Simulating Formation of Structures in the Universe

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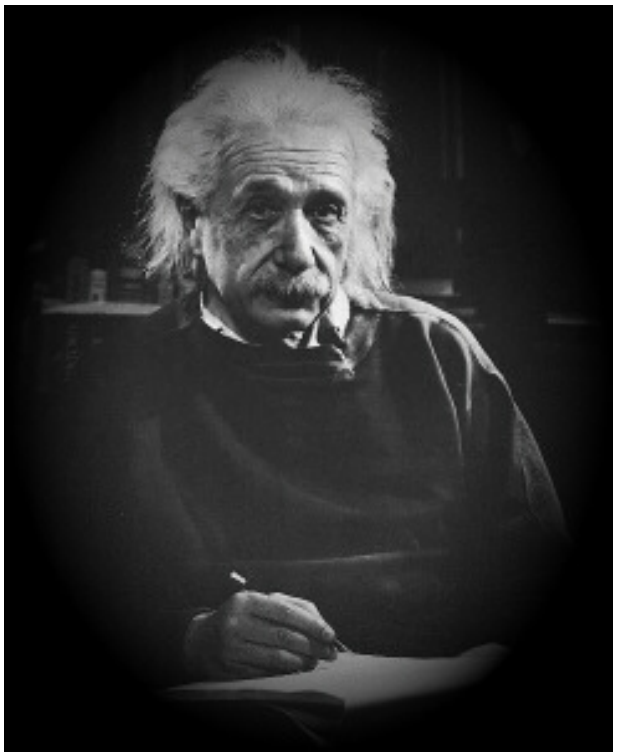
http://astro.uchicago.edu/~andrey/talks/shortcourse05/

Einstein's Cosmological Principle: the foundation of cosmology



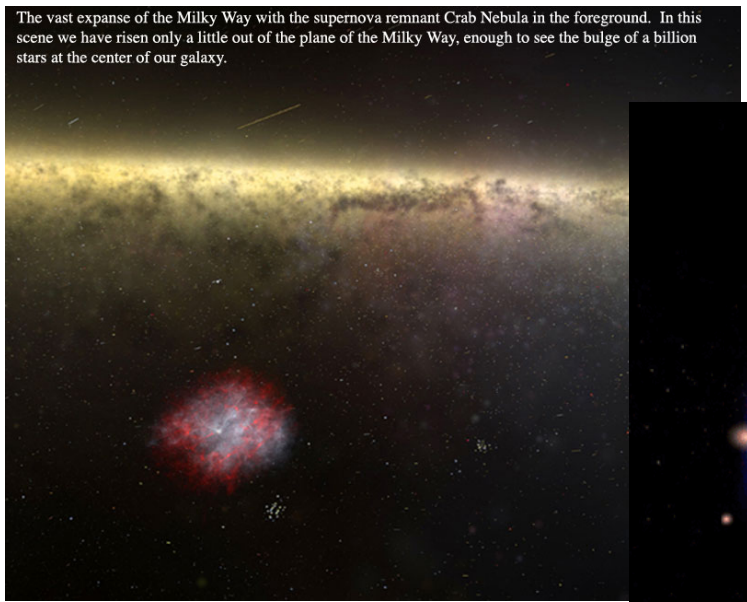
Albert Einstein
(1878-1955)

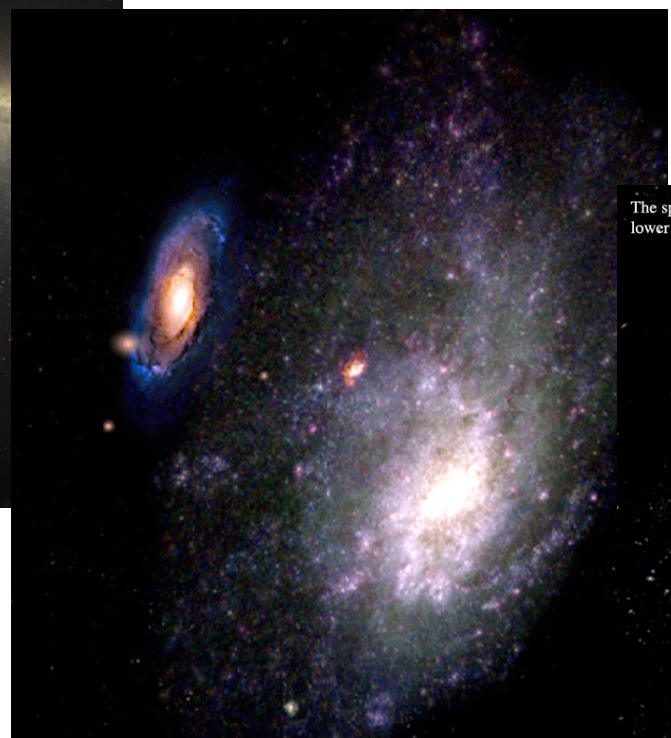
The Universe, on average, is

homogeneous (equal density everywhere if averaged over a sufficiently large volume) and ***isotropic*** (it looks the same in all directions)

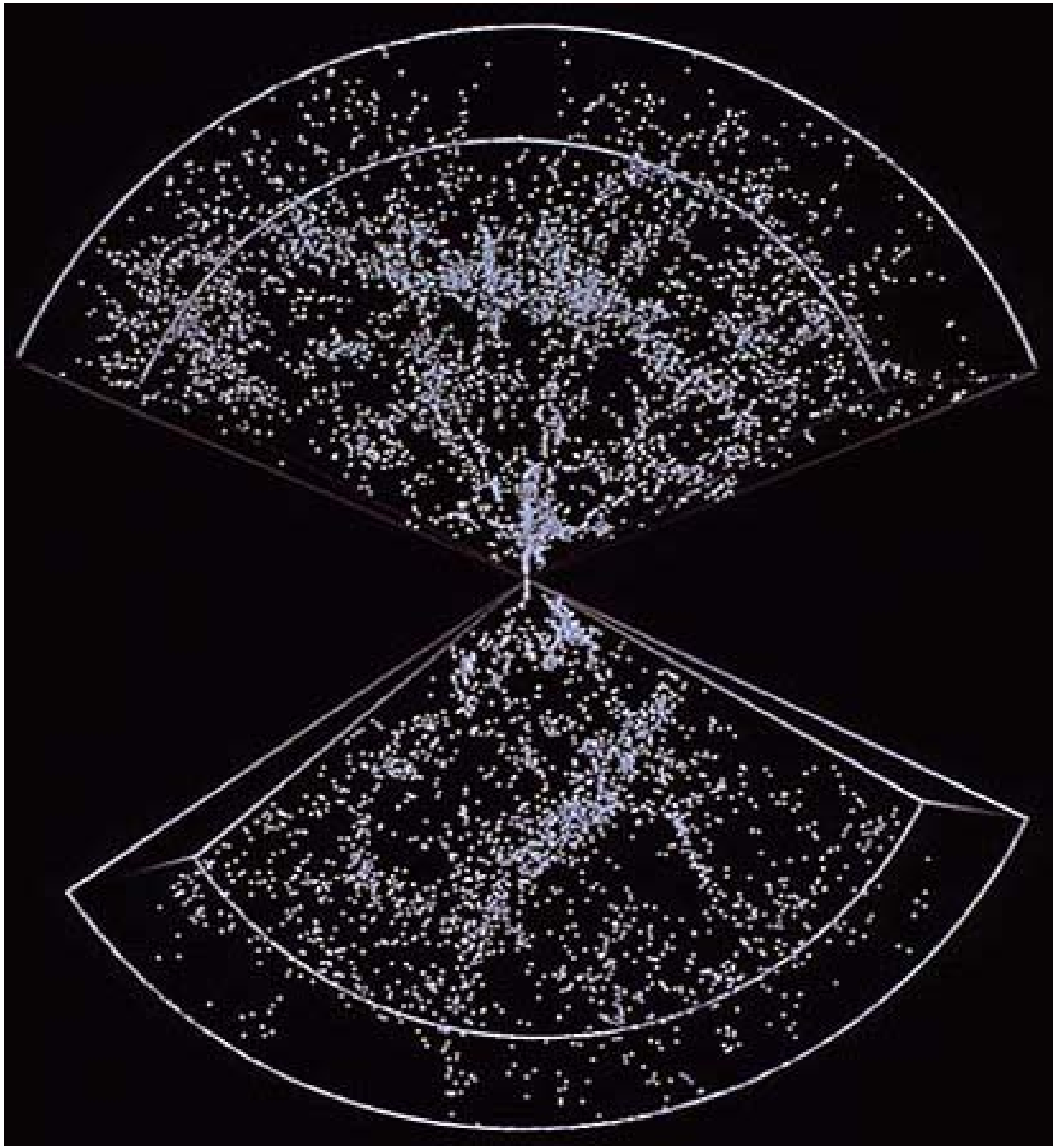
Are observations consistent with this?

Structures in the neaby Universe:
from the Milky Way to the Local Supercluster





Images, animation, data are from Brent Tully's excellent page
http://www.ifa.hawaii.edu/~tully/outreach/

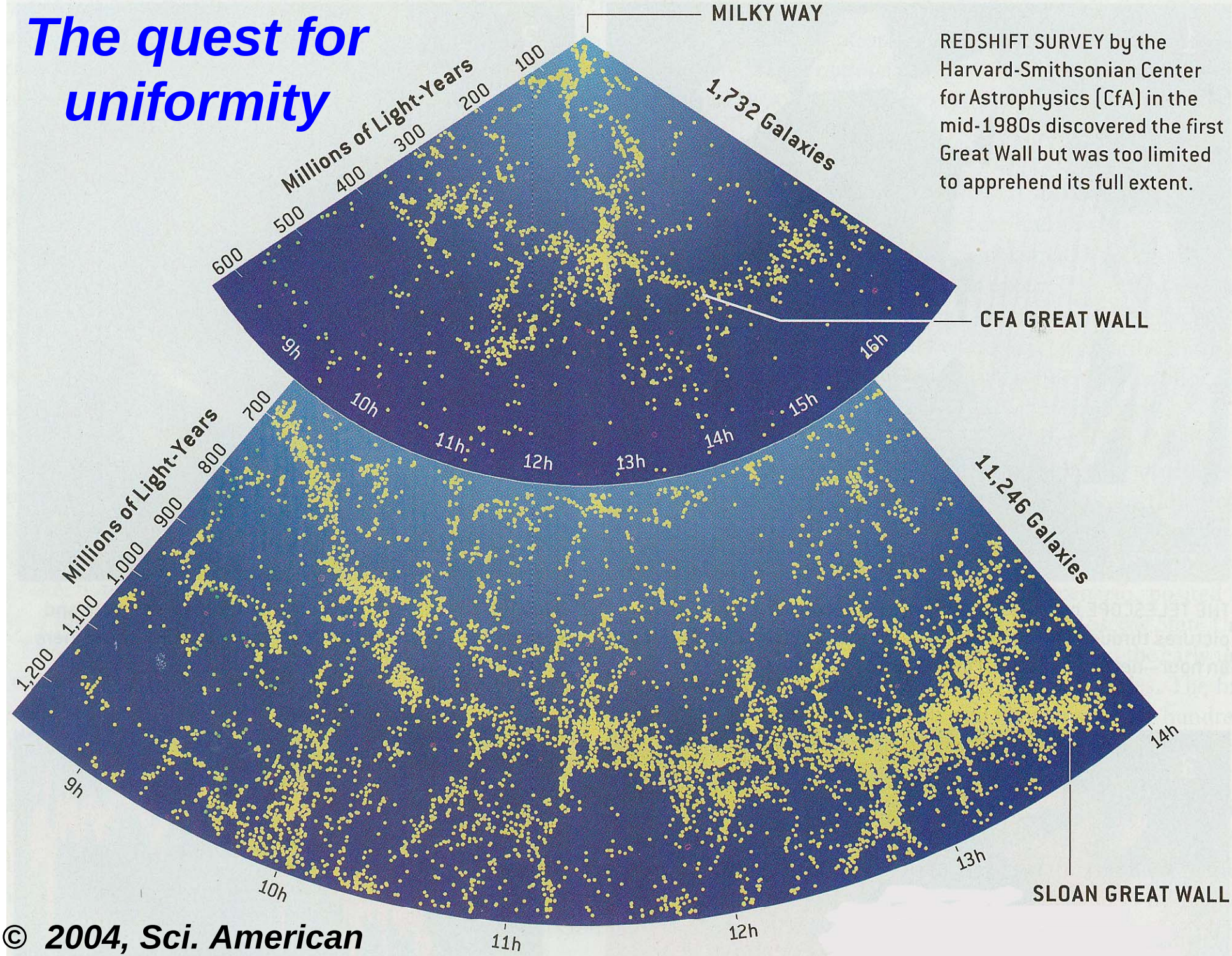


Large-scale distribution of galaxies

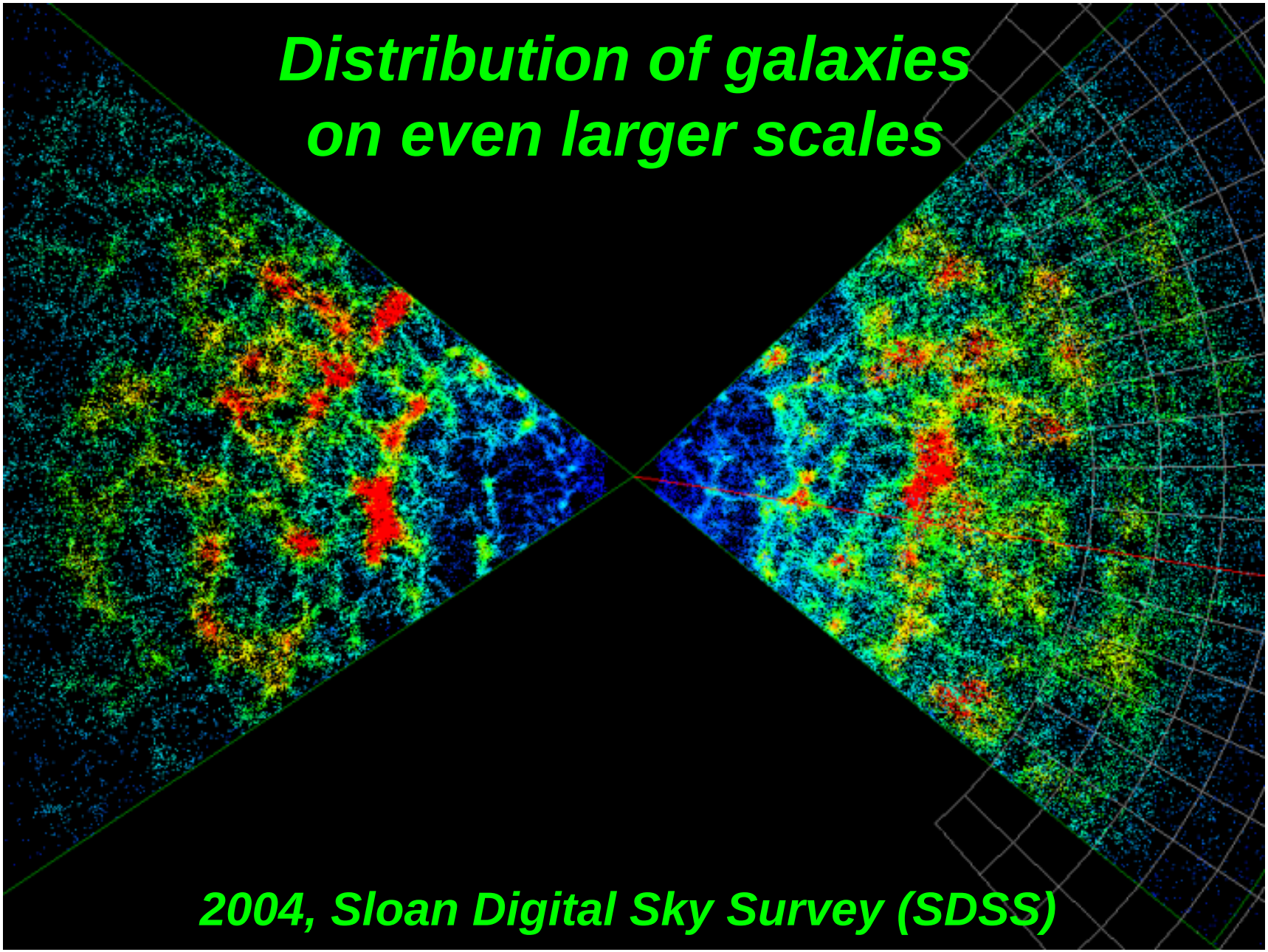
at distances less than [300 million light years]

