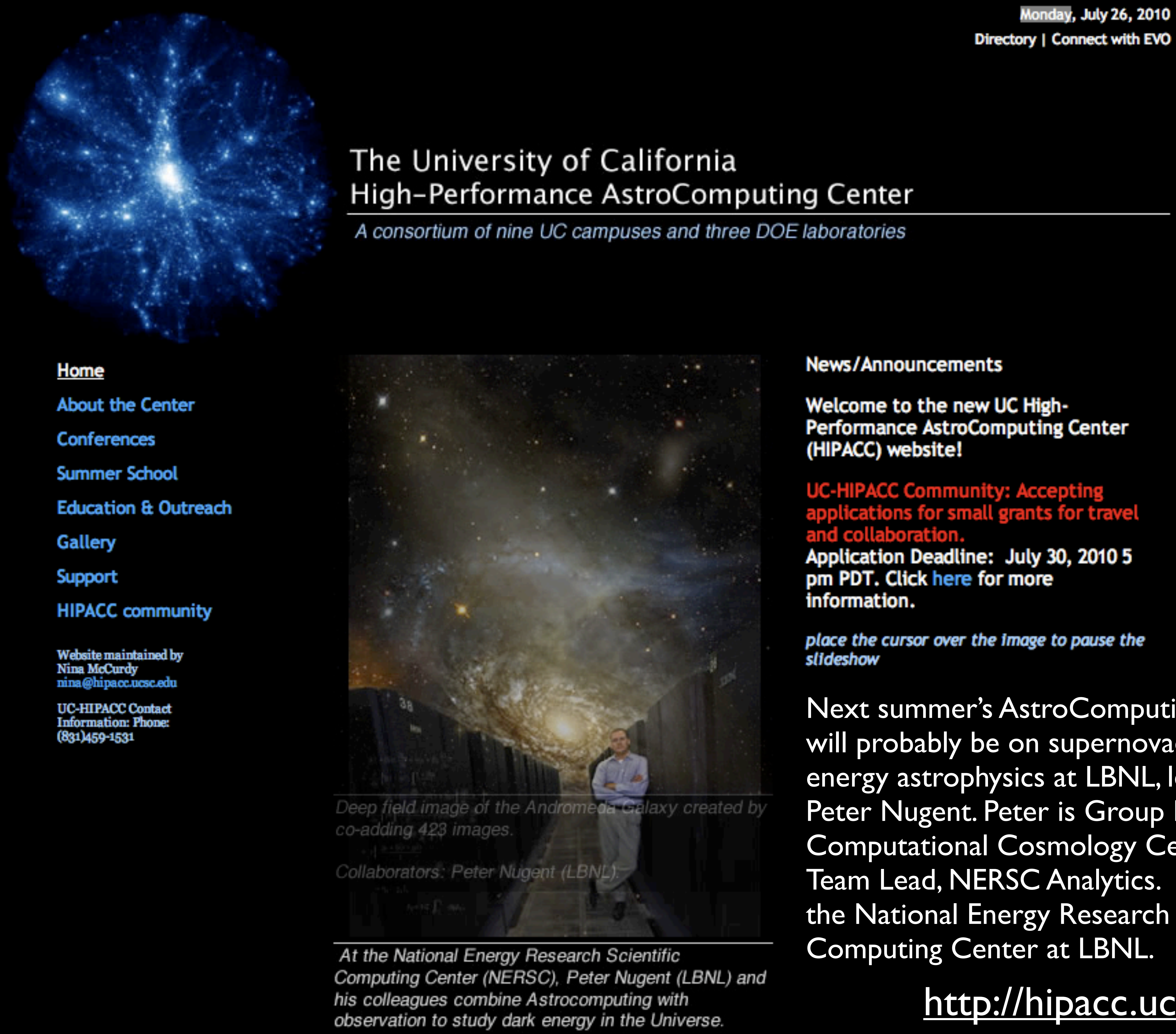
The 2010 International Summer School on Astro-Computing: Galaxy Simulations

July 26 - August 13

COSMOLOGY & UC-HIPACC

JOEL PRIMACK
UCSC



Monday, July 26, 2010

Directory | Connect with EVO

The University of California
High-Performance AstroComputing Center

A consortium of nine UC campuses and three DOE laboratories

Website maintained by
Nina McCurdy
nina@hipacc.ucsc.edu

UC-HIPACC Contact
Information: Phone:
(831)459-1531

Deep field image of the Andromeda Galaxy created by co-adding 423 images.

Collaborators: Peter Nugent (LBNL).

At the National Energy Research Scientific Computing Center (NERSC), Peter Nugent (LBNL) and his colleagues combine Astrocomputing with observation to study dark energy in the Universe.

News/Announcements

Welcome to the new UC High-Performance AstroComputing Center (HIPACC) website!

UC-HIPACC Community: Accepting applications for small grants for travel and collaboration.
Application Deadline: July 30, 2010 5 pm PDT. Click here for more information.

place the cursor over the image to pause the slideshow

Next summer's AstroComputing school will probably be on supernovae and high energy astrophysics at LBNL, led by Peter Nugent. Peter is Group Lead, Computational Cosmology Center, and Team Lead, NERSC Analytics. NERSC is the National Energy Research Scientific Computing Center at LBNL.

http://hipacc.ucsc.edu/

The AEGIS Survey...

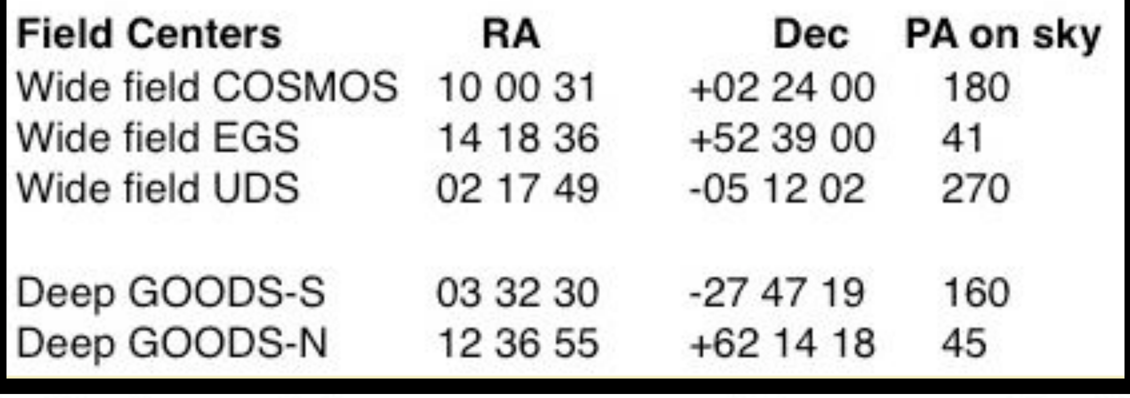
...is unlocking the secrets of galaxy and large-scale structure formation over the last 9 billion years.

AEGIS is targeted on a special area of the sky, called the Extended Groth Strip (EGS), that has been observed with the world's most powerful telescopes on the ground and in space, from X-rays to radio waves.

Each telescope contributes its own key information to create a complete portrait of every galaxy. By looking out far into space and back in time, AEGIS literally shows us galaxies in all their glory that are emerging from infancy into adulthood. More...

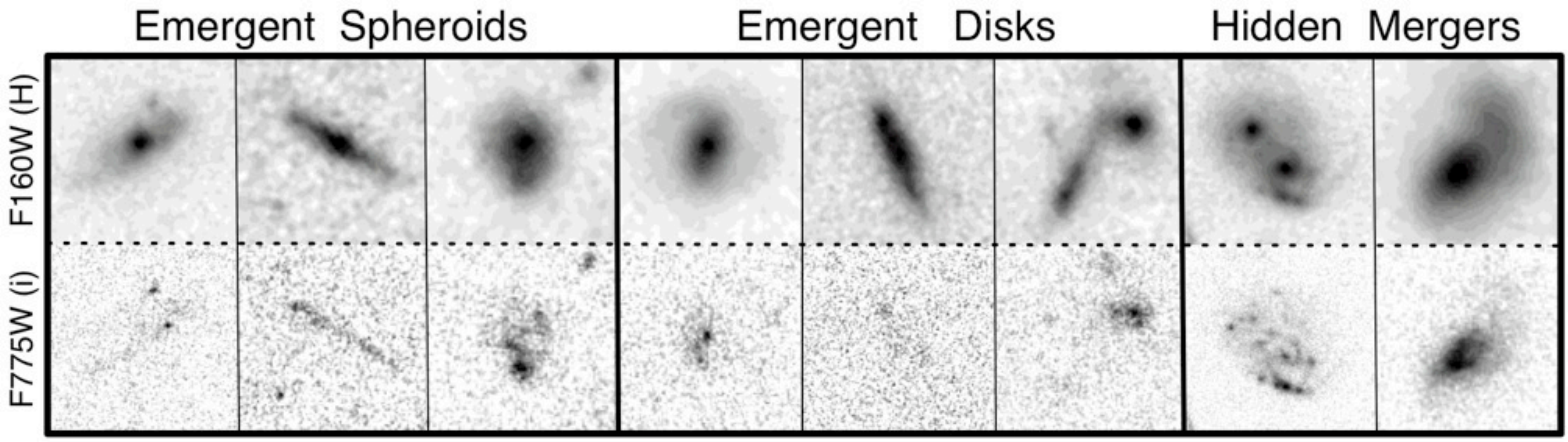
http://aegis.ucolick.org/

CANDELS



Field Centers	RA	Dec	PA on sky
Wide field COSMOS	10 00 31	+02 24 00	180
Wide field EGS	14 18 36	+52 39 00	41
Wide field UDS	02 17 49	-05 12 02	270
Deep GOODS-S	03 32 30	-27 47 19	160
Deep GOODS-N	12 36 55	+62 14 18	45

Leaders - PI: Sandra Faber (UCSC)
Assoc. PI: Harry Ferguson (STScI)



The Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS, http://csmct.ucolick.org/) is a Hubble Space Telescope Multi-Cycle Treasury project awarded 902 orbits with WFC3 and ACS during 2010-2013. CANDELS will obtain data on 250,000 galaxies to complete Hubble's legacy in the area of deep lookback observations of galaxy evolution. A time-domain search will discover Type Ia supernovae at $z>1.5$ to determine their progenitors and possible evolution. The Deep survey covers ~0.04 deg^2 in the GOODS fields to a 5-sigma AB depth of H=28, including UV data in GOODS-N. The Wide survey covers ~0.2 deg^2 to H=27 in the same fields plus COSMOS, EGS, and UDS and is tuned to study rarer objects such as massive galaxies and AGN.

COSMOLOGY: Ripe Questions Now

Nature of Dark Matter - ΛCDM $n_{\text{halos}}(V_{\max},z)$, clustering vs. observations

Nature of Dark Energy - expansion history of the universe, structure formation

How Galaxies Form and Evolve

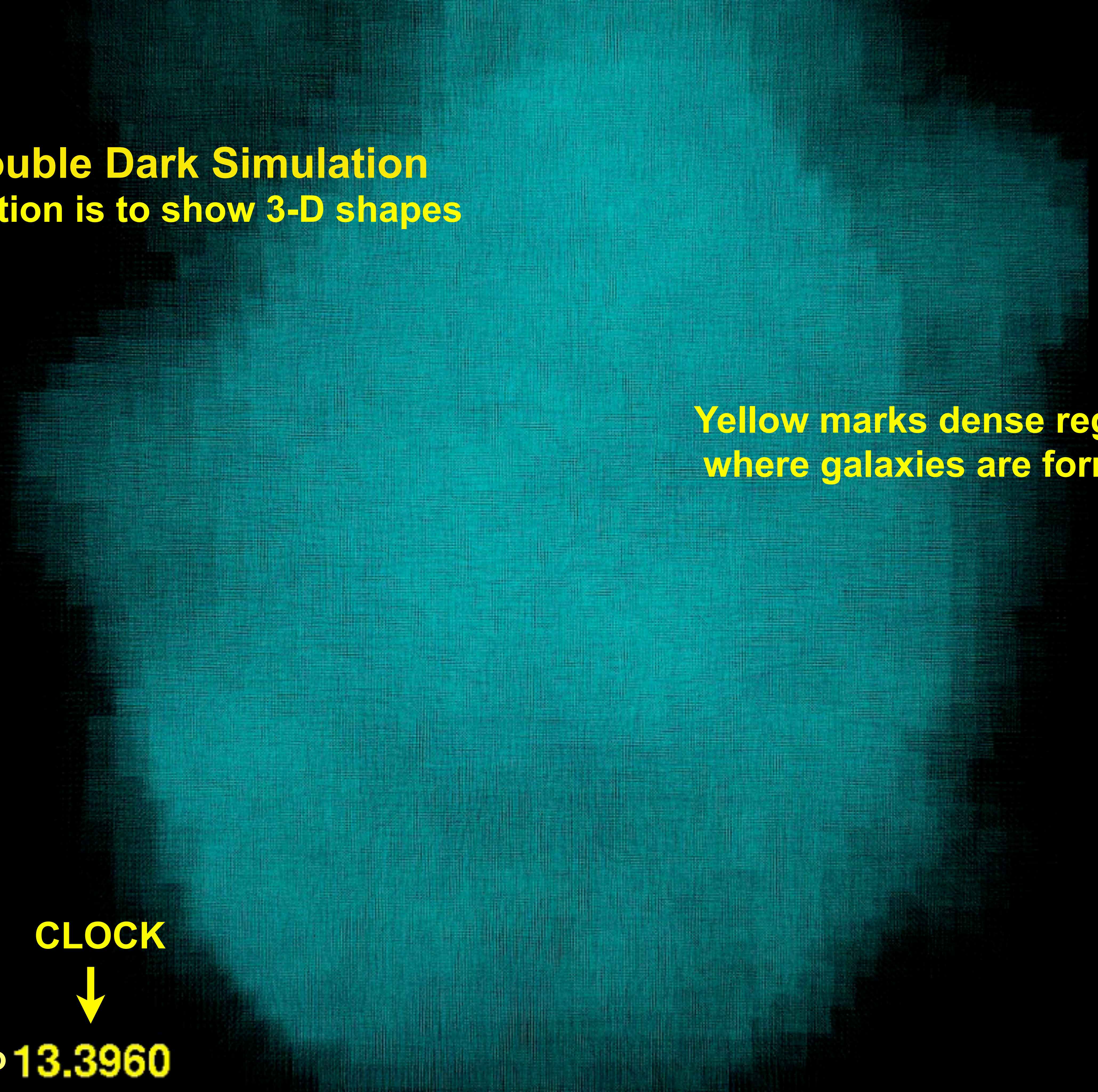
- Early galaxies and reionization: pop III?, escape fraction, upsizing
- Mechanisms of early SF and AGN: gas-rich mergers *vs.* cold inflows
- What quenches SF: AGN, shock heating for $M_{\text{halo}} > 10^{12}\,M_{\text{sun}}$, morphology
- Evolution of galaxy morphology: need new morphology measures
- Evolution of galaxy kinematics and metallicity (need spectra)
- Extragalactic Background Light (EBL): measure, constrain with γ-rays

Theoretical Approaches

- Simulations: dissipationless, hydrodynamic
- Mock catalogs, Sub-Halo Abundance Matching (“SHAM”)
- Semi-Analytic Models (SAMs) constrained by simulations & observations
- Toy Models to clarify key astrophysical processes

Double Dark Simulation

Rotation is to show 3-D shapes



Yellow marks dense regions
where galaxies are forming

Dark
Matter
Simulation:

Columbia
Super-
Computer

NASA
Ames
Laboratory

CLOCK
↓

Billion
years ago 13.3960

COSMOLOGY: Ripe Questions Now

Nature of Dark Matter - **ΛCDM $n_{\text{halos}}(V_{\text{max}},z)$, clustering vs. observations**

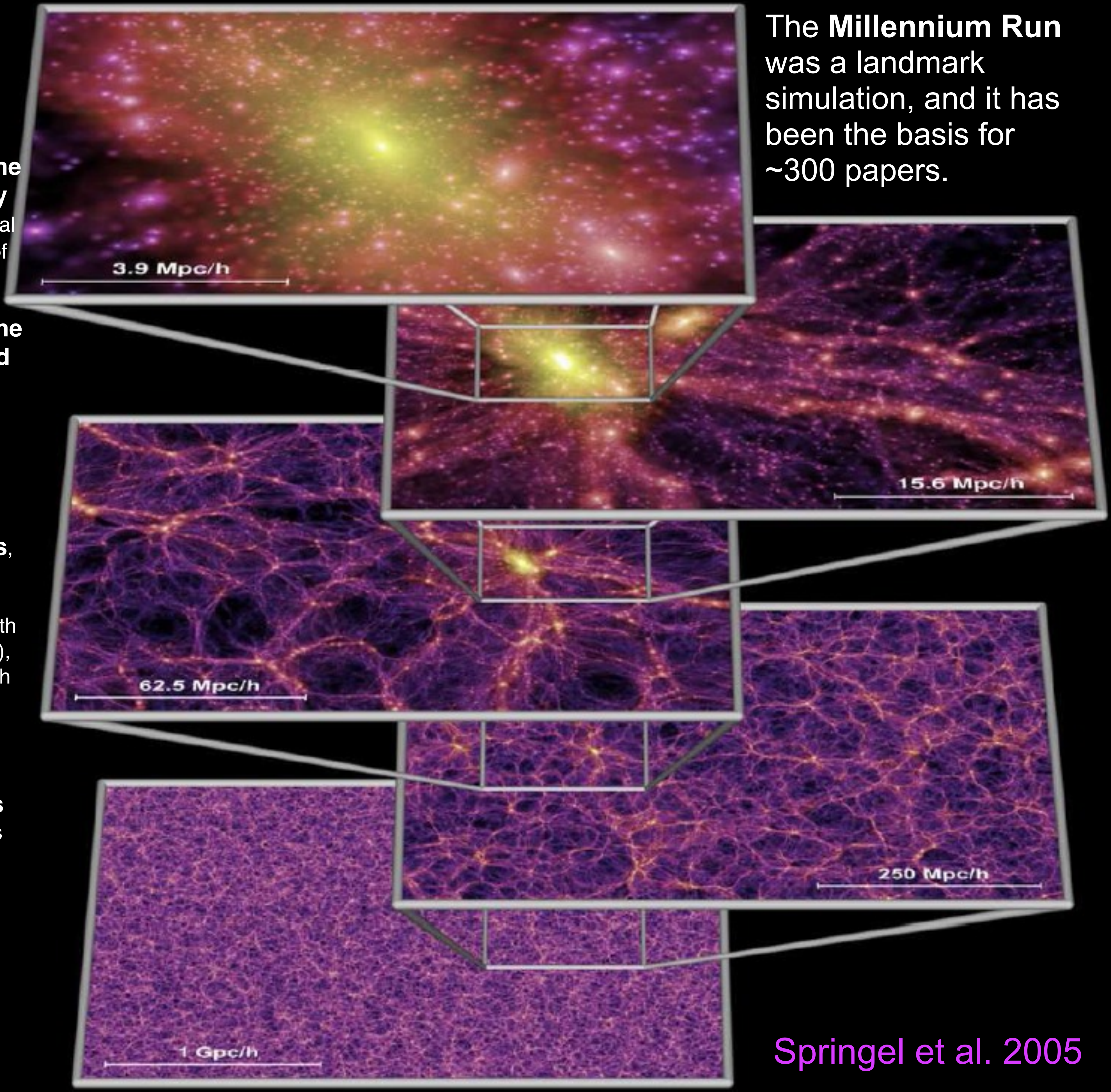
Nature of Dark Energy - **expansion history, structure formation history**

How Galaxies Form and Evolve
- Main ways to make big galaxies: gas-rich mergers *vs.* cold inflows

Theoretical Approaches
- **Simulations**: **dissipationless**, hydrodynamic
- **Sub-Halo Abundance Matching (“SHAM”)**
- Semi-Analytic Models (SAMs) constrained by simulations & observations

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 as- sembly 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

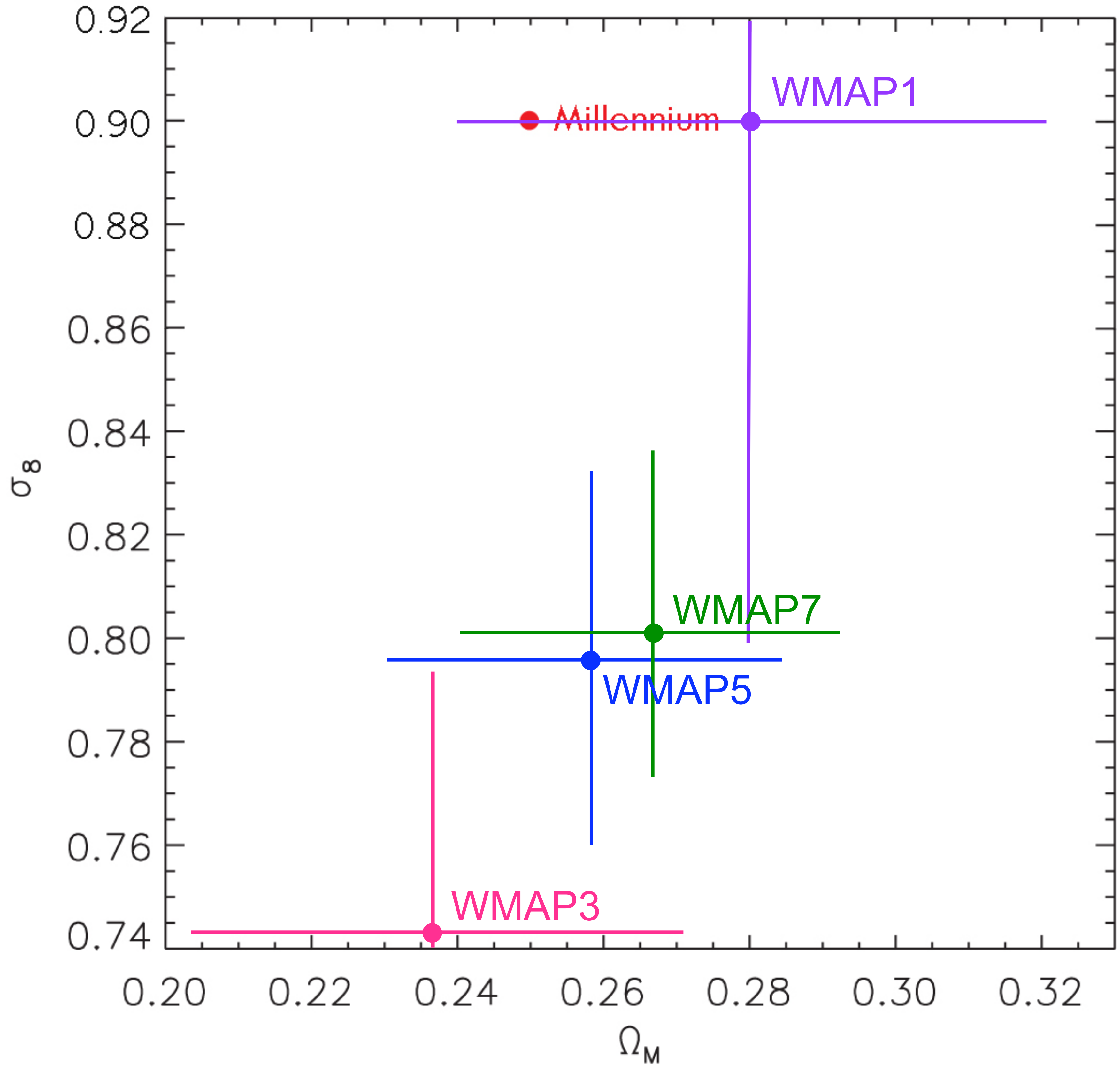


The **Millennium Run** was a landmark simulation, and it has been the basis for ~300 papers.

