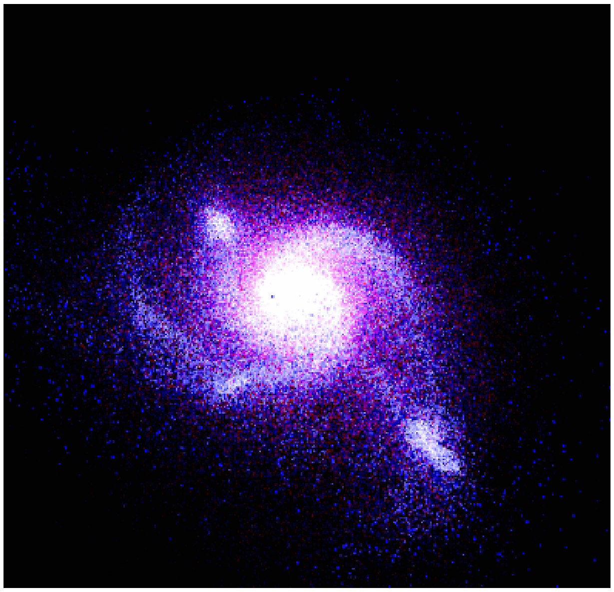
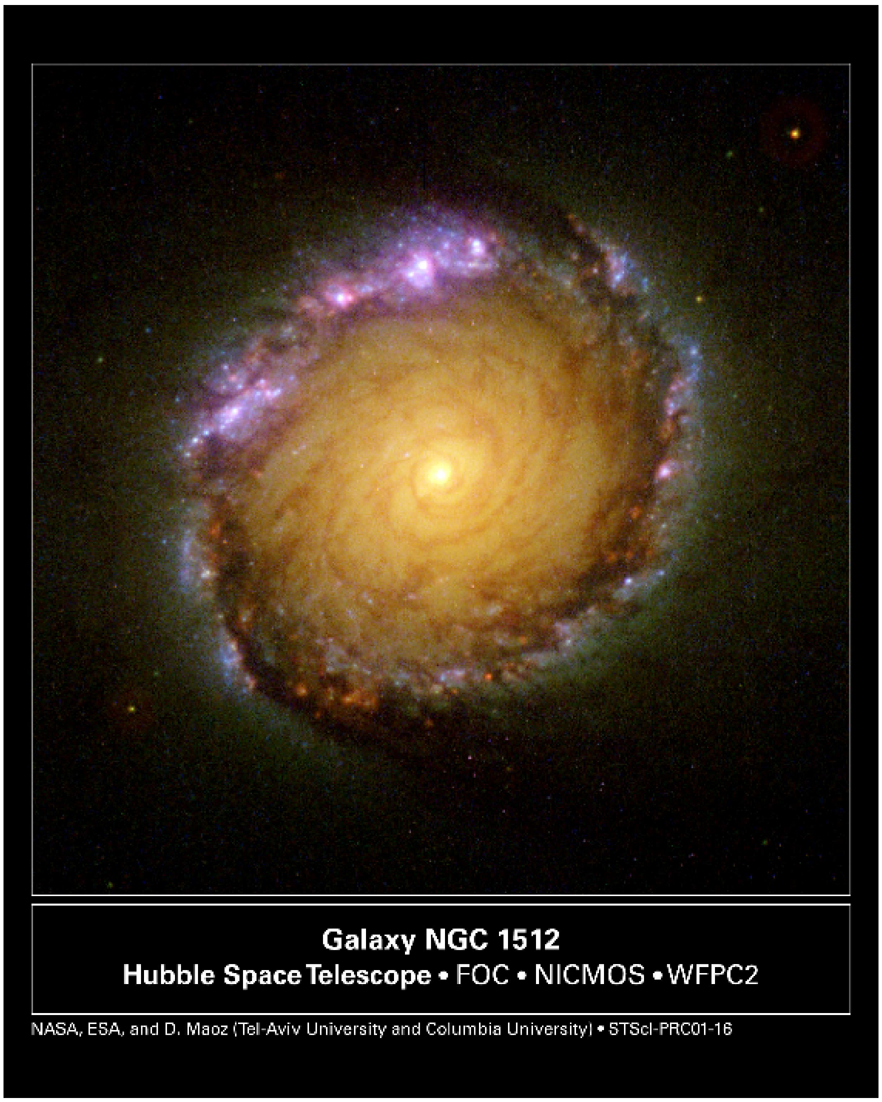
Universe in a box:
simulating formation of cosmic structures



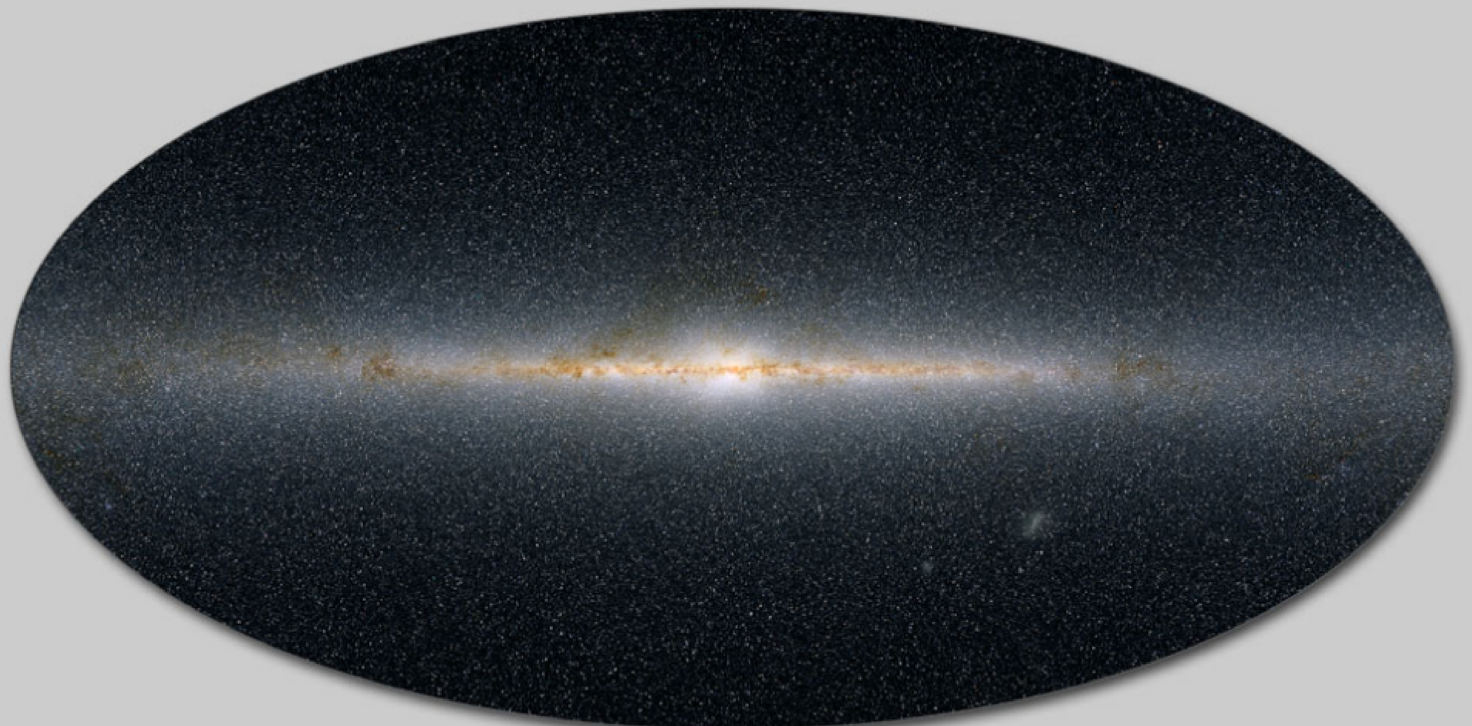
Andrey Kravtsov
Department of Astronomy & Astrophysics
Center for Cosmological Physics (CfCP)
University of Chicago

