Simulating the Sky

Or: Creating, Testing, and Using
Simulations of the Galaxy Population
in the era of surveys of 10 billion galaxies

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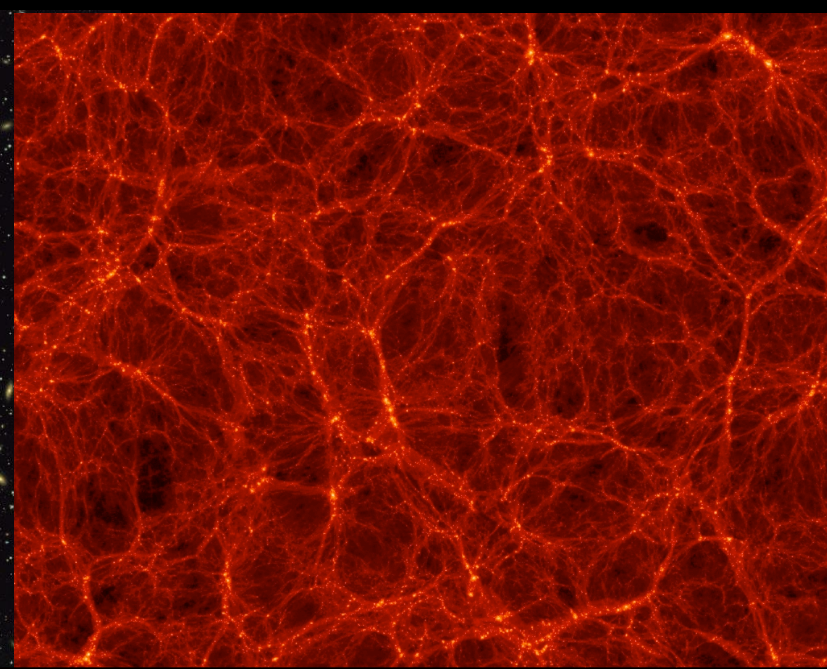
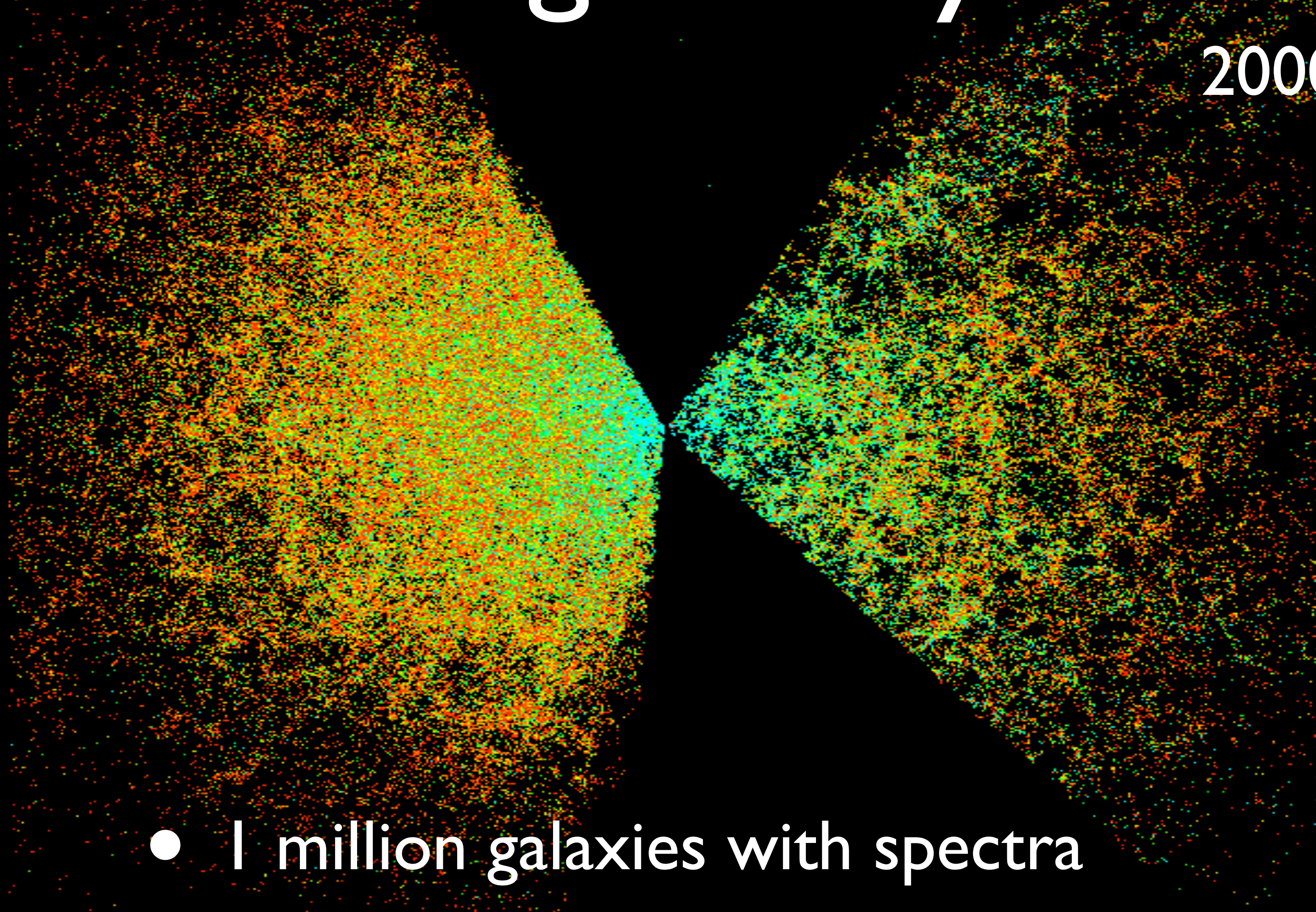