- **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



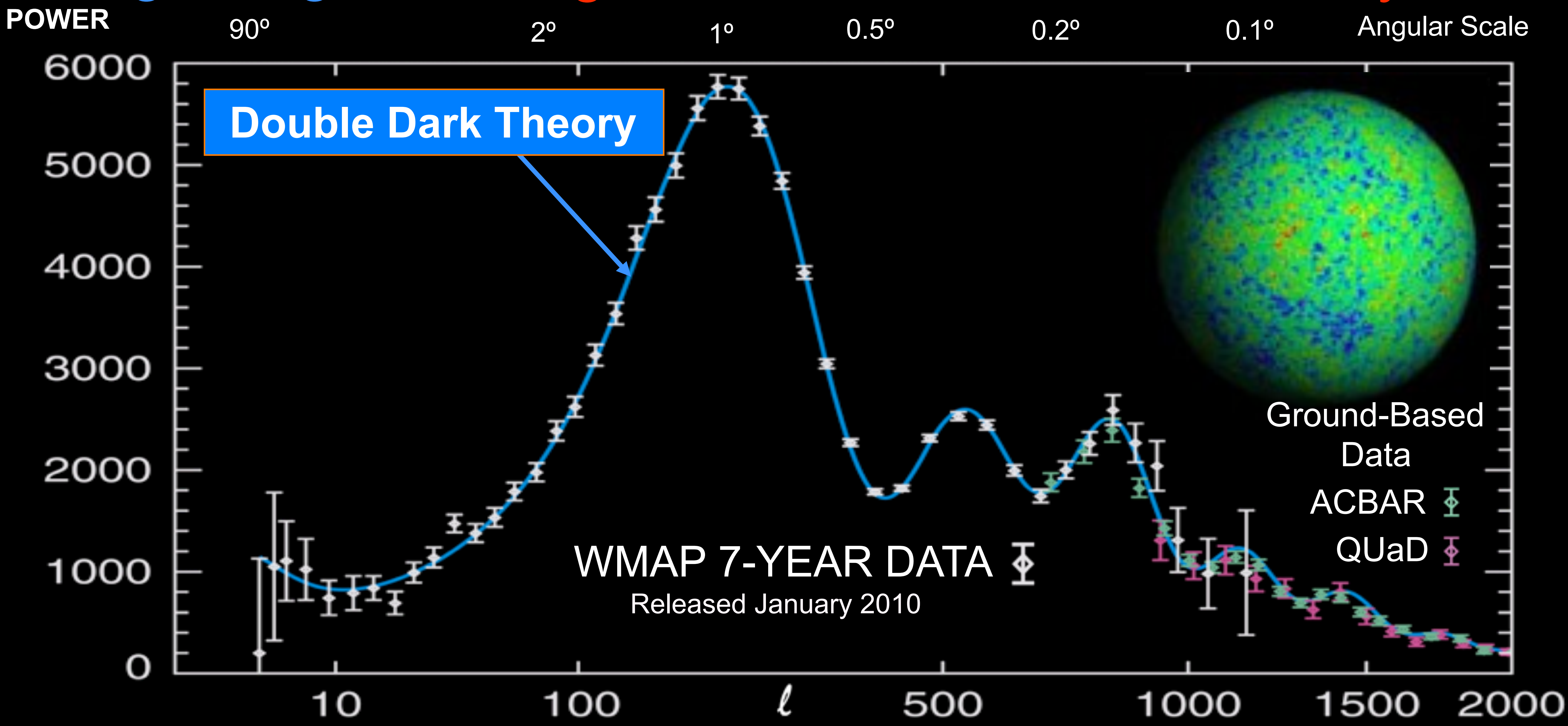
2003

2010

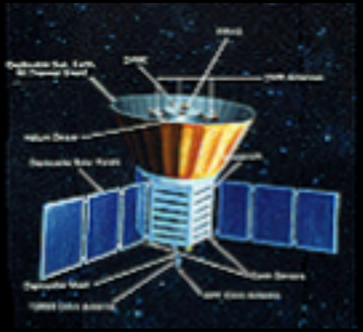
2008

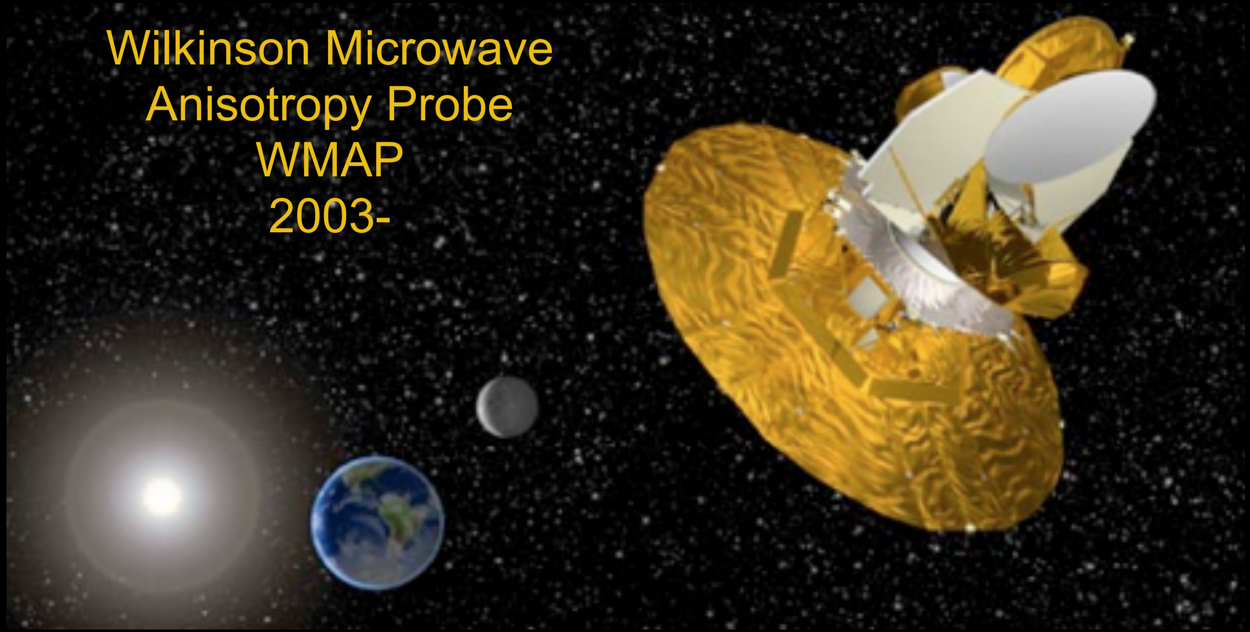
2006

Big Bang Data Agrees with Double Dark Theory!



Cosmic
Background
Explorer
COBE
1992

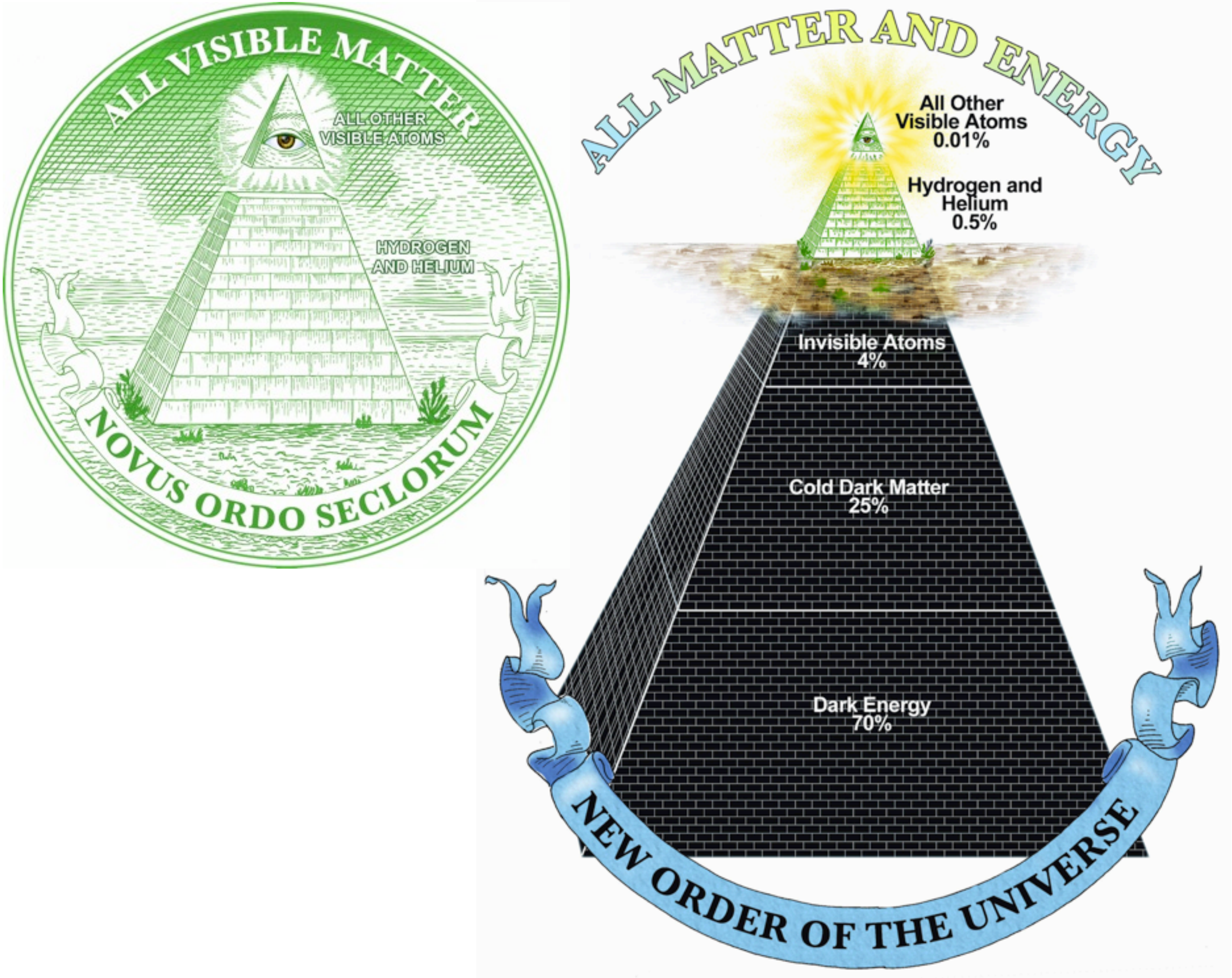




Wilkinson Microwave
Anisotropy Probe
WMAP
2003-

ACBAR

QUaD


ALL VISIBLE MATTER
ALL OTHER VISIBLE ATOMS
HYDROGEN AND HELIUM
NOVUS ORDO SECLORUM
ALL MATTER AND ENERGY
All Other Visible Atoms 0.01%
Hydrogen and Helium 0.5%
Invisible Atoms 4%
Cold Dark Matter 25%
Dark Energy 70%
NEW ORDER OF THE UNIVERSE

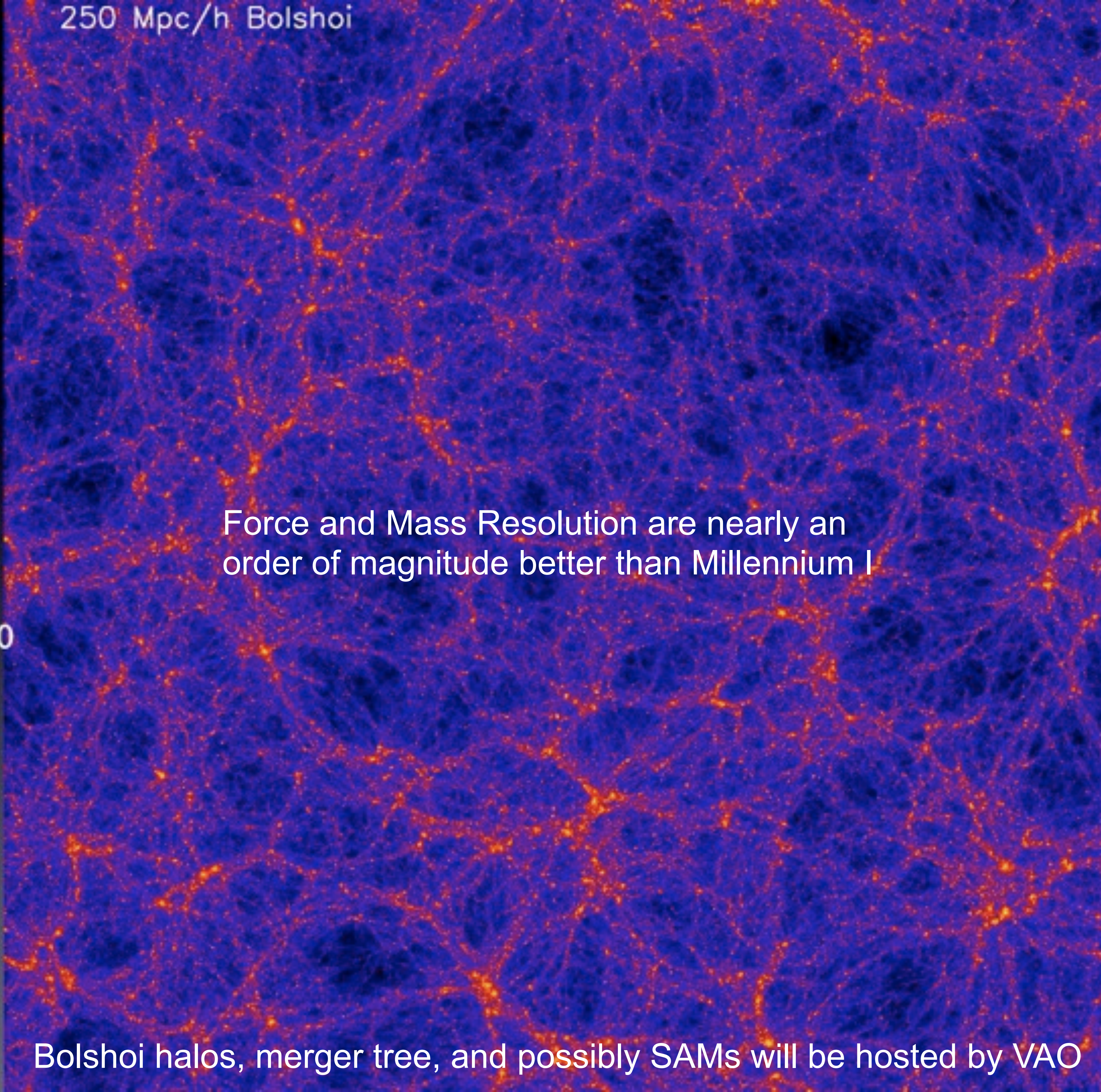
The Bolshoi simulation

ART code

250Mpc/h Box
LCDM
$\sigma_8 = 0.82$
h = 0.73
8G particles
1kpc/h force resolution
1e8 Msun/h mass res

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

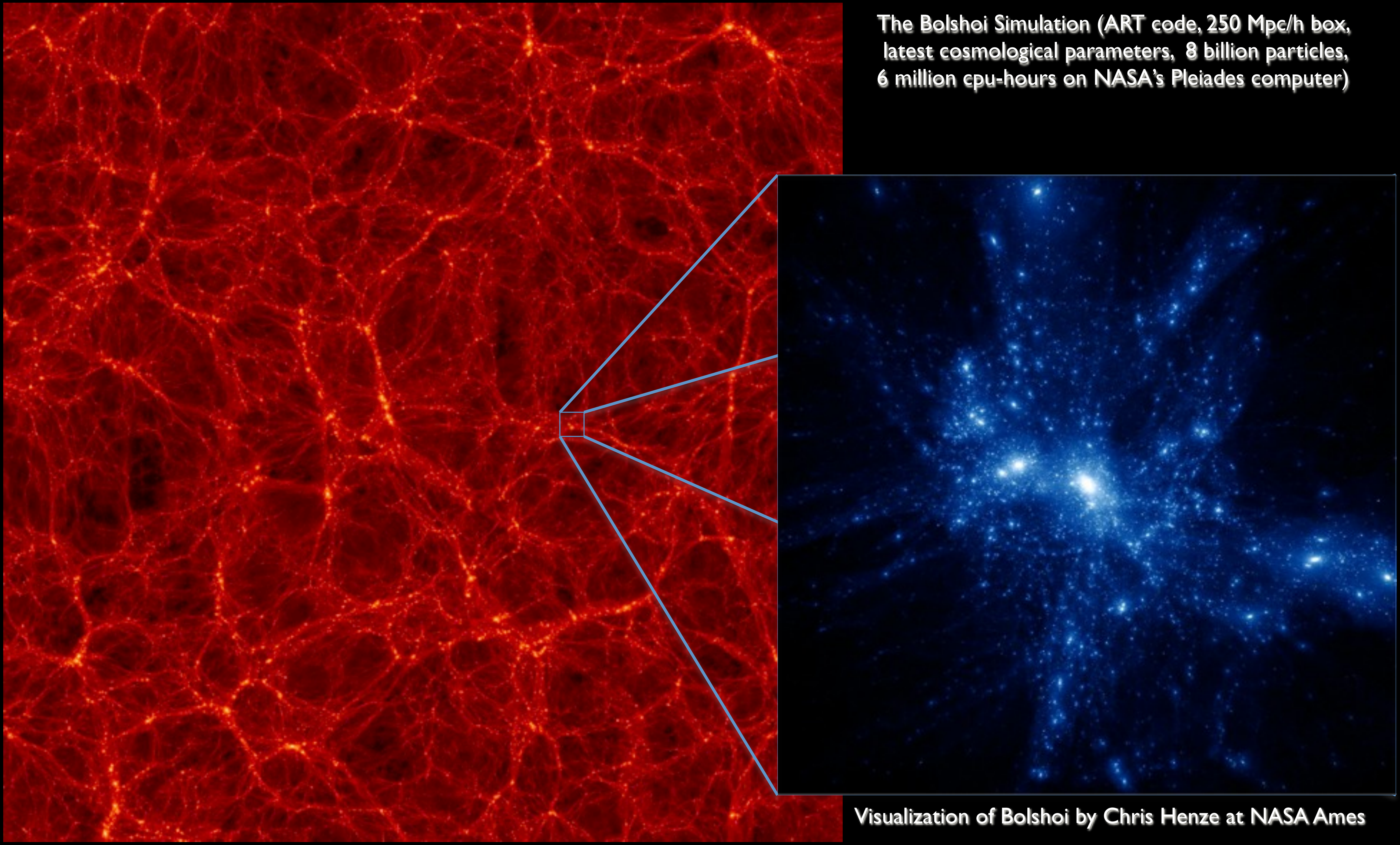
NASA AMES
supercomputing center
Pleiades computer
13824 cores
12TB RAM
75TB disk storage
6M cpu hrs
18 days wall-clock time