http://astro.uchicago.edu/~andrey/talks/
http://cfcp.uchicago.edu/lss/

Galaxies

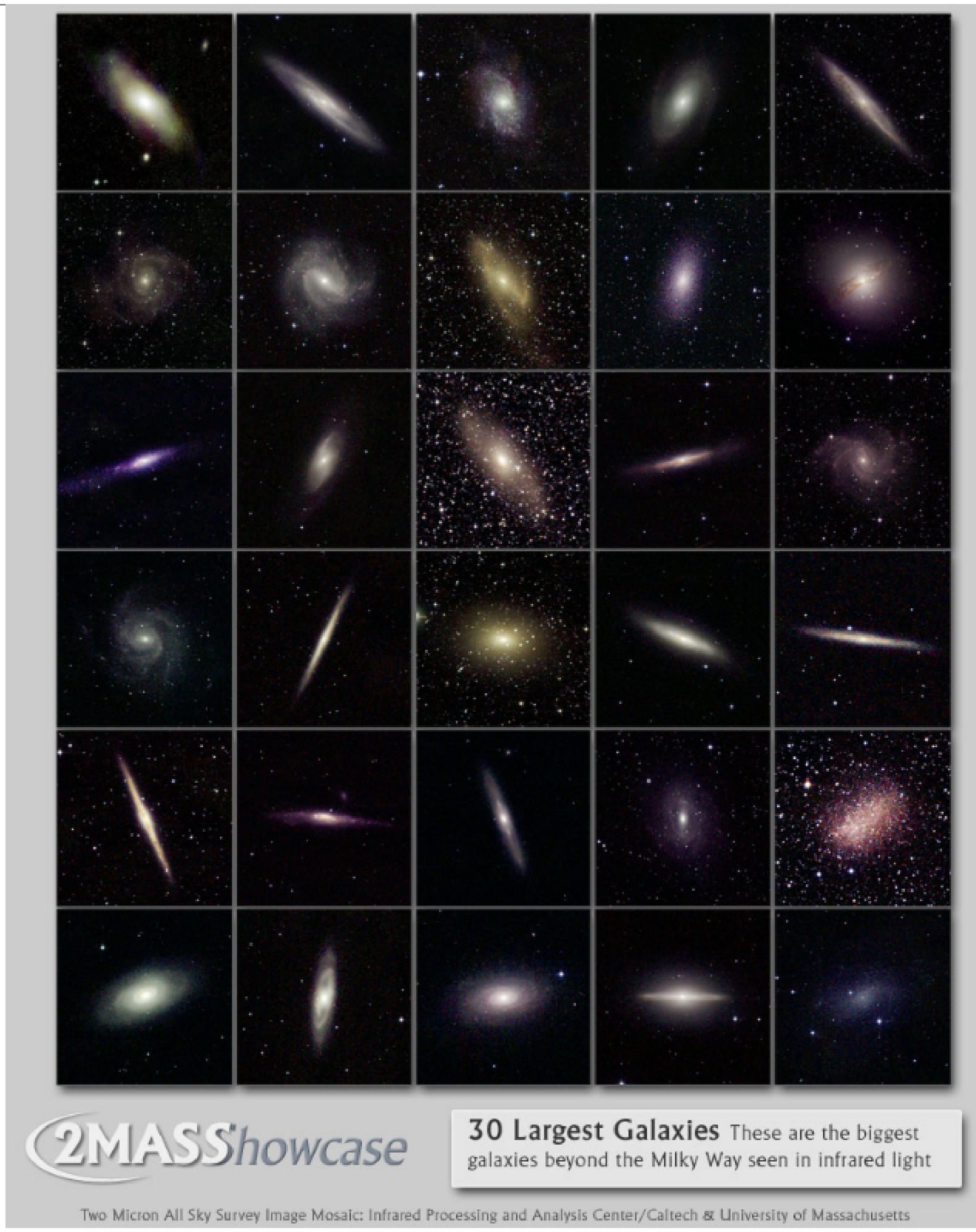

Galaxy NGC 1512
Hubble Space Telescope • FOC • NICMOS • WFPC2
NASA, ESA, and D. Maoz (Tel-Aviv University and Columbia University) • STScI-PRC01-16

2MASS Showcase

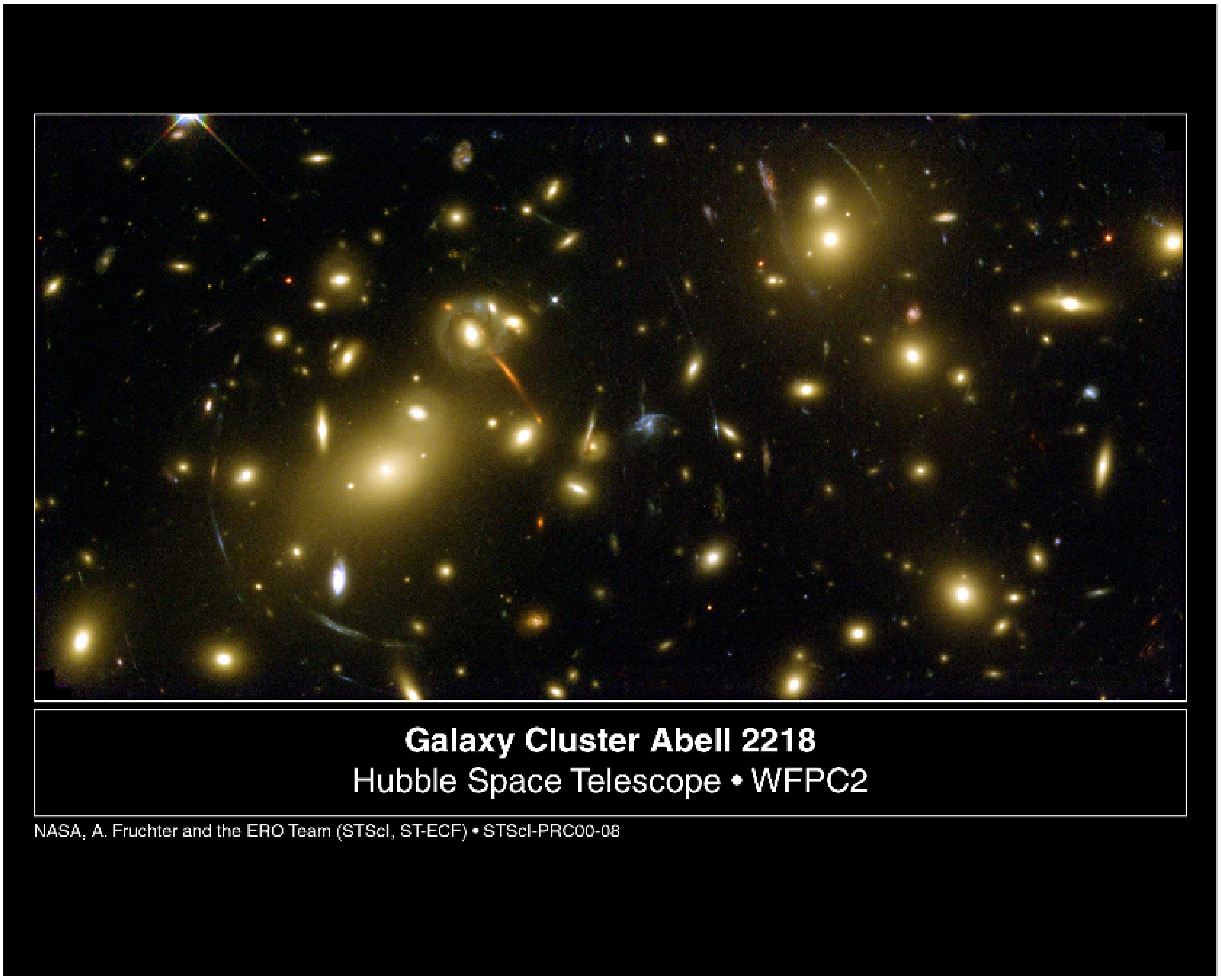


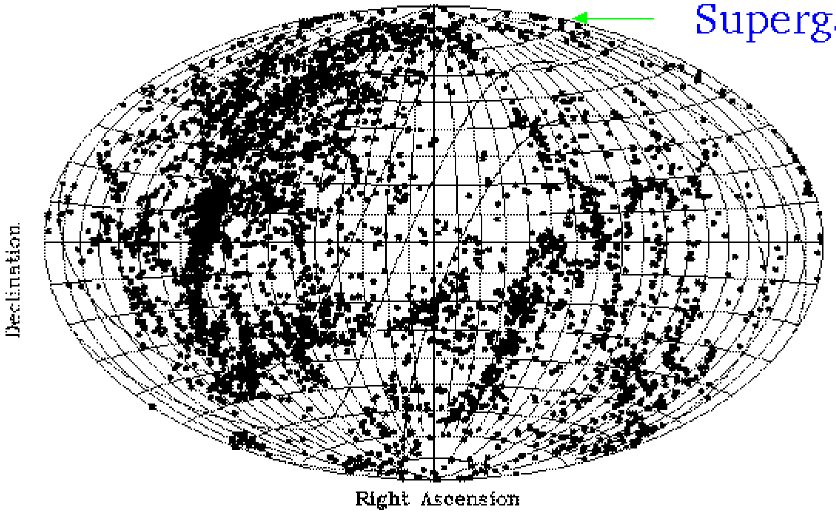
The Infrared Milky Way This map of the infrared sky includes the light of a half billion stars