what are we trying to simulate?

Sloan Digital Sky Survey

2000-2010



- 1 million galaxies with spectra
- 200 million galaxies with photometry
- 1/4 of the sky

Deep Surveys

Hubble Ultra Deep Field

~10000 galaxies over

1/13 millionth of the sky

implies ~100 billion galaxies to this depth

CANDELS

2010-2013

- Largest ever HST project (902 orbits)
- ~250,000 galaxies from $1 < z < 8$
- deep multi-wavelength data
- 800 sq. arcminutes (1 /200,000th of the sky)

BOSS

2010-2014

- 1.3 million spectra
- 1/4 sky
- primarily red luminous galaxies from $0.45 < z < 0.7$

The Dark Energy Survey

2012-2018

300 million galaxies

1/8 of the sky

~ 2.5 magnitudes deeper than SDSS

g,r,i,z,Y + overlap with VISTA (JHK) + SPT

first light October 2012

LSST

2018-2028

- 10 billion galaxies
- half the sky
- 5 magnitudes deeper than SDSS
- image every 3 nights
- 30 TB/night, ~100 PB over 10 years

and many more

- PANSTARRS
- Skymapper
- BigBoss
- JWST
- Euclid
- WFIRST
- large HI surveys
- deep spectroscopy on 30 m
- next generation spectroscopic surveys...

what aspects are important?

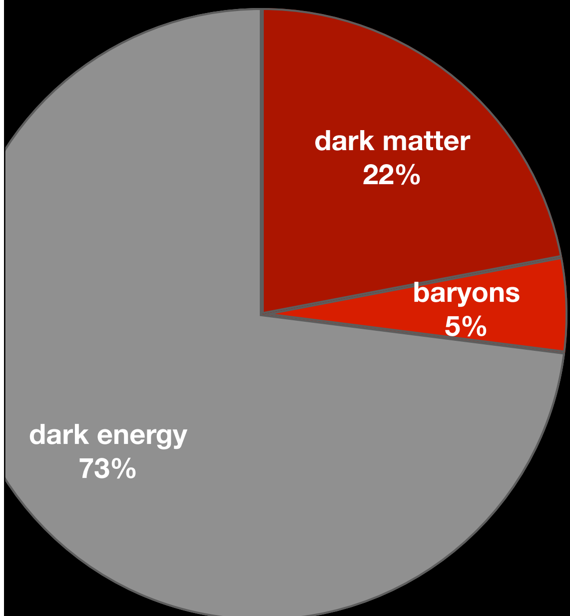
- galaxy positions
- magnitudes
- colors
- SEDS
- shapes
- sizes
- morphologies, including substructure within galaxies
- impact of lensing (shear, magnification, multiple images)
- impact of the atmosphere and telescope
- correlations between all of the above
- scales from very small (object detection) to very large (size of surveys; several Gpc)

almost
everything.

changing paradigm of simulations in astronomy

- old: simulations provide basic properties, e.g. mass function, power spectrum, links between one galaxy population and another, tool for exploring physics and basic physical understanding.
- new: simulations are integrated into analysis framework. analysis is done in parallel on real and simulated data. in many cases robust & meaningful scientific conclusions are not possible without simulations.

the cosmological model



- we have a standard cosmological model

current cosmological model can be described by
7 cosmological parameters --
amount of:
dark matter, baryons, dark energy
+ neutrinos (<0.1%)
expansion rate (h)
size of the fluctuations (A/s8)
how the fluctuations vary with scale (n)
+ the optical depth to reionization