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

Bolshoi halos, merger tree, and possibly SAMs will be hosted by VAO

Cosmological Simulation of the Large Scale Structure of the Universe

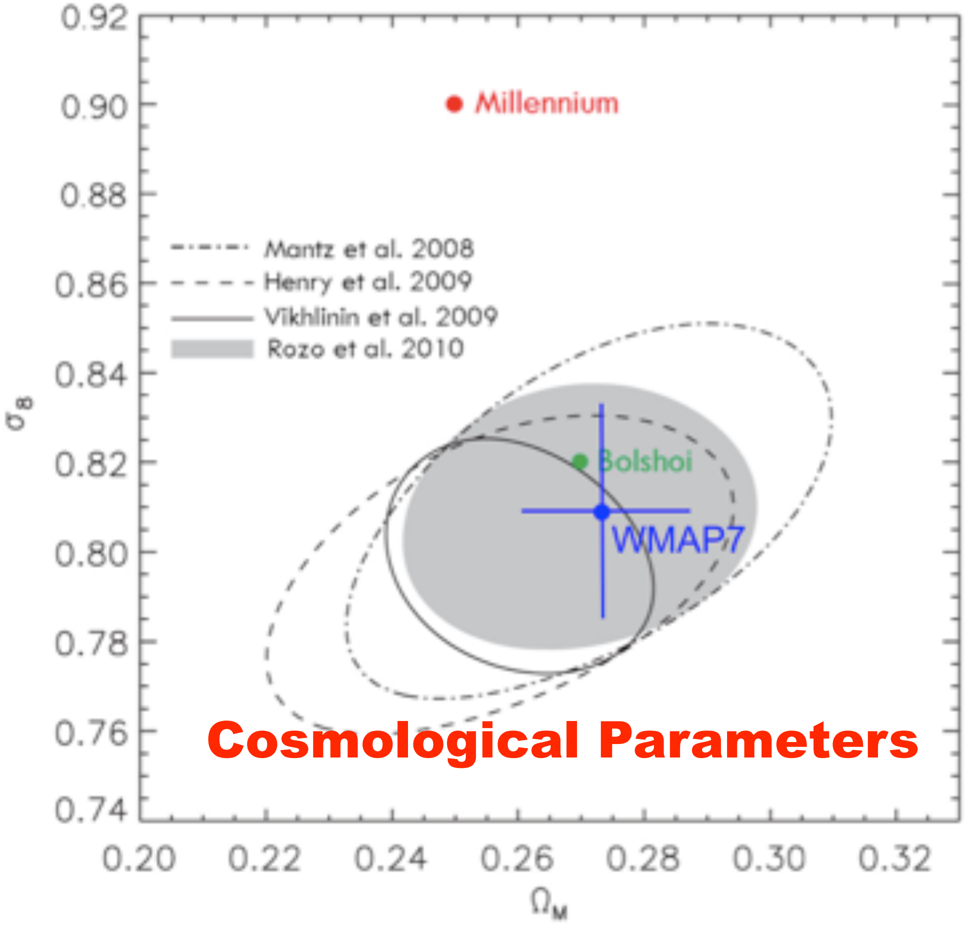


The Bolshoi Simulation (ART code, 250 Mpc/h box, latest cosmological parameters, 8 billion particles, 6 million cpu-hours on NASA's Pleiades computer)

Visualization of Bolshoi by Chris Henze at NASA Ames

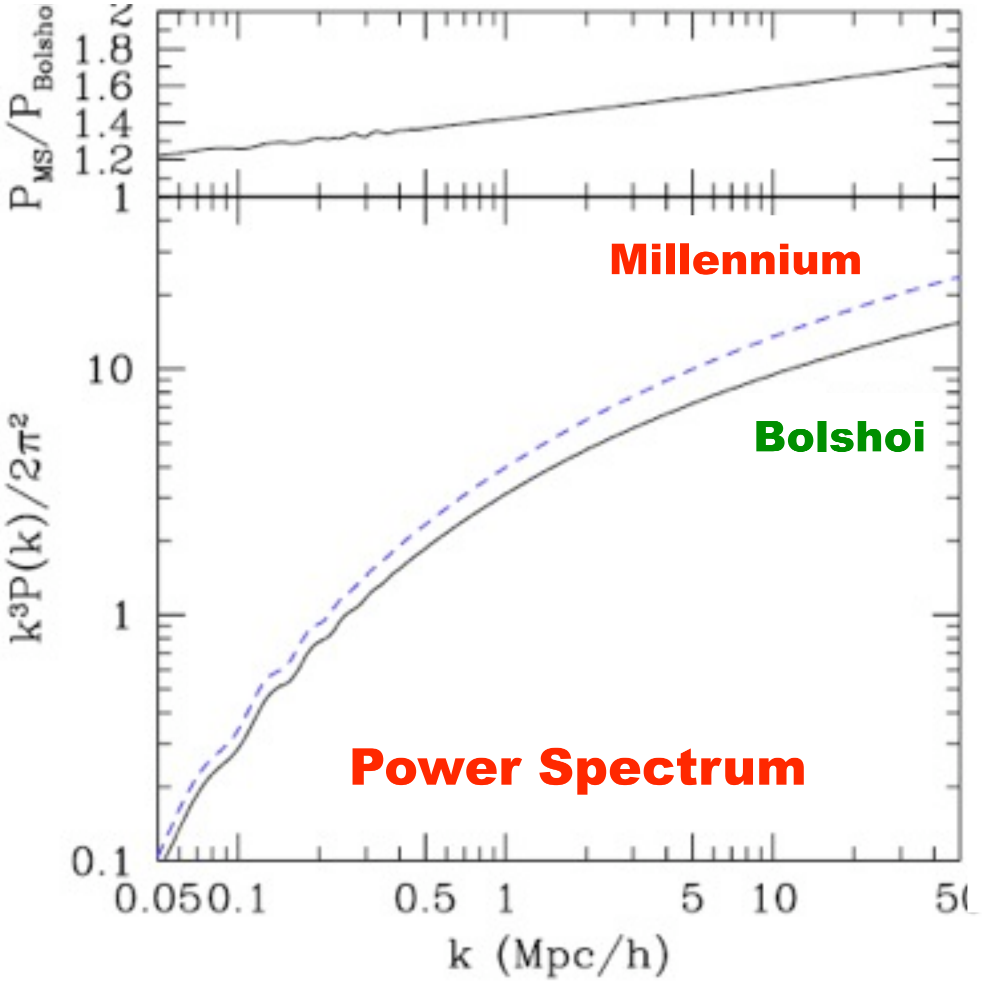
The visible material in the universe – stars, gas, dust, planets, etc. – accounts for only about 0.5% of the cosmic density. The remaining 99.5% of the universe is invisible. Most of it is non-atomic dark matter (~23%) and dark energy (~72%), with non-luminous atomic matter making up ~4%. In order to describe the evolution and structure of the universe, it is essential to show the distribution of dark matter and the relationship of dark matter to visible structures.

Halos and galaxies: results from the Bolshoi simulation

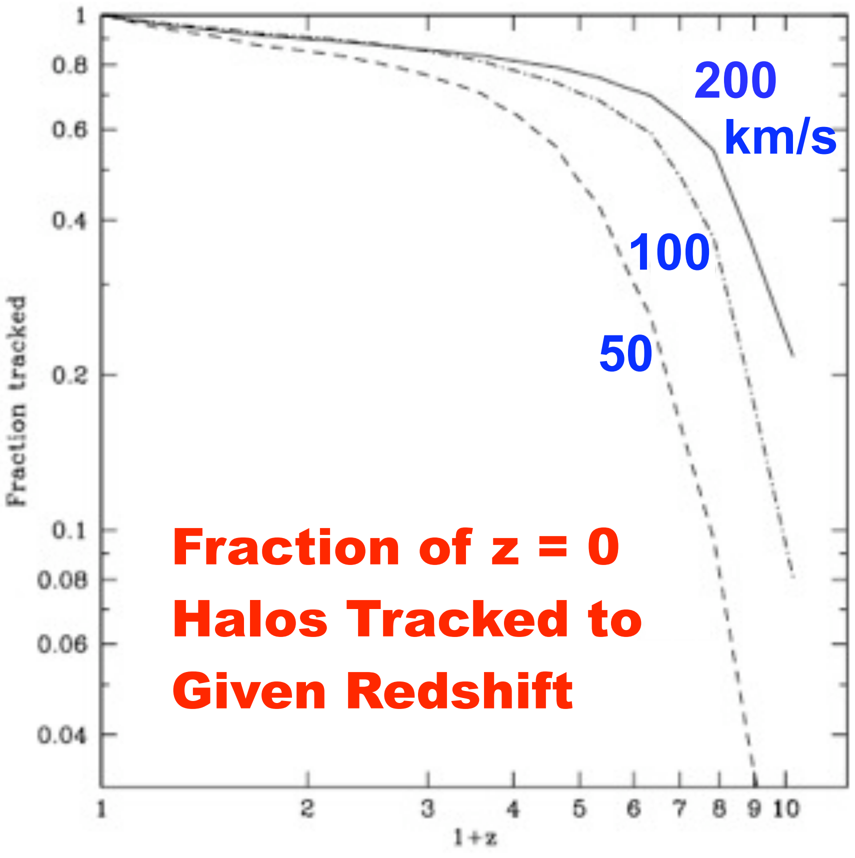


Cosmological Parameters

The **Millennium Run** (Springel+05) was a landmark simulation, and it has been the basis for ~300 papers. However, it and the new Millennium-II simulations were run using WMAP1 (2003) parameters, and the Millennium-I resolution was inadequate to see many subhalos. The new **Bolshoi** simulation (Klypin, Trujillo & Primack 2010) used the WMAP5 parameters (consistent with WMAP7) and has nearly an order of magnitude better mass and force resolution than Millennium-I. We have now found halos in all 180 stored timesteps, and we have complete merger trees. on based on Bolshoi.

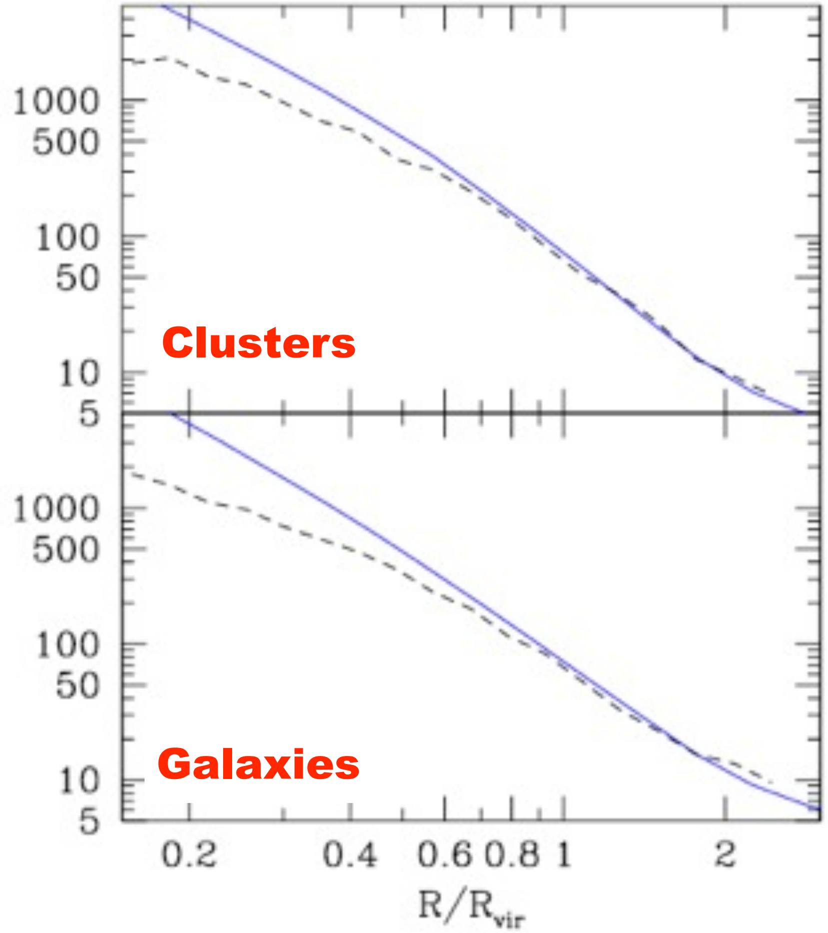


Power Spectrum

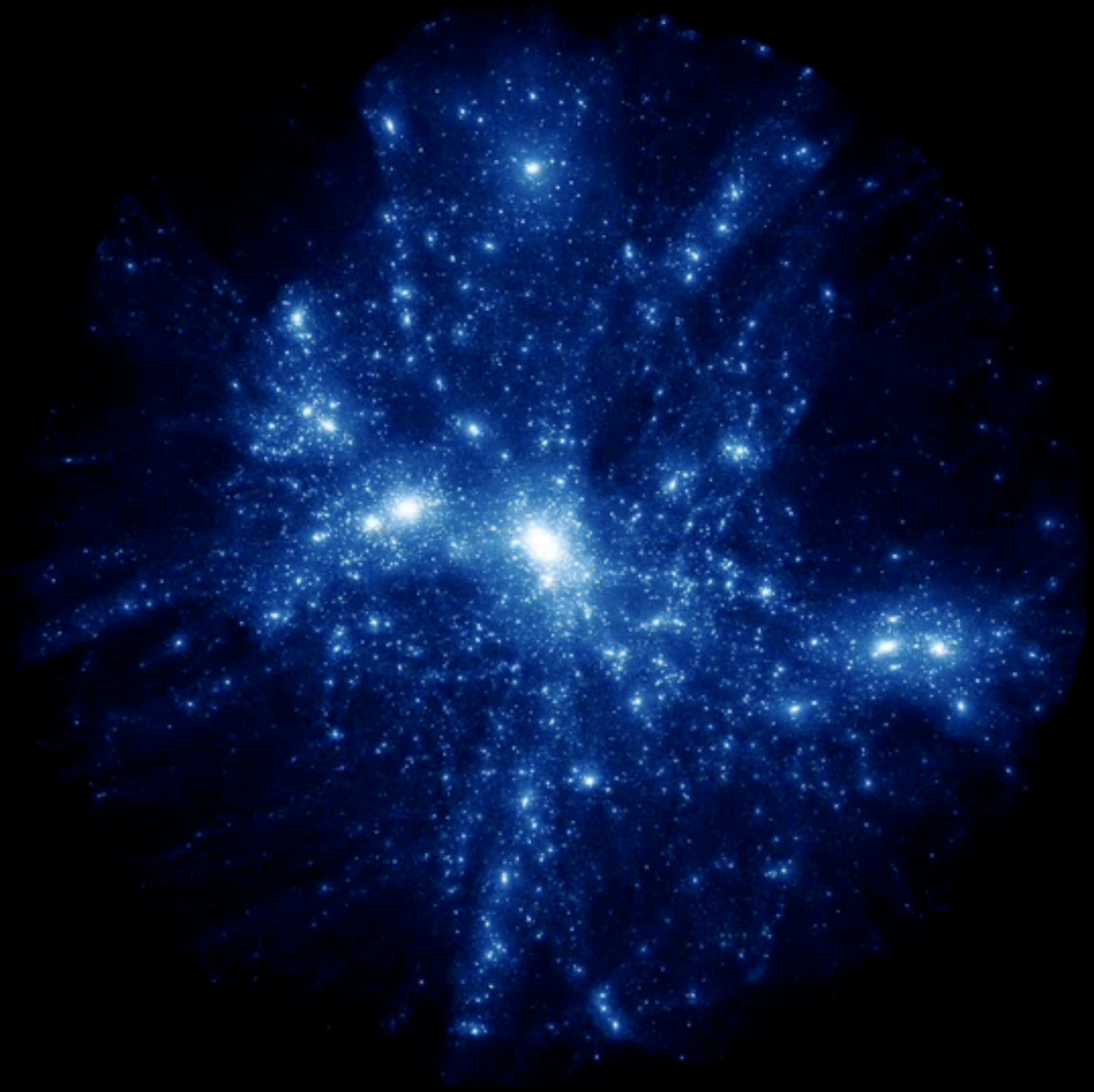


Fraction of z = 0 Halos Tracked to Given Redshift

Subhalos follow the dark matter distribution



BOLSHOI SIMULATION FLY-THROUGH



$<10^{-3}$
of the
Bolshoi
Simulation
Volume

BOLSHOI SIMULATION FLY-THROUGH

$<10^{-3}$
of the
Bolshoi
Simulation
Volume

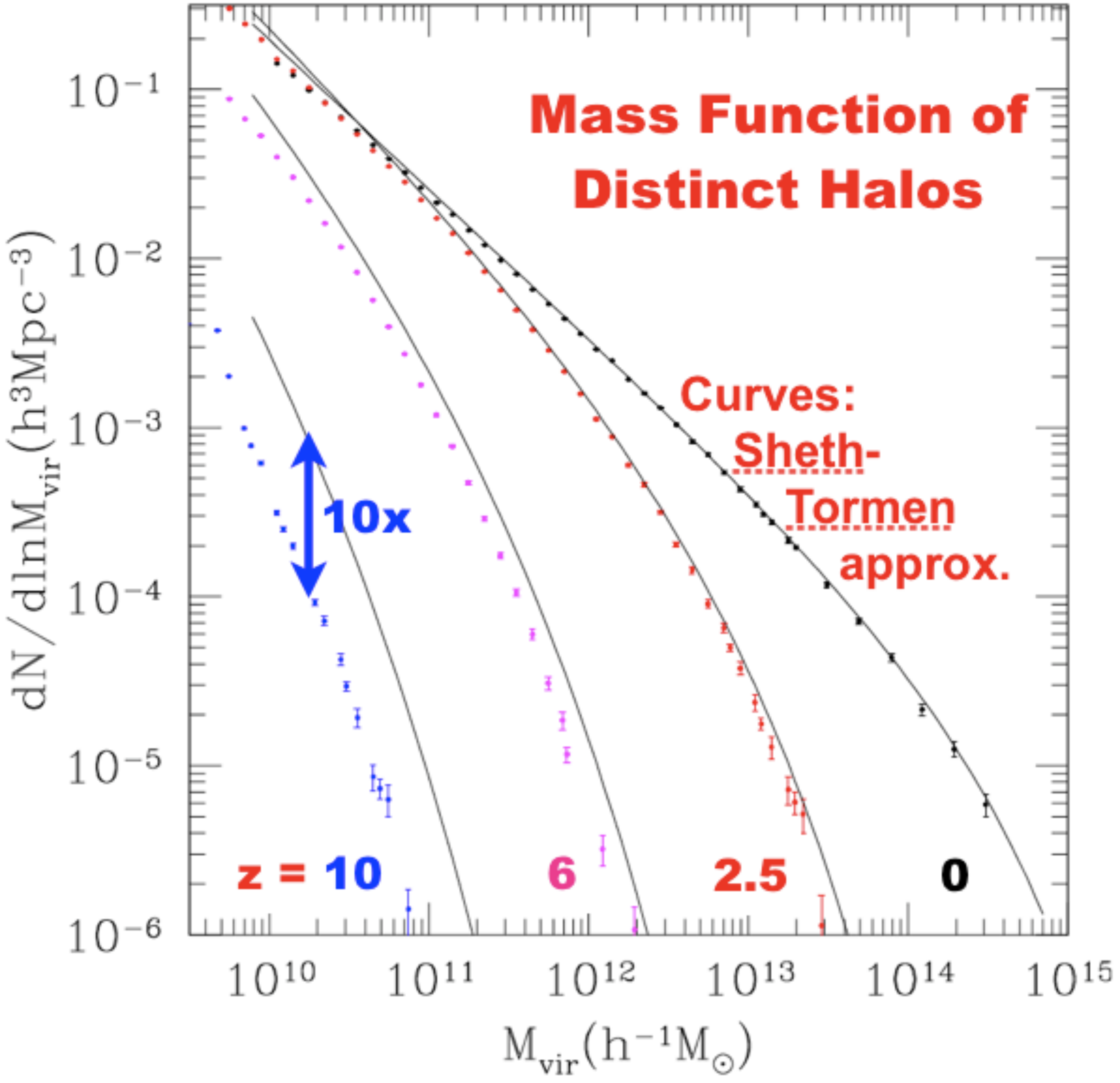
```
Time: 13293 Myr Ago
Timestep Redshift: 8.775
Radius Mode: Rvir
Focus Distance: 10.3
Aperture: 40.0
World Rotation: (209.9, 0.08, -0.94, -0.34)
Trackball Rotation: (0.0, 0.00, 0.00, 0.00)
Camera Position: (0.0, 0.0, -10.3)
```