CfA galaxy survey 1980-1990

The quest for uniformity



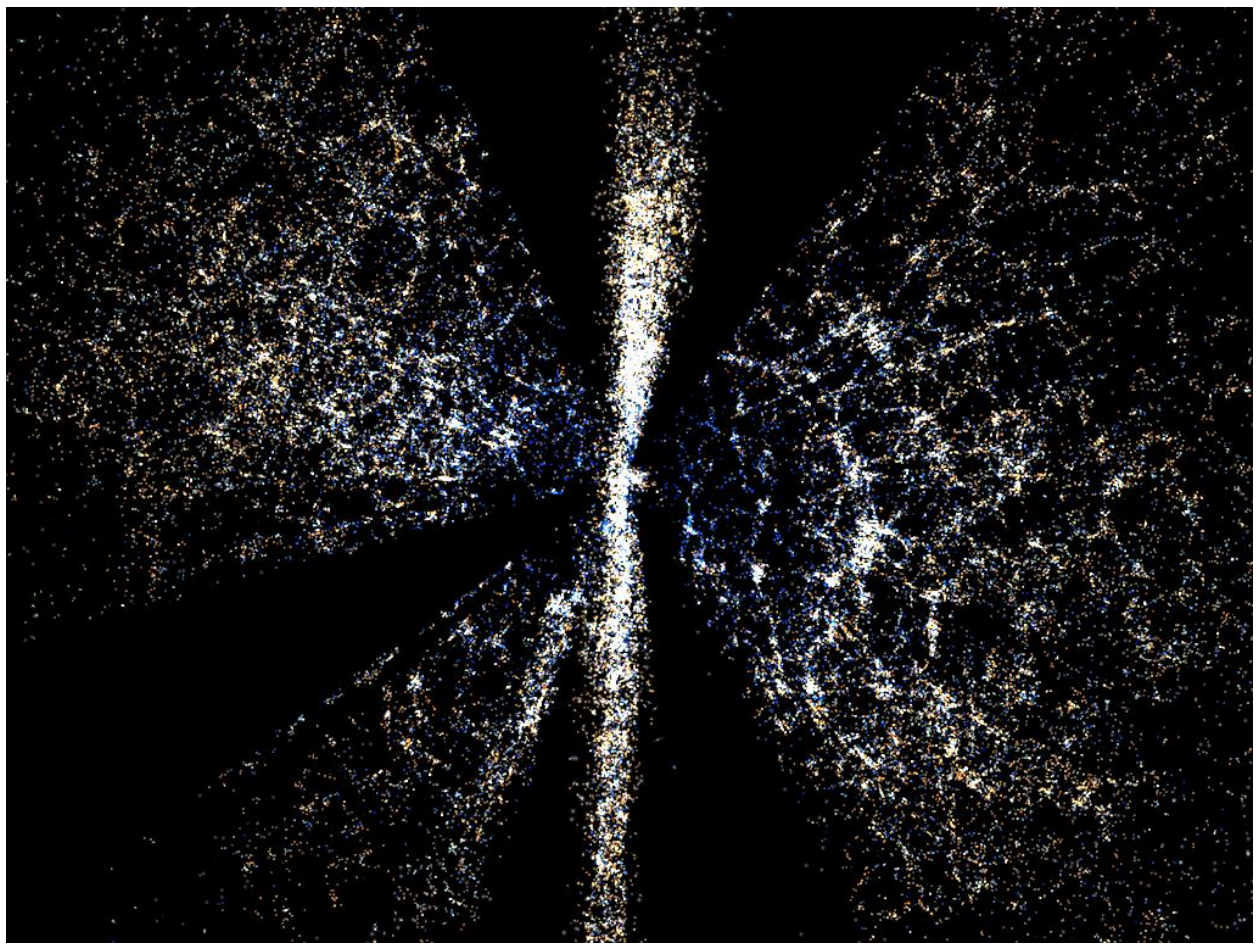
The end of greatness...



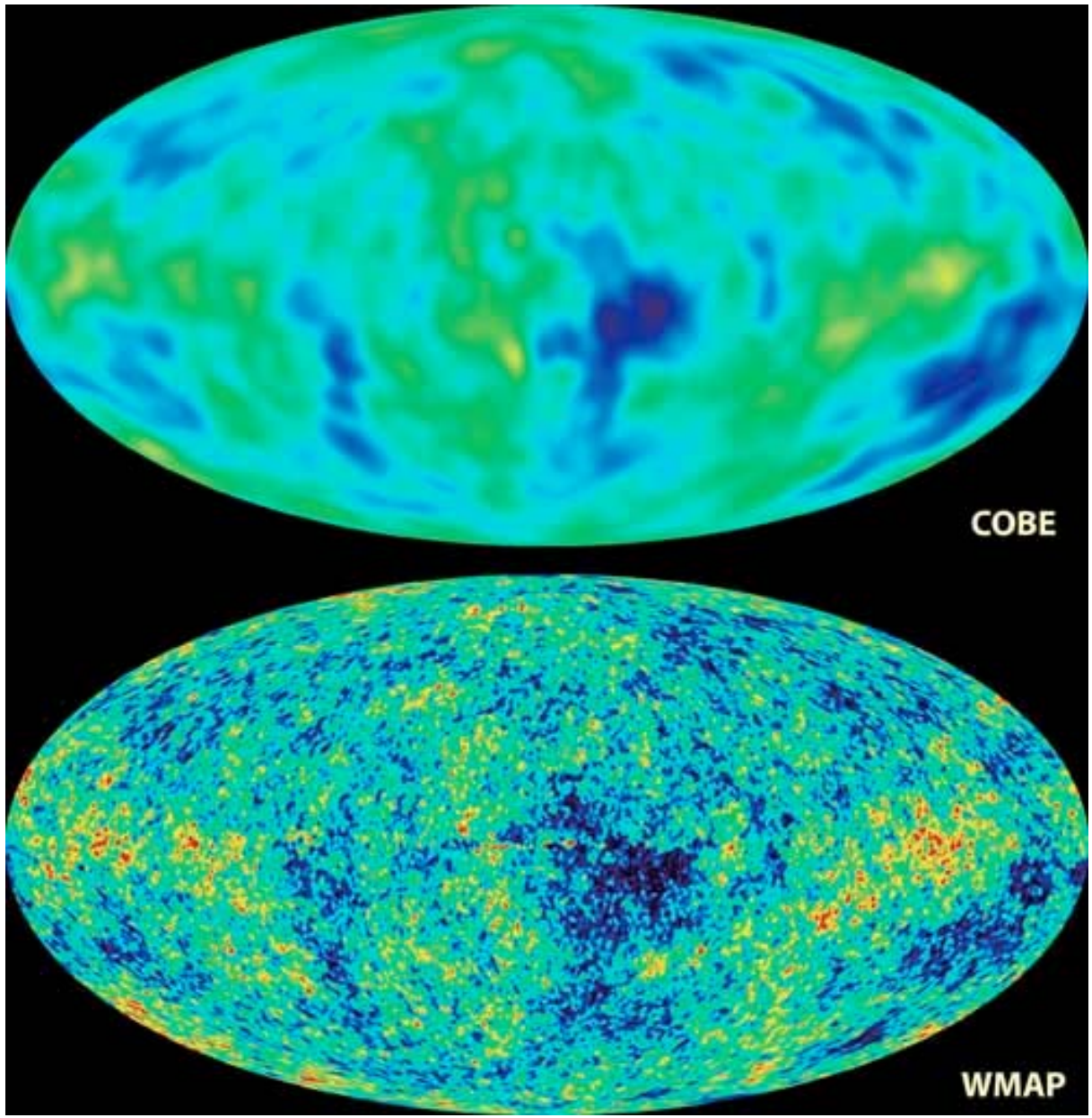
Deep Space:

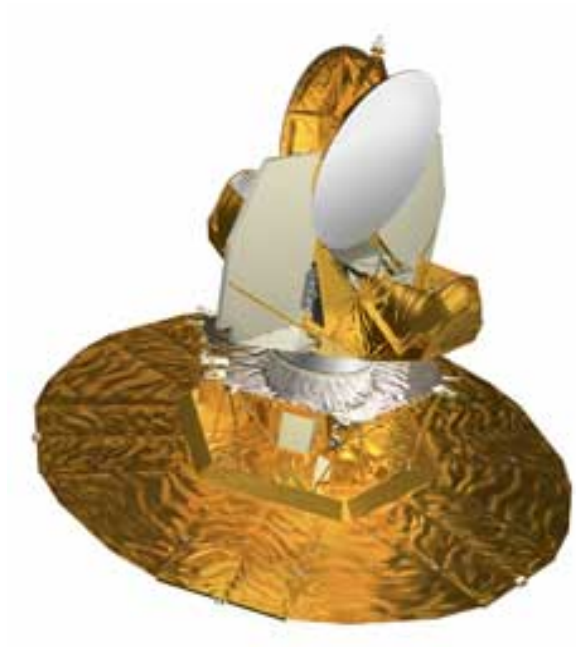
flight through galaxy distribution in the Sloan Digital Sky Survey

By Mark SubbaRao (Adler/U.Chicago)
Dinoj Surendran, and Randy Landsberg (U.Chicago)
http://astro.uchicago.edu/cosmus/



CMB temperature fluctuations: Seeds of Structures in the Universe

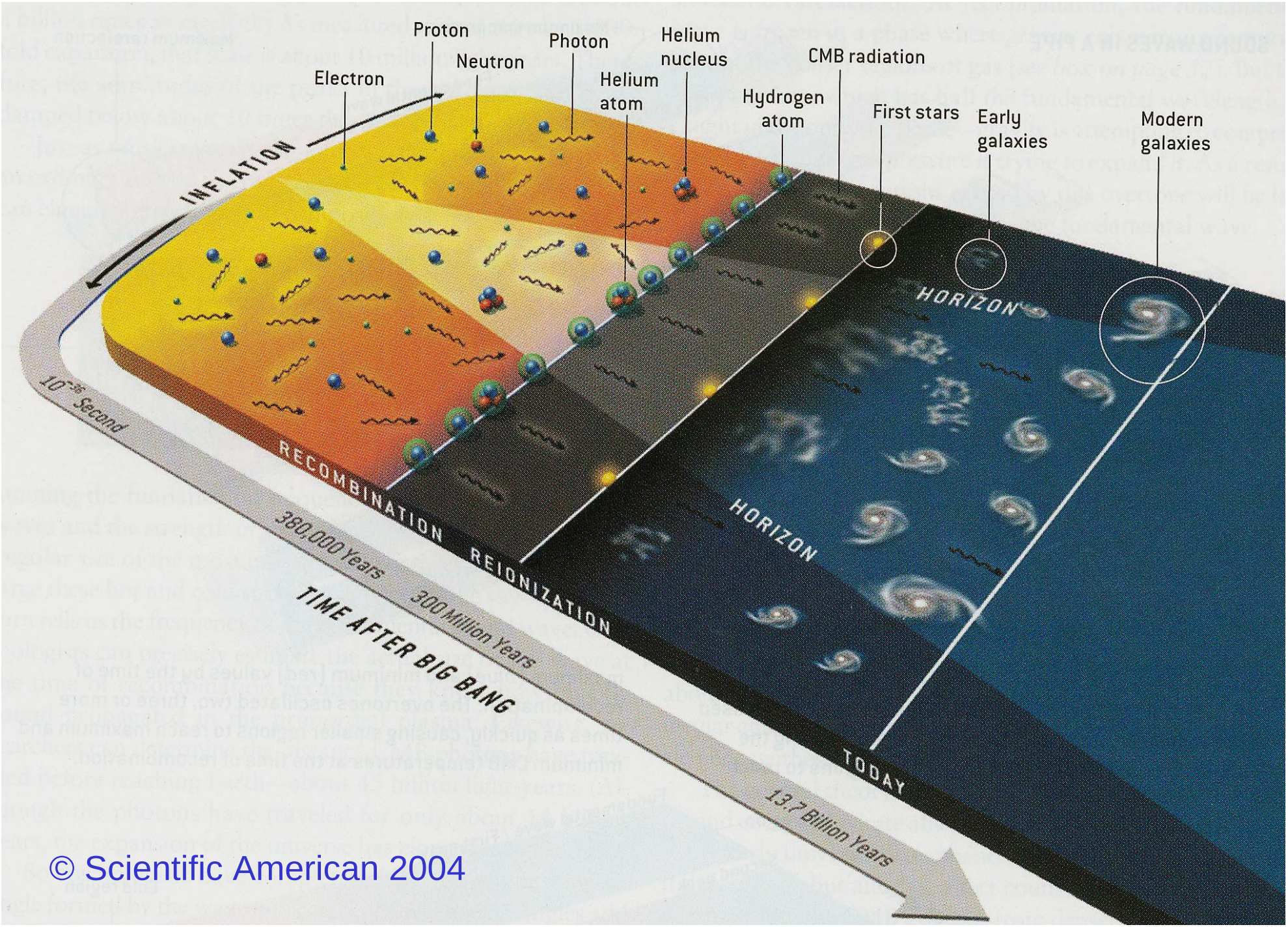




Wilkinson Microwave Anistoropy Probe (WMAP) satellite

http://map.gsfc.nasa.gov/m_mm.html

A Brief History of the Universe



Computer Simulations: Why?

- *Simple predictions are accurate only while inhomogeneities are small (<10% fluctuations with respect to the mean density of the Universe)*
- *When inhomogeneities grow due to gravity, the evolution becomes “nonlinear” and has to be solved for numerically on a (super) computer*
- *Simulations are initialized at an epoch before analytic predictions break down, during the so-called "Dark Ages“*
- *Numerical simulations are used to follow formation of structures and make accurate predictions at later epochs where analytic calculations break down*
- *Have been the main tool driving progress in our understanding of structure formation for the last ~30 years*

Computer Simulations: How?

- *If the content of the Universe is assumed, theory predicts the initial conditions (see Wayne Hu's talk tomorrow)*

  these predictions are used to set up initial conditions of the simulations at an early "Dark Ages" epoch

- *If the content of the Universe is assumed, we know the expansion history of the Universe*

  Simulations then assume expansion history specific to the assumed cosmological model

- *Space and time are discretized and equations governing the evolution of matter in the universe are solved numerically on a (super) computer.*

Why does content of the Universe matter?

Einstein's theory of General Relativity:

curvature of space = matter + energy

Content of the Universe:

all existing components (protons, neutrons, hypothetical dark matter) contribute to gravity and can influence the rate with which the Universe expands

The contribution of each component is measured in units of

critical density: $\Omega_i = \rho / \rho_{crit}$

$$\rho_{\rm crit} = 3H_0^2/8\pi G = 1.8788 \times 10^{-29} h^2 \, {\rm g\,cm^{-3}}$$

Content of the Universe: observational probes

- *Ripples in the Cosmic Microwave Background*

  physical processes causing tiny fluctuations in the temperature of the relic microwave radiation are well understood. we can predict them much better than the weather!