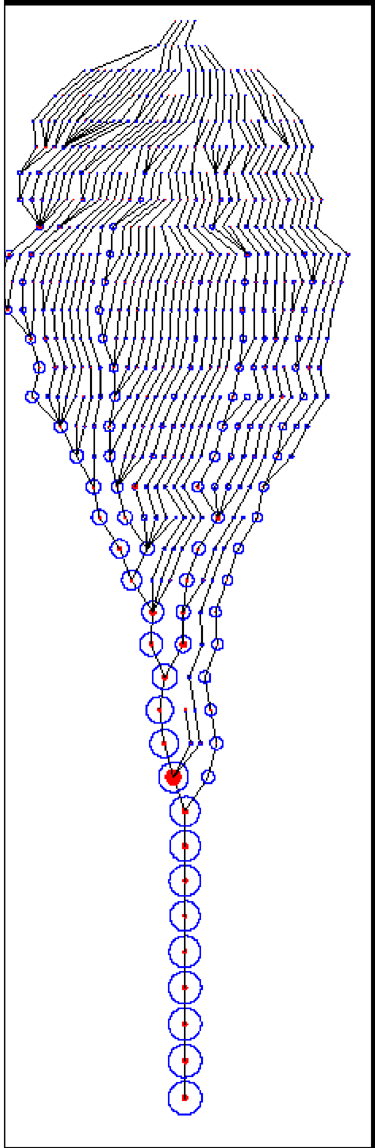
is this model correct in detail?

need to make detailed
predictions for what the
universe looks like,
in the context of this model,
and test them against the data.

simulations:
Wu, Hahn & Wechsler
visualization: Ralf Kaehler

dark matter halos are the basic unit of
structure formation and of galaxy formation

galaxy formation



- we have a basic paradigm.
- galaxies form in dark matter halos - every halo massive enough to form stars hosts a galaxy
- we know how these dark matter halos form and grow over time; this controls how galaxies merge and grow
- most physical processes that might contribute are understood at a basic level.
- relative importance, interactions still unclear

galaxy formation

determining which physical processes
dominate in galaxy formation
requires exploring parameter space
with both detailed hydrodynamical
simulations and semi-analytic models

dark matter

- 85% of the mass in the Universe.
- surveys are mapping out *where* it is, in precise detail.
- determining *what* it is requires detailed predictions of the cosmological model.

dark matter

determining the mass and cross section of the dark matter particle will take both particle physics and astrophysics

examples of where we need large simulations:

(a) need to understand the cosmological context of the MW: very large volume.

(b) need to understand very small substructures and the impact of baryons: very high resolution.

dark energy

(+ inflation, neutrino mass, modified gravity, etc.)

- galaxy clustering (BAO, galaxy power spectrum, small scale clustering)
- galaxy cluster abundance
- weak lensing (shear power spectrum, galaxy galaxy lensing)

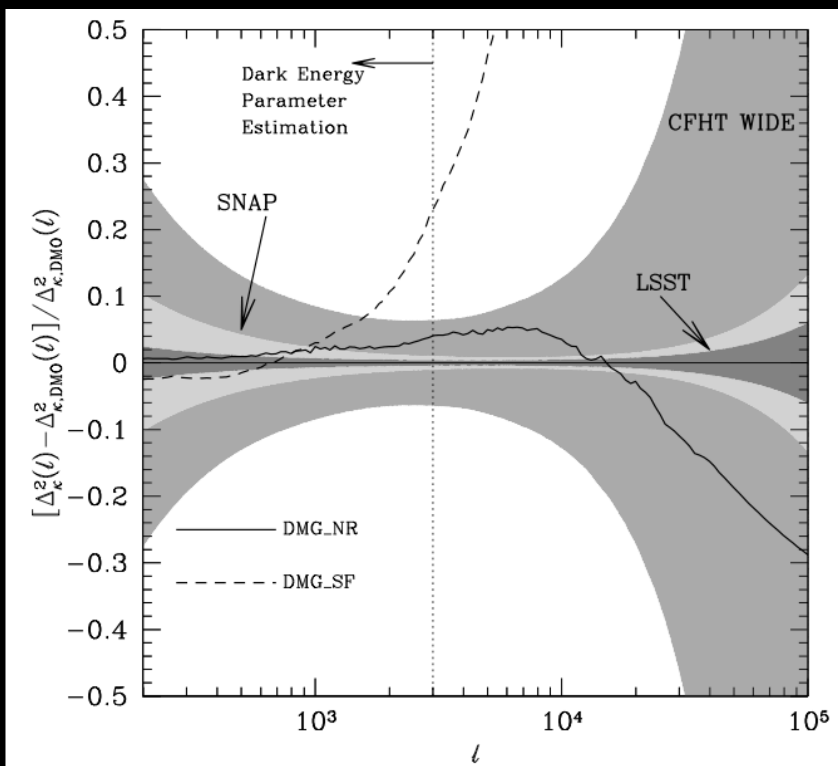
dark energy

main cosmological probes already are or soon will be in the systematics dominated regime