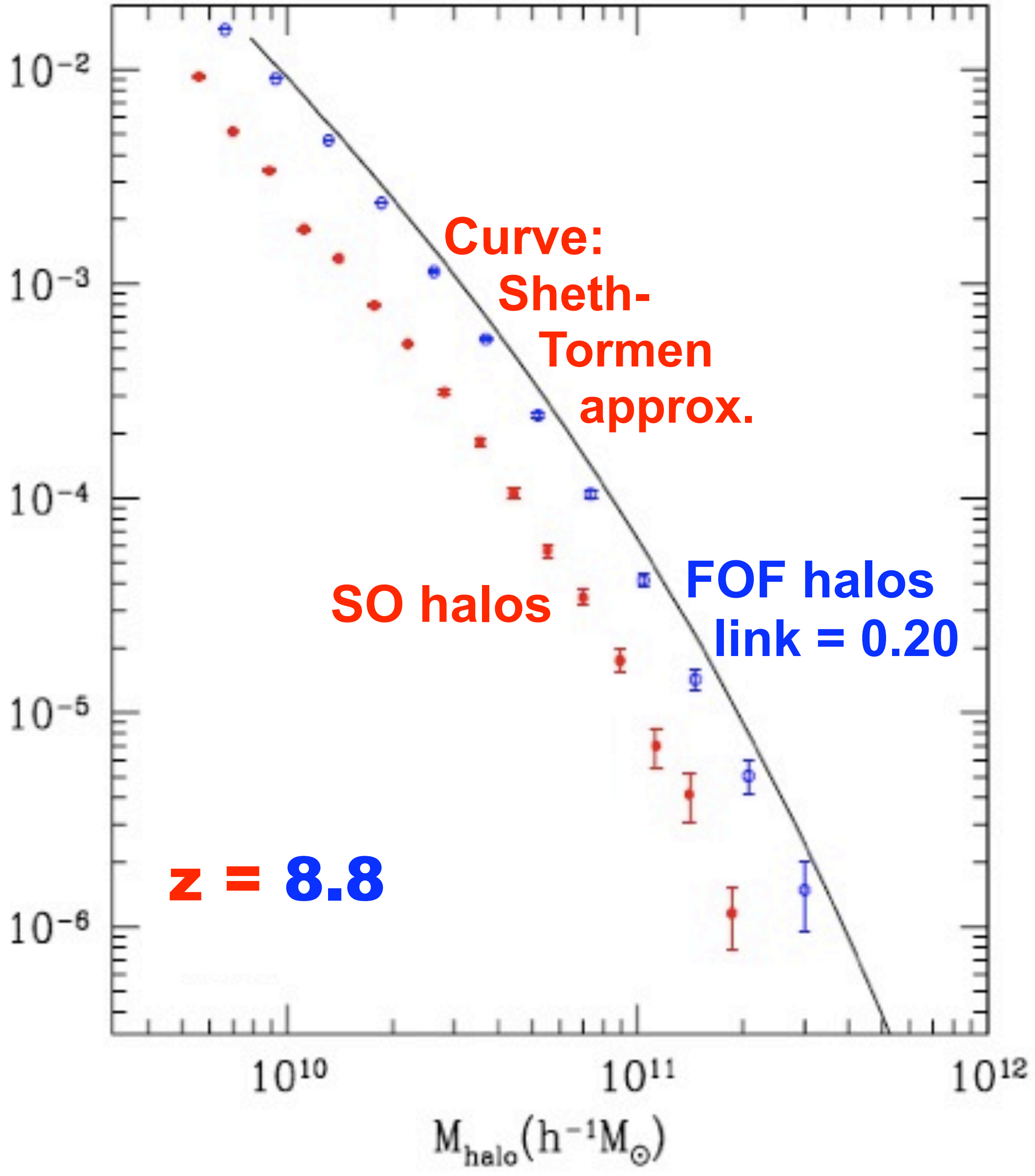
BOLSHOI

Merger Tree

Peter Behroozi,
Risa Wechsler, &
Mike Busha

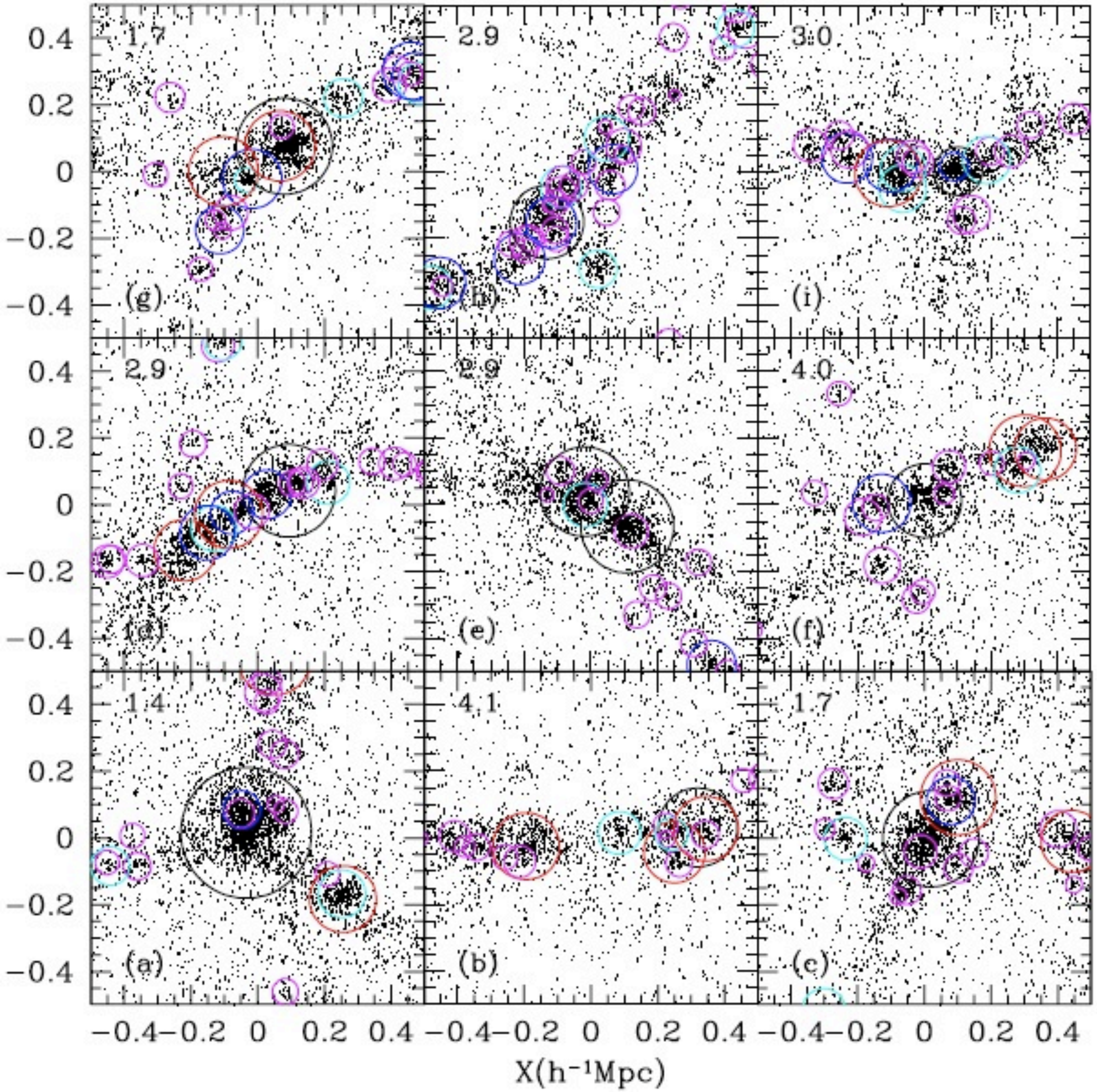
Sheth-Tormen Fails at High Redshifts

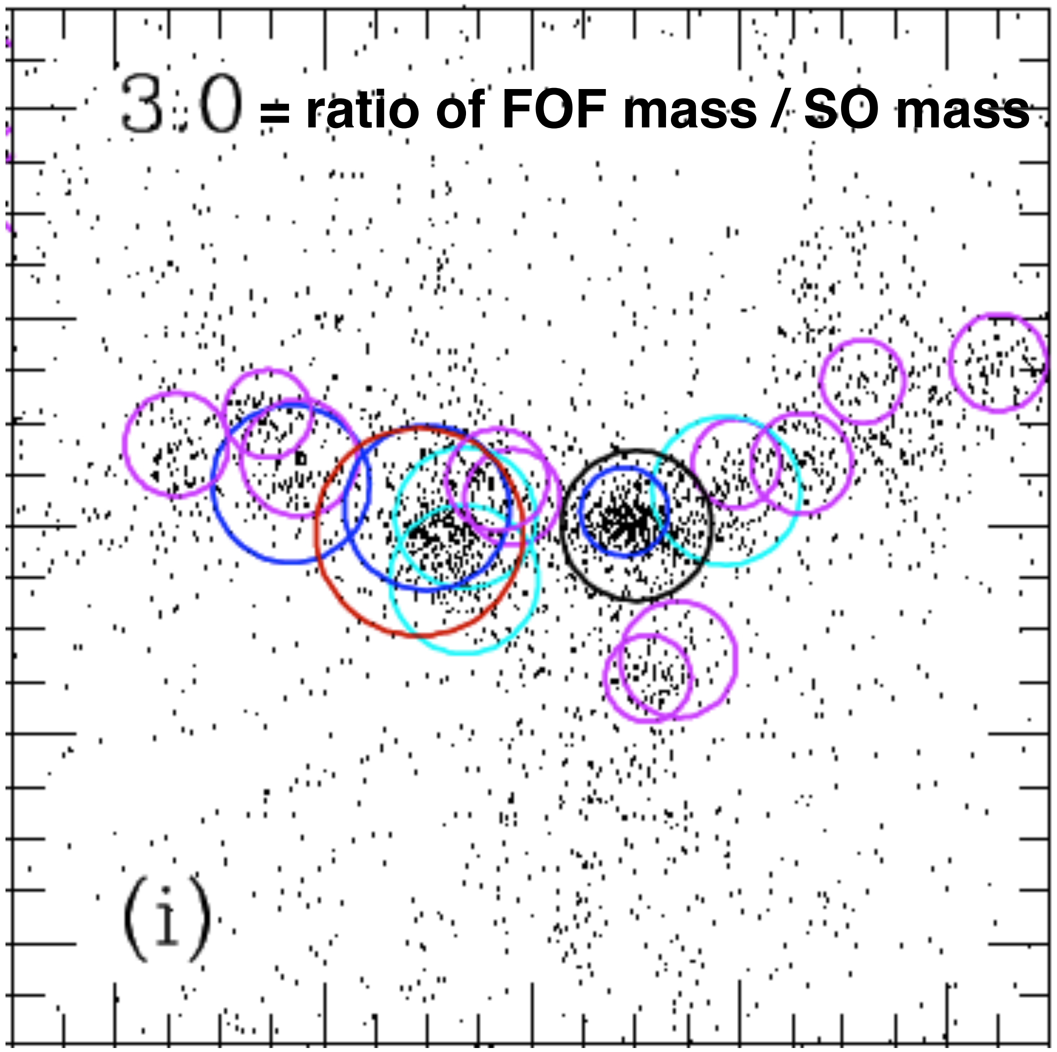




The Sheth-Tormen approximation with the same WMAP5 parameters used for the Bolshoi simulation very accurately agrees with abundance of halos at low redshifts, but increasingly overpredicts bound spherical overdensity halo abundance at higher redshifts. ST agrees well with FOF halo abundances, but FOF halos have unrealistically large masses at high *z*.

Klypin, Trujillo-Gomez, & Primack, arXiv: 1002.3660 ApJ in press





3.0 = ratio of FOF mass / SO mass

FOF linked together a chain of halos that formed in long and dense filaments (also in panels b, d, f, h; e = major merger)

Each panel shows 1/2 of the dark matter particles in cubes of 1h^{-1} Mpc size. The center of each cube is the exact position of the center of mass of the corresponding FOF halo. The effective radius of each FOF halo in the plots is 150 – 200 h^{-1} kpc. Circles indicate virial radii of distinct halos and subhalos identified by the spherical overdensity algorithm BDM.

Klypin, Trujillo-Gomez, & Primack, arXiv: 1002.3660 ApJ in press

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

The Bolshoi simulation predicts the likelihood of this

Statistics of MW-satellite analogs

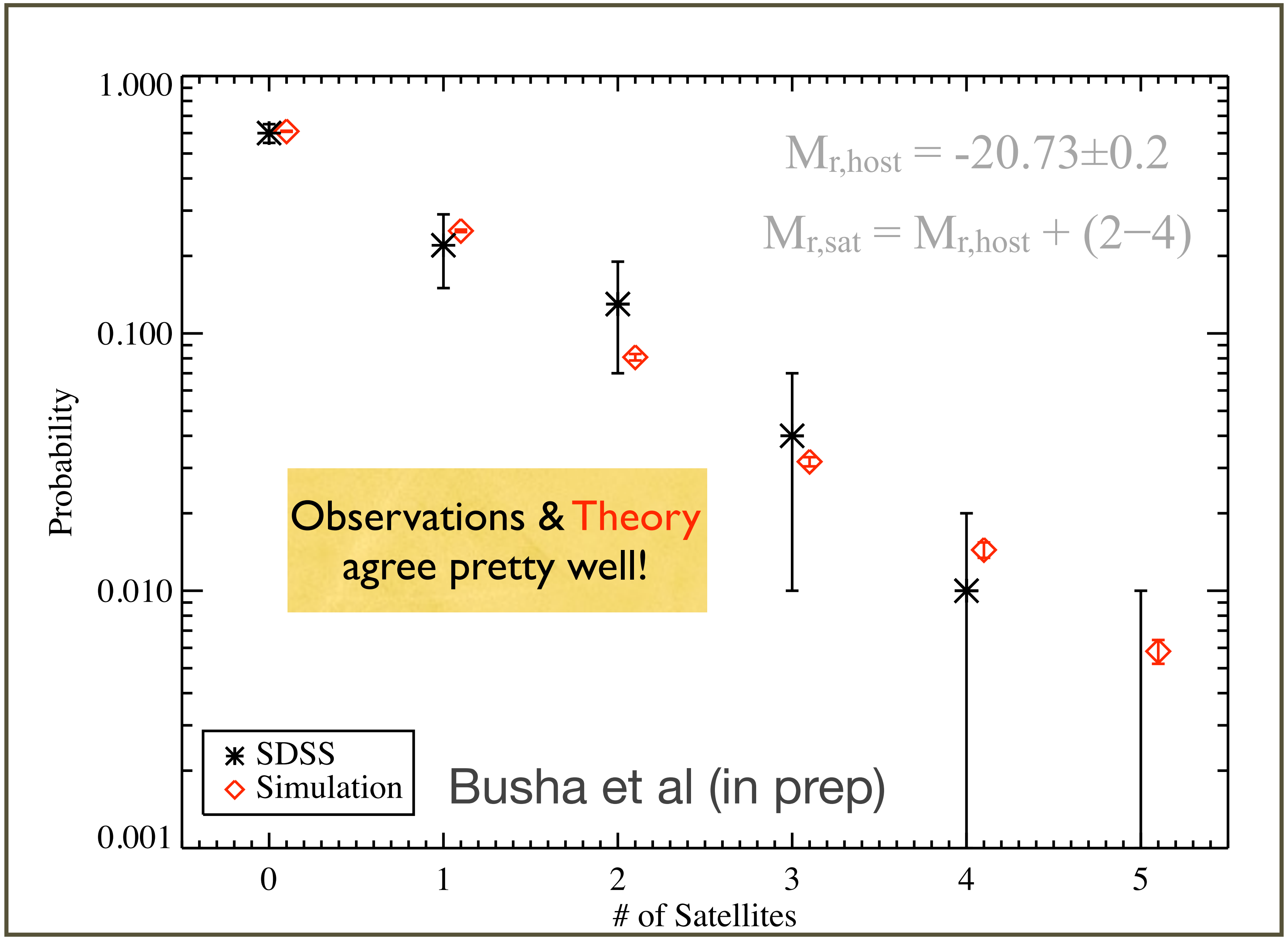
Liu, Gerke & Wechsler (in prep)

- Search SDSS DR7 Co-Add data to look for analogues of the LMC/SMC in extragalactic hosts
- SDSS Co-Add Data:
  - Stripe-82 in the SDSS was observed ~370 times, complete to observed magnitude limit $M_r = 23.6$ over ~270 sq. deg; main sample spectroscopy (mostly) complete down to $M_r = 17.77$
  - Photometric redshifts calculated for the remaining objects using a template method.
    - Training/validation set taken from CNOC2, SDSS main, and DEEP2 samples.
    - Measured scatter: $\Delta z = 0.02$
  - 23,000 spectroscopic galaxy (non-QSO) candidates in Stripe 82 with $m_r < 17.77$
- Magnitude Cuts:
  - Identify all objects with absolute ${}^{0.1}M_r = -20.73 \pm 0.2$ and observed $m_r < 17.6$
  - Lets us probe out to $z = 0.15$, a volume of roughly 500 $(\mathrm{Mpc}/h)^3$
  - leaves us with 3,200 objects.
- Isolation Criteria: exclude objects in clusters, since those are likely biased -- exclude candidates with neighbors brighter than itself within a cylinder defined by:
    - radial distance 1000 km/s -- the velocity dispersion of a typical cluster and $\Delta z \approx 0.01$ at our relevant redshifts.
    - projected angular distance $R_{iso} = 0.7$ Mpc
    - leaves us with 1,332 hosts.

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

- Apply the same absolute magnitude and isolation cuts to Bolshoi+SHAM galaxies as to SDSS:
  - Identify all objects with absolute $^{0.1}M_r = -20.73\pm0.2$ 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%



Observations & Theory agree pretty well!

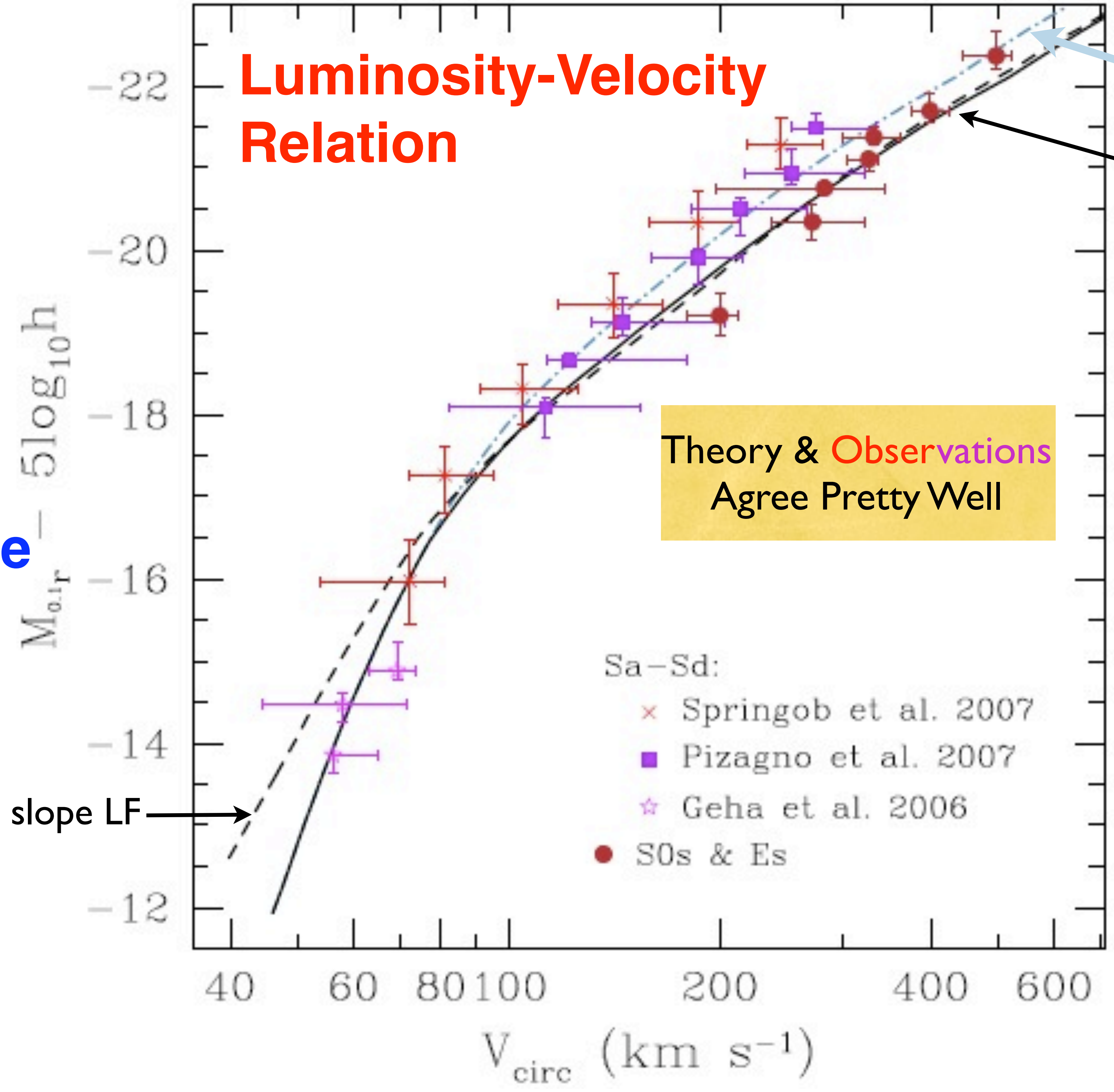
Busha et al (in prep)

Every case agrees within observational errors!