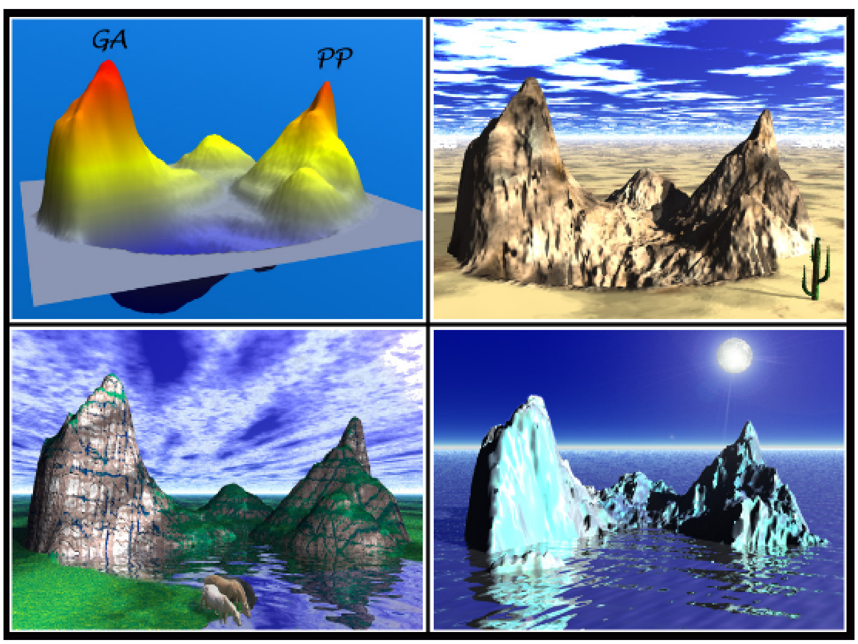
Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts


2MASS Showcase
30 Largest Galaxies These are the biggest galaxies beyond the Milky Way seen in infrared light
Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

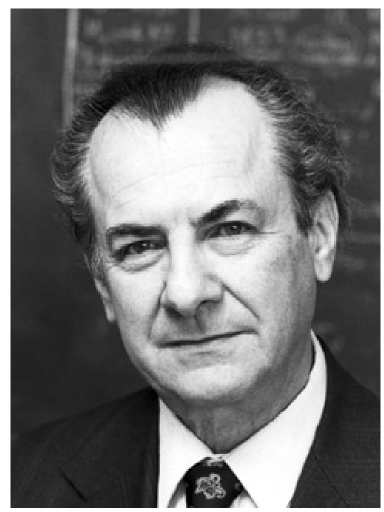
Galaxy Clusters







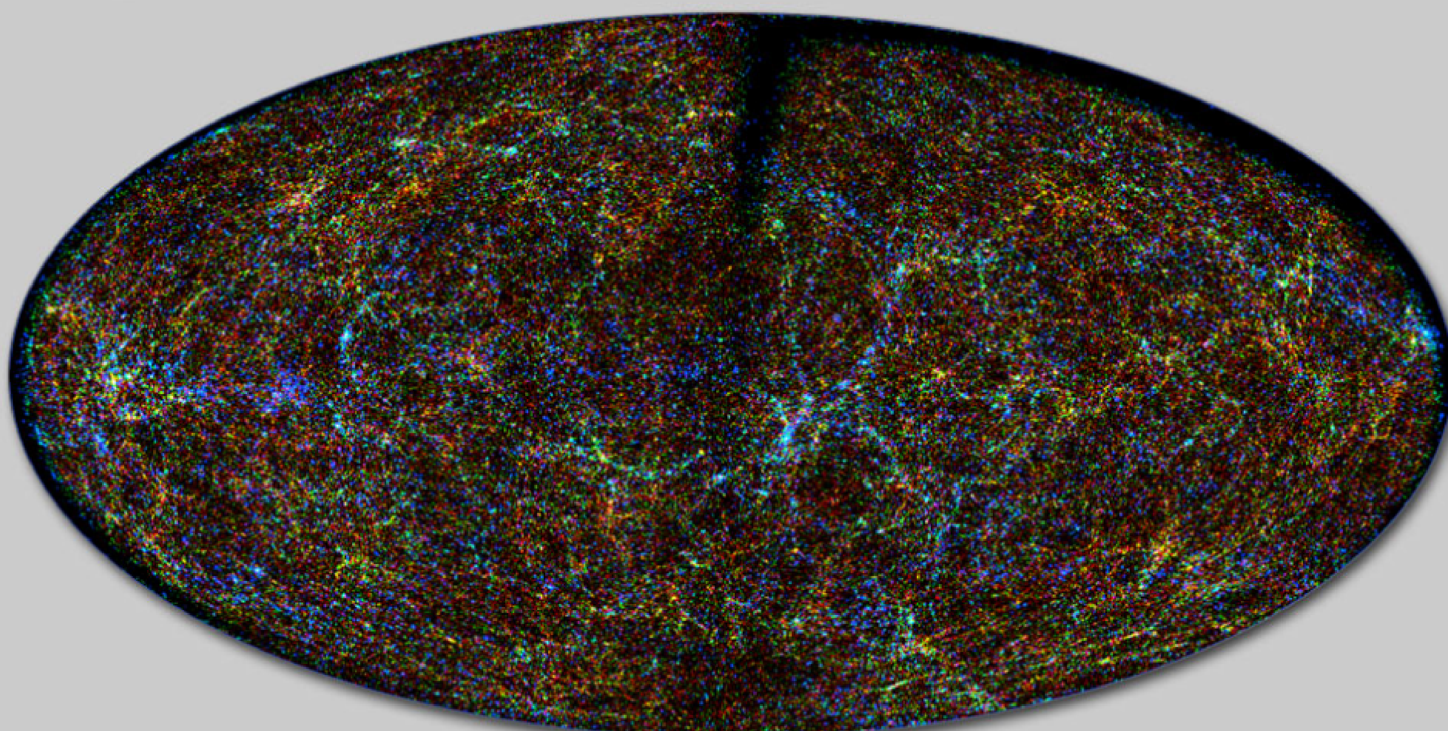
The Local Supercluster



Gerard de Vaucouleurs
1918- 1995

G. de Vaucouleurs

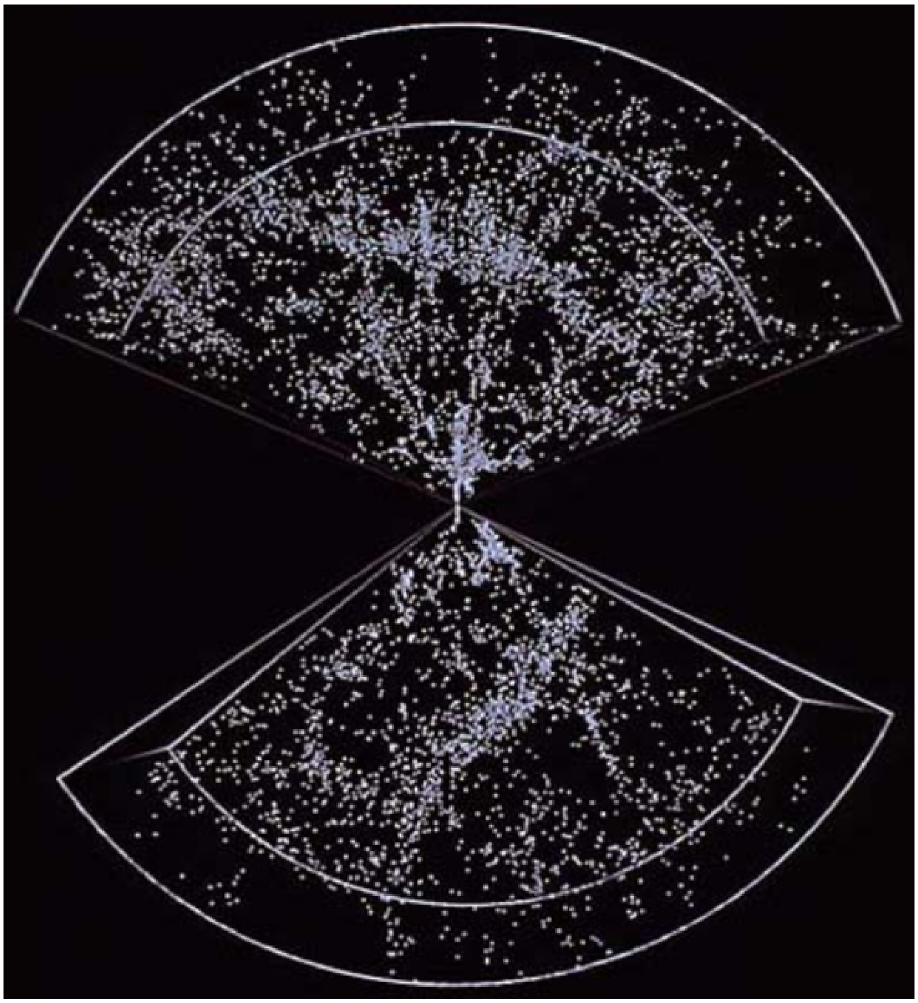
2MASS Showcase



Galaxies of the Infrared Sky Near and far structures in the local universe are color-coded by galaxy brightness