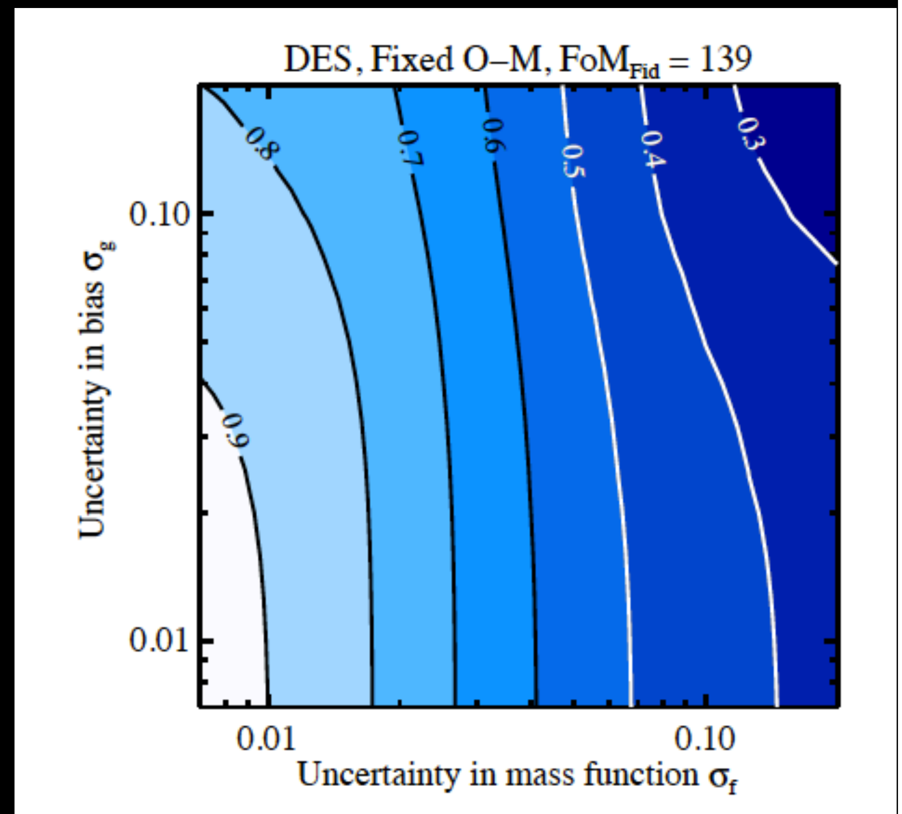
theory systematics: need to get from ~7++ parameters specifying the cosmological model to better than 1% predictions for structure formation and its *observable tracers*, e.g. observable properties of clusters, observable impact of shear, observable galaxy clustering

observational systematics: e.g. star-galaxy separation, deblending, photometry, cluster miscentering

precise requirements



Rudd, Zentner & Kravtsov et al 2008



Wu, Zentner & Wechsler et al 2010

use of simulations in interpreting survey data

★ several goals that require the same sort of simulations, e.g.:

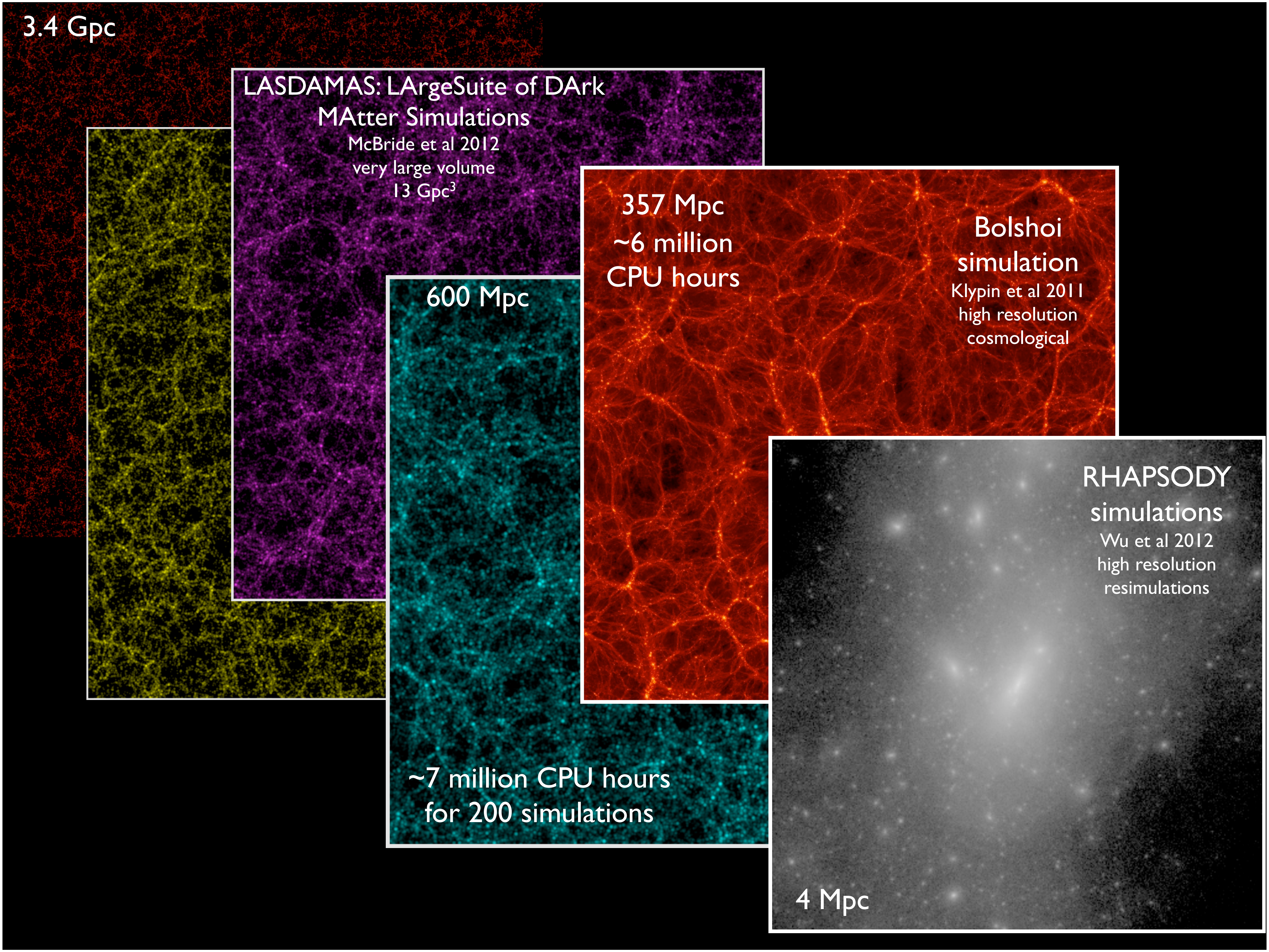
- precise predictions for a variety of structure formation probes
- development and *verification* of science ready codes to work on large volumes
- understanding the instrument
- understanding observational systematics
- covariance matrices to determine error bars. needed not just for one measurement, but for many (e.g.: lensing, galaxy clustering, galaxy clusters)
- impact of galaxy formation & galaxy selection (type dependent bias)