Risa Wechsler

Luminosity-Velocity Relation

Bolshoi Sub-Halo Abundance Matching



median Vcirc without AC

median Vcirc with AC

steeper slope LF

Theory & Observations Agree Pretty Well

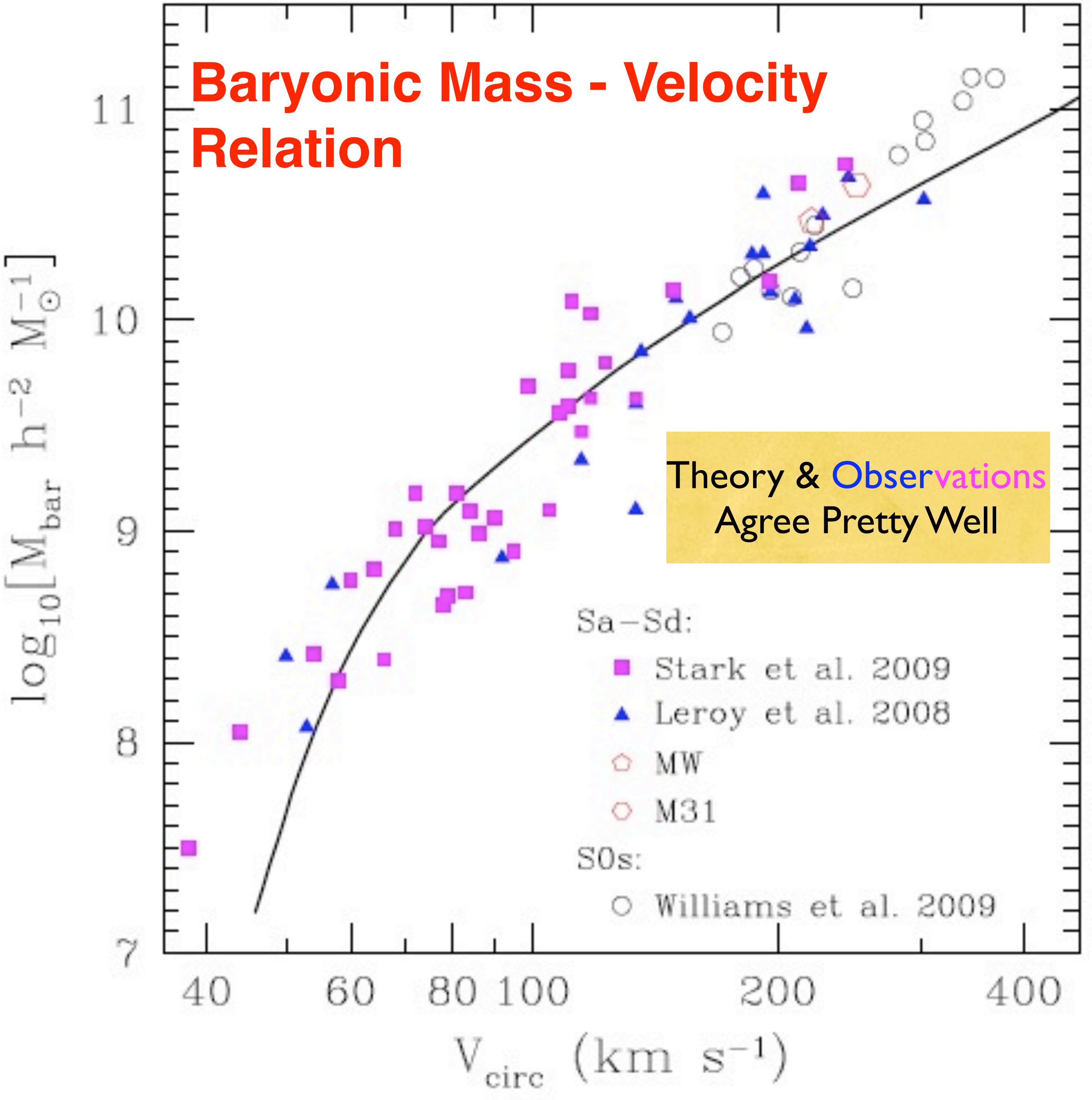
"AC" = Adiabatic Contraction of dark matter halos when baryons cool & condense to halo centers, following Blumenthal, Faber, Flores, & Primack 1986

Trujillo-Gomez, Klypin, Primack, & Romanowsky arXiv: 1005.1289 ApJ in press

Fig. 4.— Comparison of the observed Luminosity Velocity relation with the predictions of the ΛCDM model. The solid curve shows the median values of $^{0.1}r$-band luminosity vs. circular velocity for the model galaxy sample. The circular velocity for each model galaxy is based on the peak circular velocity of its host halo over its entire history, measured at a distance of 10 kpc from the center including the cold baryonic mass and the standard correction due to adiabatic halo contraction. The dashed curve show results for a steeper ($\alpha = -1.34$) slope of the LF. The dot-dashed curve shows predictions after adding the baryon mass but without adiabatic contraction. Points show representative observational samples.

Baryonic Mass - Velocity Relation

Bolshoi Sub-Halo Abundance Matching



Theory & Observations
Agree Pretty Well

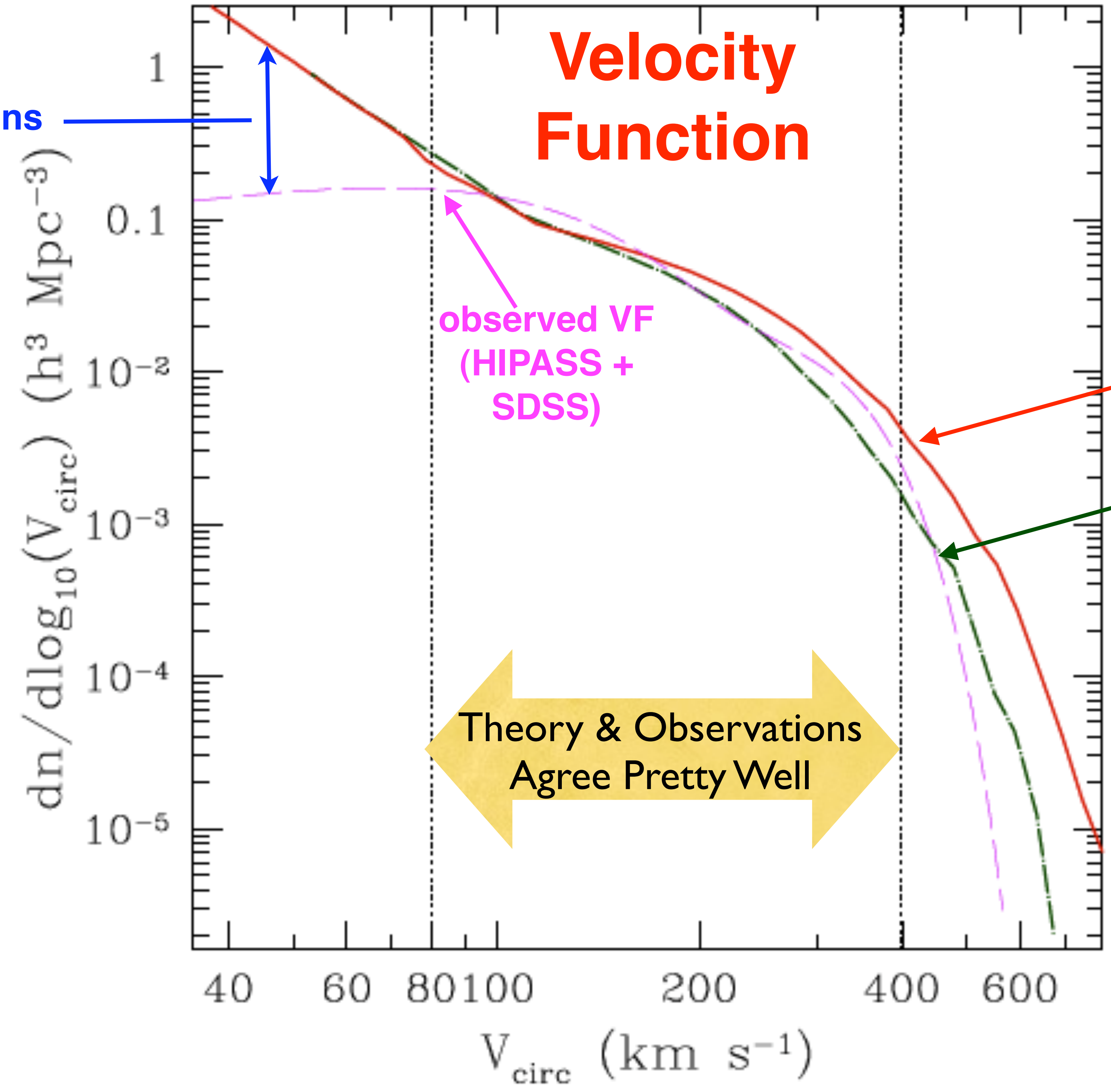
Trujillo-Gomez, Klypin, Primack, & Romanowsky
arXiv: 1005.1289
ApJ in press

Fig. 10.— Mass of baryons as a function of circular velocity. The solid curve shows median values for the ΛCDM model. The total baryonic mass includes stars and cold gas and the circular velocity is measured at 10 kpc from the center while including the effect of adiabatic contraction. For comparison we show the individual galaxies of several galaxy samples. Intermediate mass galaxies such as the Milky Way and M31 lie very close to our model results.

Velocity Function

Bolshoi Sub-Halo Abundance Matching

Discrepancy due to incomplete observations or ΛCDM failure?



observed VF (HIPASS + SDSS)

theoretical VF with AC

theoretical VF without AC

Theory & Observations Agree Pretty Well

Trujillo-Gomez, Klypin, Primack, & Romanowsky arXiv: 100.1289

Fig. 11.— Comparison of theoretical (dot-dashed and thick solid curves) and observational (dashed curve) circular velocity functions. The dot-dashed line shows the effect of adding the baryons (stellar and cold gas components) to the central region of each DM halo and measuring the circular velocity at 10 kpc. The thick solid line is the distribution obtained when the adiabatic contraction of the DM halos is considered. Because of uncertainties in the AC models, realistic theoretical predictions should lie between the dot-dashed and solid curves. Both the theory and observations are highly uncertain for rare galaxies with $V_{\rm circ} > 400$ km s^{-1}. Two vertical dotted lines divide the VF into three domains: $V_{\rm circ} > 400$ km s^{-1} with large observational and theoretical uncertainties; $<$ 80 km $s^{-1} < V_{\rm circ} <$ 400 km s^{-1} with a reasonable agreement, and $V_{\rm circ} < 80$ km s^{-1}, where the theory significantly overpredicts the number of dwarfs.

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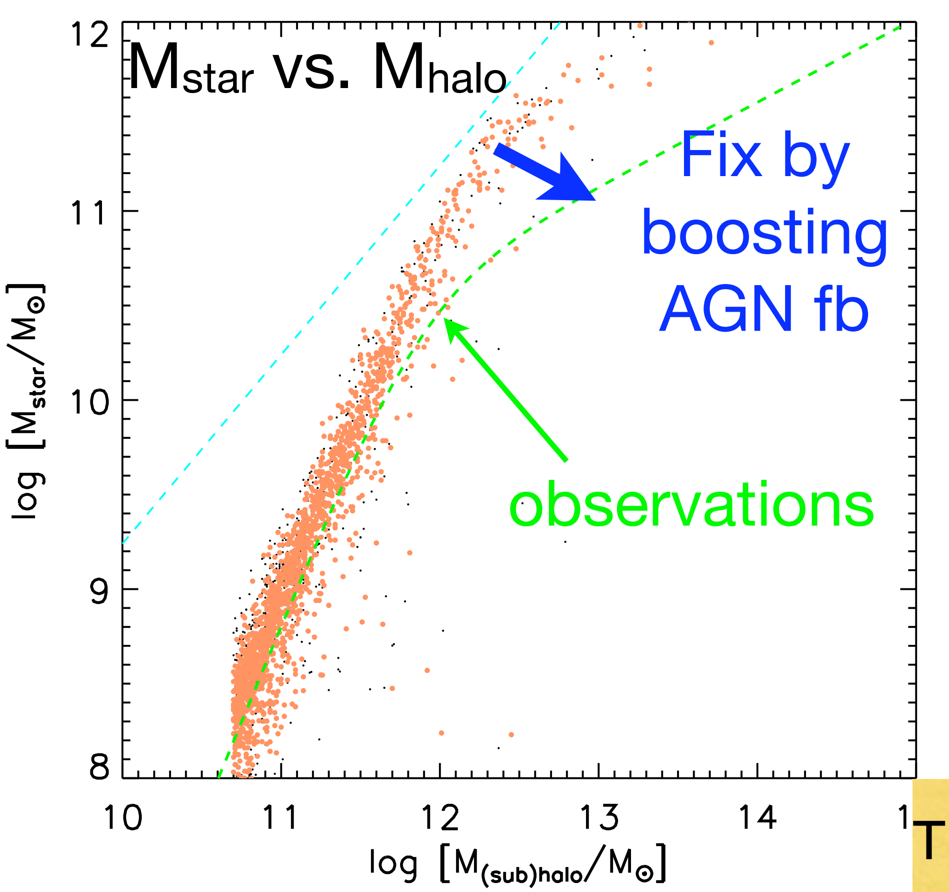
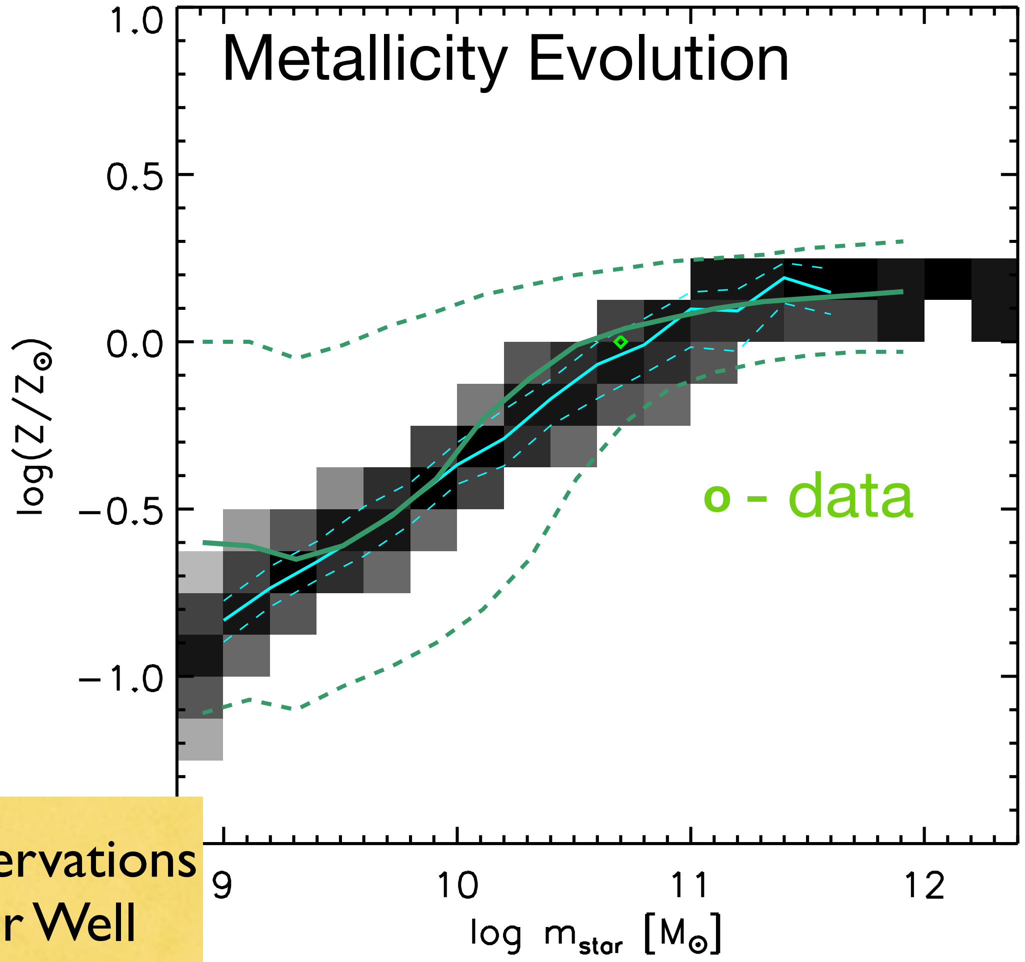
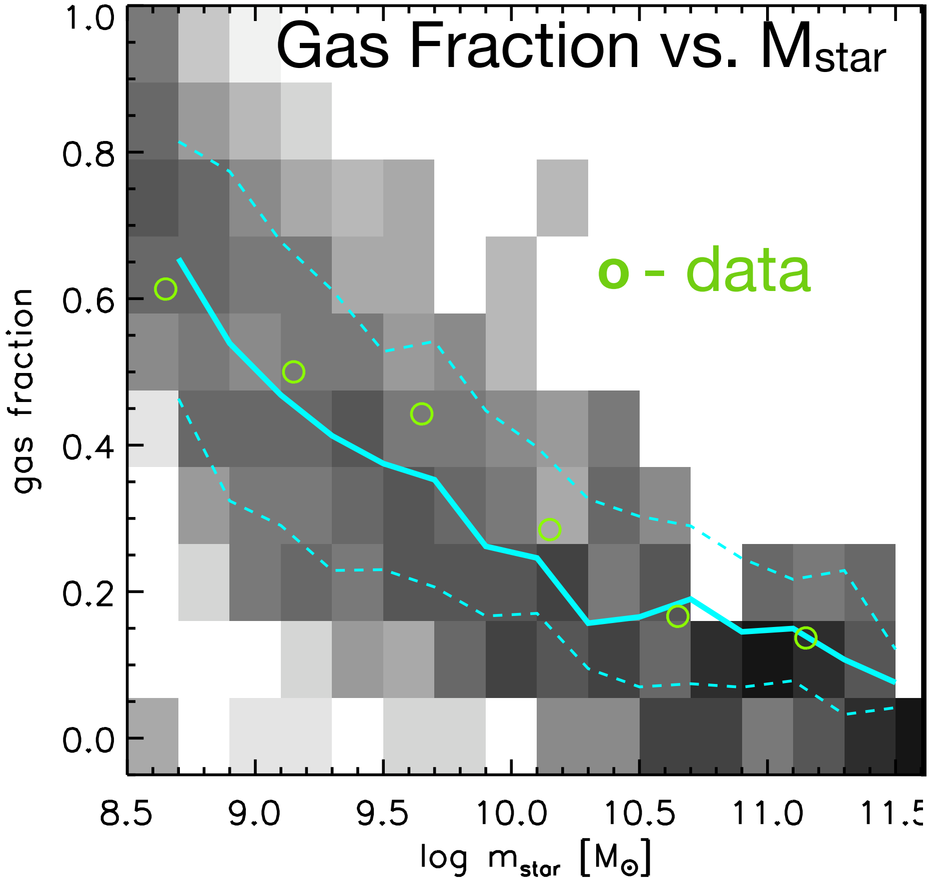
- **Semi-Analytic Models (SAMs) compared with observations**