- *Large-scale structure of the Universe*

  galaxies, galaxy clusters, filaments

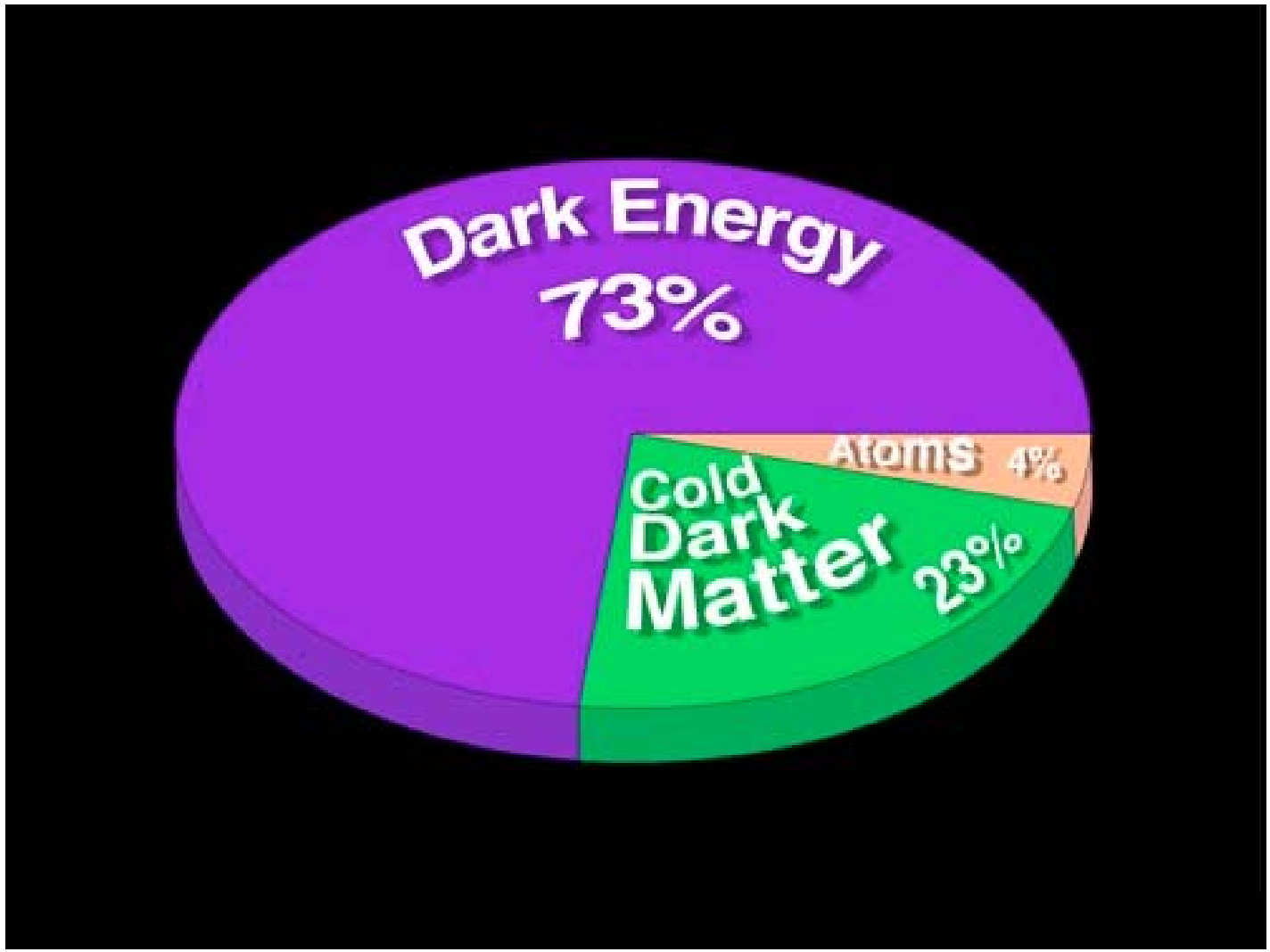
- *Standard "candles"*

  any object whose intrinsic brightness is known or can be deduced from observations without using distance. SNIa are currently the best cosmological standard candles known

- *Standard rulers (systems with known intrinsic size)*

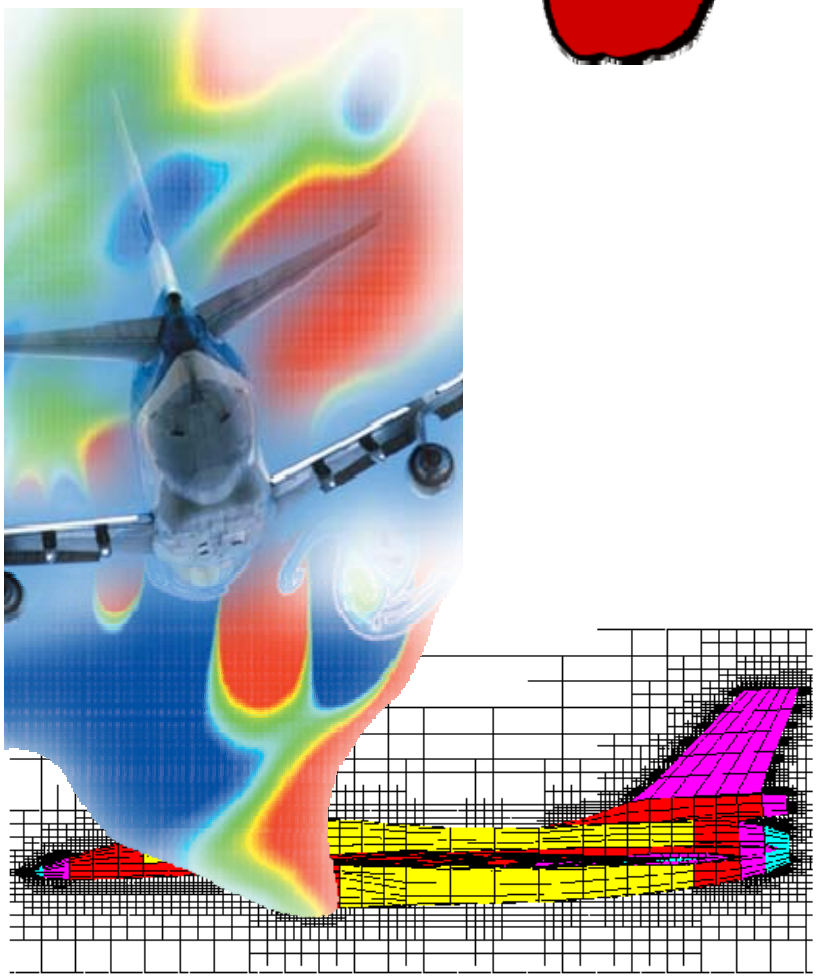
  Acoustic oscillations of baryons during the Big Bang imprint characteristic scales in the large-scale structure, the best cosmological standard rulers known (Wayne Hu's and Dragan Huterer's talks tomorrow)

Cosmic Pie



Courtesy of Sean Carroll

Computer Simulations:
equations that govern evolution



- *Gravity is the king*

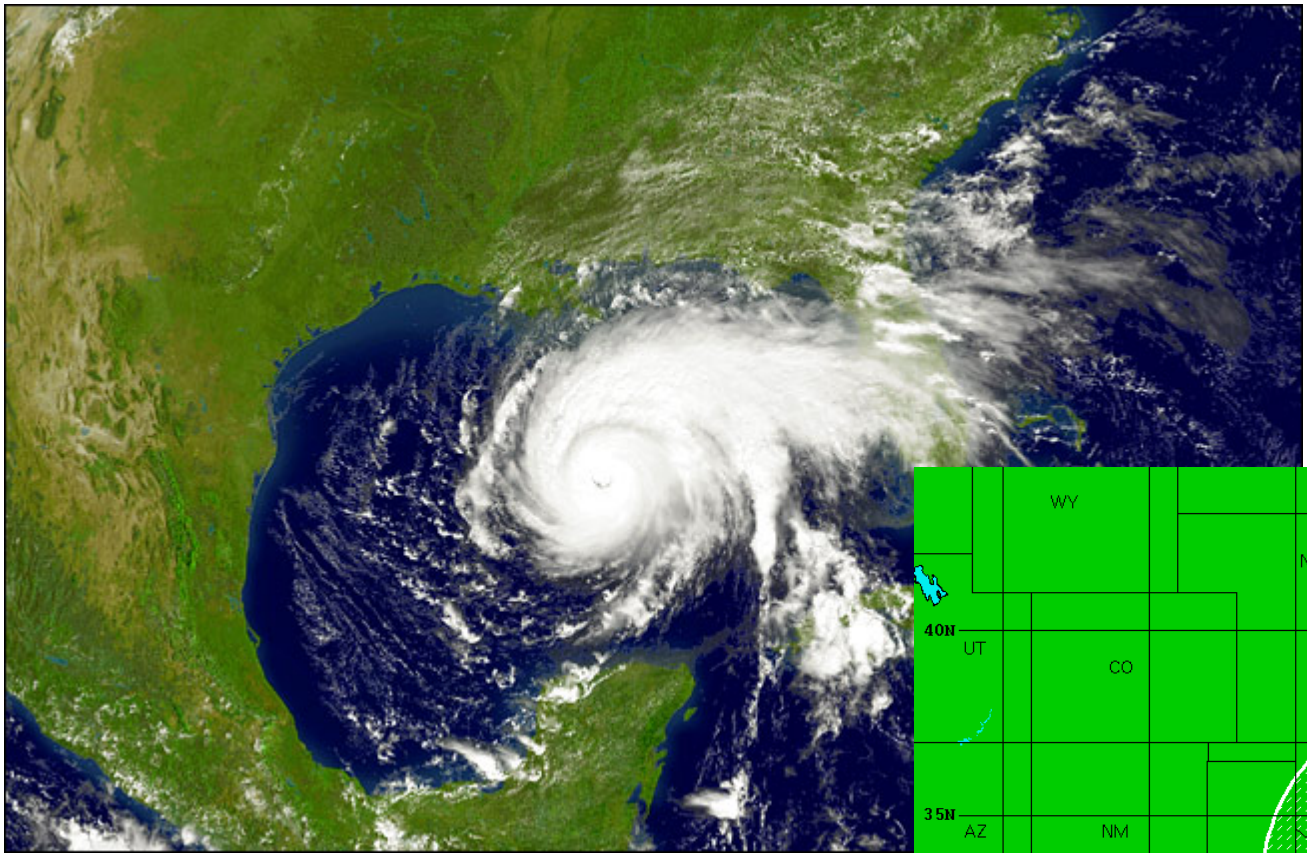
  gravity is by far the strongest force on the large scales. gravitational interactions are modelled using Newton's laws

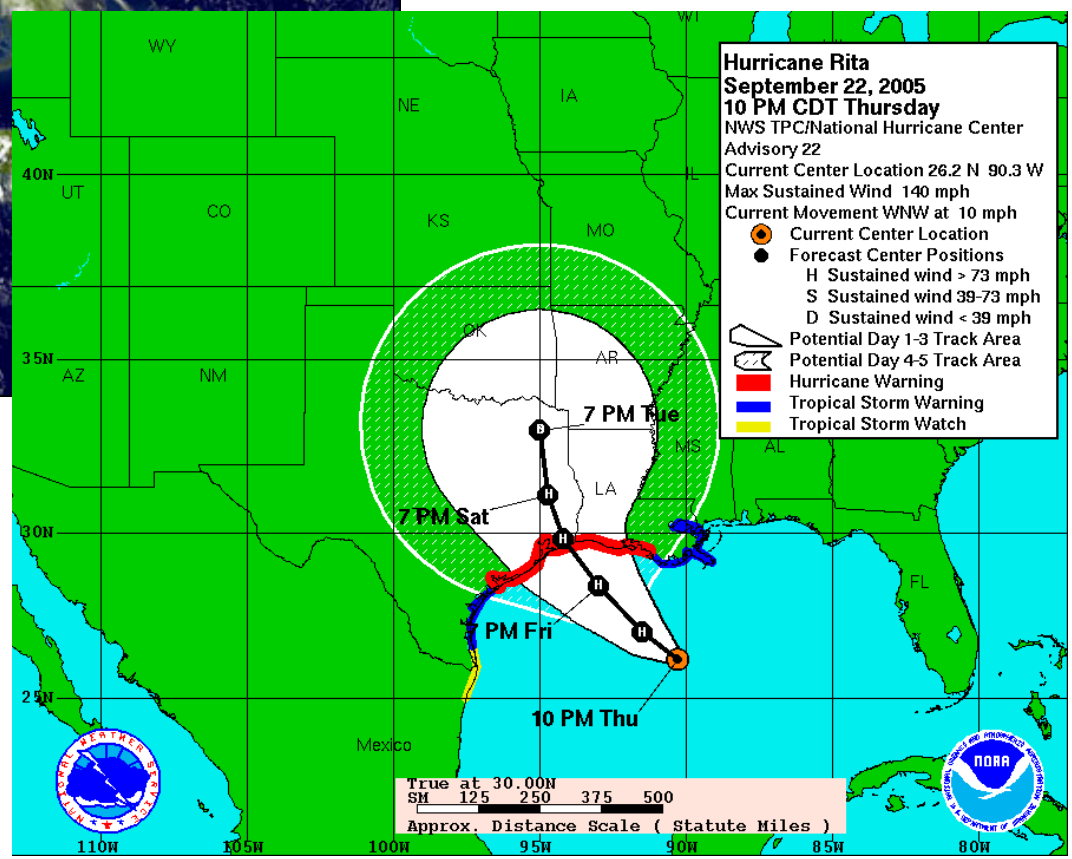
- *Other forces may need to be included depending on the composition of the Universe and scales considered*

  ordinary matter, the baryons, experiences pressure forces if compressed to sufficiently high densities. these "hydrodynamic" forces are included in simulations that include baryons

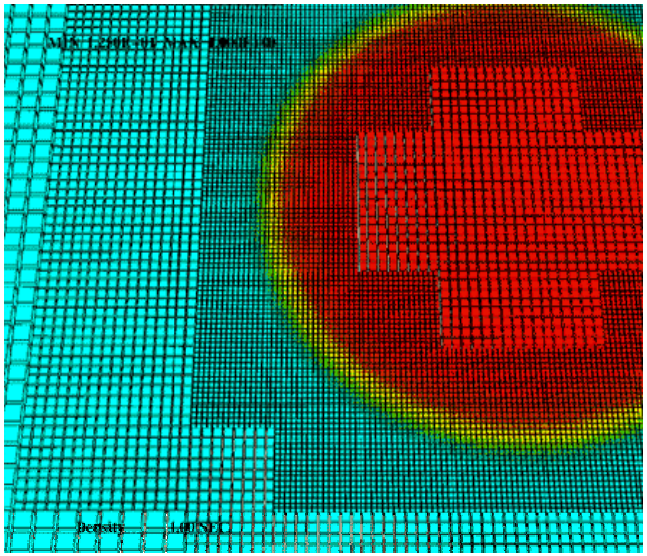
- *The equations are solved in expanding system of coordinates (because Universe expands)*

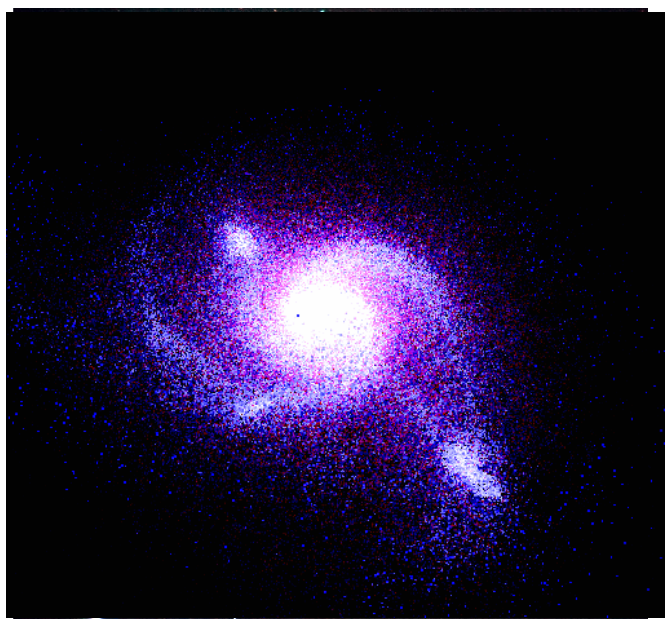
Not unlike more familiar computer models…





Computer Simulations: discretizing matter and space





- *Space and time are continuous on macroscopic scales, but computers can only deal with discrete numbers*
- *Memory and CPU speed limit the number of volume elements and particles that we can simulate*

in the standard theories, 10^{51}-10^{82} dark matter particles are expected in a cubic Megaparsec

current supercomputers can handle only up to a ~10 billion particles

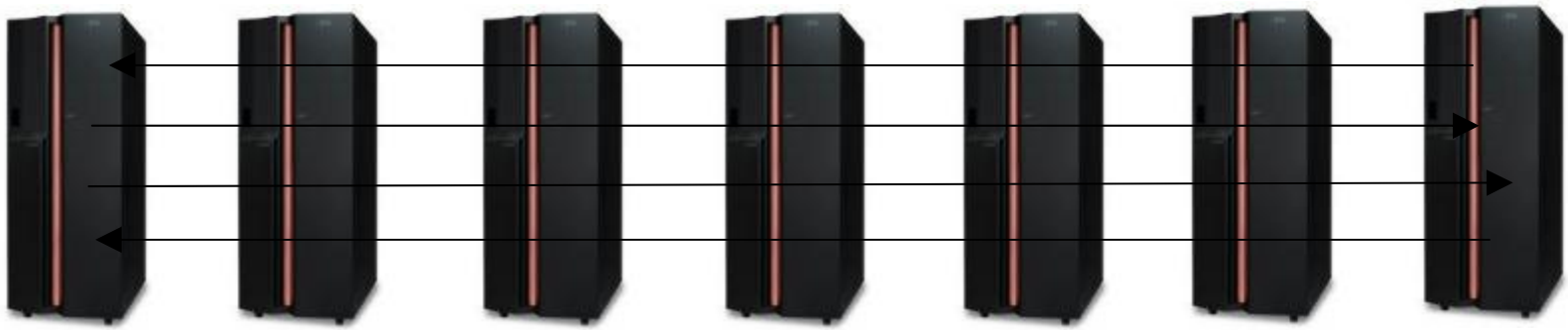
----> need to discretize

Hardware

Supercomputers at National Centers and Labs

(e.g., the National Center for Supercomputer Applications - NCSA)