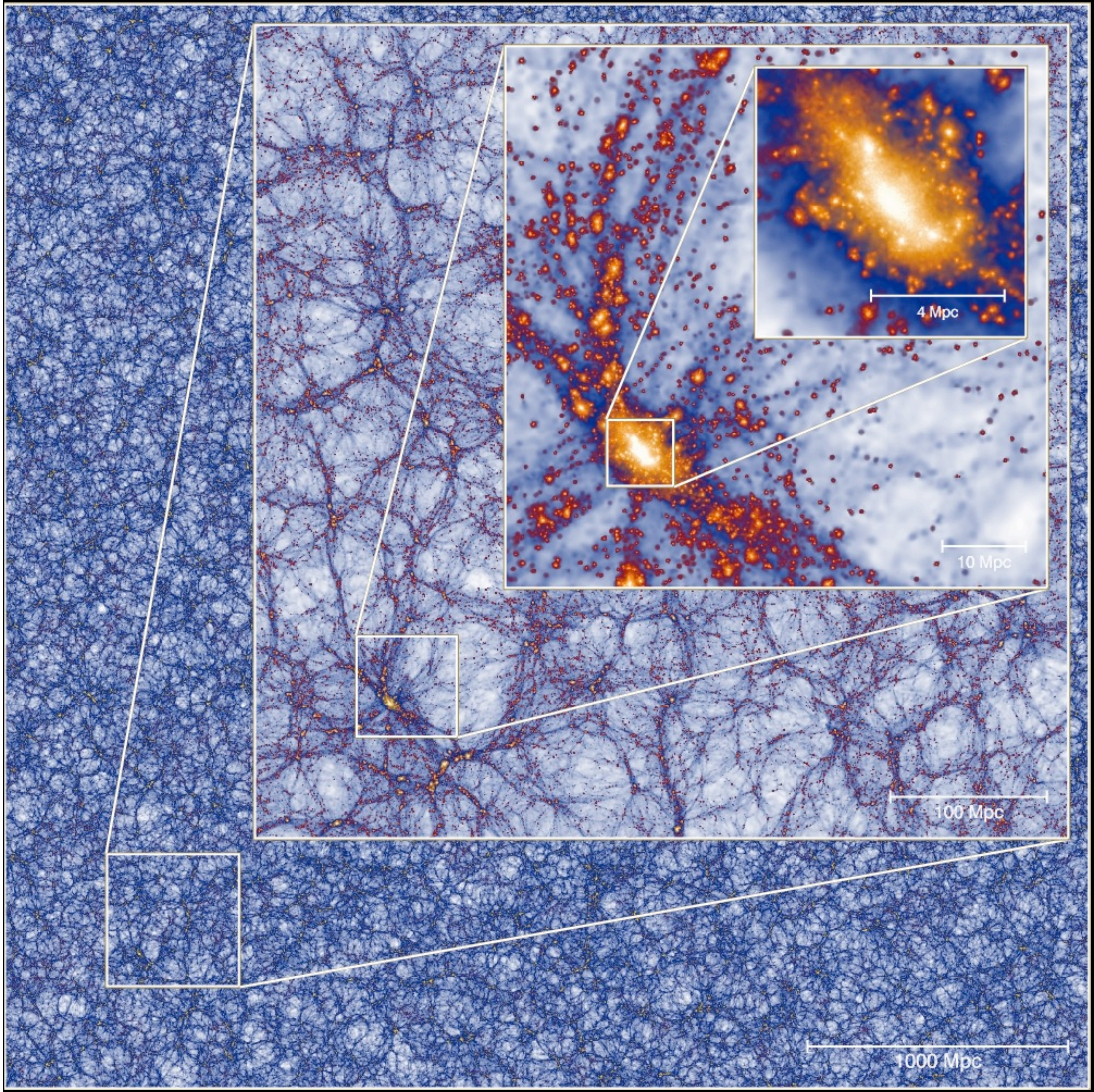
okay.

- so you want to simulate 10-100 million galaxies over the whole sky.
- you want to understand the impact of
  - cosmological model
  - galaxy formation physics
  - observational systematics

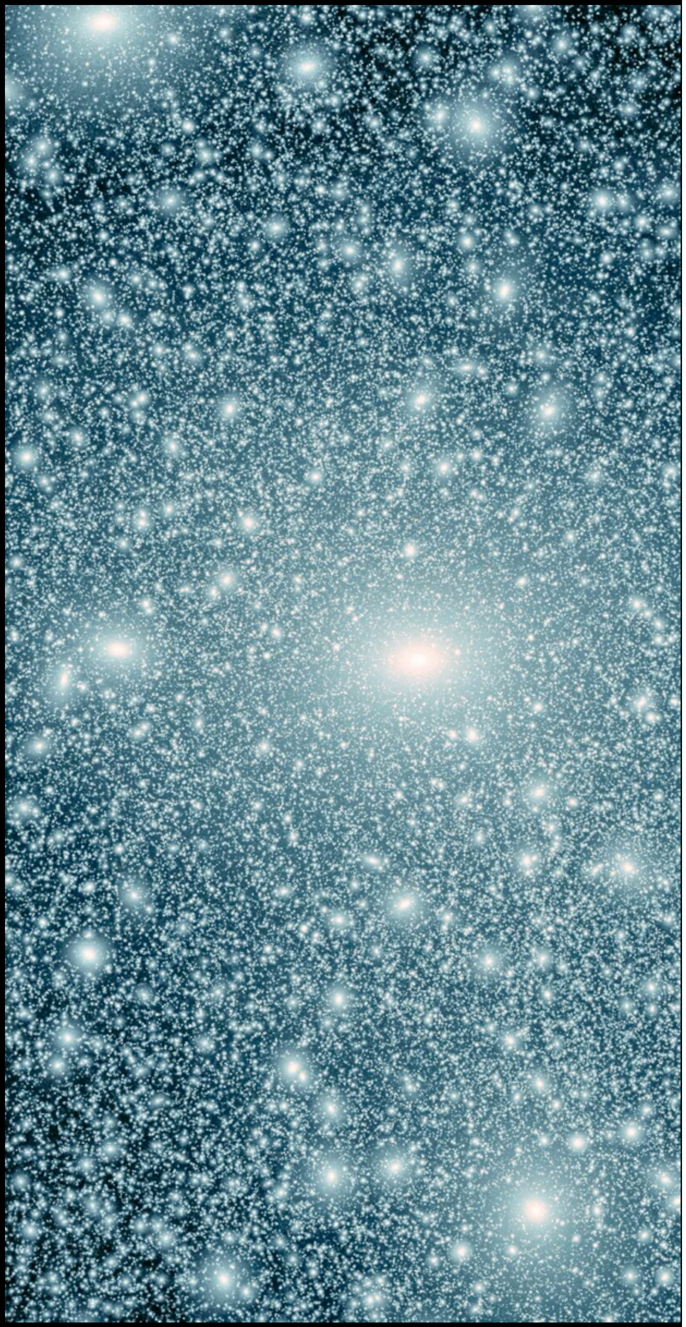
  on the observables of this galaxy population.
- you want to do this to better than 1% accuracy for several observables.
- you want to do it in more volume than is observed.