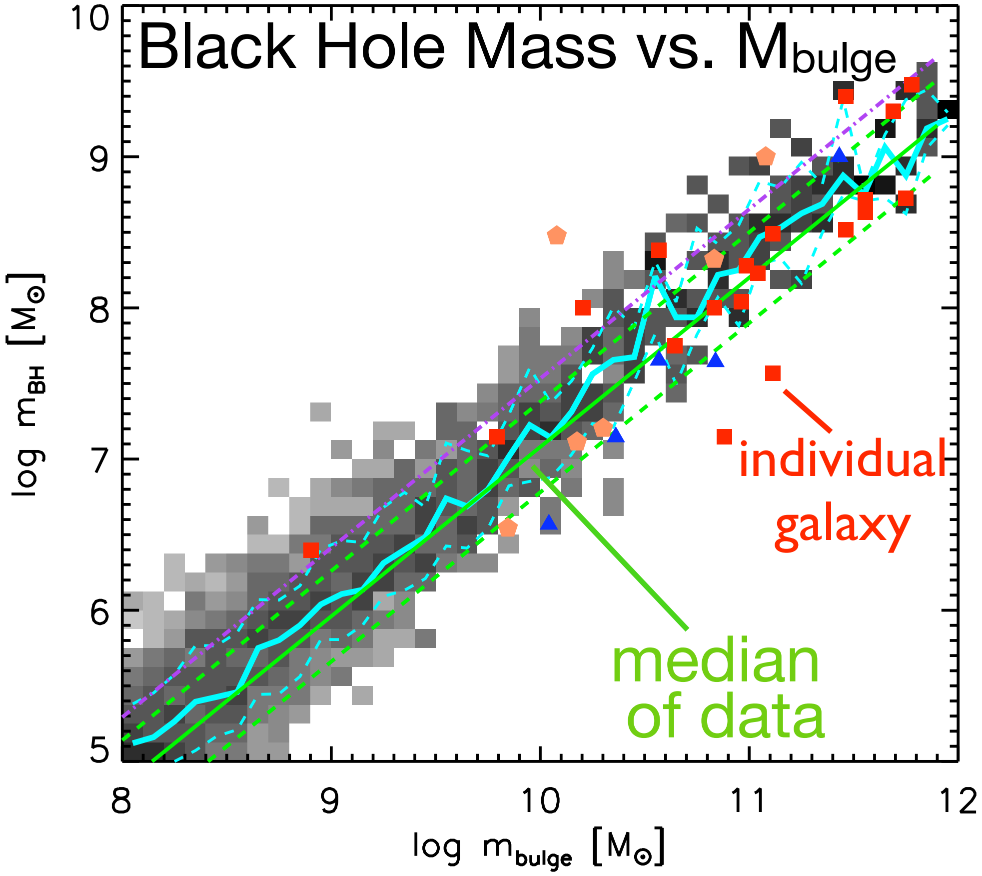
First SAM galaxy results with Bolshoi - Rachel Somerville





Theory & Observations Agree Rather Well





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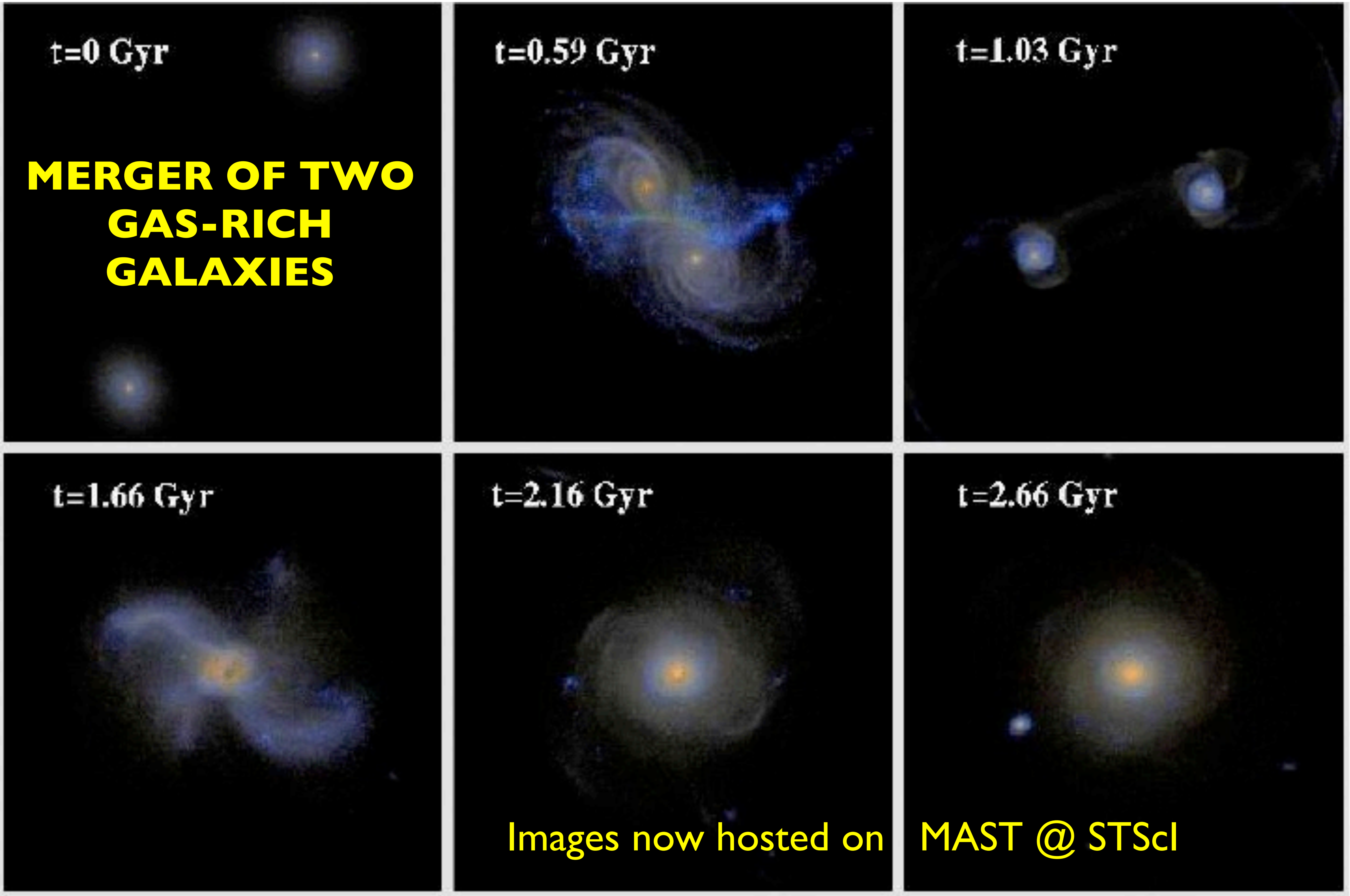
Nature of Dark Energy - expansion history, structure formation history

How Galaxies Form and Evolve
- **Main ways to make big galaxies: gas-rich mergers *vs.* cold inflows**

Theoretical Approaches
- **Simulations**: dissipationless, **hydrodynamic** **TOPIC OF THIS SCHOOL!**
- Sub-Halo Abundance Matching (“SHAM”)
- Semi-Analytic Models (SAMs) compared with observations



MERGER OF TWO GAS-RICH GALAXIES

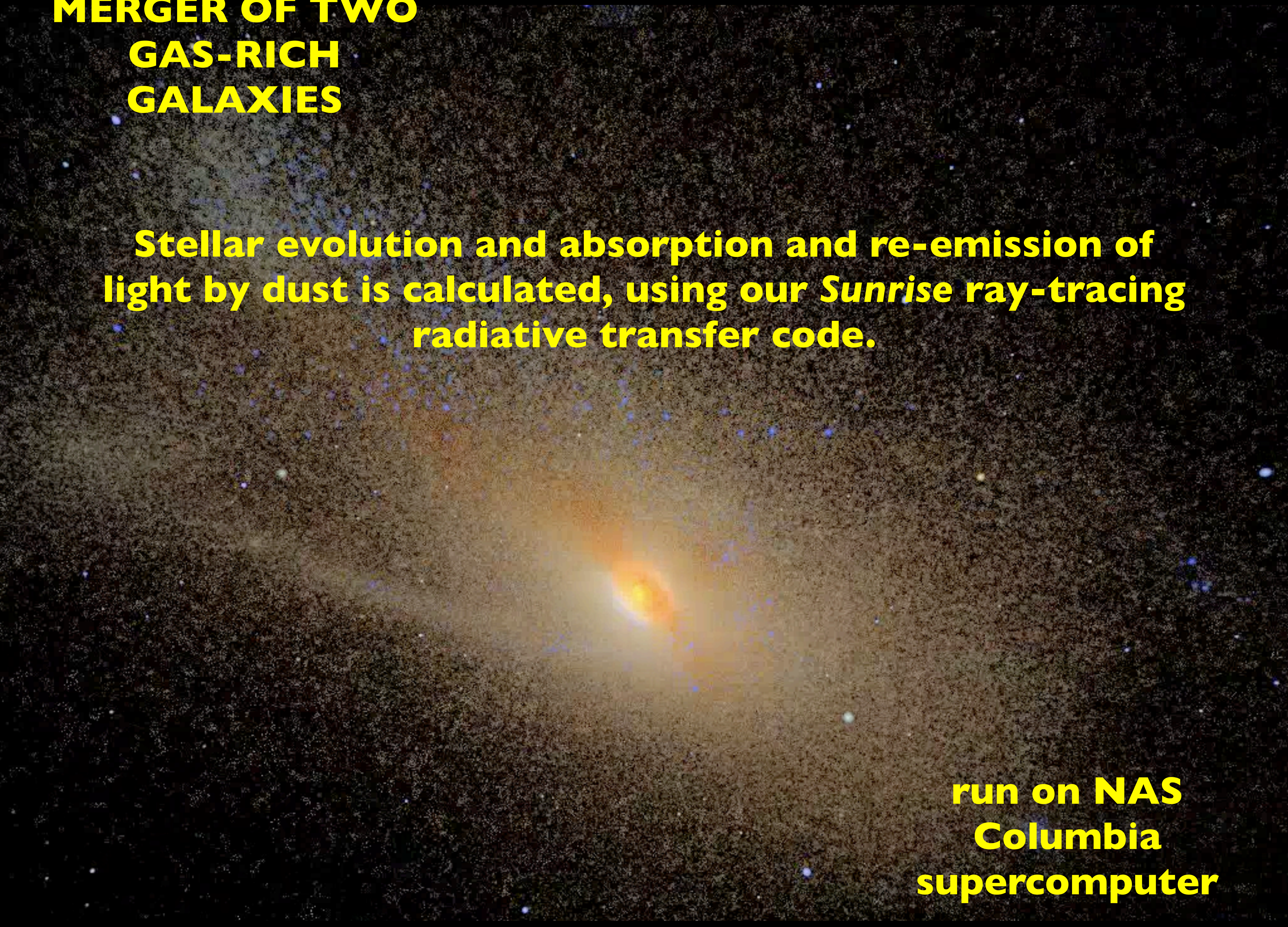
Images now hosted on MAST @ STScI

Lotz, Jonsson, Cox, Primack 2008, 2010 Galaxy Merger Morphologies and Time-Scales from Simulations to determine observability timescales using CAS, G-M_{20}, & pairs → merger rates

MERGER OF TWO GAS-RICH GALAXIES

run on NAS
Columbia
supercomputer

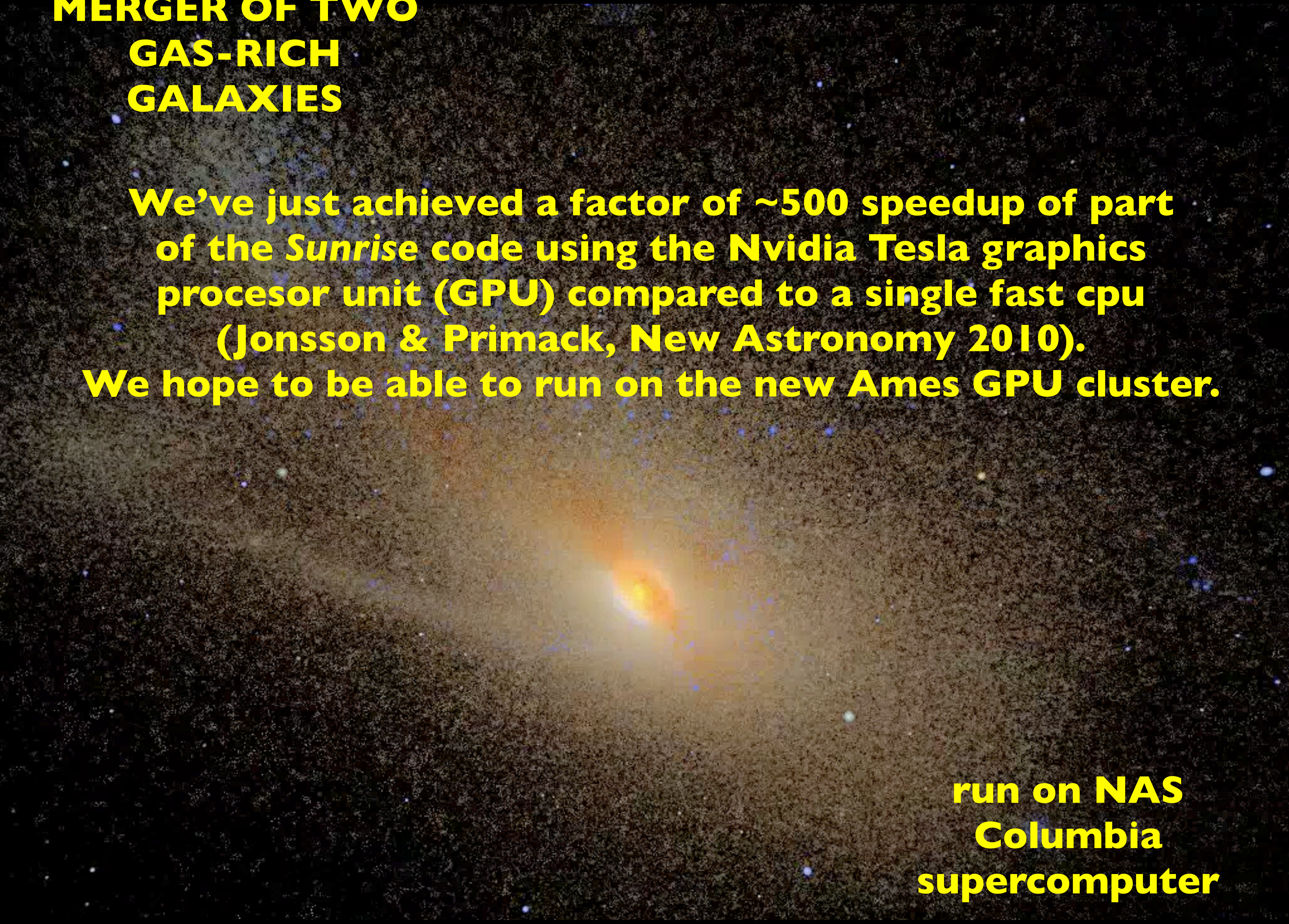
MERGER OF TWO GAS-RICH GALAXIES



Stellar evolution and absorption and re-emission of light by dust is calculated, using our *Sunrise* ray-tracing radiative transfer code.

run on NAS
Columbia
supercomputer

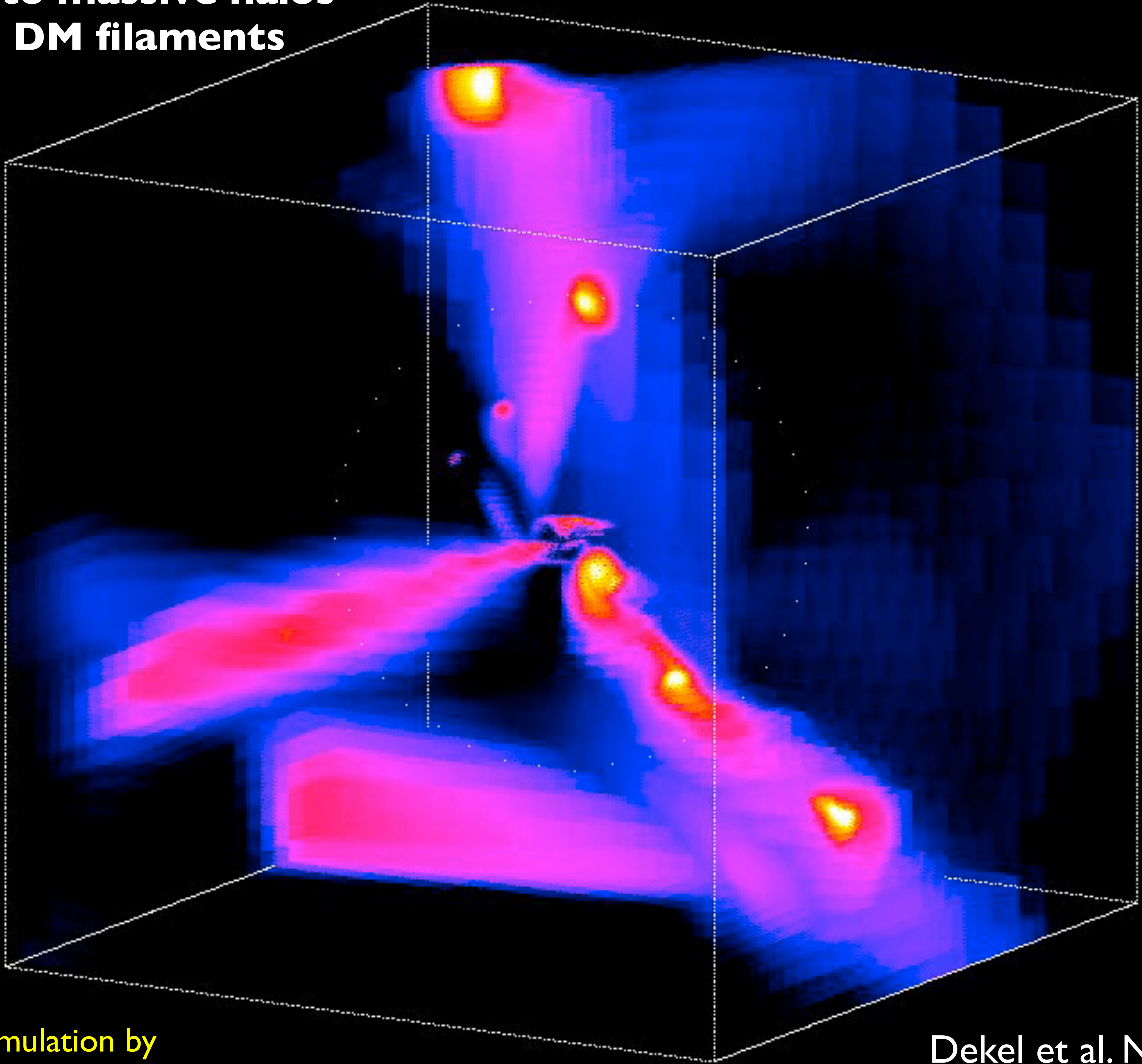
MERGER OF TWO GAS-RICH GALAXIES



We've just achieved a factor of ~500 speedup of part of the *Sunrise* code using the Nvidia Tesla graphics procesor unit (GPU) compared to a single fast cpu (Jonsson & Primack, New Astronomy 2010).
We hope to be able to run on the new Ames GPU cluster.