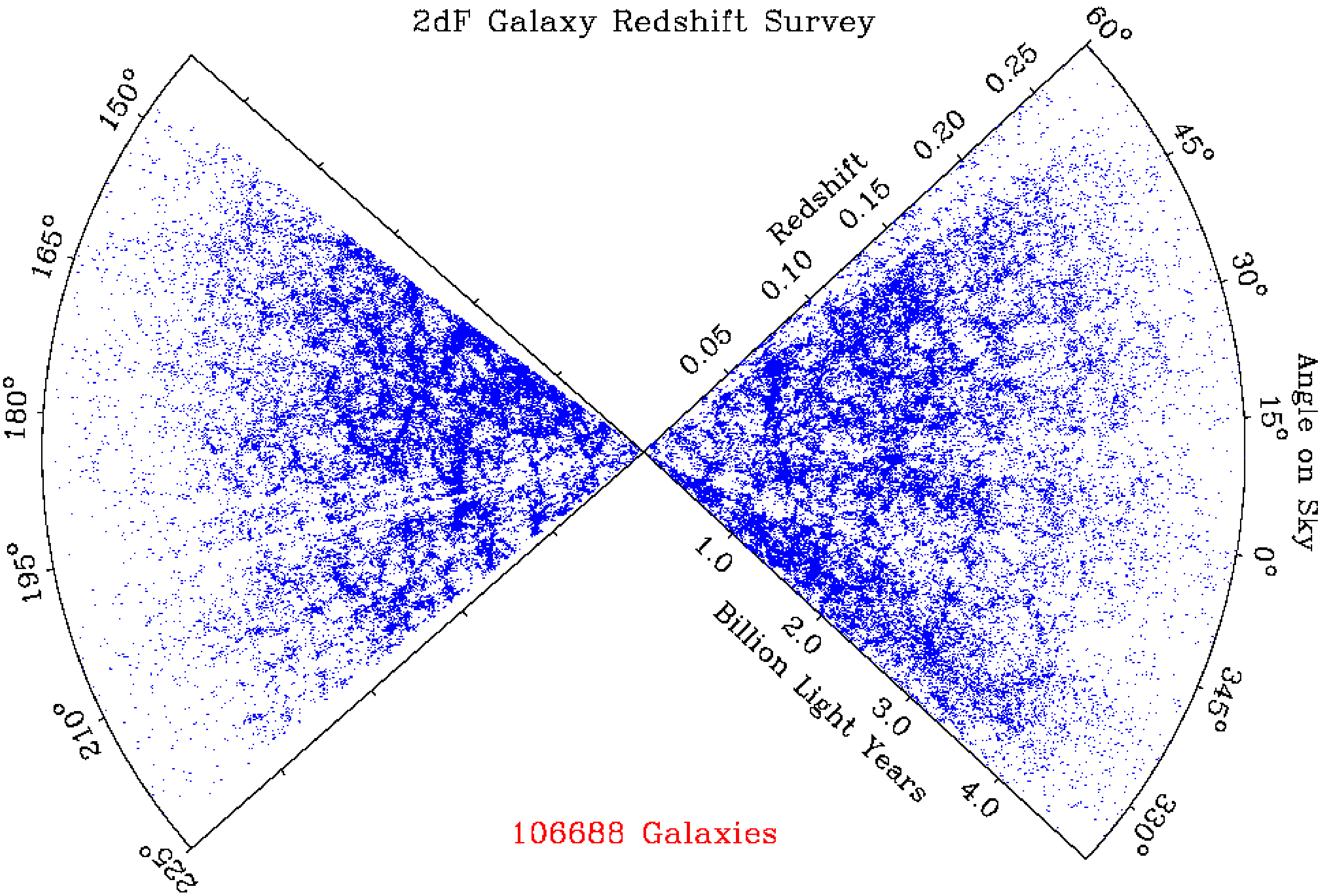
Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

Large- scale structure of the Universe

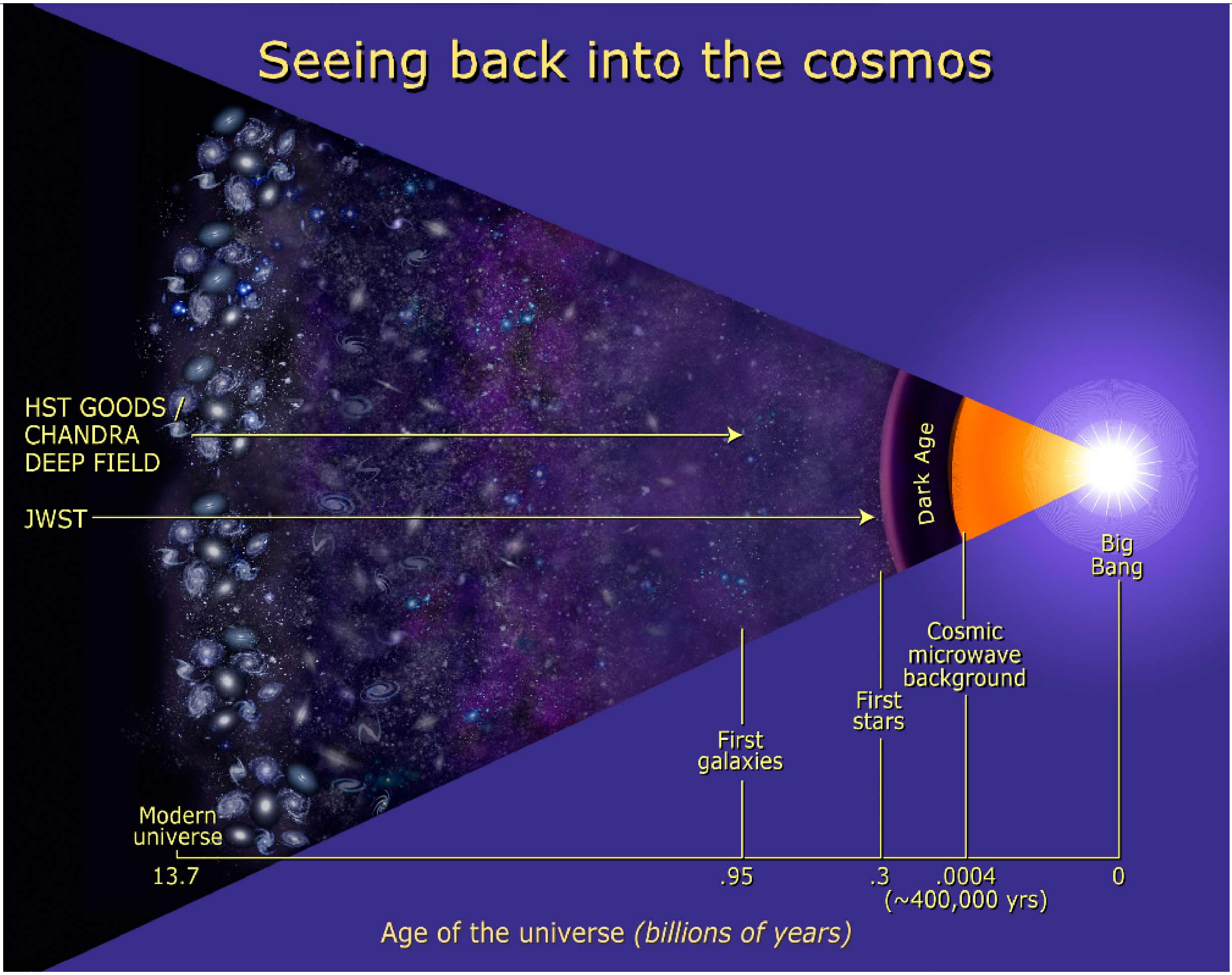


as seen
by the
CfA survey

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



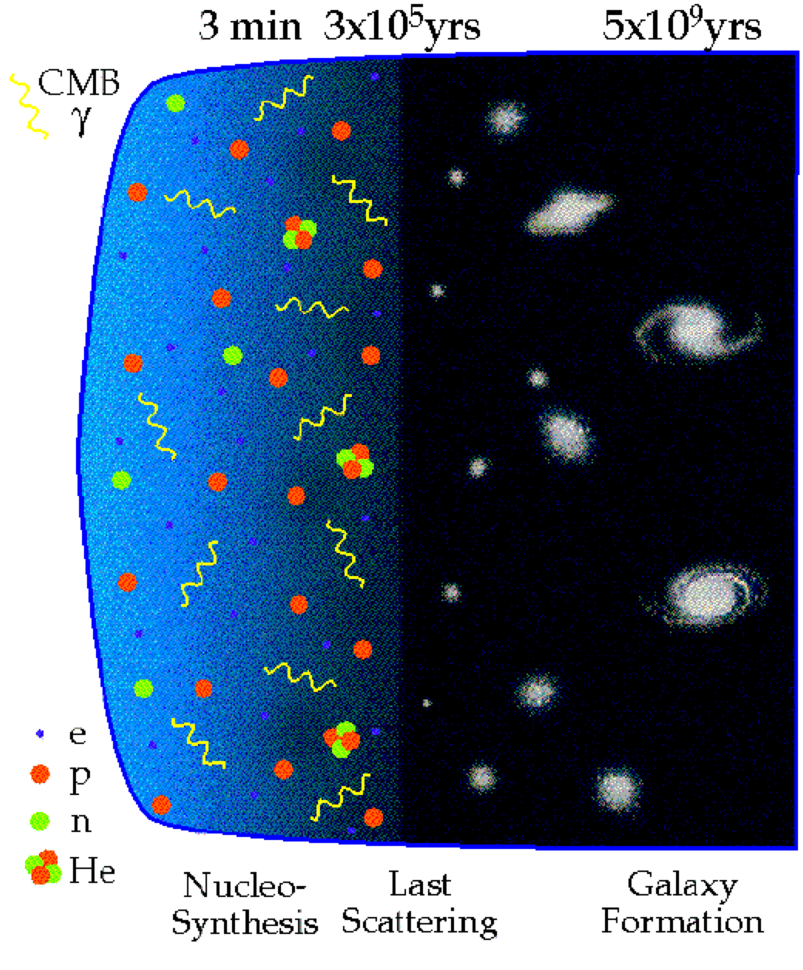

The Hubble Deep Field North
HUBBLESITE.org



Seeing back into the cosmos
HST GOODS / CHANDRA DEEP FIELD
JWST
Dark Age
Big Bang
Cosmic microwave background
First stars
First galaxies
Modern universe
13.7
.95
.3
.0004 (~400,000 yrs)
0
Age of the universe (billions of years)

