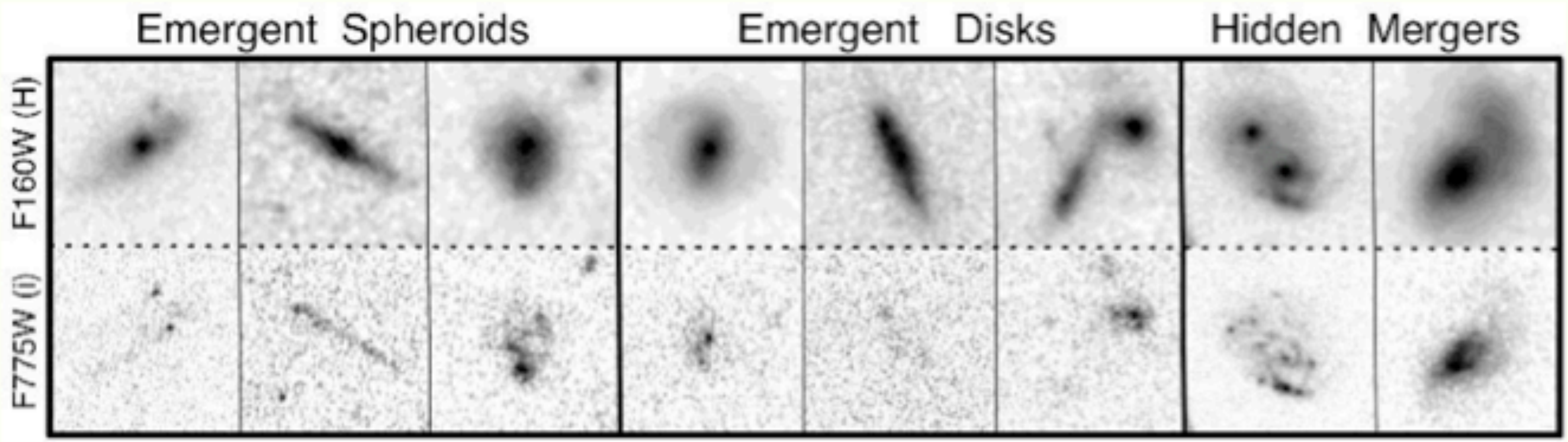


Ly alpha blobs from same simulation



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

The CANDELS Survey



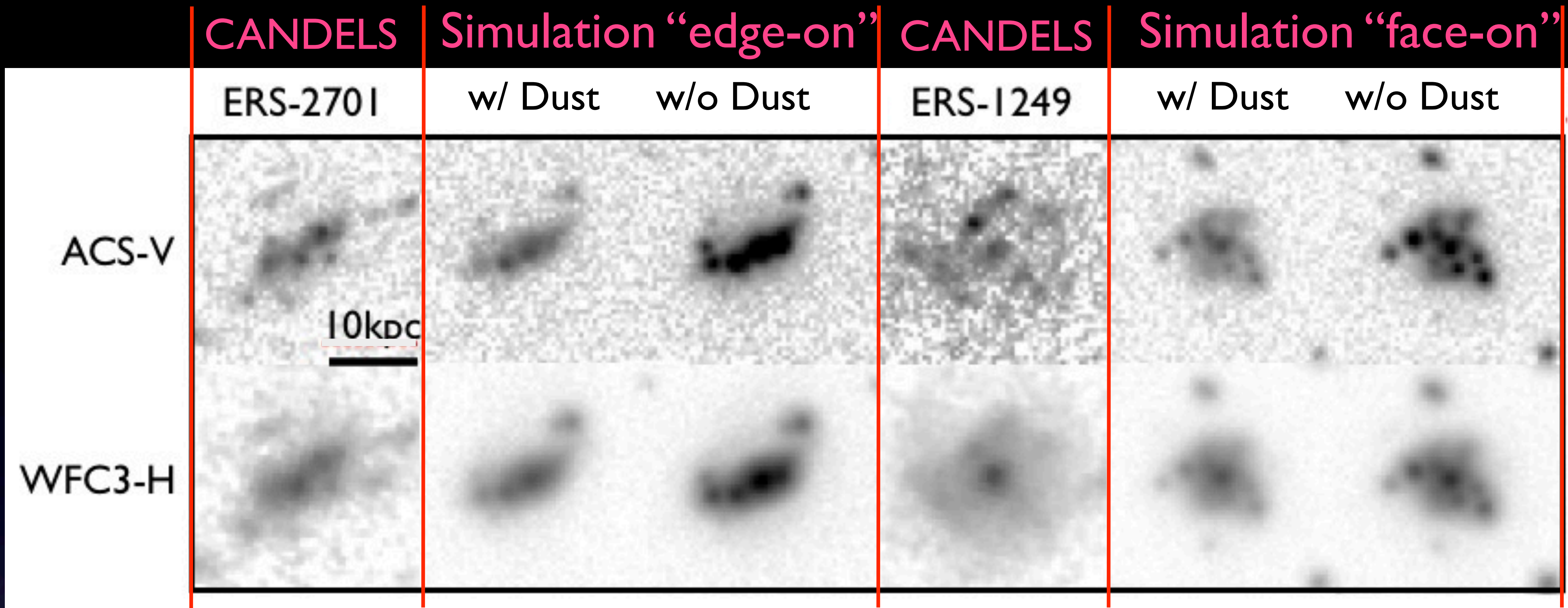
CANDELS makes use of the near-infrared WFC3 camera (top row) and the visible-light ACS camera (bottom row). Using these two cameras, CANDELS will reveal new details of the distant Universe and test the reality of cosmic dark energy.

http://candels.ucolick.org

CANDELS: A Cosmic Odyssey

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.