www.ncsa.uiuc.edu



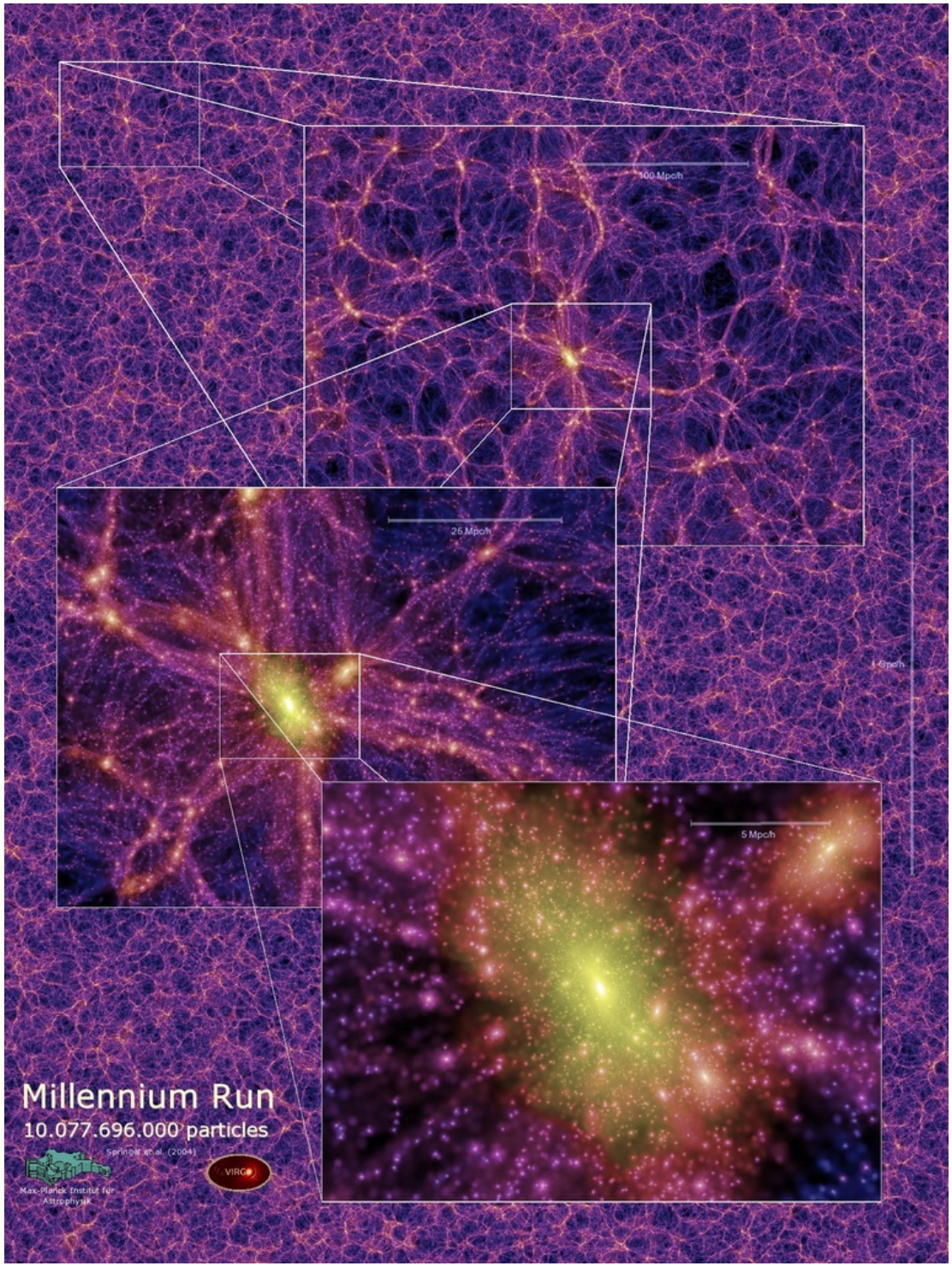
+ *Lots and lots of storage...*

Many Many Lines of Software

```
c     ---------------------------------
      subroutine Split ( Level , mtot )
c     ---------------------------------
c
c     purpose: splits cells marked to split
c
c     input  : Level - level to process
c     output : mtot  - # of cells just split
c
#     include "a_def.h"
      include 'a_tree.h'
      include 'a_control.h'
c
      integer mtot, Level
      integer idcell
      real*8 e_kin, e_ip
      real*8 whvar(nhvar), wvar1, wvar2, wvar3
      dimension iPyr(nchild,3)    ! interpolation pyramid vertices
c
      data iPyr / 1, 2, 1, 2, 1, 2, 1, 2,
     &            3, 3, 4, 4, 3, 3, 4, 4,
     &            5, 5, 5, 5, 6, 6, 6, 6  /
c
c.... Warning! The loops below are to be executed SERIALLY
c
      IF ( Level .eq. MinLevel ) THEN
        do ic1 = 1 , ncell0
          if ( vnw(1,ic1) .gt. wsplit ) then
            ires = iSplitCell ( ic1 )
            if ( ires .eq. nil ) then
              mtot = mtot + 1
              iOC = iOctCh(ic1)
              v_p   = hvar(3,ic1)**2 +
     &                hvar(4,ic1)**2 +
     &                hvar(5,ic1)**2
```

```
else
  if ( sta(1) .gt. eps ) then
    xxl = ( al * p_1  + bl ) / ( p_1 + cl )
    w2l = 1./sqrt(max(small_R, xxl * stl(1) * (p_1 + stl(3))))
    ul1 = stl(2) + ( stl(3) - p_1 ) * w2l
    xxr = ( ar * p_1  + br ) / ( p_1 + cr )
    w2r = 1./sqrt(max(small_R, xxr * str(1) * ( p_1 + str(3))))
    ur1 = str(2) + ( p_1 - str(3) ) * w2r
    p2  = max ( small_R , 1.0000001 * p_1 - ( ur1 - ul1 )
     :                                  * abs ( p_1 - p_0 )
     :                                  / (   abs ( ur1 - ur_0 )
     :                                      + abs ( ul1 - ul_0 )
     :                                      + small_R ) )
    p_0    = p_1
    p_1    = p2
    ul_0   = ul1
    ur_0   = ur1
    devi   = abs ( p2 - p_1 ) / ( p2 + p_1 )
    sta(1) = devi
    dev    = max ( dev , devi )
  endif
end if
iter = iter + 1
if ( iter .le. maxit .and. dev .gt. eps ) go to 1

 Bad news !!!

if ( dev .gt. eps ) then
  write(*,'(1x,''Riemann_l solver iteration failure'')')
  stop
end if

State at x/t=0

  u      = 0.5 * ( ul_0 + ur_0 )
  ind_r  = int ( 0.9 - sign ( onehalf , u ) )
  rho_s  = ind_r * (str(1) - stl(1)) + stl(1)
  u_s    = ind_r * (str(2) - stl(2)) + stl(2)
  p_s    = ind_r * (str(3) - stl(3)) + stl(3)
  bgam_s = ind_r * (str(4) - stl(4)) + stl(4)
  qam_s  = ind_r * (str(5) - stl(5)) + stl(5)
```

progress is driven by advances in hardware and In computer codes…



From largest to "small" scales

Millenium Simulation:

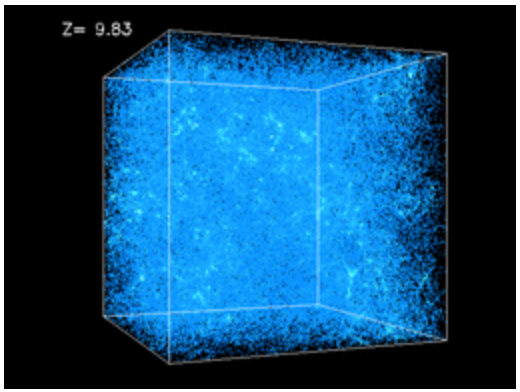
significant fraction of the total volume of the Universe
~10 billion particles

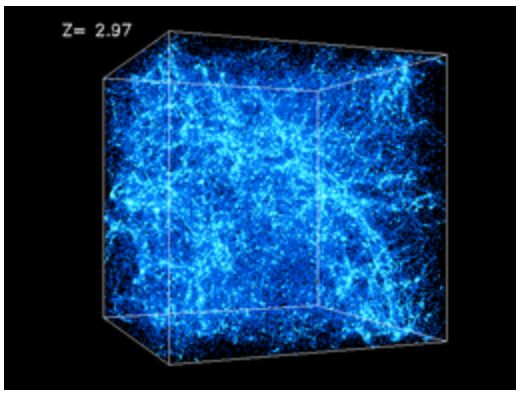
~300000 CPU hours on 512 processors of an IBM SP4 supercomputer

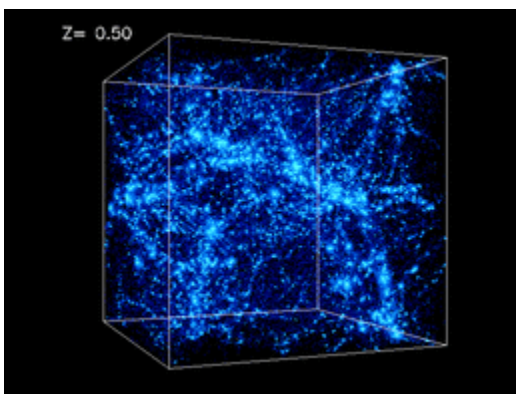
Images, animations, information:

http://www.mpa-garching.mpg.de/galform/virgo/millennium/index.shtml

Hierarchical structure formation: the basics







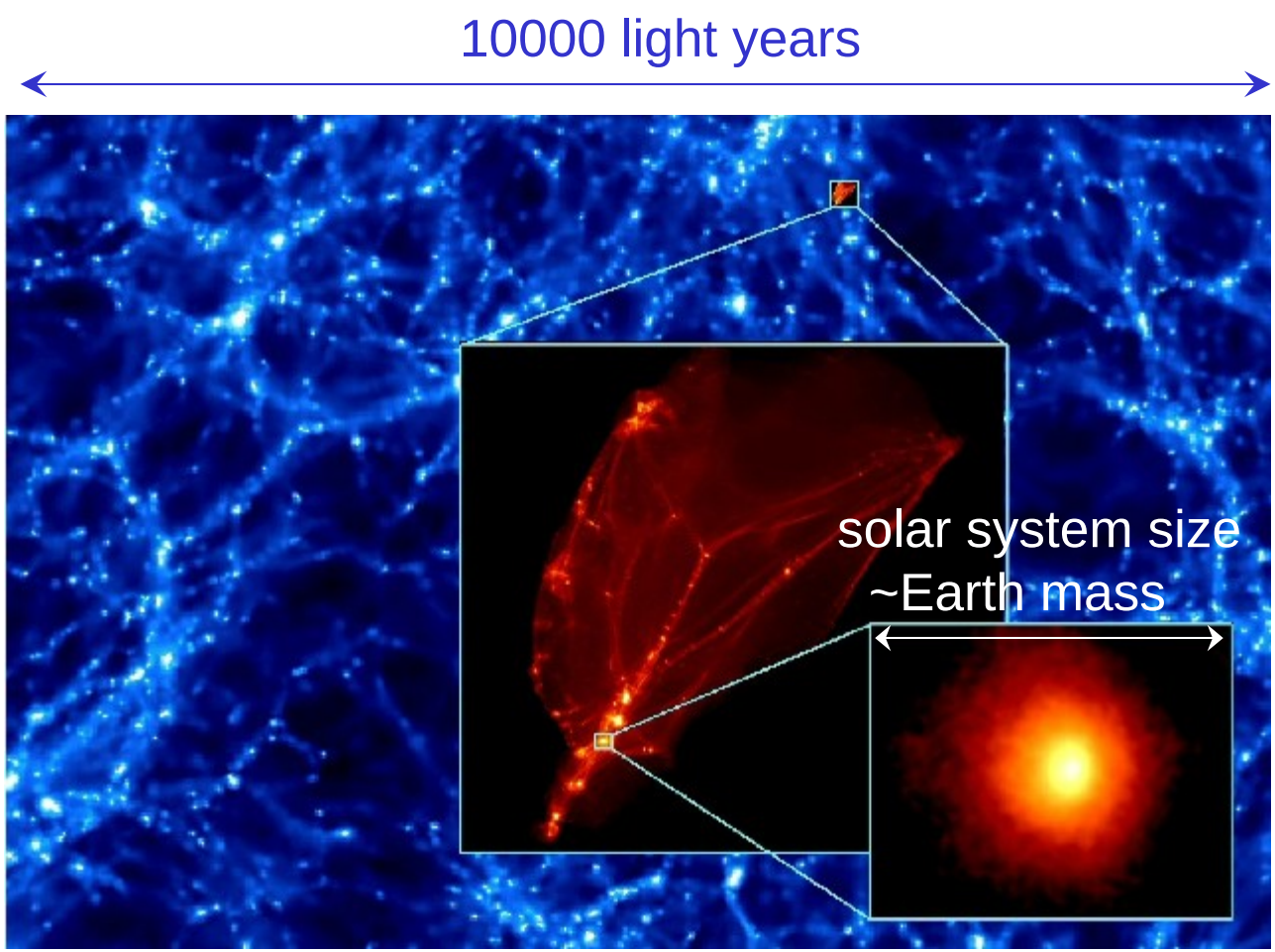
- *Small initial fluctuations grow with time due to gravity: regions denser than average become denser, lower density regions become less dense*

  (i.e., the rich get richer, and the poor get poorer)

- *Expansion of the Universe counteracts the pool of gravity, slowing down, and sometimes even completely halting the collapse*

- *Very small objects (~the Earth mass) collapse first and then go through a hierarchy of merging with other objects to form systems of ever larger mass*

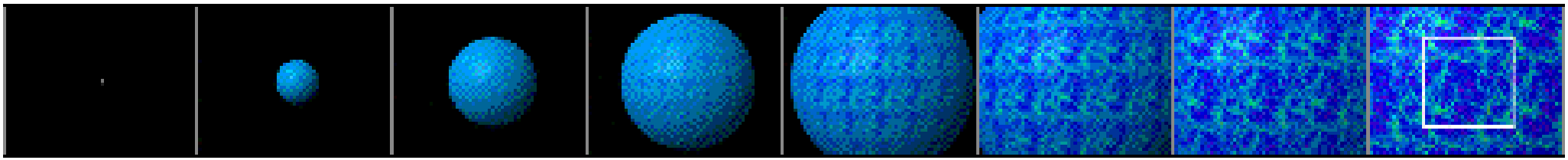
The first objects to collapse could be of the Earth mass!

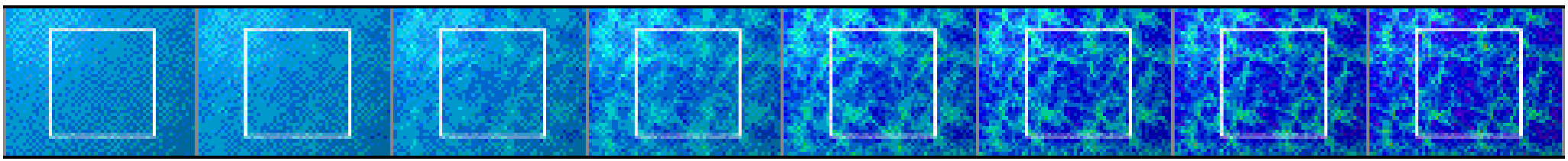


Courtesy of Ben Moore (U. of Zurich)
Images, animations, information:

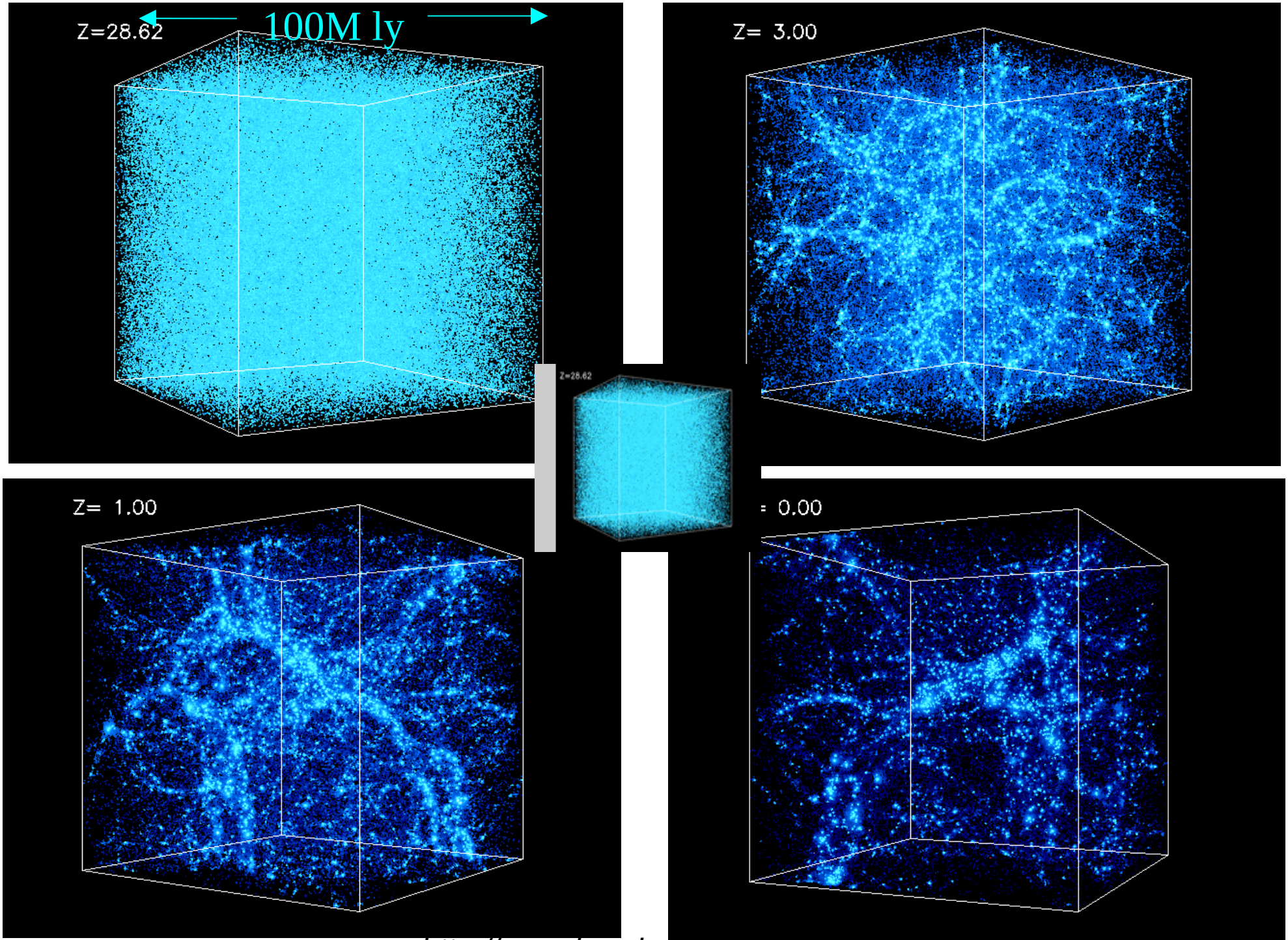
http://www.nbody.net

We all live in



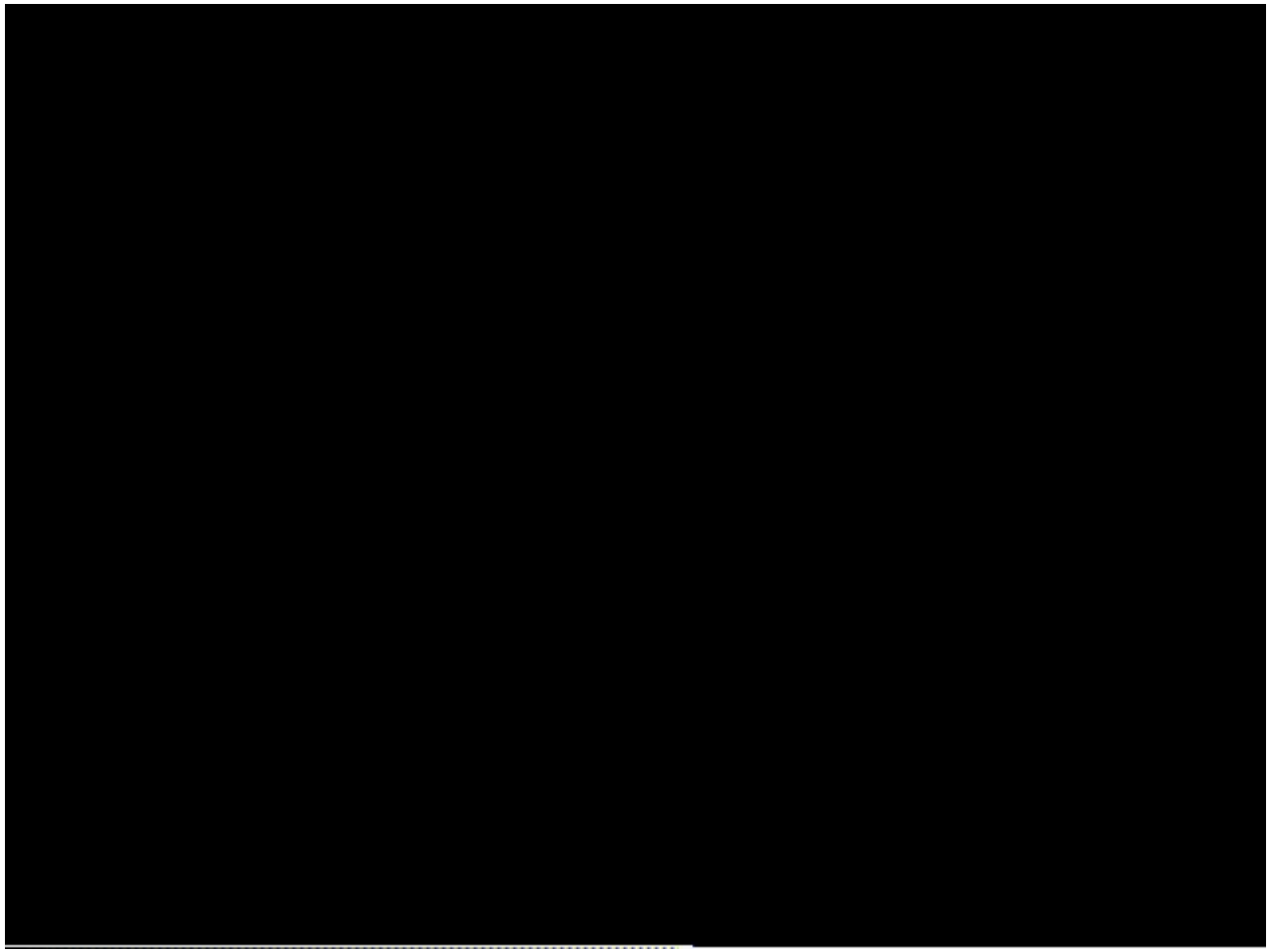


Universe in a box: formation of a filament



http://cosmicweb.uchicago.edu

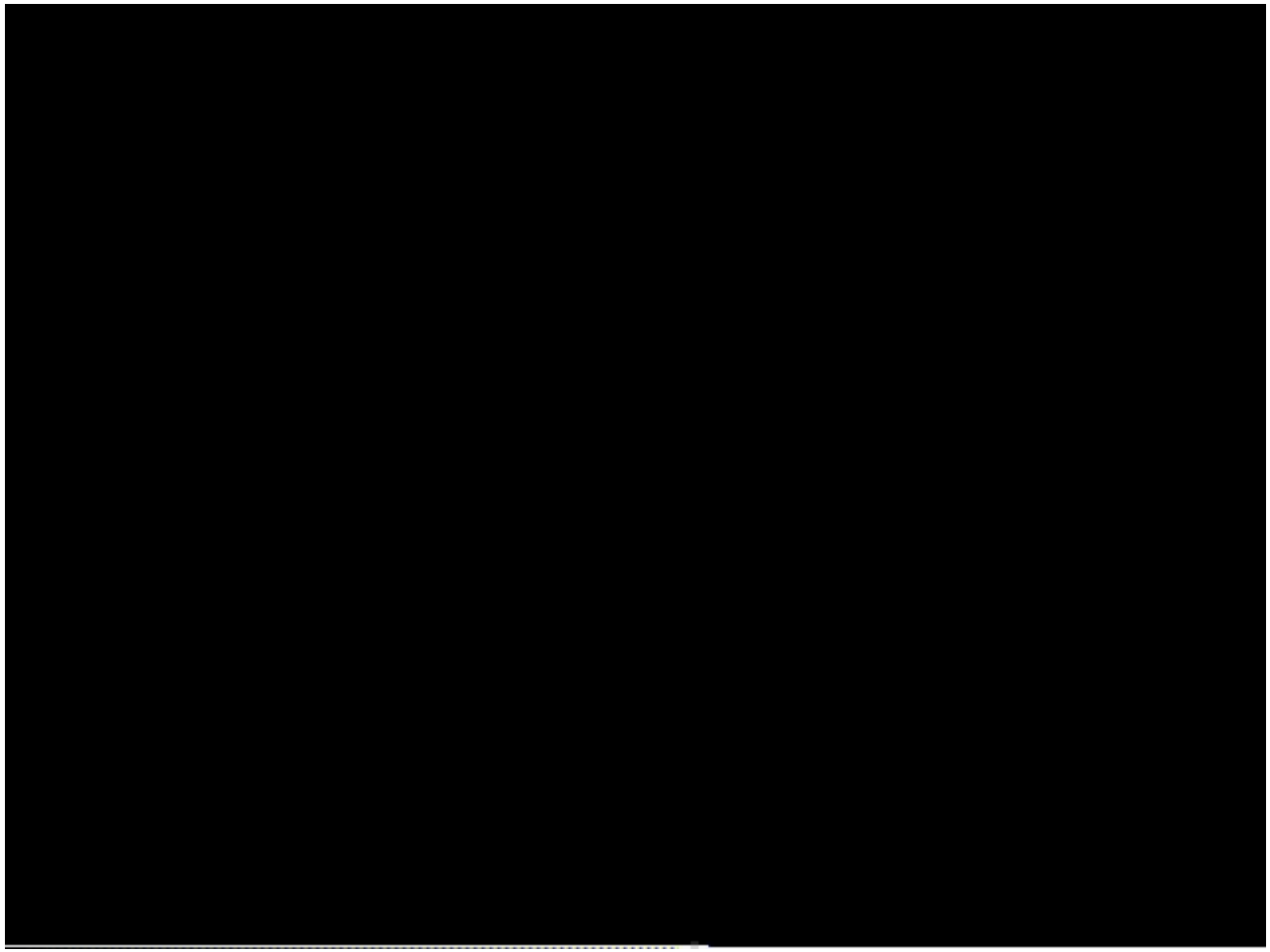
Formation of filaments



http://cosmicweb.uchicago.edu

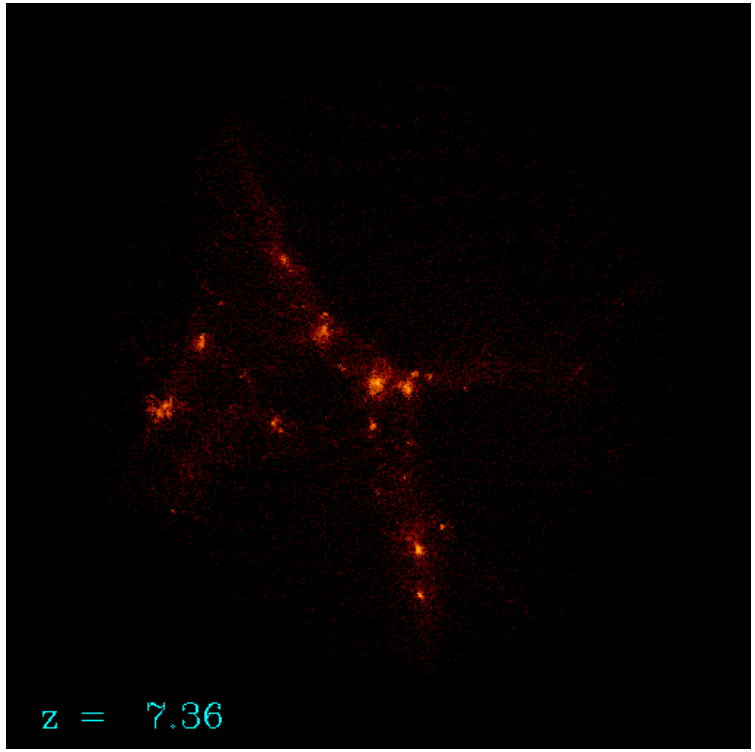
Formation of the "Local Group"

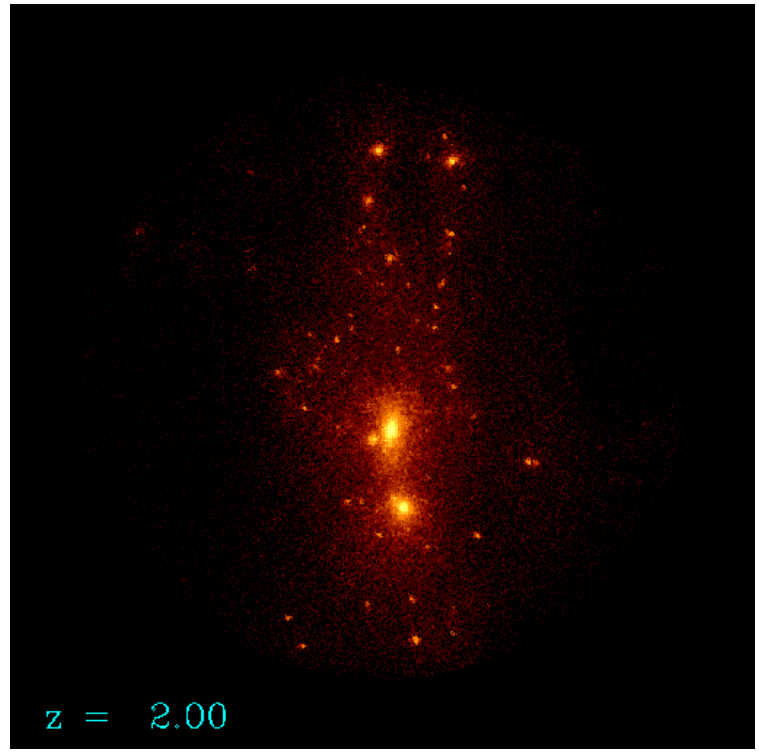
note the hierarchy of mergers!