Structures in the Universe

(Very) Brief History



graphics from Wayne Hu (background.uchicago.edu/~whu)

Formation of structures

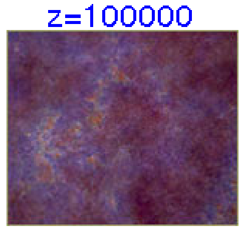
Big Bang

$z=10^{66}$

First particles form

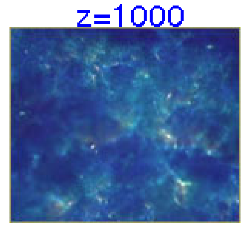
Light elements (H, He, Li) form

z=100000



Universe becomes neutral

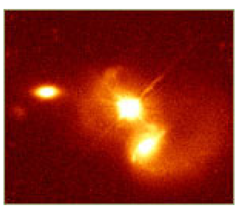
z=1000



First stars form
Universe is reionized
z~10

Galaxies form

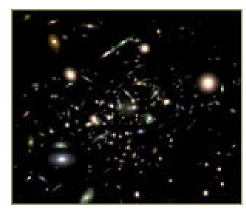
z~1- 5



Solar system forms
z~0.4

Present day

z=0



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

- ☐ Cosmic Microwave Background ripples

  physics causing 10^{-5} deviations from the uniform black body temperature is very well understood in a given model. Observable statistics of fluctuations (e.g., angular correlation function or power spectrum) depend on cosmological parameters, including matter and energy content.

- ☐ Large- scale structure of the Universe

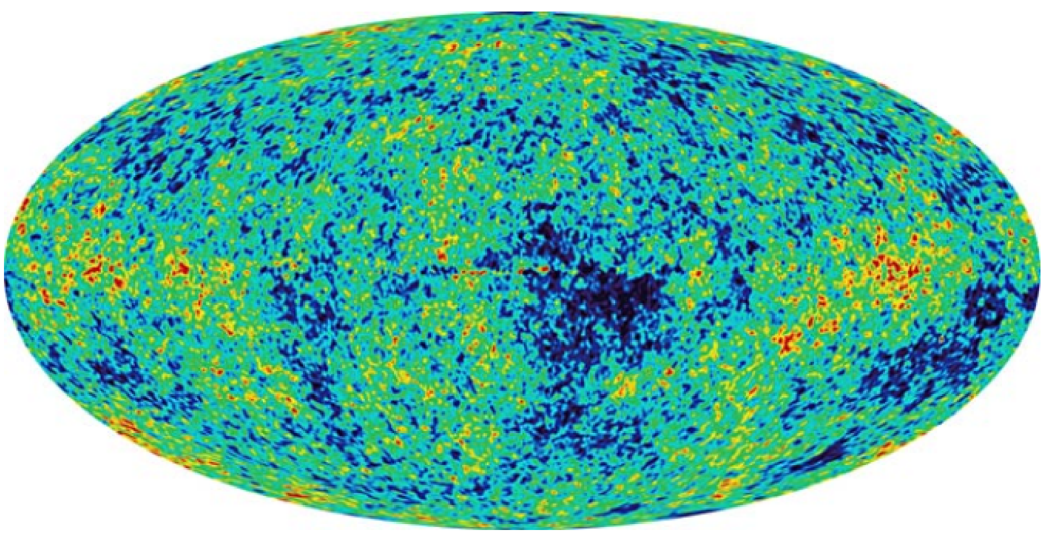
  galaxies, galaxy clusters, filaments

- ☐ 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

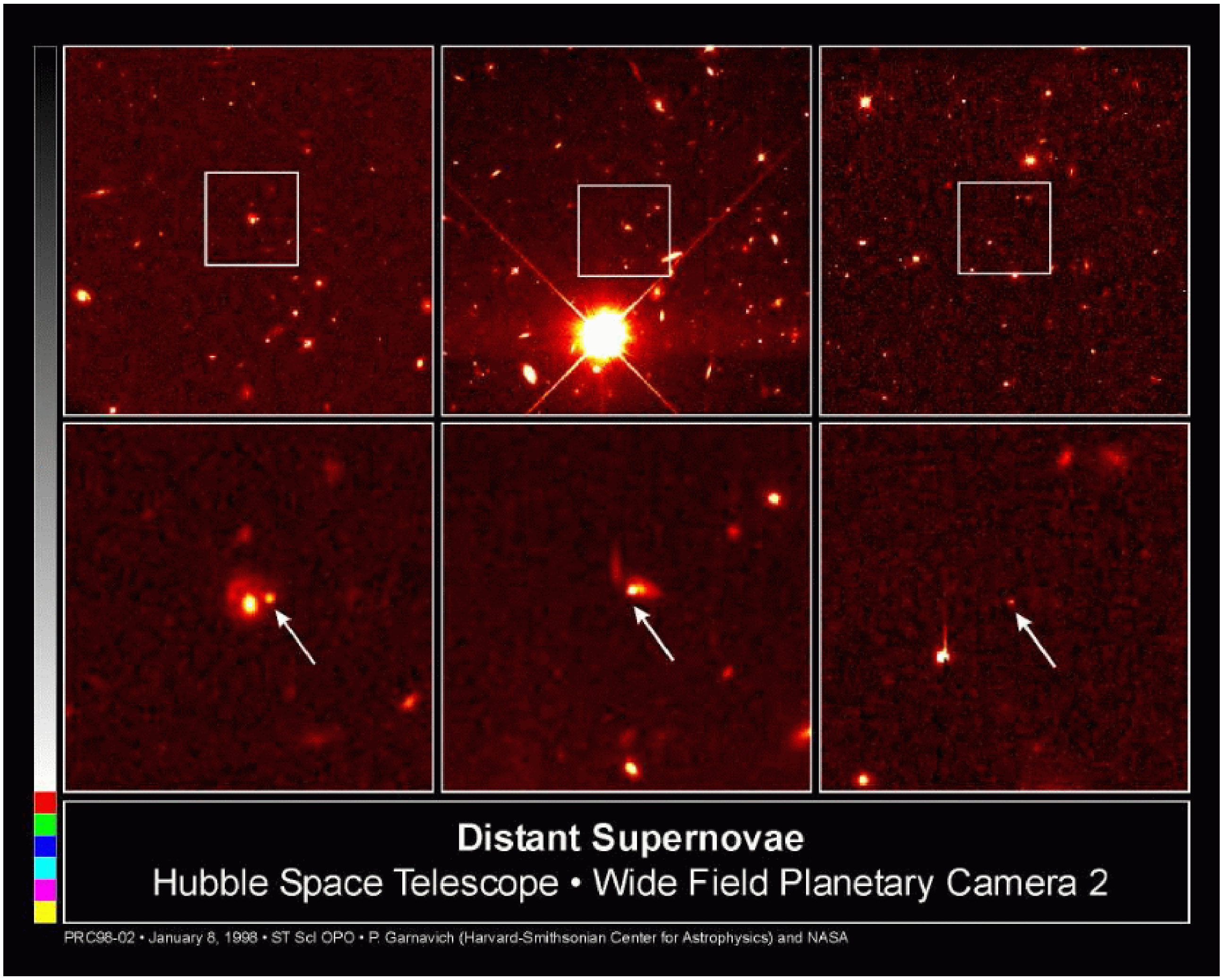
- ☐ Standard rulers (systems with known intrinsic size)