sounds easy :)

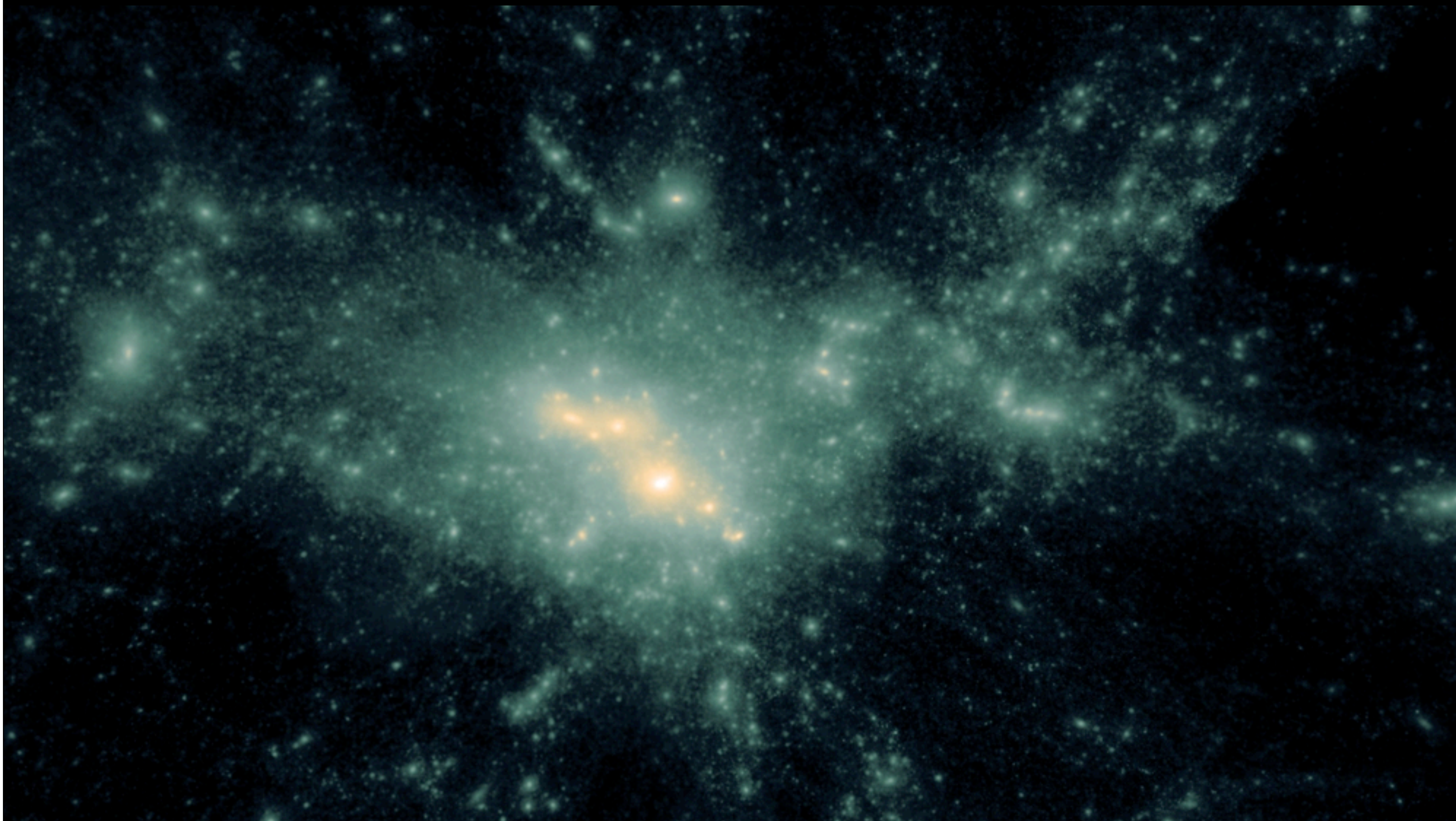

3.4 Gpc
LASDAMAS: LArgeSuite of DArk MAtter Simulations
McBride et al 2012
very large volume
13 Gpc^3
600 Mpc
~7 million CPU hours
for 200 simulations
357 Mpc
~6 million
CPU hours
Bolshoi
simulation
Klypin et al 2011
high resolution
cosmological
RHAPSODY
simulations
Wu et al 2012
high resolution
resimulations
4 Mpc



largest single simulation: Millennium XXL
(300 billion particles)