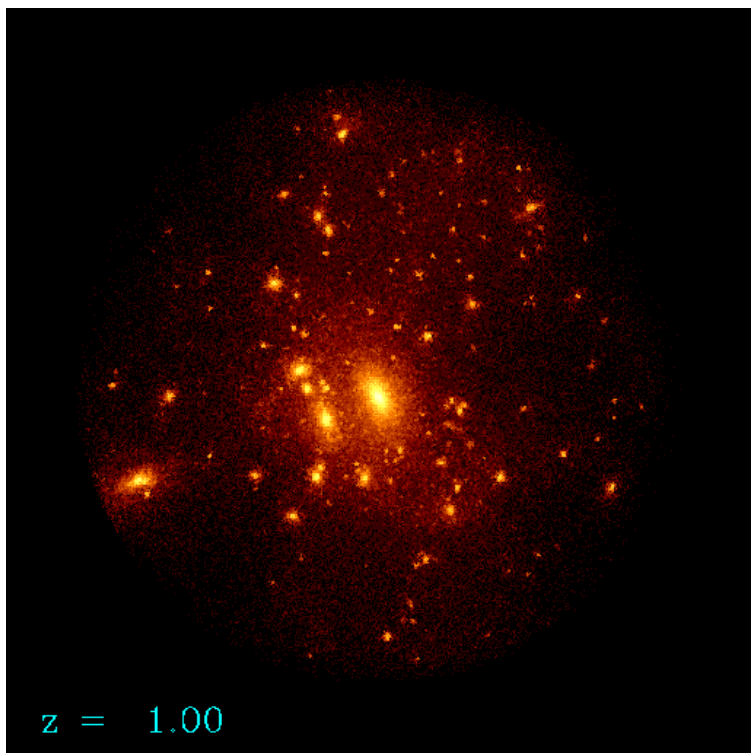
http://cosmicweb.uchicago.edu

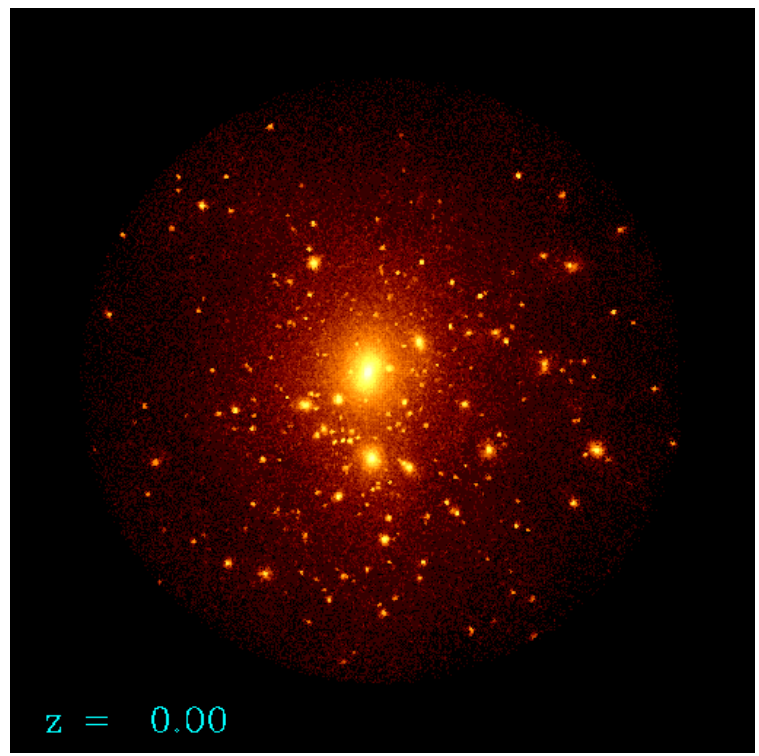
modeling formation of a galaxy cluster



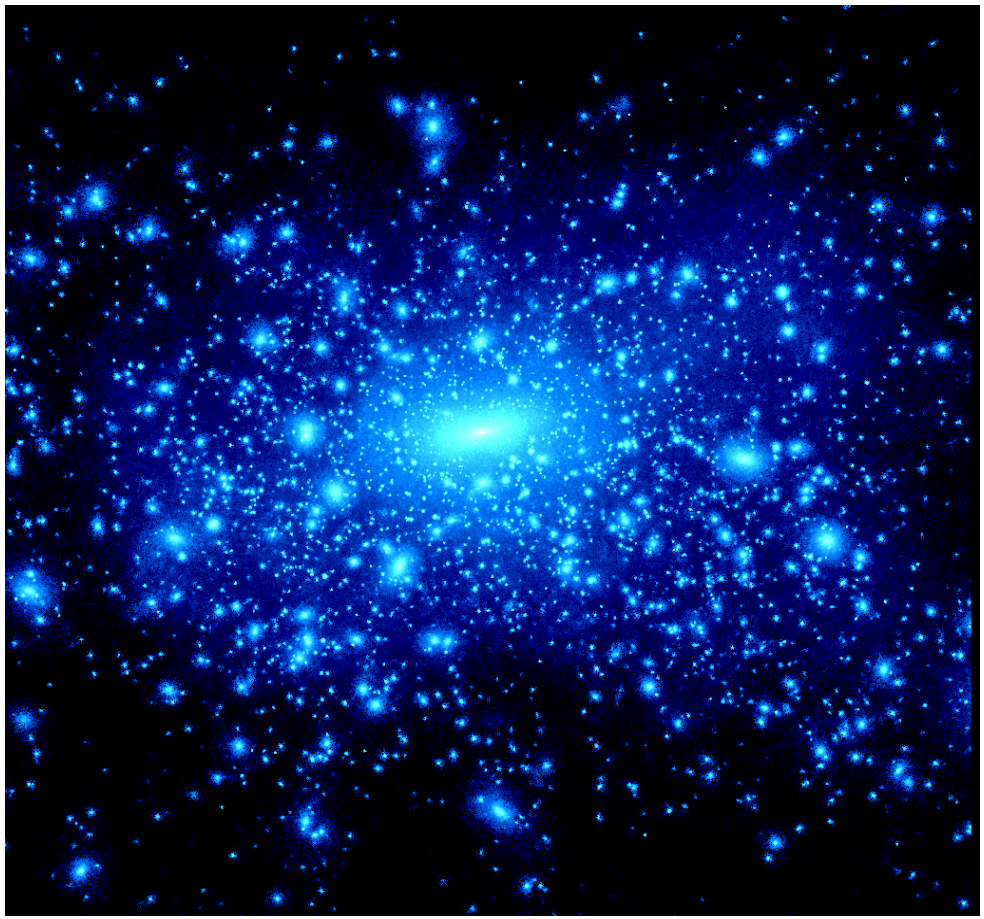


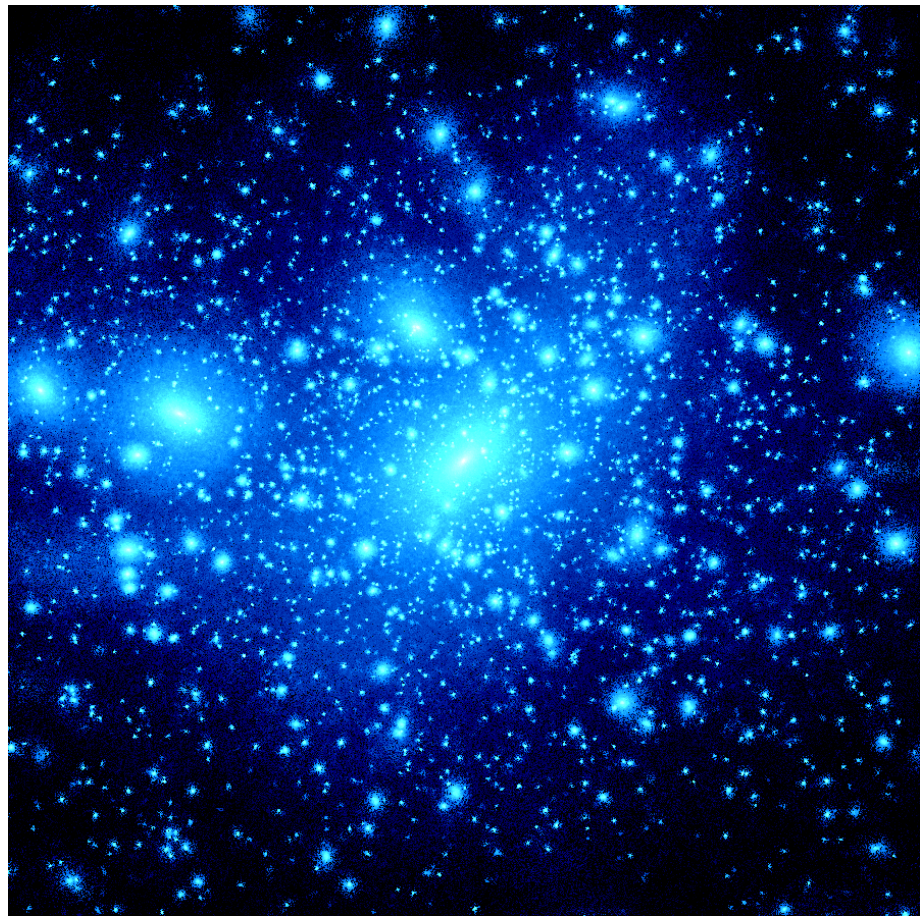
10 million light years





A Clumpy Universe



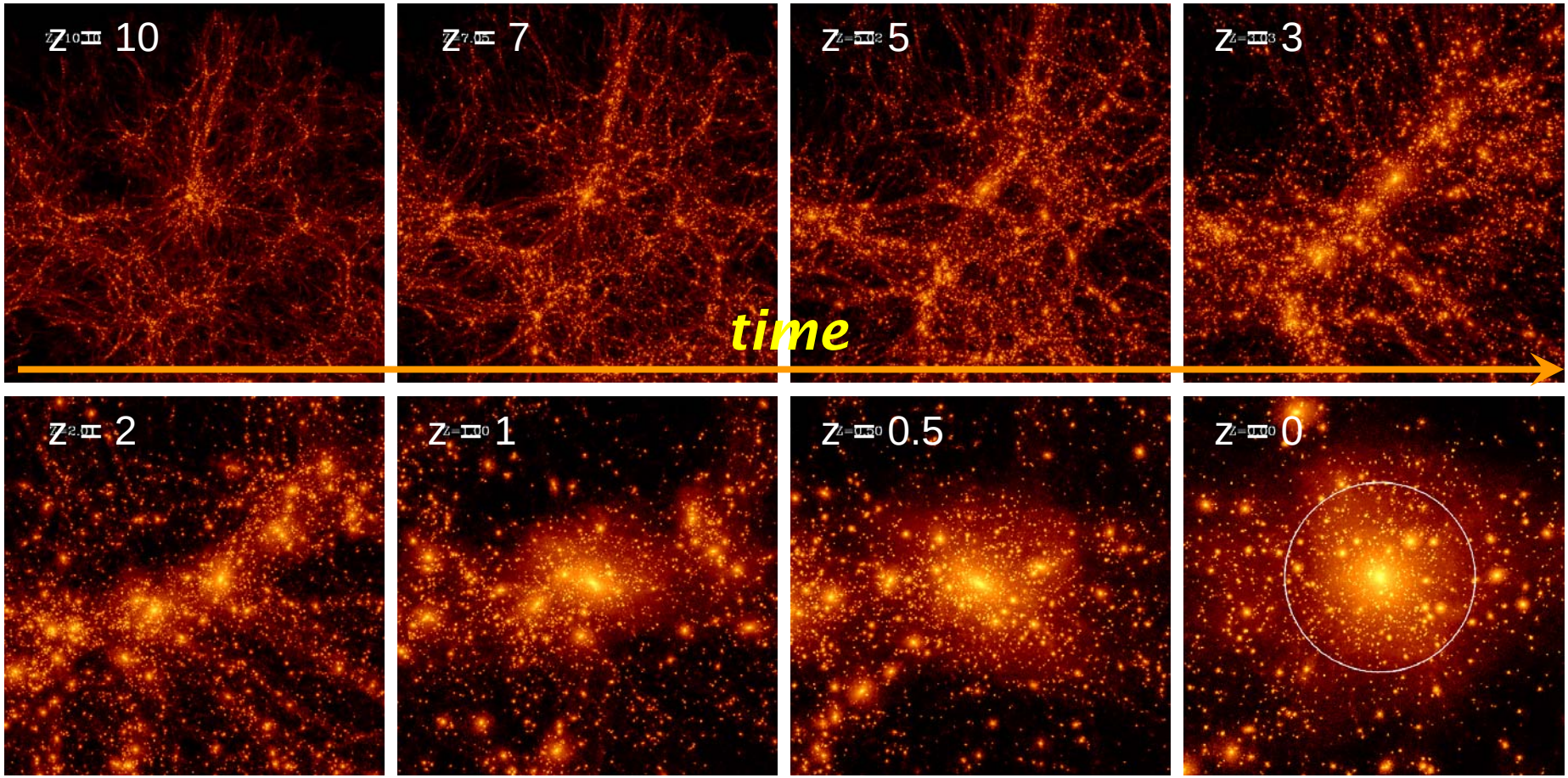


A cluster or a galaxy?

http://cosmicweb.uchicago.edu

Formation of a Milky Way-sized halo

"You can observe a lot just by watching." – Yogi Berra

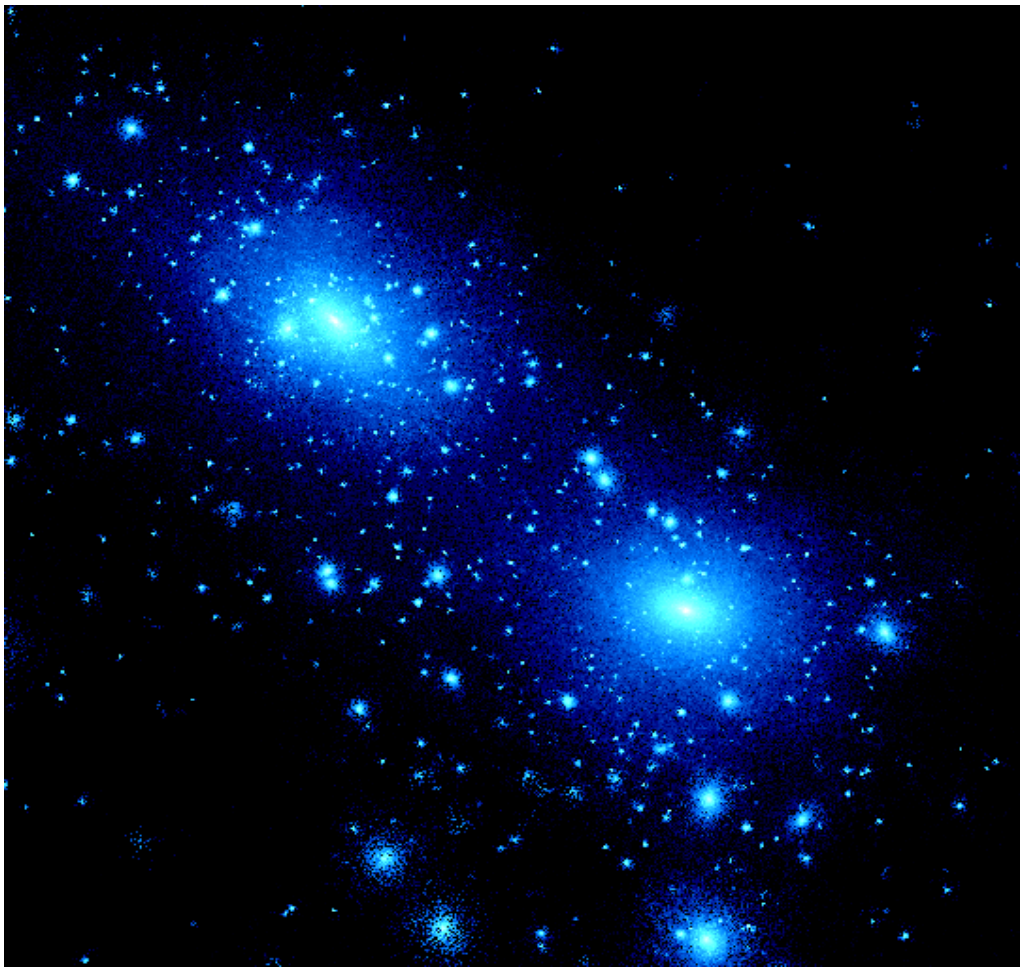


ART code simulation:

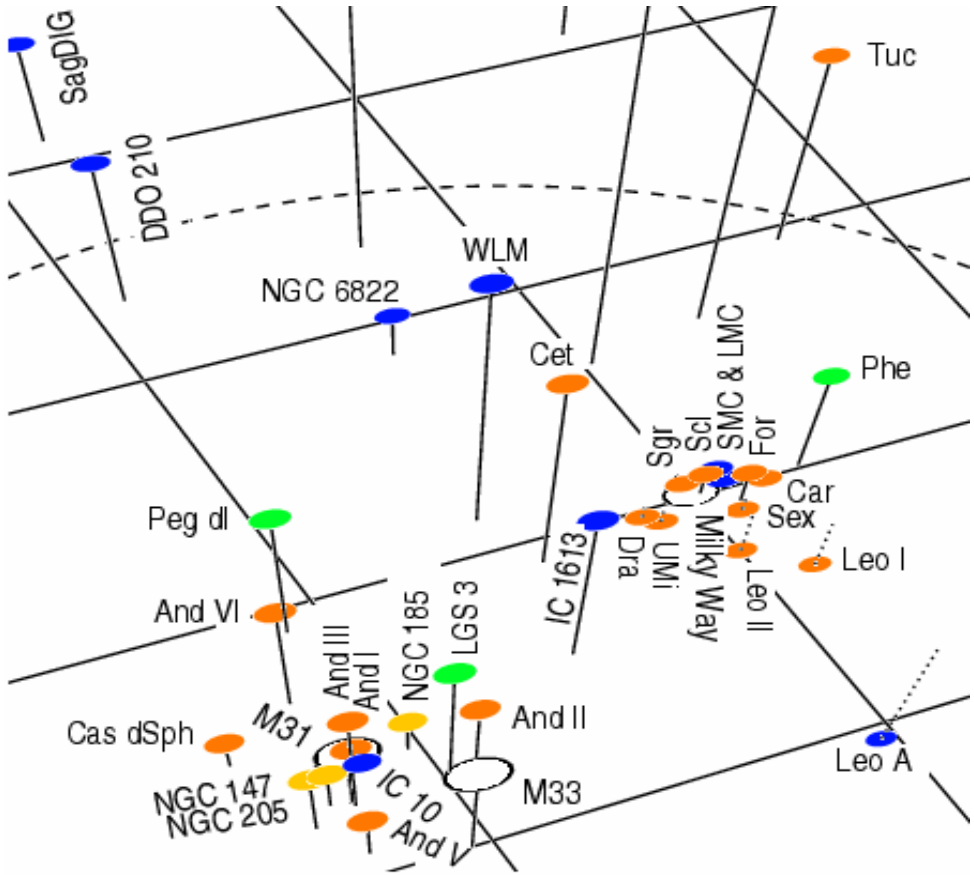
standard LCDM, $\sigma 8=0.9$; mp=$6\times10^{5}h^{-1}$ Msun; $\varepsilon = 0.1h^{-1}$ kpc

*M*vir=$3\times10^{12}h^{-1}$ Msun; *R*vir=$293h^{-1}$ kpc; ~5×10^{6} particles within Rvir