Cosmic Microwave Background (CMB) Temperature Anisotropies

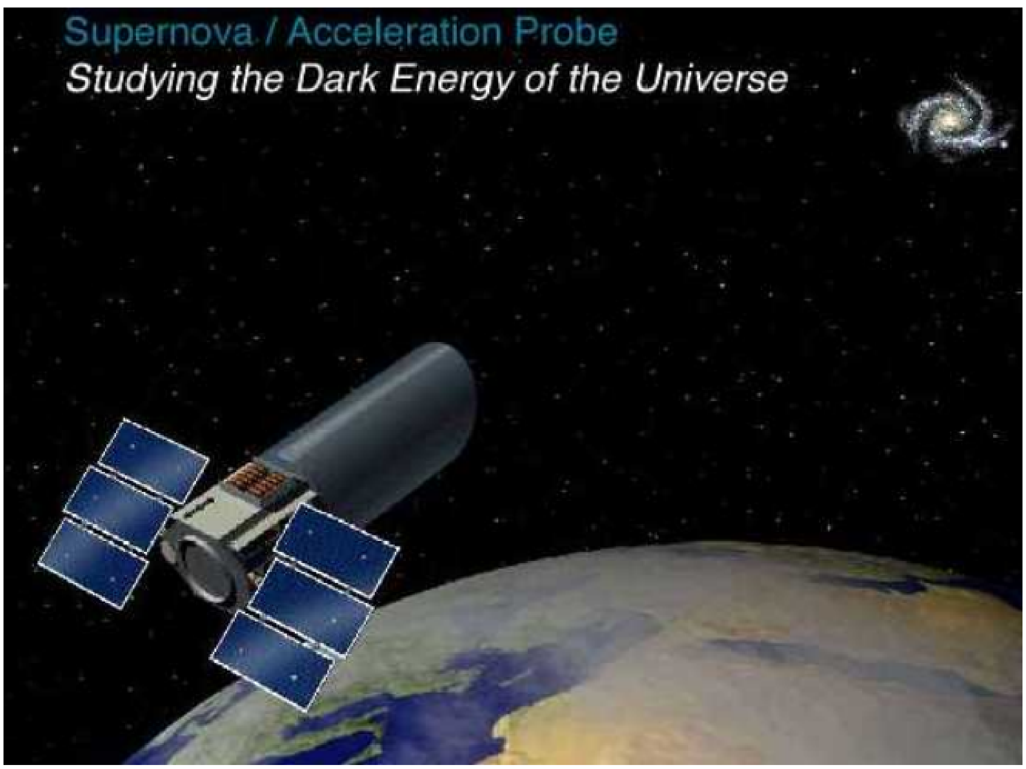


Wilkinson Microwave Anistropy Probe (WMAP) satellite results
circa February 2003

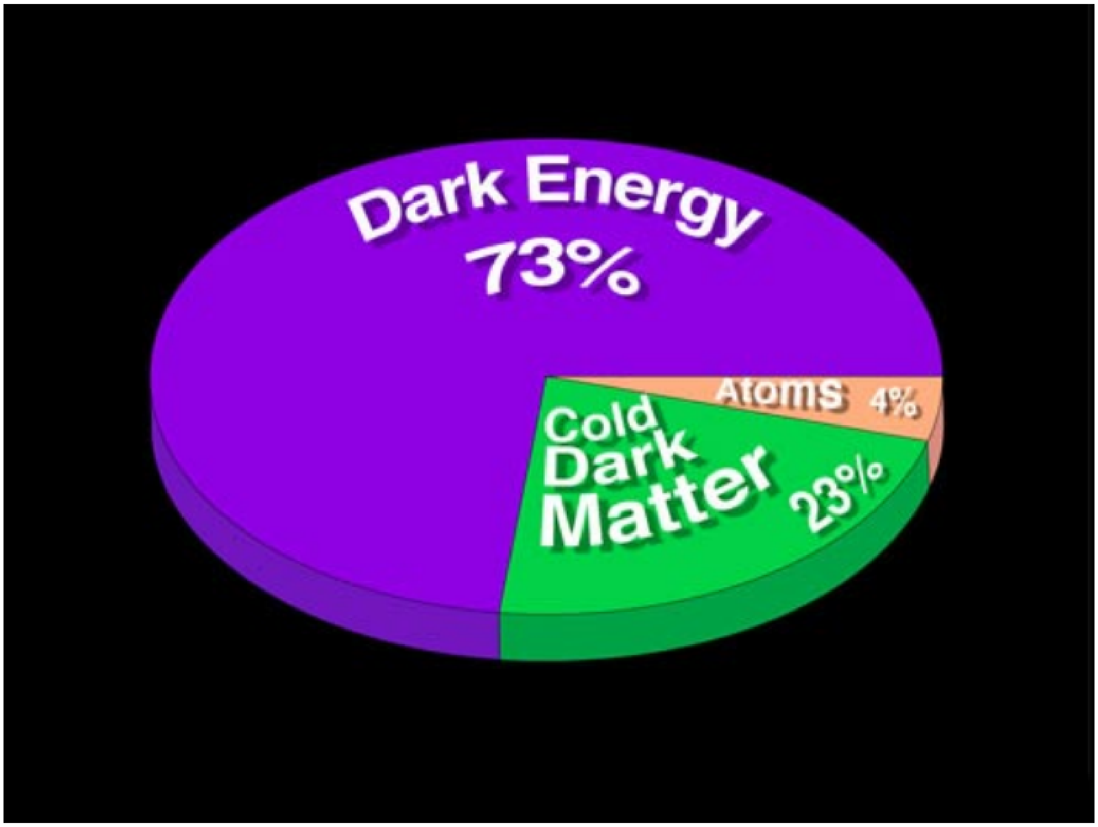
High redshift supernovae type Ia



SNAP satellite proposal



Cosmic Pie



Computer Simulations: How to set up and where to begin?

- ☐ If the content of the Universe is assumed, theory predicts the statistical properties of inhomogeneities in matter distribution

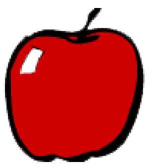
  these predictions are used to set up initial conditions of the simulations

- ☐ Simple analytic predictions are accurate only while inhomogeneities are small (<10% fluctuations with respect to the mean density of the Universe)

  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

Computer Simulations: How do we model?

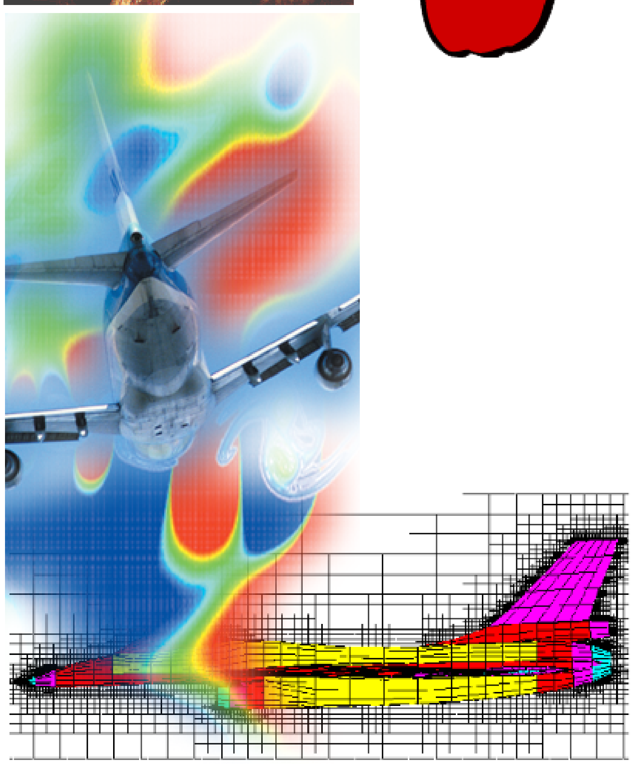


- Gravity is the king

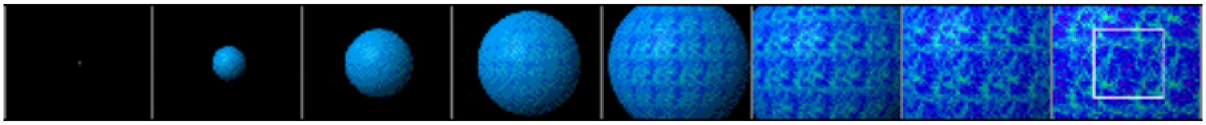
  gravity is by far the strongest force on the large scales. gravitational interactions are modelled using Newton's laws

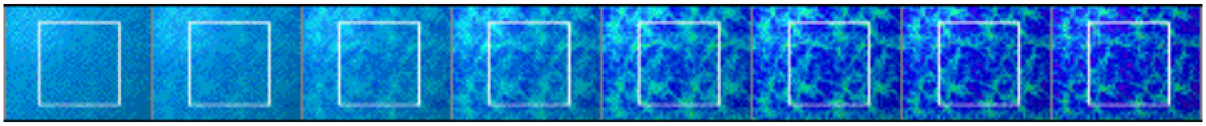
- Other forces may need to be included depending on the composition of the Universe and scales considered