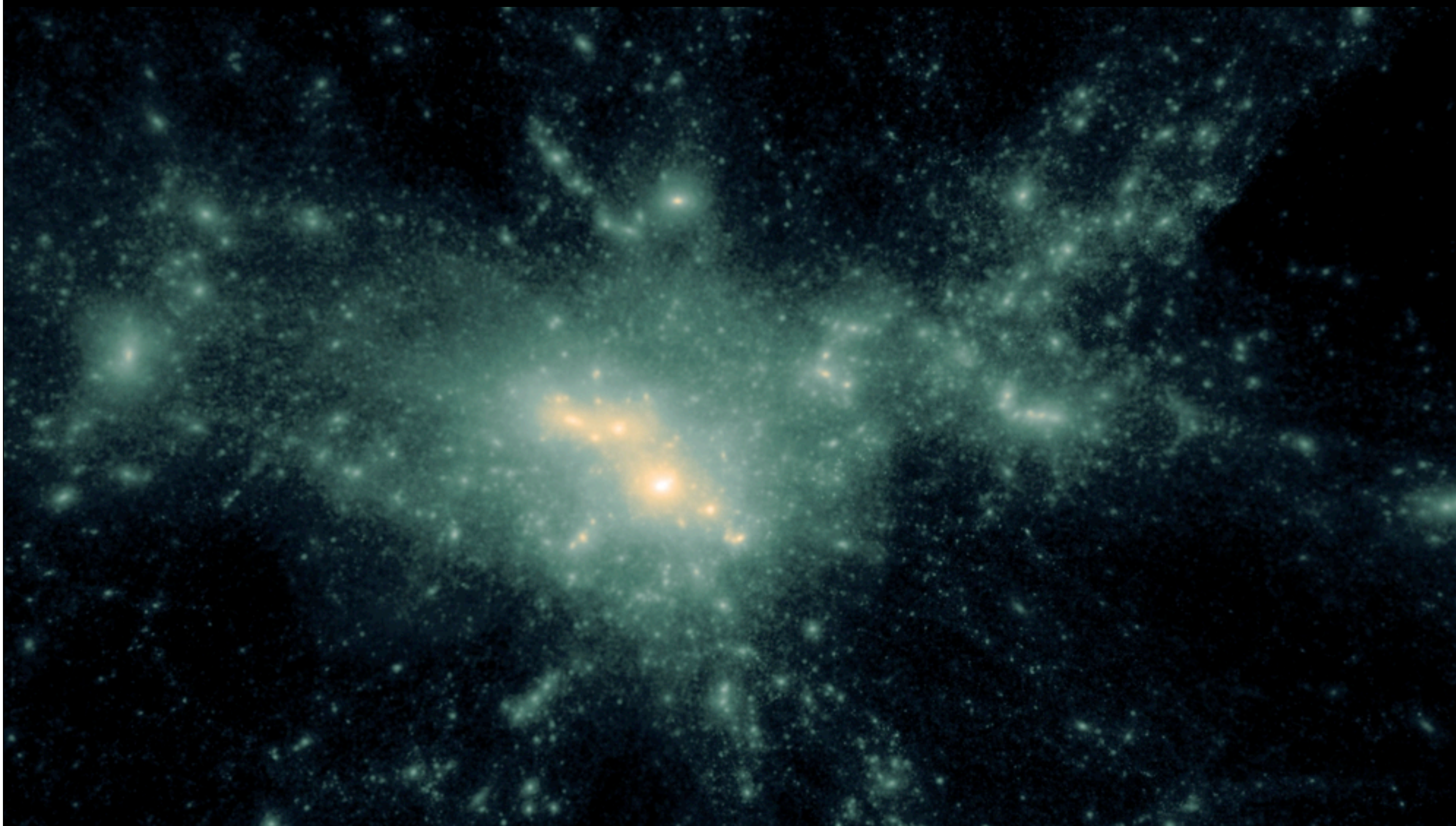


largest single halos:
Phoenix, Ghalo, Aquarius, via Lactea



dark matter halos are the basic unit of structure formation and of galaxy formation

resolve
dark matter halos
for the galaxies
you want to model
properly.



galaxies also live in substructures

resolve
dark matter halos
and substructures
for the galaxies
you want to model
properly.