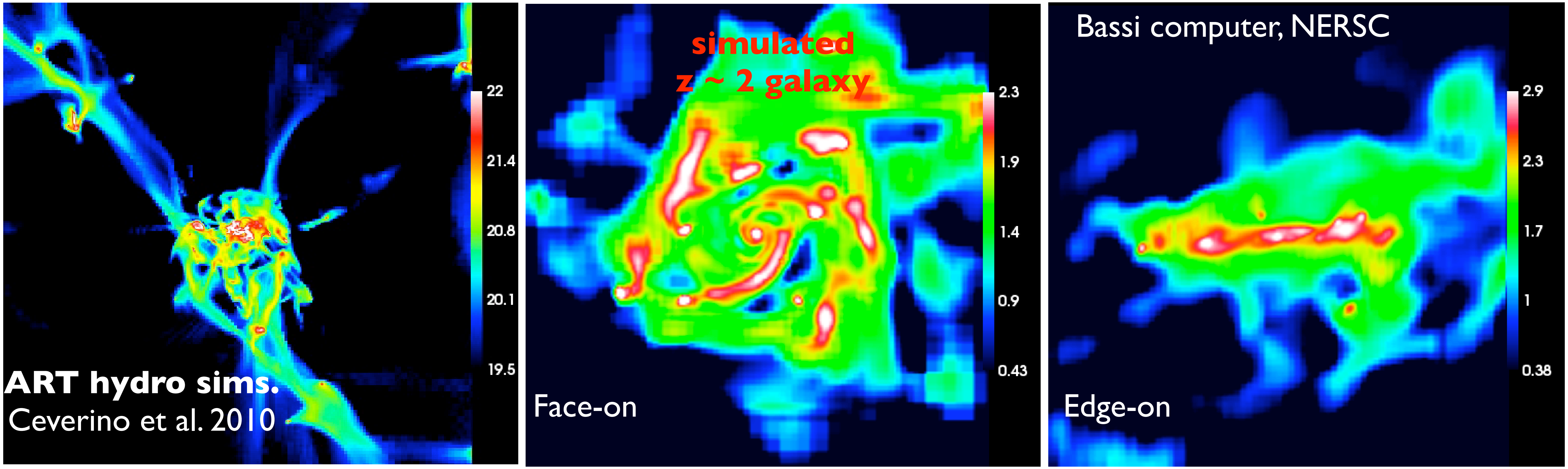
run on NAS Columbia supercomputer

Inflows to massive halos along DM filaments



RAMSES simulation by
Romain Teyssier on Mare Nostrum supercomputer, Barcelona

Dekel et al. Nature 2009



ART hydro sims.
Ceverino et al. 2010

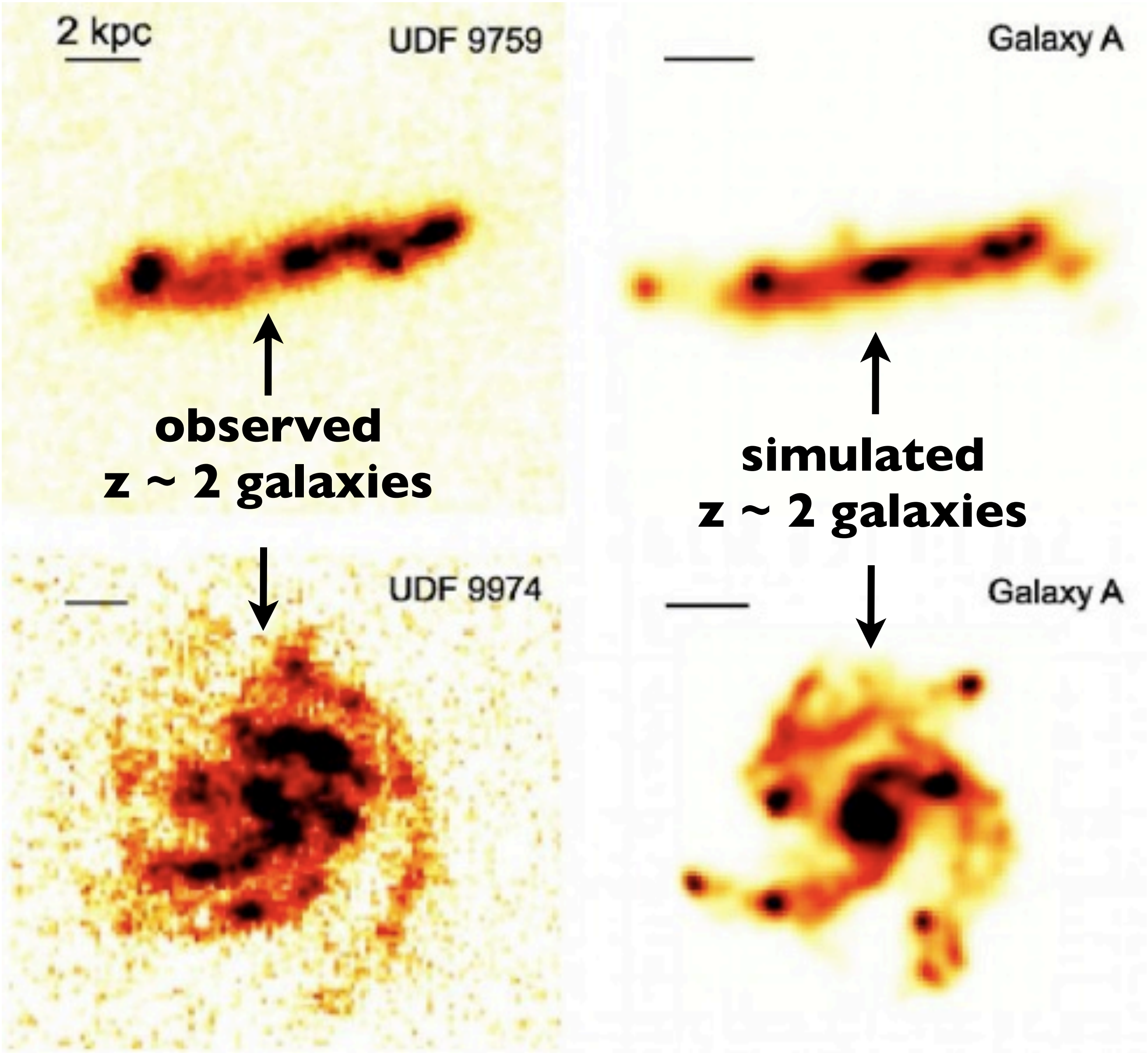
simulated z ~ 2 galaxy

Face-on

Bassi computer, NERSC

Edge-on

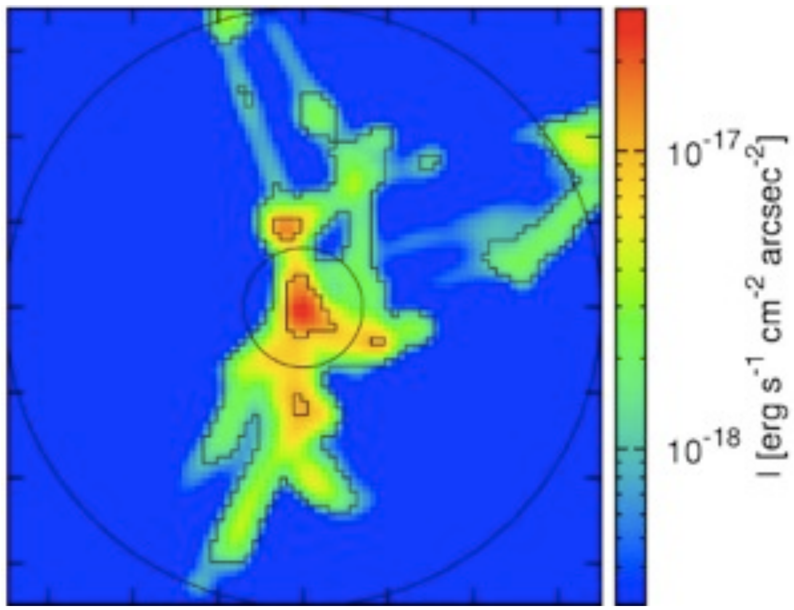
now running on NAS
Schirra computer



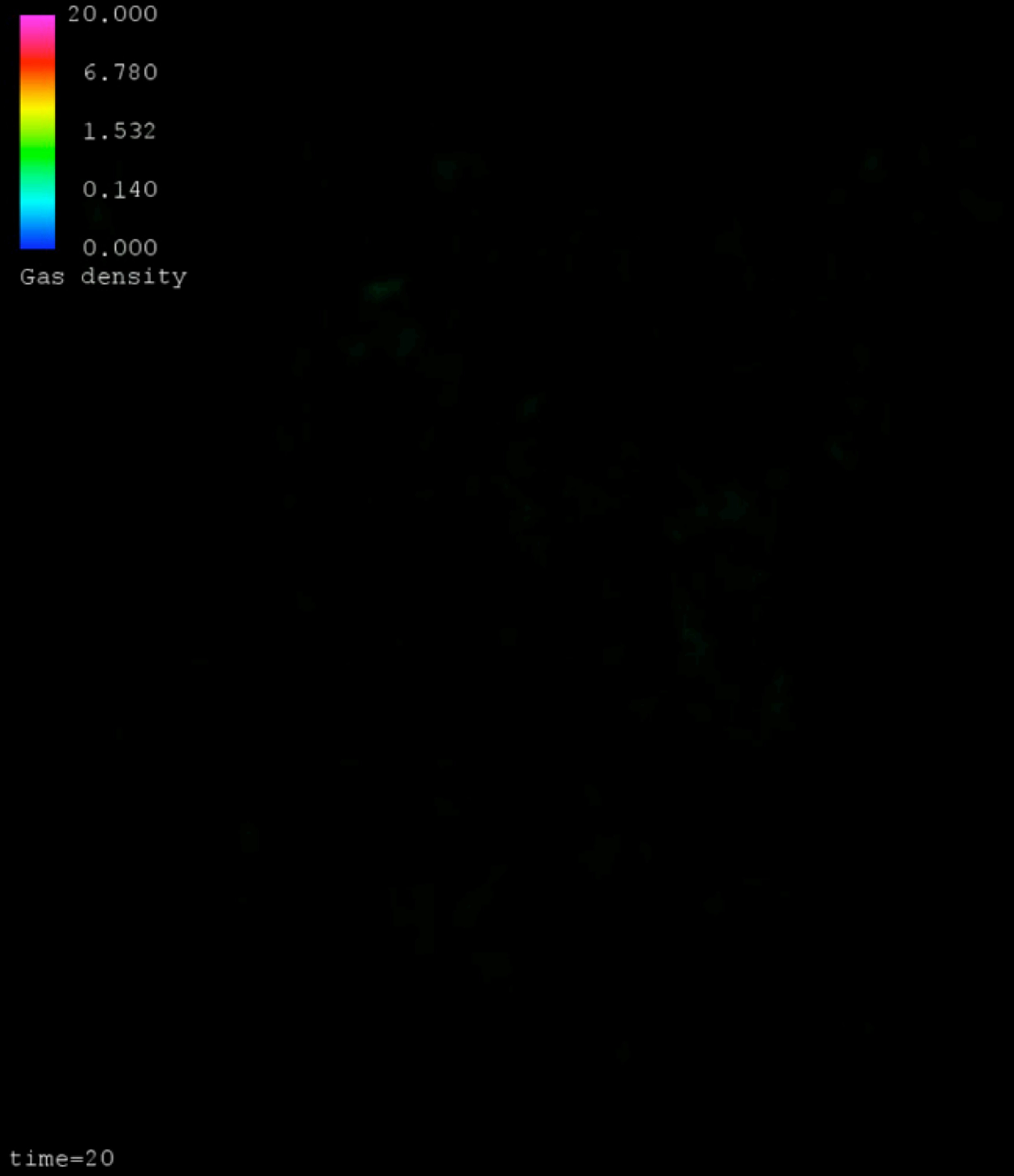
observed z ~ 2 galaxies

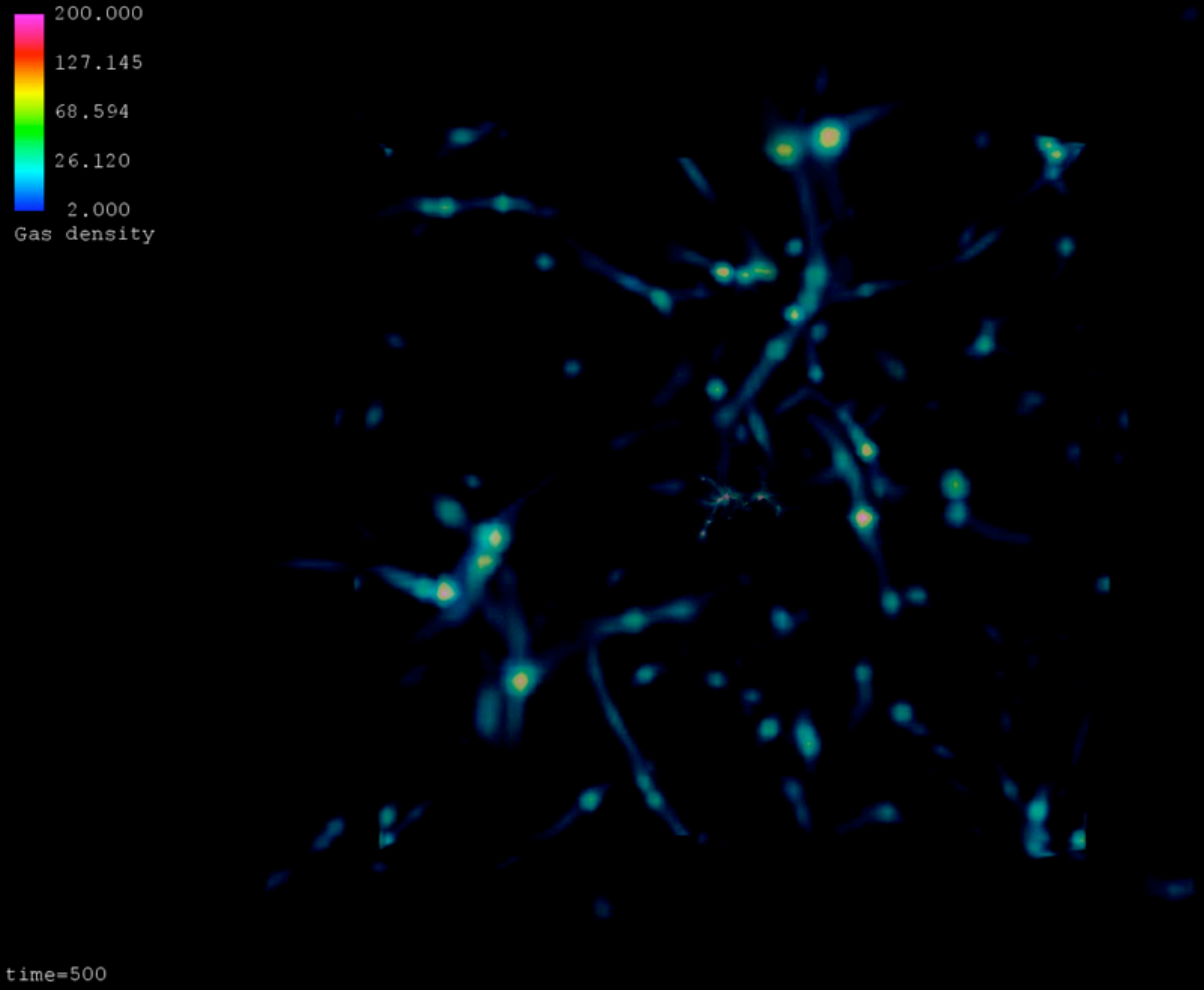
simulated z ~ 2 galaxies

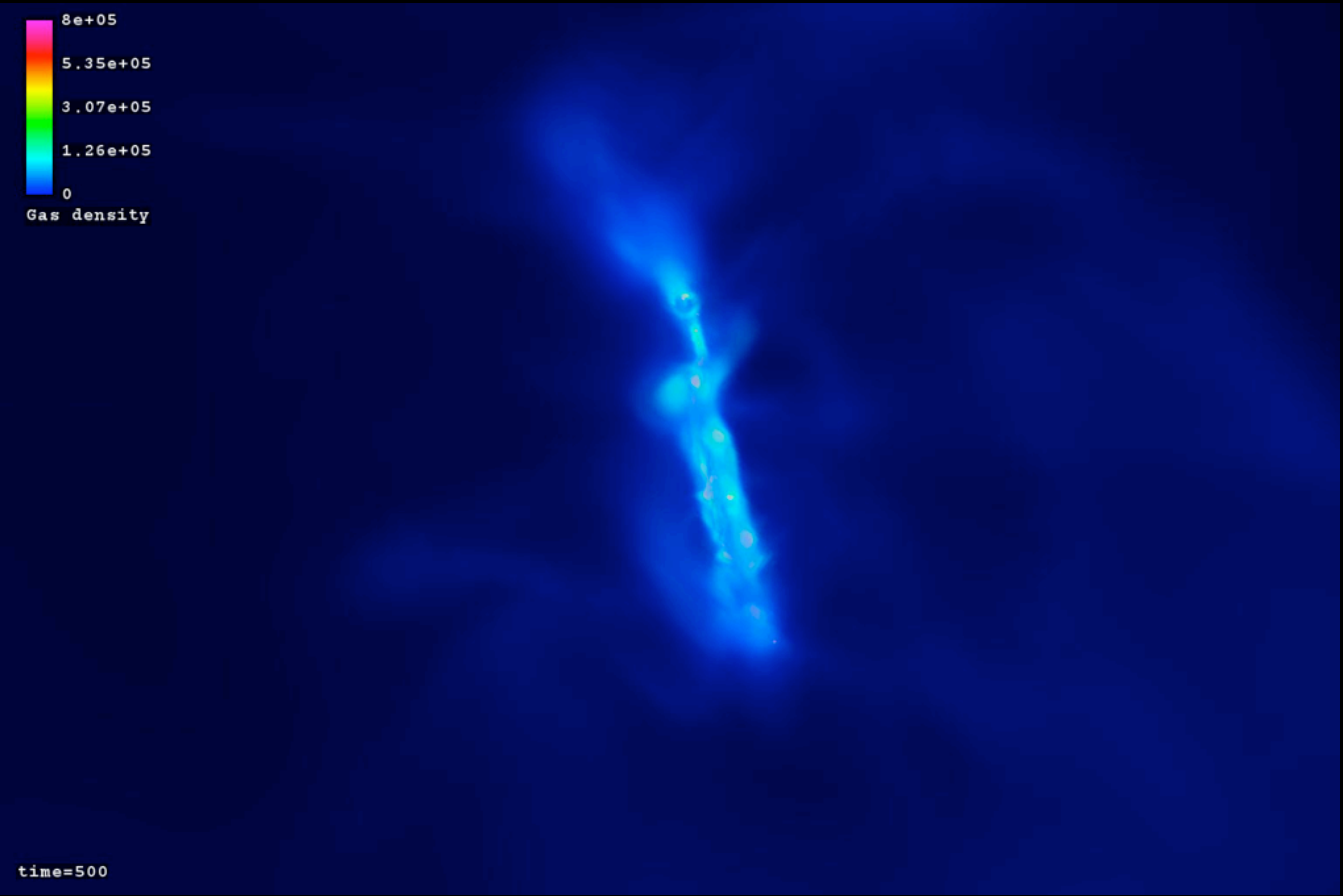
simulated z ~ 2 galaxy



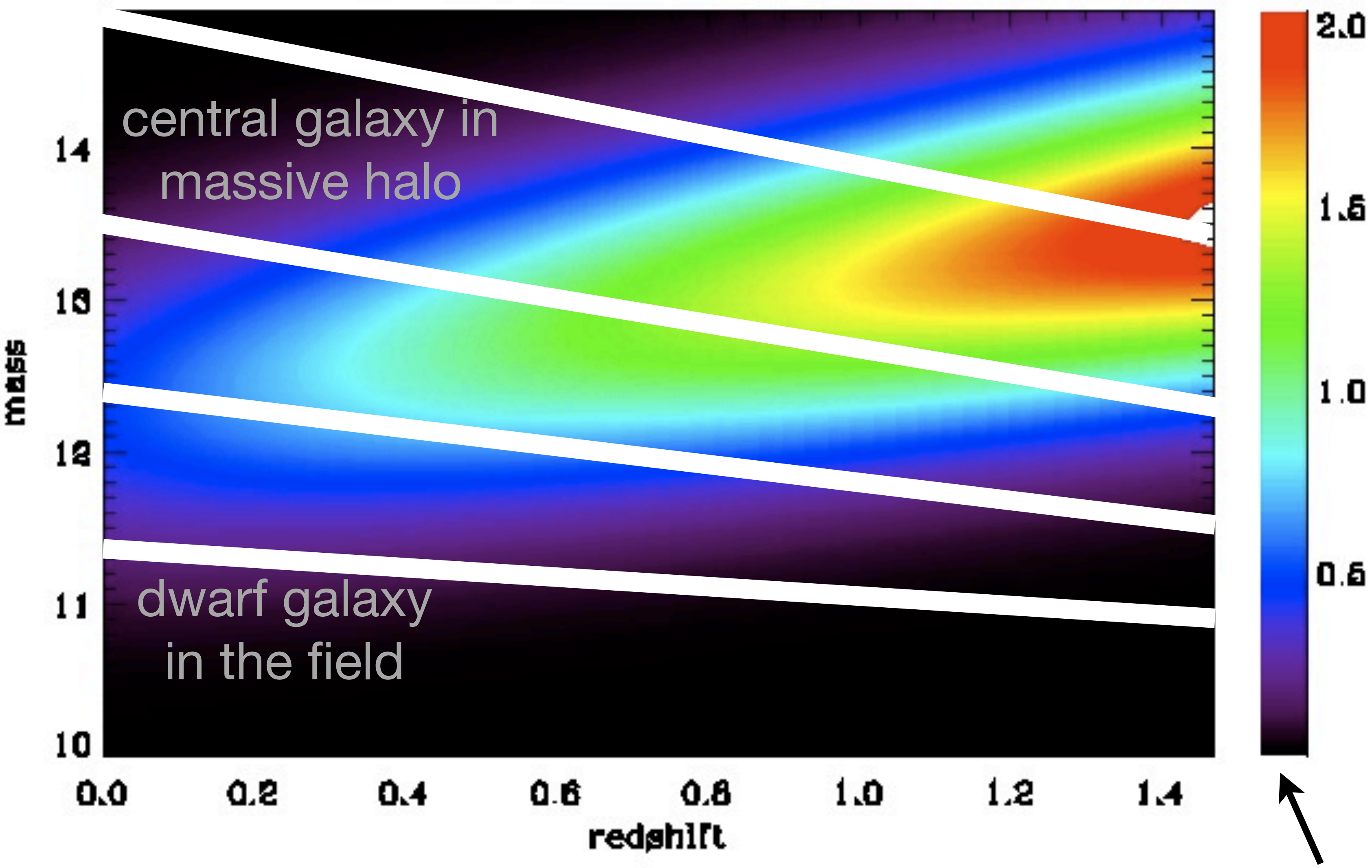
Ly alpha blobs from same simulation
Goerdt et al. 2010