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

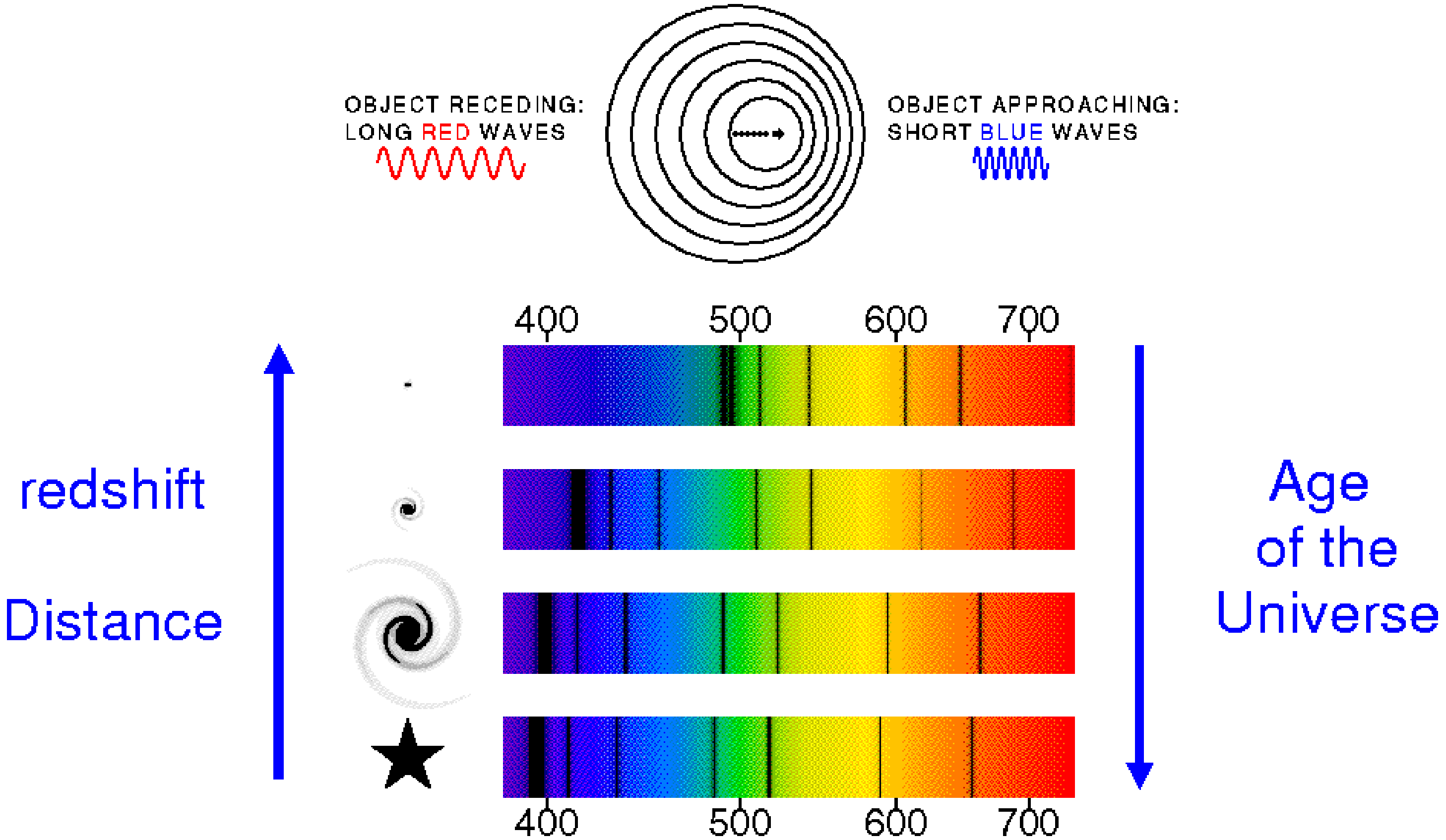


We all live in

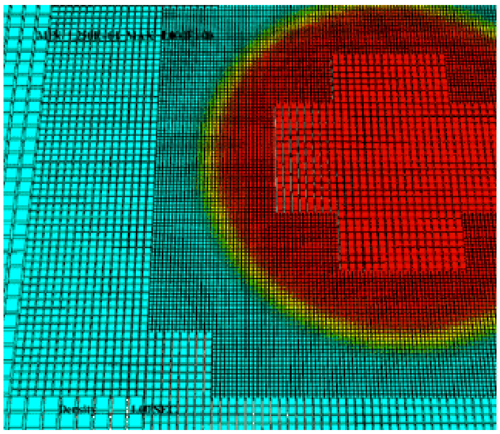


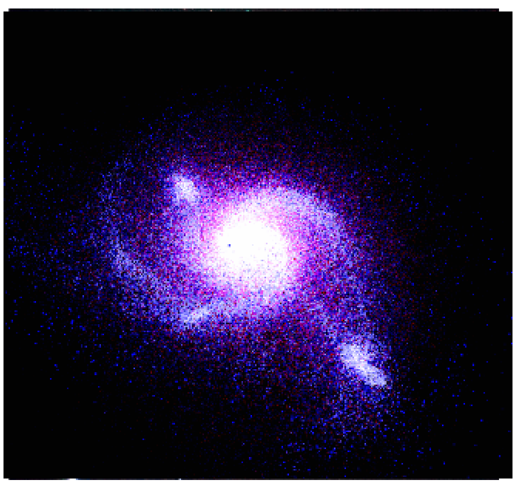


Cosmological Redshift
as a measure of distance and time



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 computers can handle only up to a billion particles

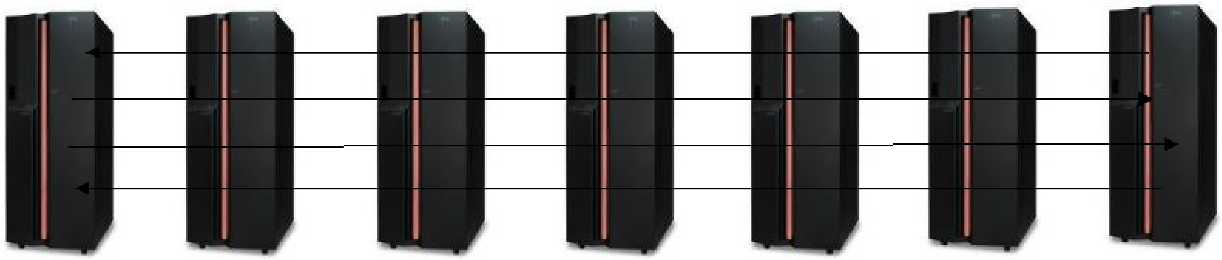
- - - - > need to discretize

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...

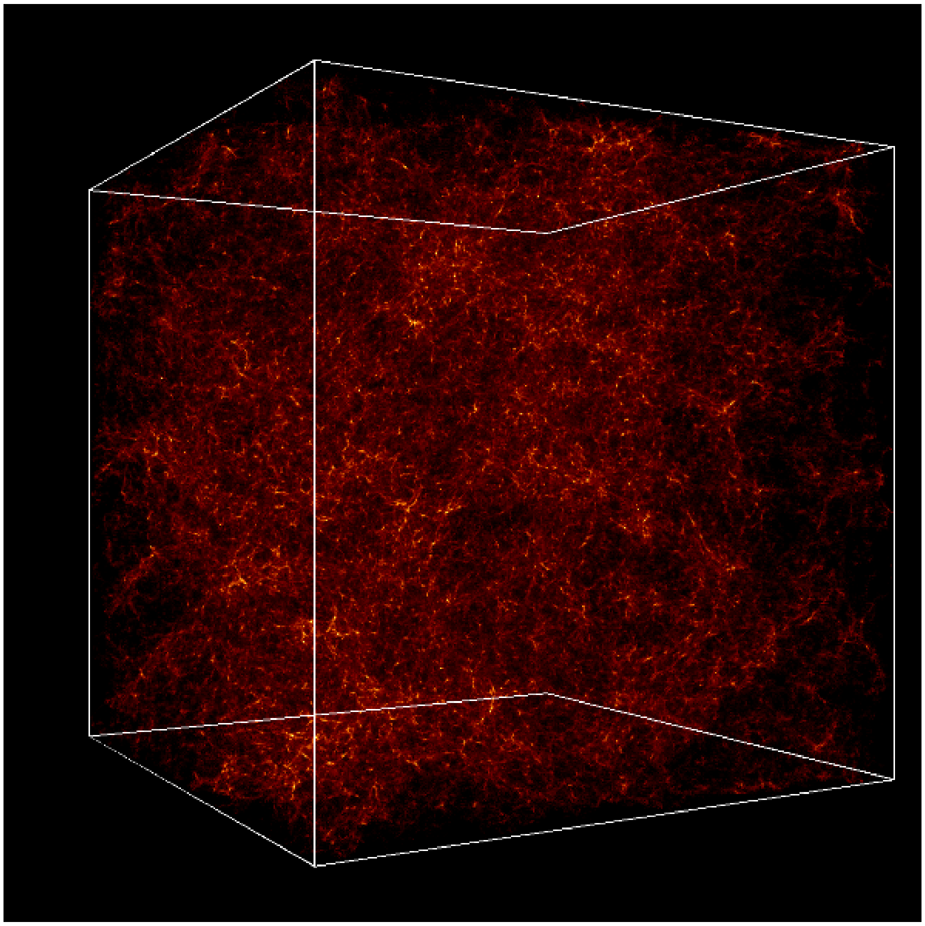
Many Many Lines of Software

```
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

c     Bad news !!!

      if ( dev .gt. eps ) then
        write(*,'(1x,''Riemann_1 solver iteration failure'')')
        stop
      end if

c     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)
        gam_s  = ind_r * (str(5) - stl(5)) + stl(5)
```