Simulation shown is MW3 at z=2.33 'imaged' to match the CANDELS observations in ACS-Vband and WFC3-Hband

- 0.06" Pixel scale
- convolved with simulated psfs
- noise and background derived from ERS observations (same field as examples shown)

MW3 was imaged at 'face-on' and 'edge-on' viewing angles both with and without including dust models

Summary: the big cosmic questions now

- The nature of the dark matter
- The nature of the dark energy (the future of the Universe)
- The early evolution of the Universe
  - Formation of the first tiny galaxies and the first stars
  - How the universe reionized
- How the entire population of galaxies forms and evolves
  - From direct observations from the ground and space
  - Interpreted with the help of cosmological simulations:
    - Including star formation and feedback
    - Formation and feedback from supermassive black holes
    - etc.

THE UNIVERSITY OF CALIFORNIA HIGH-PERFORMANCE ASTROCOMPUTING CENTER (UC-HiPACC)

PRESENTS A

SCIENCE/ENGINEERING JOURNALISM BOOT CAMP

ON

COMPUTATIONAL ASTRONOMY : FROM PLANETS TO COSMOS

Sunday, June 24 – Wednesday, June 27, 2012
University of California, Santa Cruz

WHAT: A Science/Engineering Journalism Boot Camp on "Computational Astronomy: From Planets to Cosmos" is a backgrounder for a select group of 12 to 16 practicing science or engineering journalists from all media—print, online, broadcast, social media, and film—whether on staff or freelance. The intensive immersion experience is sponsored by the University of California High-Performance AstroComputing Center (UC-HiPACC).

WHEN: From an evening reception, Sunday, June 24, 2012, through Wednesday, June 27, 2012.

WHERE: On Monday (June 25) and Tuesday (June 26), sessions will be held on the campus of the University of California, Santa Cruz—home to the University of California Observatories (UCO), the Center for Adaptive Optics, and the Santa Cruz Institute for Particle Physics—and will include an on-campus field trip to the famous UCO Instrument Laboratories. Wednesday (June 27) will be an all-day field trip to two institutions leading in astrocomputing and visualization: NASA Ames Research Center (to see the Pleiades supercomputer and the 128-screen Hyperwall) and the California Academy of Sciences (including the digital Morrison Planetarium).

The University of California High-Performance AstroComputing Center (UC-HiPACC), based at the University of California, Santa Cruz, is a consortium of nine University of California campuses and three Department of Energy laboratories (Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory). UC-HiPACC does not directly fund research; instead, it fosters collaborations among researchers at the various sites by offering travel and other grants. It also sponsors an annual two-week summer school on special topics in computational astronomy for graduate students, co-sponsors workshops and other meetings, and facilitates education and public outreach. More information appears at http://hipacc.ucsc.edu .

WHO: Sessions will be led by top astrophysics faculty from across the campuses of the University of California system and from affiliated Department of Energy National Laboratories. A round-table session will discuss journalistic challenges, such as accurately portraying complex techniques and exciting science when industry pressures are toward ever shorter stories.

WHY: Data-intensive techniques are revolutionizing observation and theory in astronomy, and supercomputer simulations of mysterious dark matter are transforming cosmology virtually into an experimental science. How can science journalists cover such novel findings and techniques for general readers without getting bogged down in bytes and flops?

HOW: Details, agenda, and application form are available from **http://hipacc.ucsc.edu/2012CAJBC.html**. Application form plus all supporting materials are due to UC-HiPACC by Friday, March 30, 2012. Expenses for the Journalism Boot Camp will be underwritten by UC-HiPACC. In addition to the program and field trip, participating journalists will receive housing for four nights (June 24-27), local transportation, most meals, and reimbursement of up to US $800.00 for long-distance travel. Journalists selected will be announced in April.

CONTACT: Trudy E. Bell, M.A., senior writer for UC-HiPACC, at tebell@ucsc.edu .

CONFIRMED FACULTY:

James S. Bullock, UC Irvine (Director, Center for Galaxy Evolution)
Brenda Dingus, Los Alamos National Lab (Principal Investigator, High Altitude Water Cerenkov detector)
Sandra M. Faber UC Santa Cruz, banquet speaker (University Professor of Astronomy)
George M. Fuller, UC San Diego
Steven Furlanetto, UC Los Angeles
Kim Griest, UC San Diego (Chair, US Astronomy and Astrophysics Advisory Committee)
Robert Irion, UC Santa Cruz, round-table discussion leader (Director, Science Communication Program)
Manoj Kaplinghat, UC Irvine
Mark Krumholz, UC Santa Cruz
Gregory P. Laughlin, UC Santa Cruz (Chair, UCSC Astronomy and Astrophysics Department)
Claire E. Max, UC Santa Cruz (Director, Center for Adaptive Optics)
Michael Norman, UC San Diego (Director, San Diego Supercomputer Center)
Joel R. Primack, UC Santa Cruz (Director, UC-HiPACC)
Eliot Quataert, UC Berkeley (Director, Theoretical Astrophysics Center)


Active Galactic Nucleus: Centaurus A. *NASA*


First Star Simulation. *T. Abel*


Solar Winds. *NASA*


Jupiter in Morrison Planetarium. *CalAcademy*


NASA Ames Hyperwall. *Joe McNally*


Galaxy Formation Simulations. *C. Moody*

Background image: Bolshoi cosmological simulation. *Klypin, Primack, Gottloeber*

Thanks to all of you for coming, to Trudy Bell, Sue Grasso, and Nina McCurdy for organization, and to the University of California for funding!