The Missing Satellites Problem



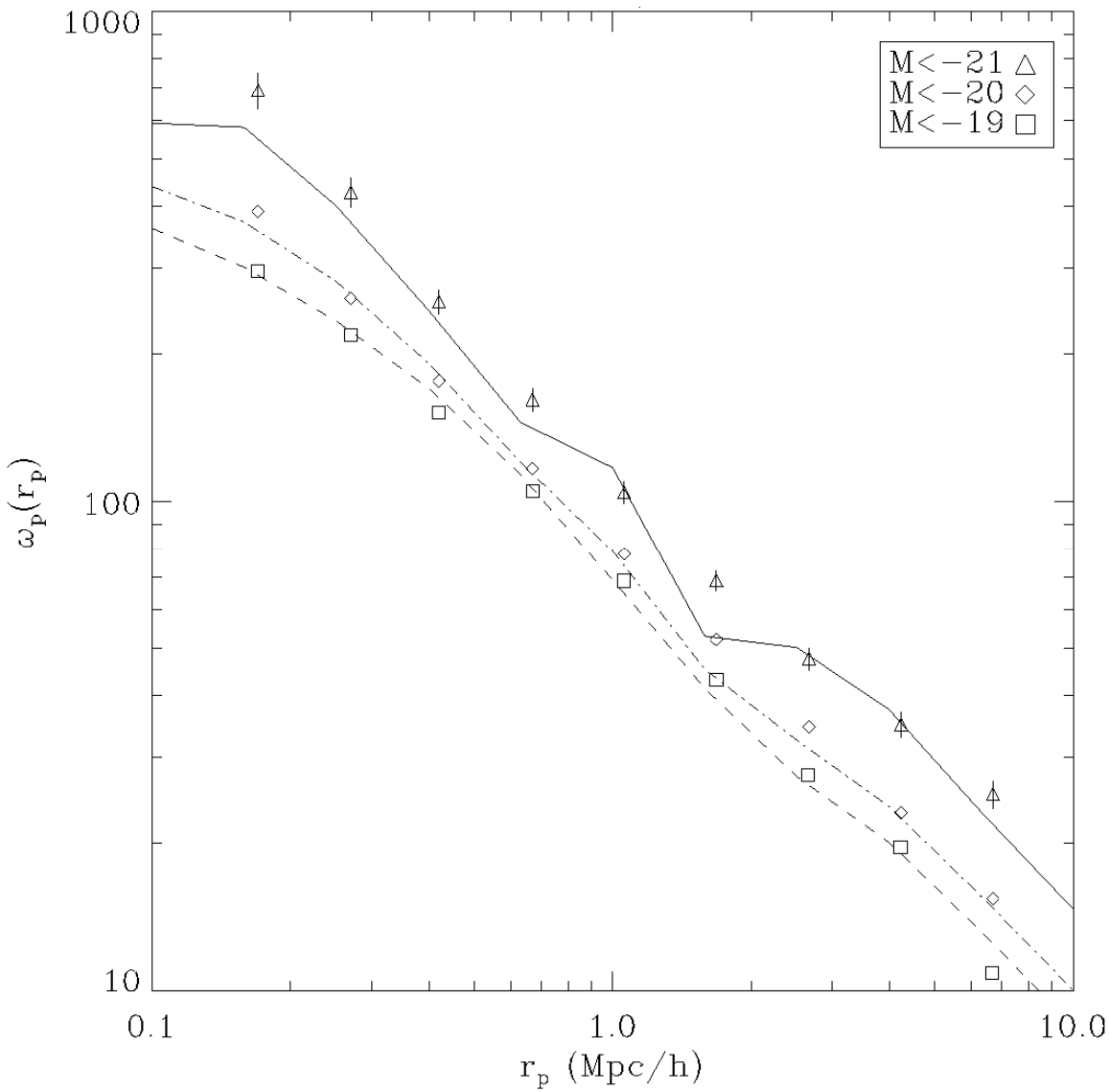
computer simulation



The Local Group

Statistical comparison of computer models and data (SDSS)

Correlation function (measures how clustered galaxies are on a given scale)

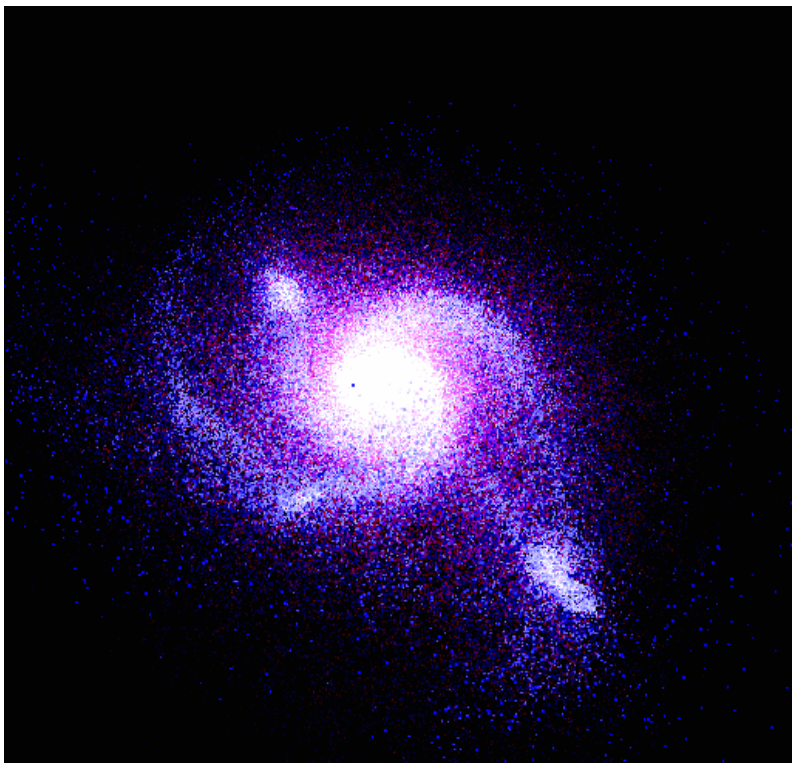


projected separation

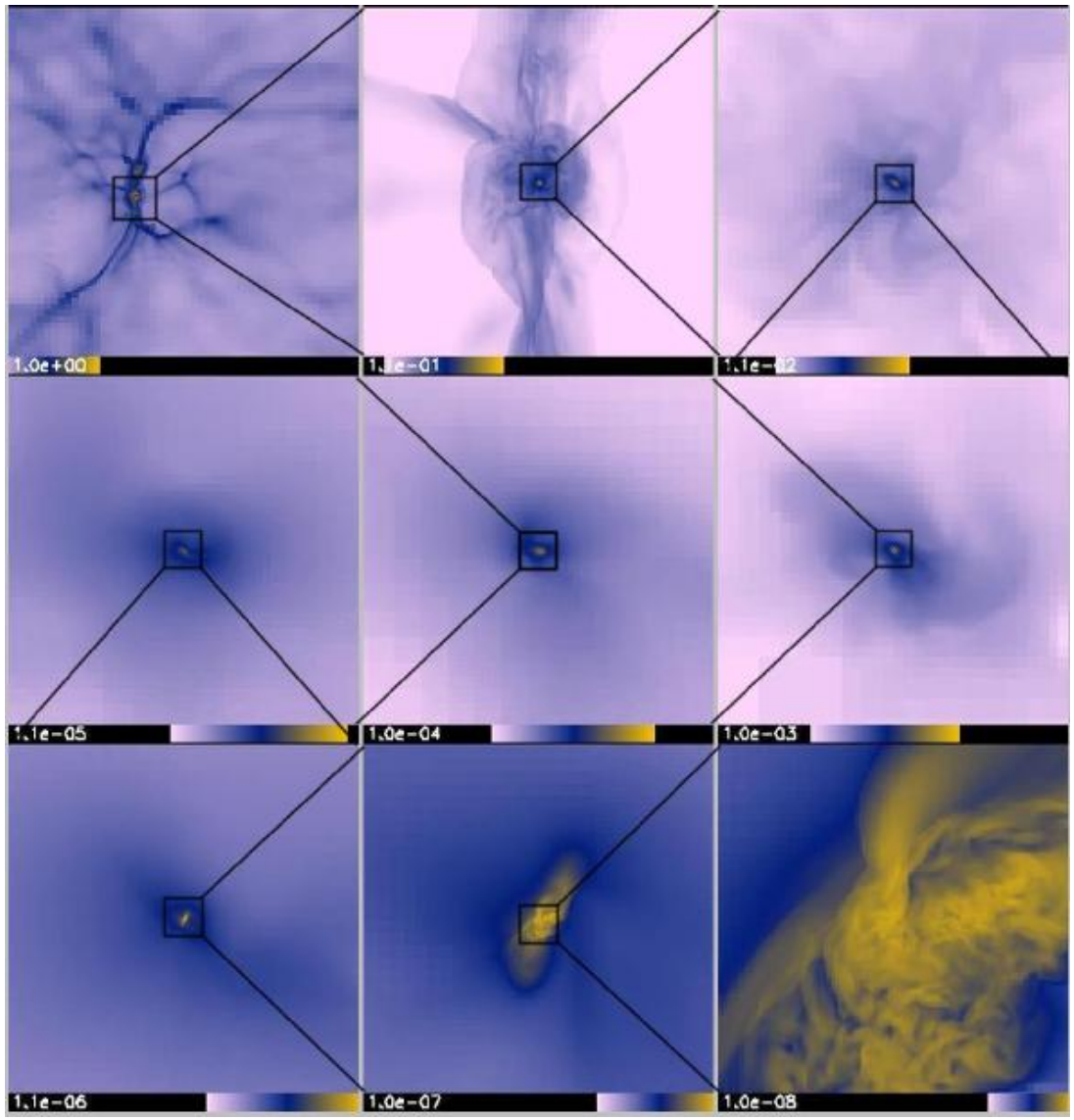
different points correspond to samples of galaxies of different Luminosities