20.000
6.780
1.532
0.140
0.000
Gas density
time=20


200.000
127.145
68.594
26.120
2.000
Gas density
time=500


8e+05
5.35e+05
3.07e+05
1.26e+05
0
Gas density
time=500

Star Formation Rate in Dark Matter Halos



Typical galaxy trajectories

log Star Formation Rate
(solar masses per year)

basic trends in galaxy formation

- massive halos host more massive galaxies (they spend more time rapidly forming stars)
- massive halos host older galaxies (they start forming stars earlier)
- massive halos host higher surface brightness galaxies (they formed more stars when the universe was denser)
- low mass galaxies always form galaxies slowly

naturally explains observed "downsizing" : massive galaxies form stars earlier

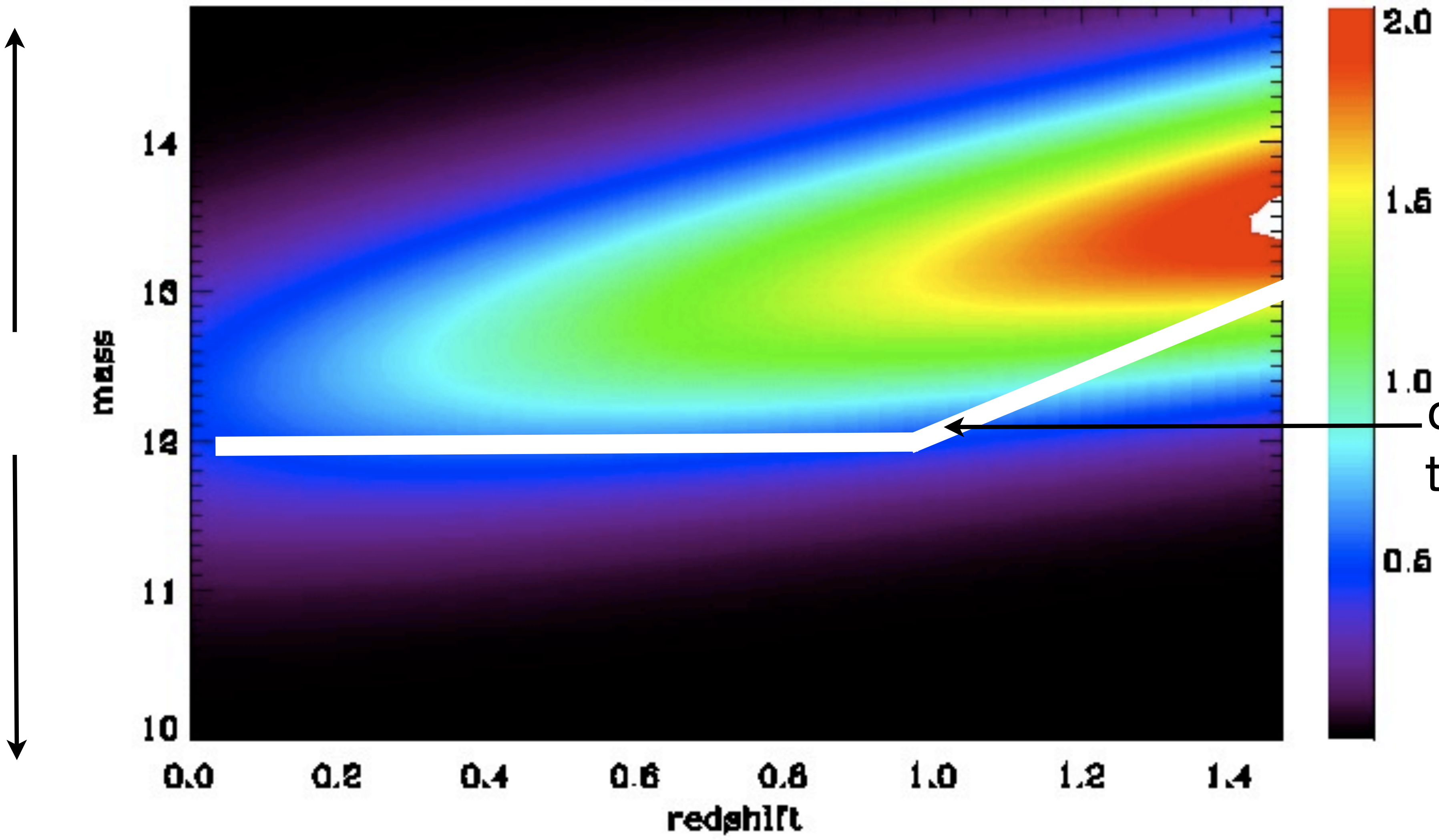
predicts "upsizing" at high redshifts: star formation rate increasing

Risa Wechsler

What does this imply about the physics?

AGN feedback
shock heating
inefficient cooling

SN feedback
feedback from SF
photoionization



cold flow
transition
mass

- Model implies that star formation slows for masses greater than M~1e12 halos (roughly the scale where galaxy bimodality sets in) today

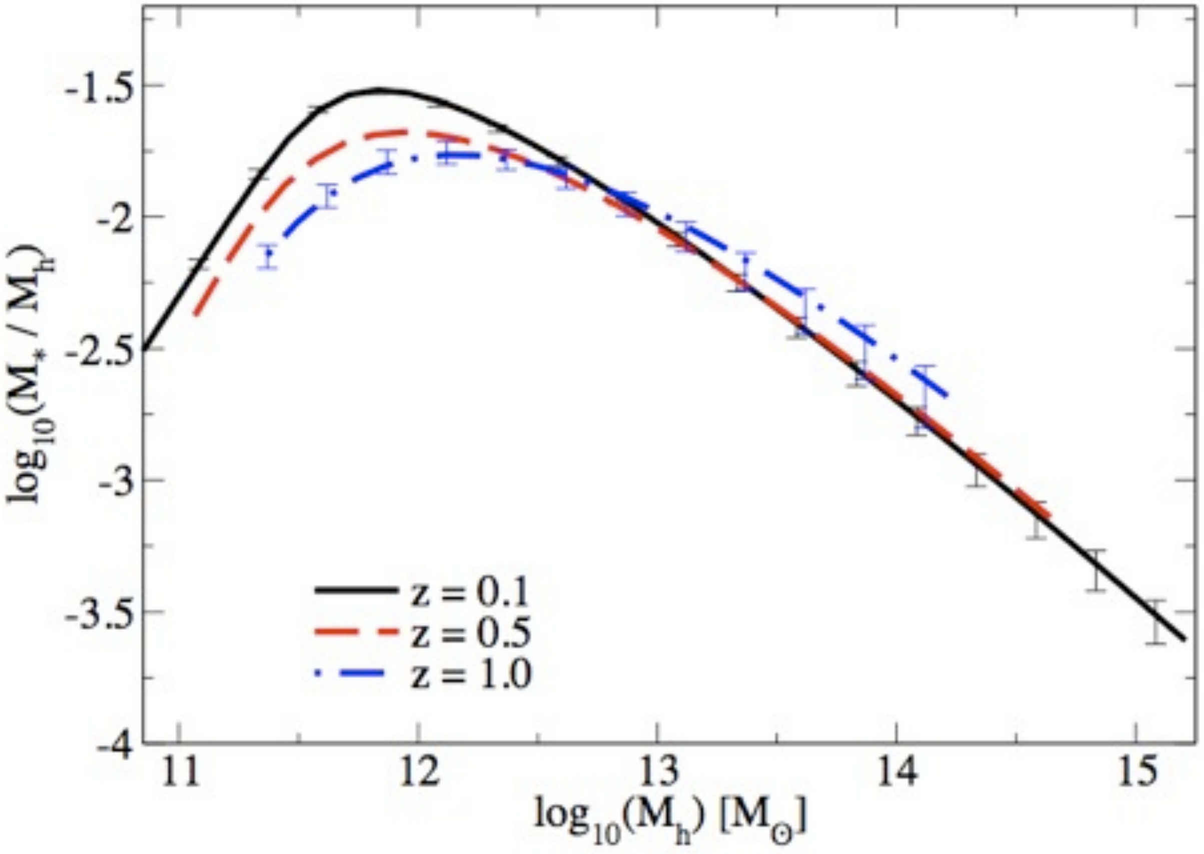
How well is this connection constrained?

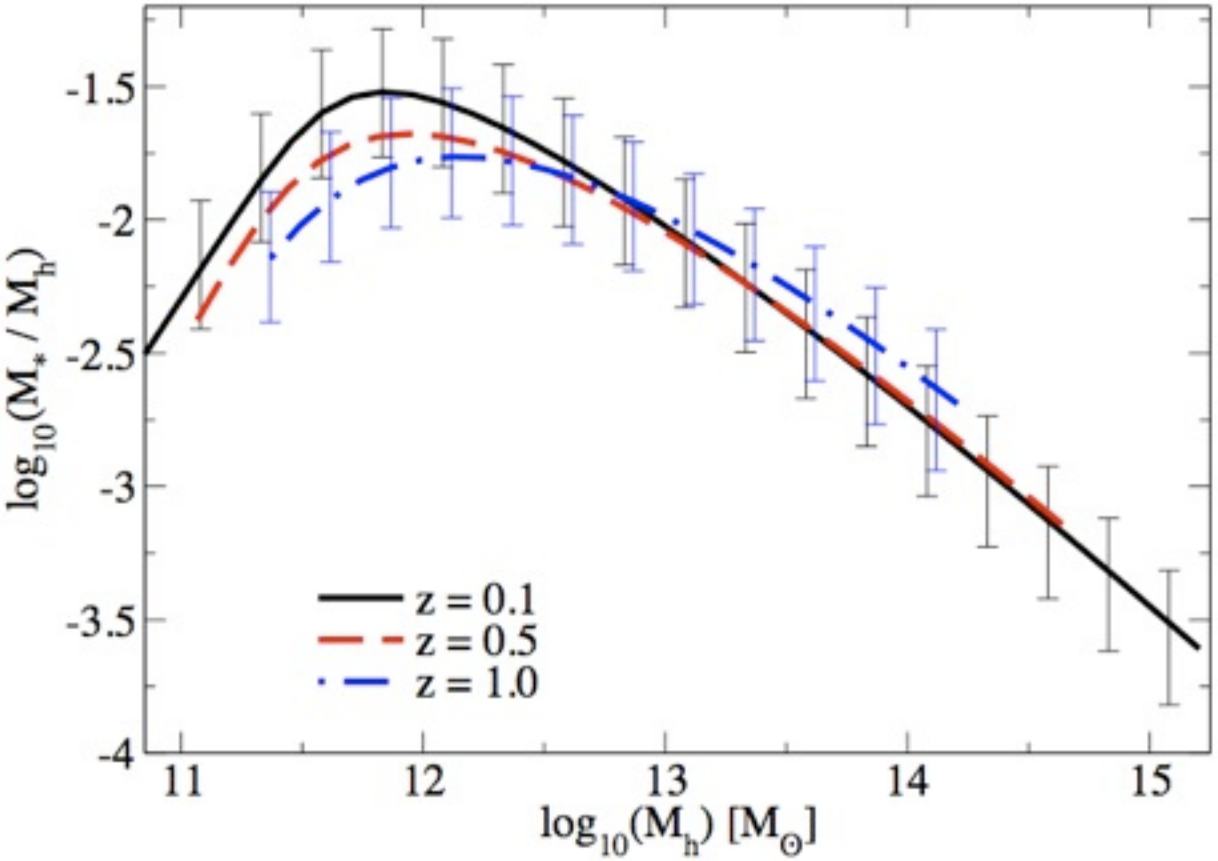
consider errors in: mass function, stellar mass function, scatter, cosmology, matching algorithm

Behroozi, Conroy & RW (2010)

statistical errors only

systematic errors





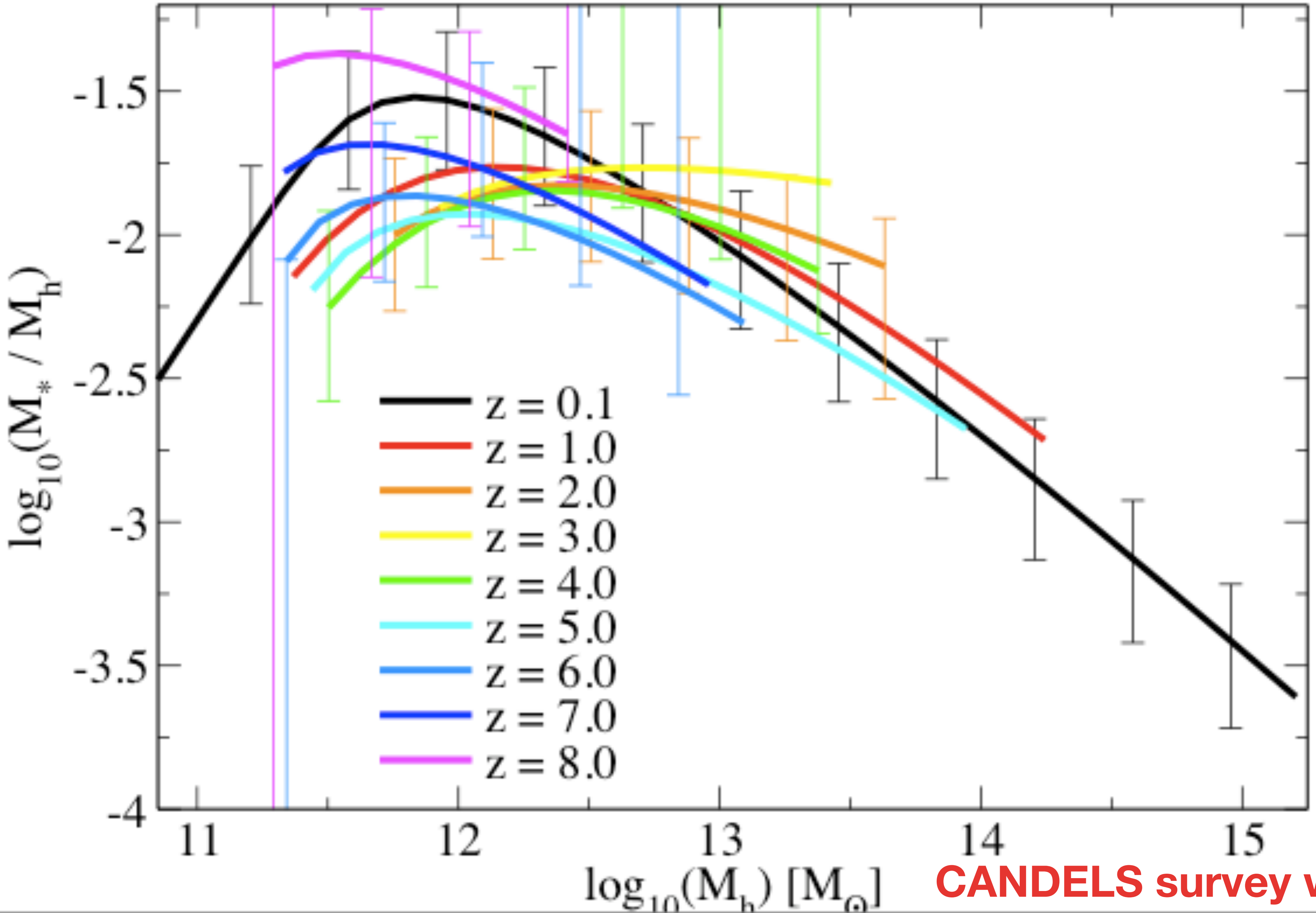
includes poisson and sample variance errors, uncertainty due to scatter in M*-M

includes random errors in stellar masses, possible systematic errors in the stellar mass function

current uncertainty due to cosmological model is smaller than systematic errors in stellar mass function

What about at very high redshift?

use Marchesini et al stellar mass function to z ~ 4; Stark et al stellar mass function z = 4-6; new HST WFC3 results (Bouwens et al , Gonzalez et al, 2010)



Risa Wechsler

CANDELS survey will help!

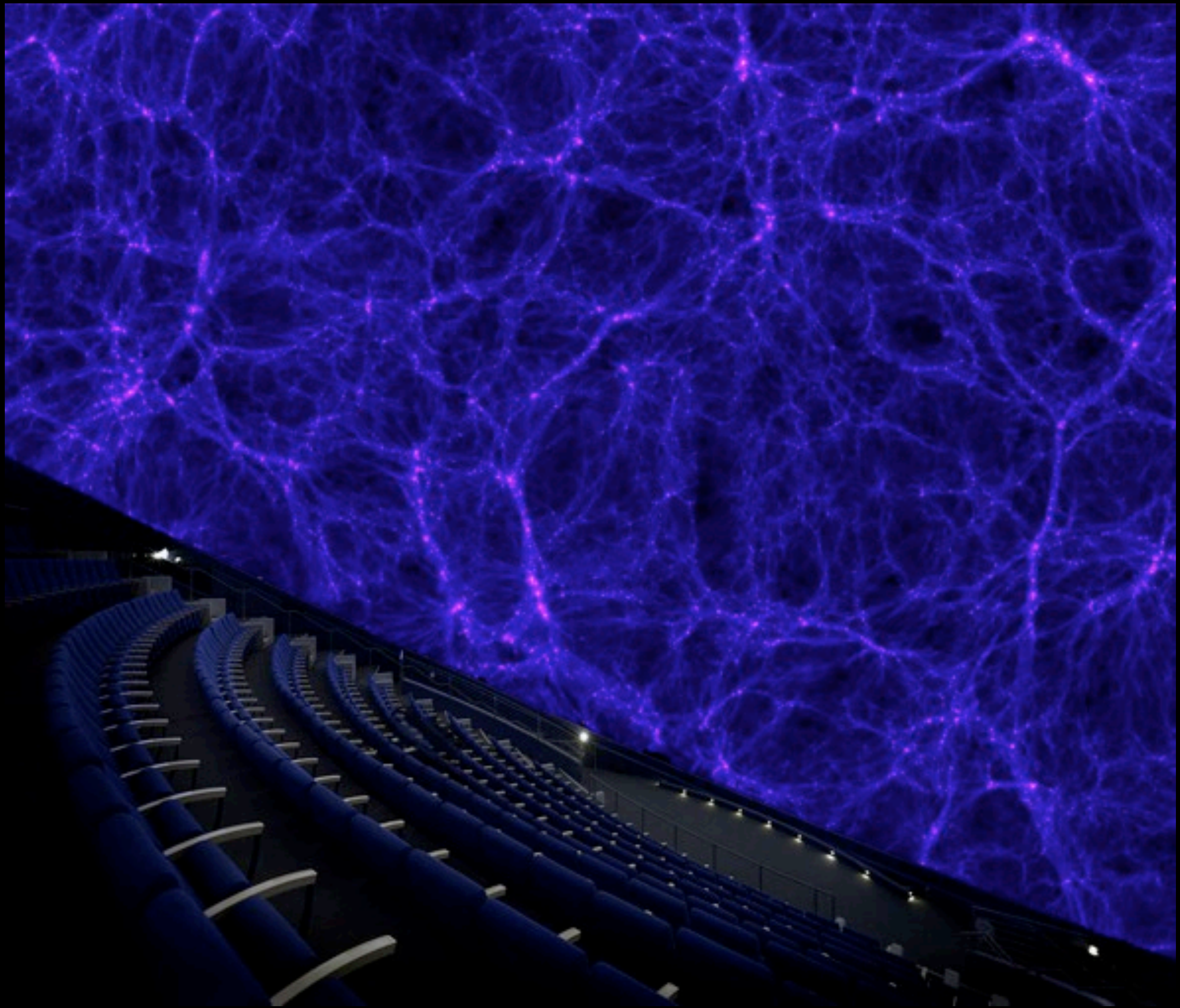
Astro-Computation Visualization and Outreach

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


Pleiades Supercomputer
NASA Ames


California
Academy of Sciences


Adler Planetarium
Chicago



HIPACC is working with the Morrison Planetarium at the California Academy of Sciences (pictured here) to show how dark matter shapes the universe. We are helping prepare their planetarium show opening fall 2010, and also working on a major planetarium show to premiere at the Adler Planetarium in spring 2011.

Galaxy Merger Simulation

Run on Columbia **Supercomputer at NASA Ames Research Center.**
Dust simulated using the Sunrise code (Patrik Jonsson, UCSC/Harvard).

Astronomical **observations** represent snapshots of particular moments in time; it is effectively the role of astrophysical simulations to produce movies that link these snapshots together into a coherent physical theory.

Showing Galaxy Merger simulations in 3D will provide a deeper, more complete picture to the **public** and scientists alike.

COSMOLOGY: Ripe Questions Now
Lots of great projects for you to do!

Nature of Dark Matter - ΛCDM $n_{\mathrm{halos}}(V_{\mathrm{max}},z)$, clustering vs. observations

Nature of Dark Energy - using SN1a

How Galaxies Form and Evolve

- Early galaxies and reionization: pop III?, escape fraction, upsizing
- Mechanisms of early SF and AGN: gas-rich mergers *vs.* cold inflows
- What quenches SF: AGN, shock heating for $M_{\mathrm{halo}} > 10^{12}\,M_{\mathrm{sun}}$, morphology
- Evolution of galaxy morphology: need new morphology measures
- Evolution of galaxy kinematics and metallicity (need spectra)
- Extragalactic Background Light (EBL): measure, constrain with γ-rays

Theoretical Approaches

- Simulations: dissipationless, hydrodynamic
- Mock catalogs, Sub-Halo Abundance Matching (“SHAM”)
- Semi-Analytic Models (SAMs) constrained by simulations & observations
- Toy Models to clarify key astrophysical processes

Thanks for your attention!

Any questions?