lines are results of computer simulations

Research Frontiers:
Towards simulating realistic galaxies

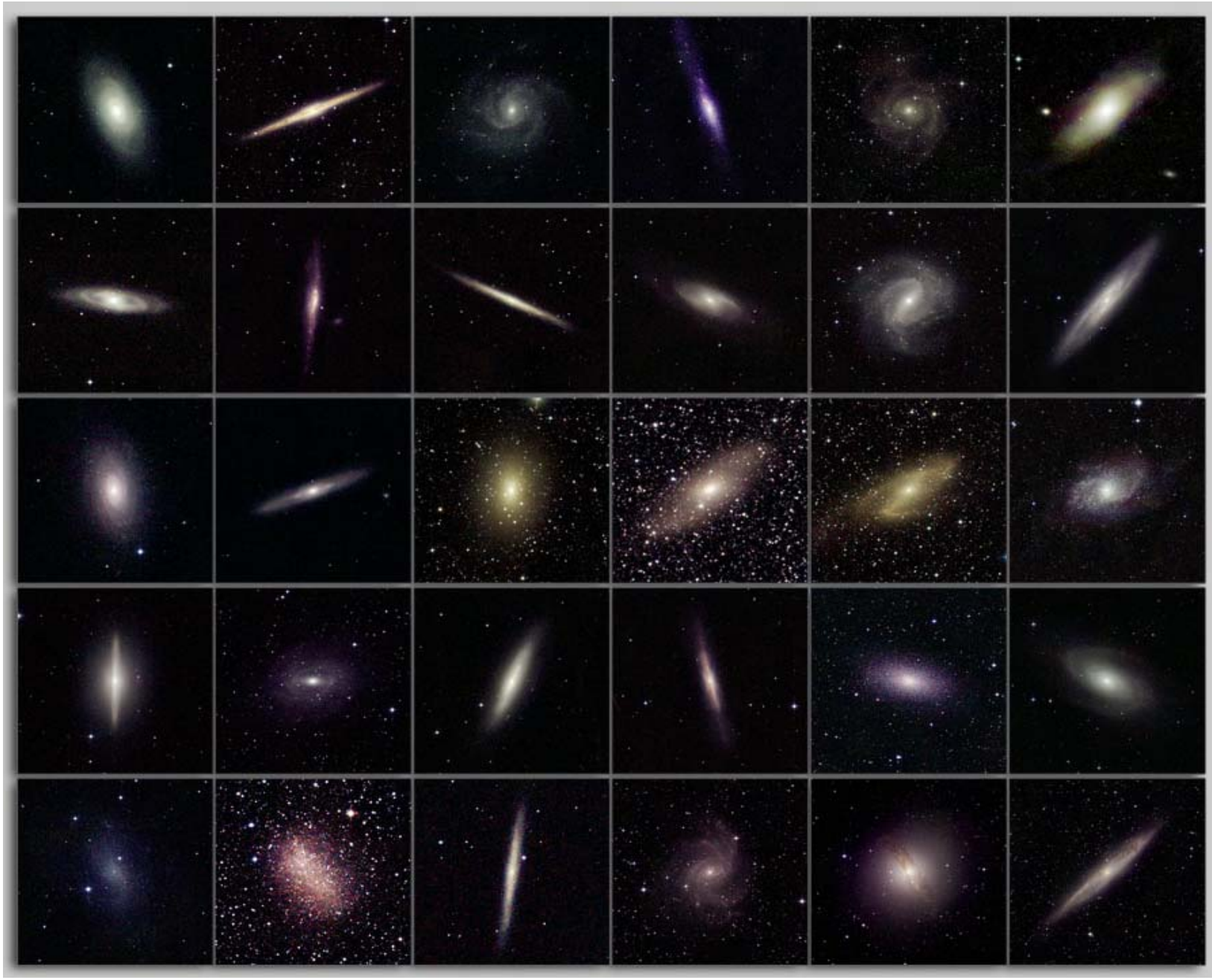


Simulating Formation of the First Star in the Universe

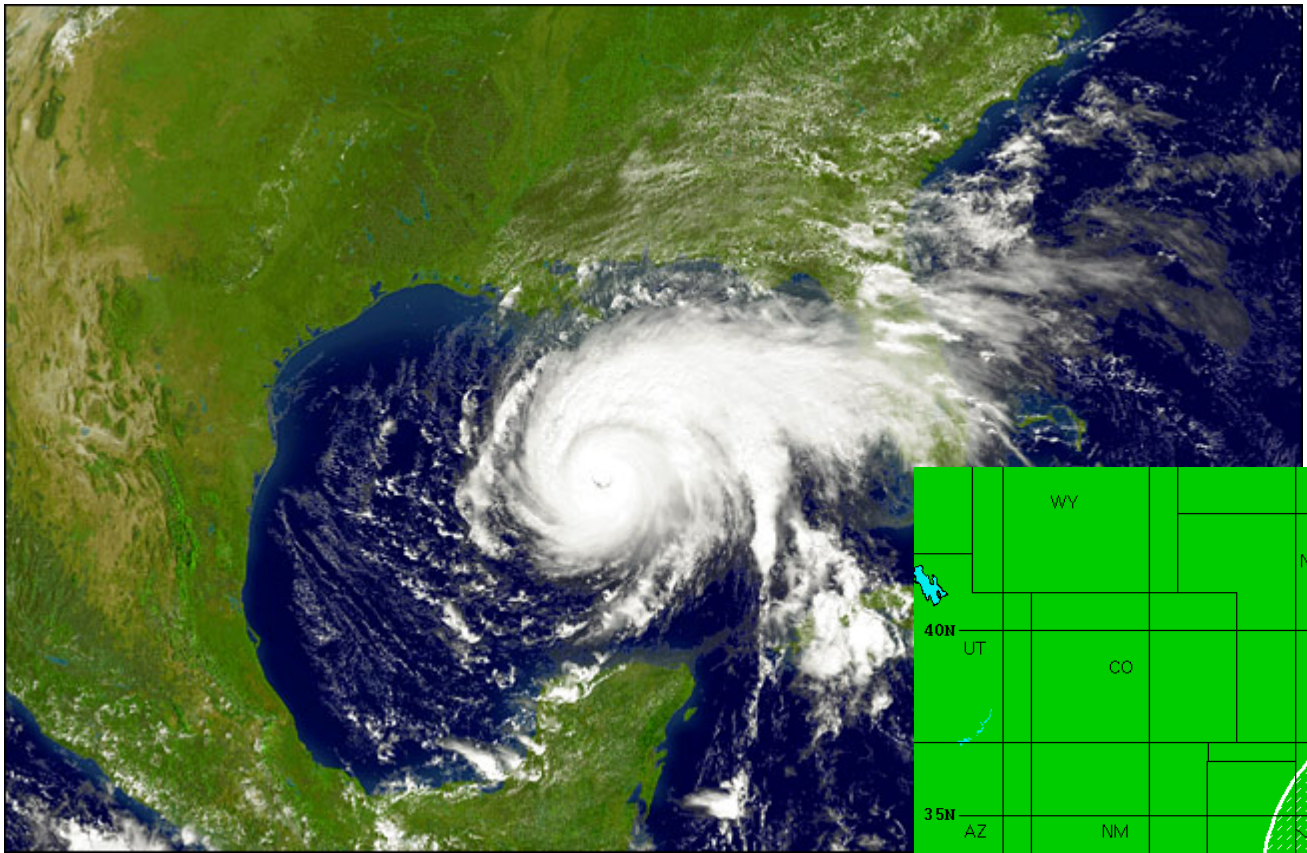


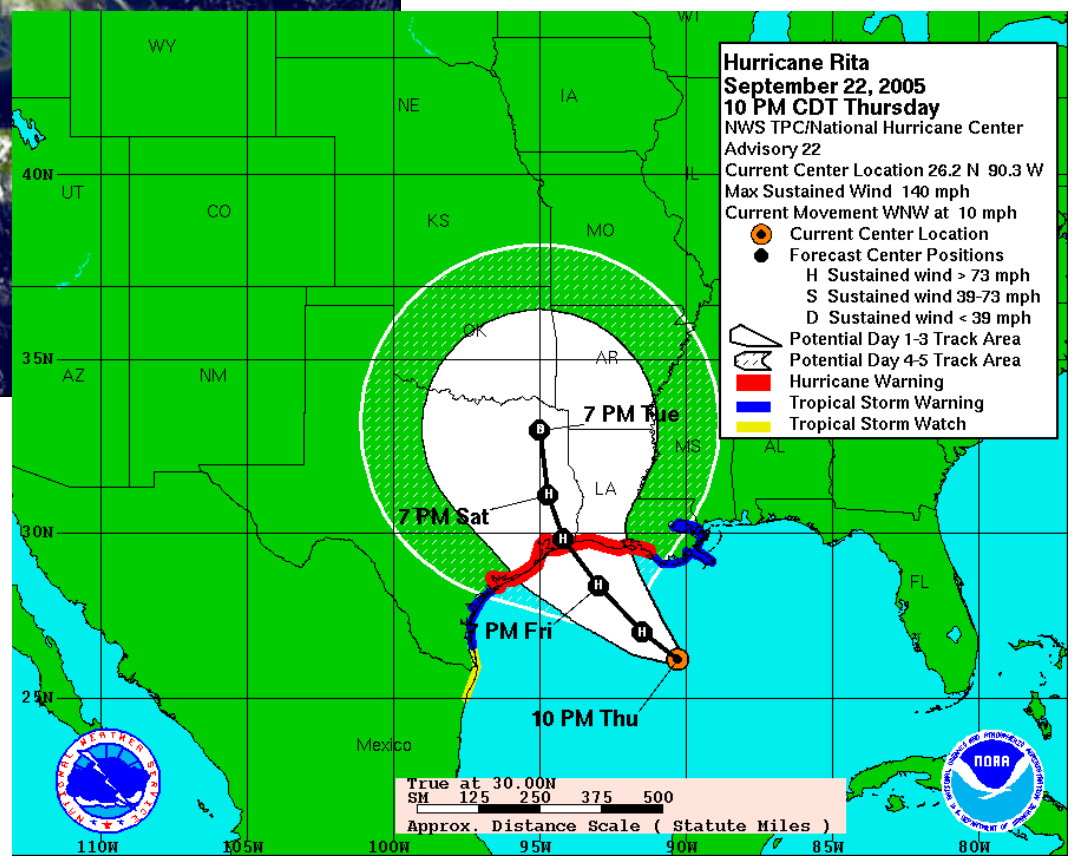
Images, animations, information: http://www.tomabel.com

Galaxies come in different shapes and sizes



Not unlike more familiar computer models…






http://hubblesite.org/
“Galaxies Across Time” IMAX Movie
by Frank Summers (STScI)
http://terpsichore.stsci.edu/~summers/viz/hgast/

Additional Info

Slides of this talk:

http://astro.uchicago.edu/~andrey/talks/shortcourse05

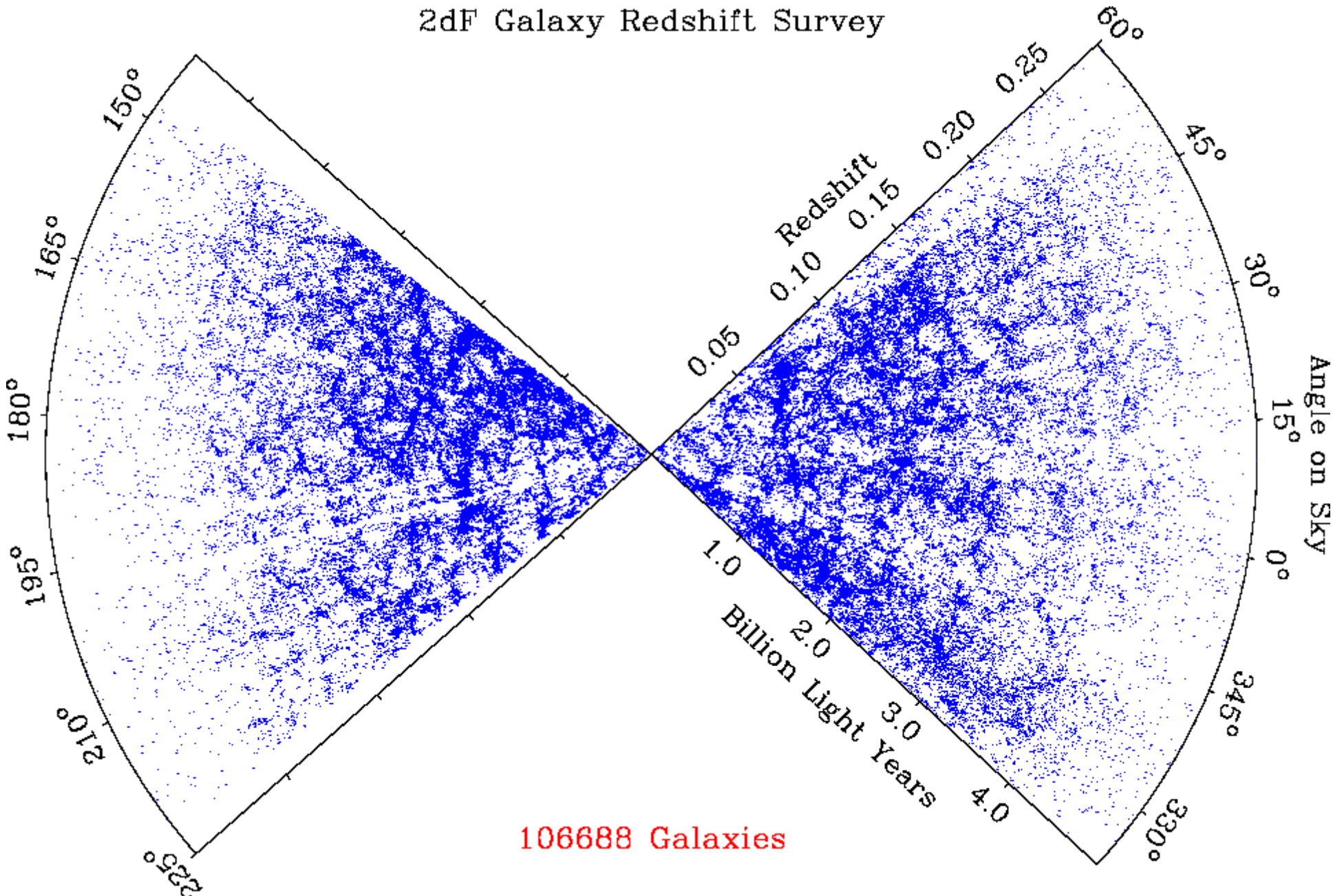
Images, animations, web links:

http://cosmicweb.uchicago.edu

Additional Reading

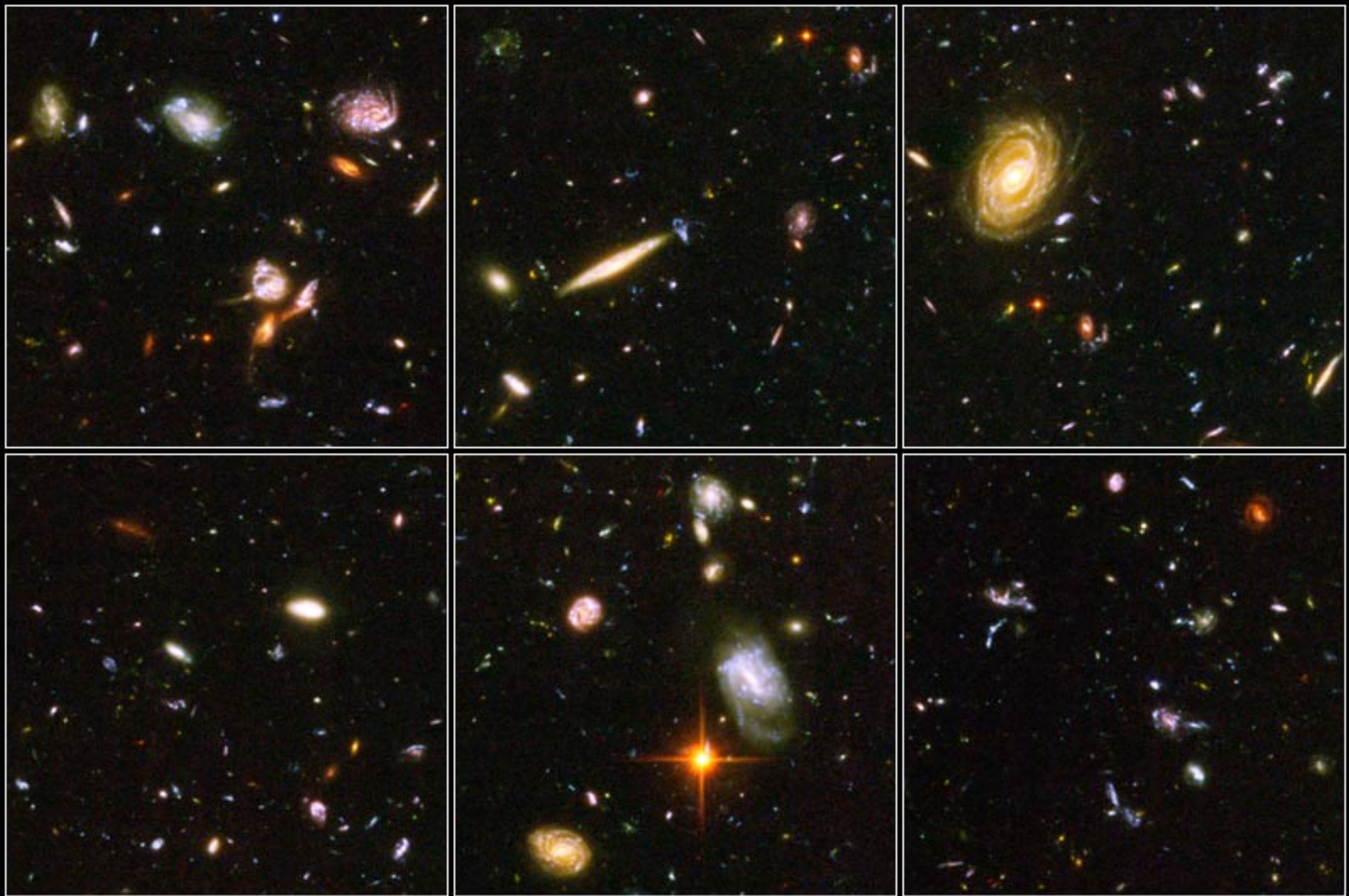
Scientific American, February 2004 issue

On even larger scales... (billions of light years)



Hubble Ultra Deep Field Details

HST ▪ ACS



NASA, ESA, S. Beckwith (STScI) and The HUDF Team

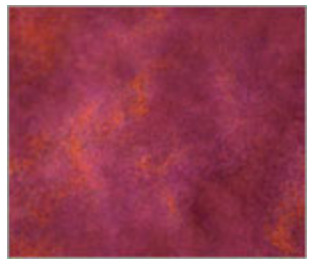
STScI-PRC04-07c

Formation of structures

Big Bang

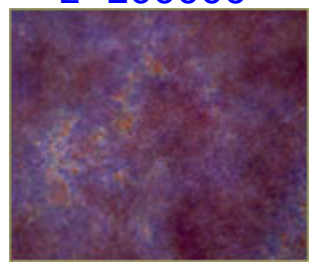
$z=10^{66}$

First particles form



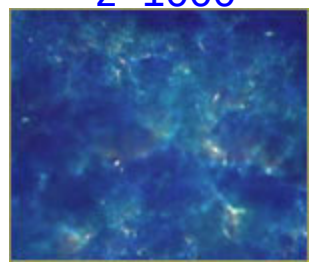
Light elements (H, He, Li) form

z=100000



Universe becomes neutral

z=1000

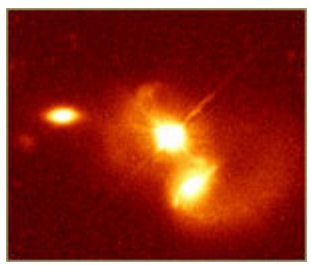


First stars form
Universe is reionized

z~10

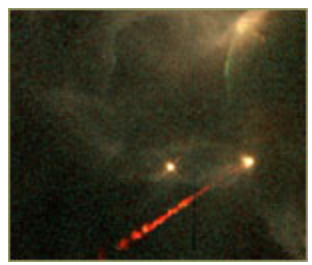
Galaxies form

z~1-5



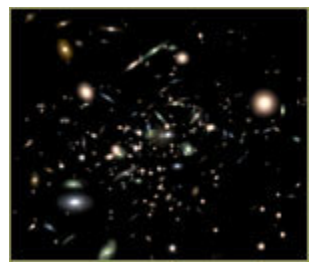
Solar system forms

z~0.4

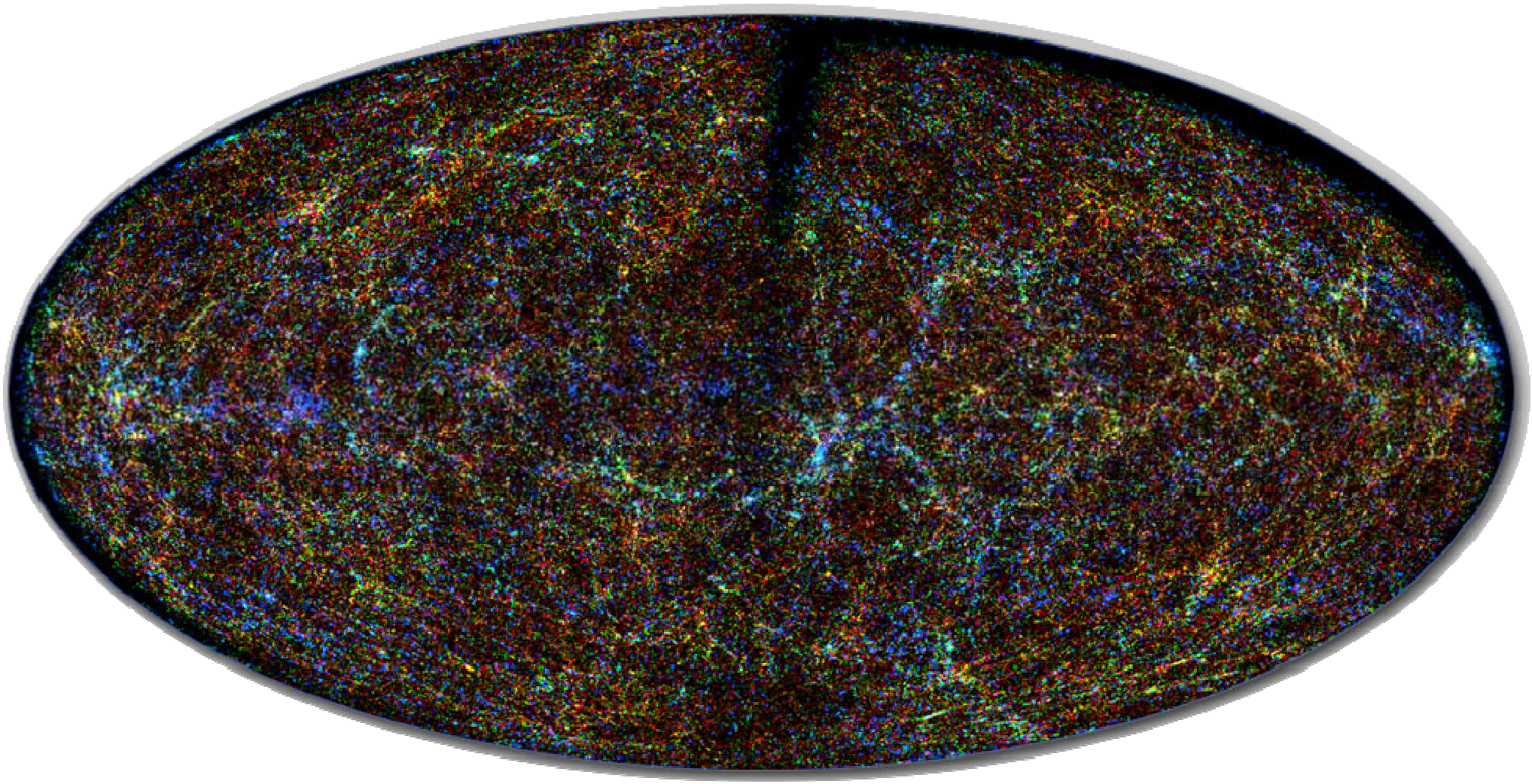


Present day

z=0



Sky Distribution of Galaxies



Towards a coherent picture: modeling structure formation in the Universe