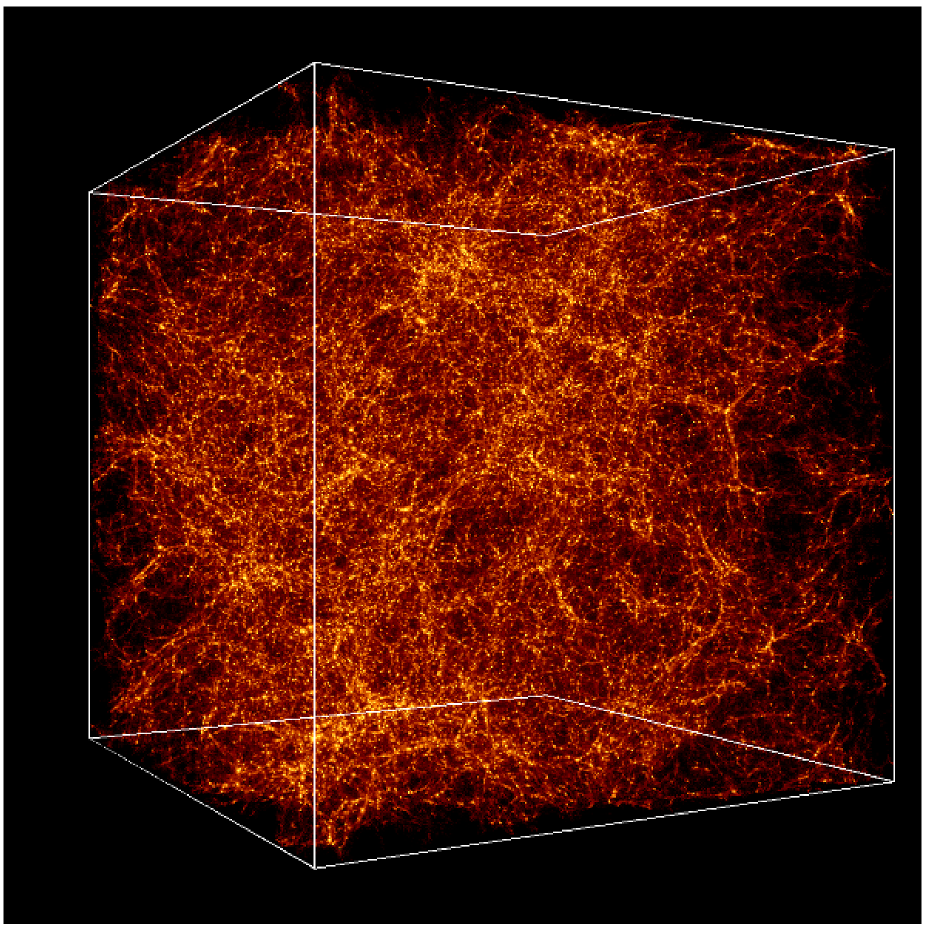
Universe in a Box: modelling formation of structures

redshift = 10; 13 billion years ago



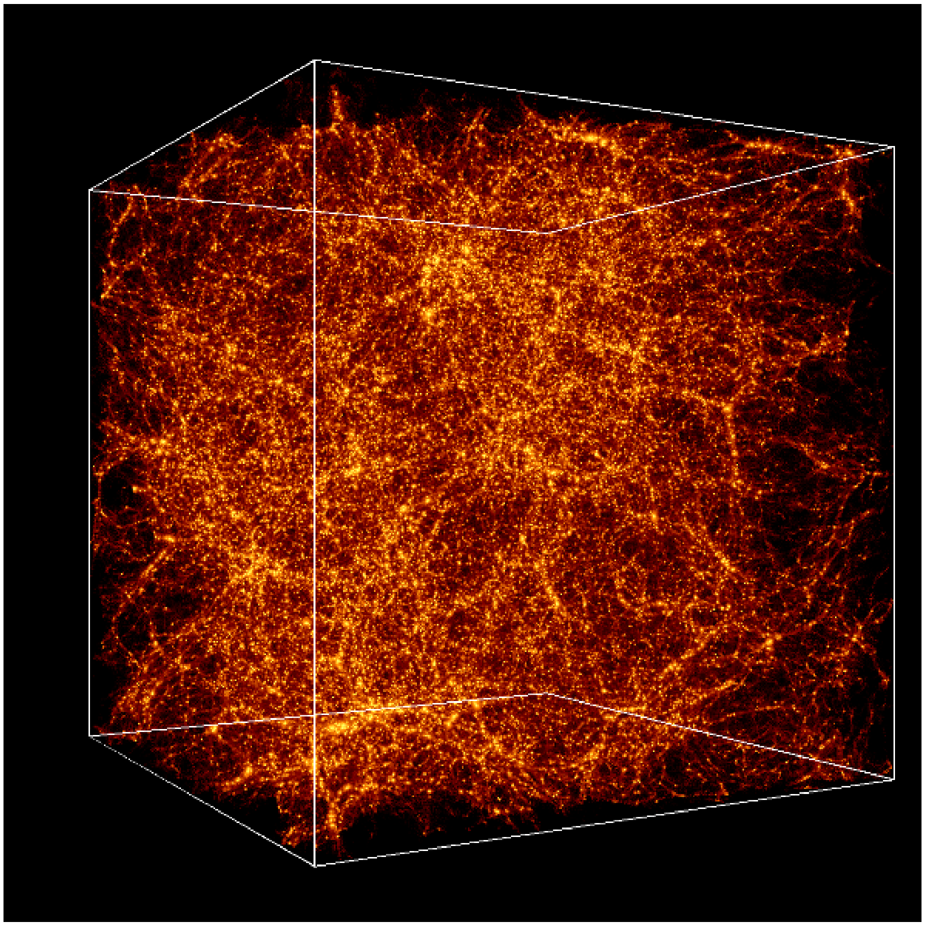
Universe in a Box: modelling formation of structures

redshift = 5; 12.3 billion years ago



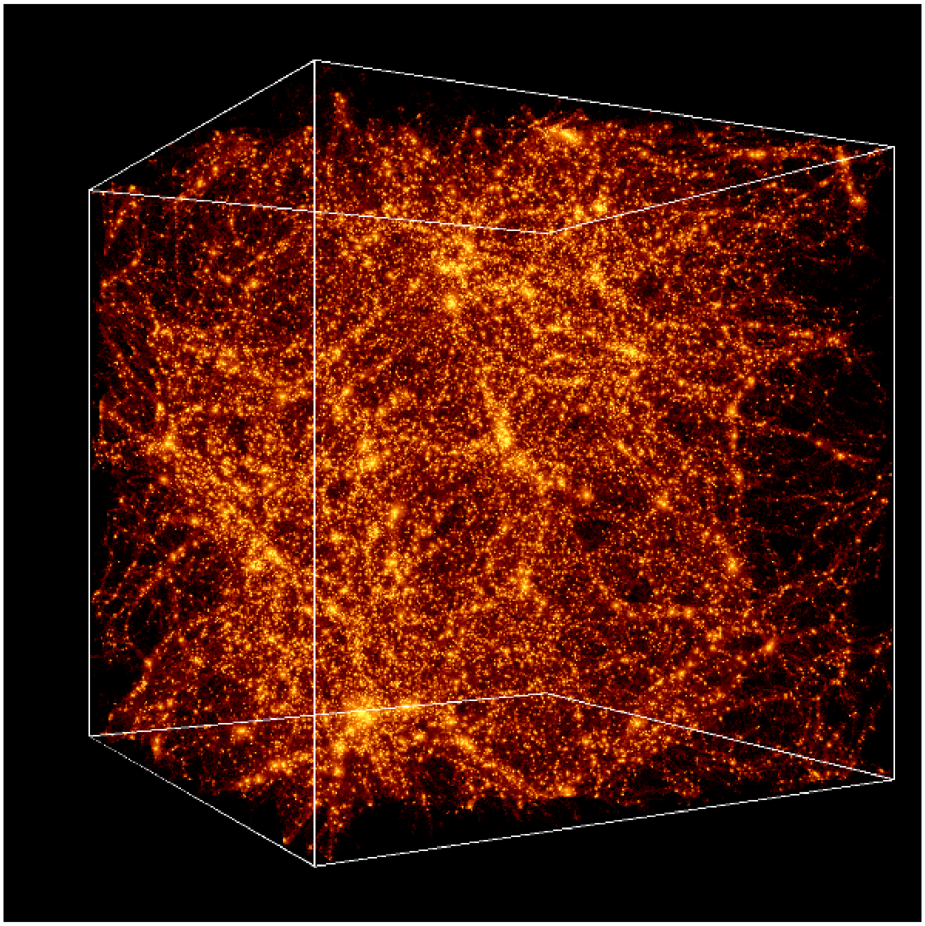
Universe in a Box: modelling formation of structures

redshift = 3; 11.4 billion years ago



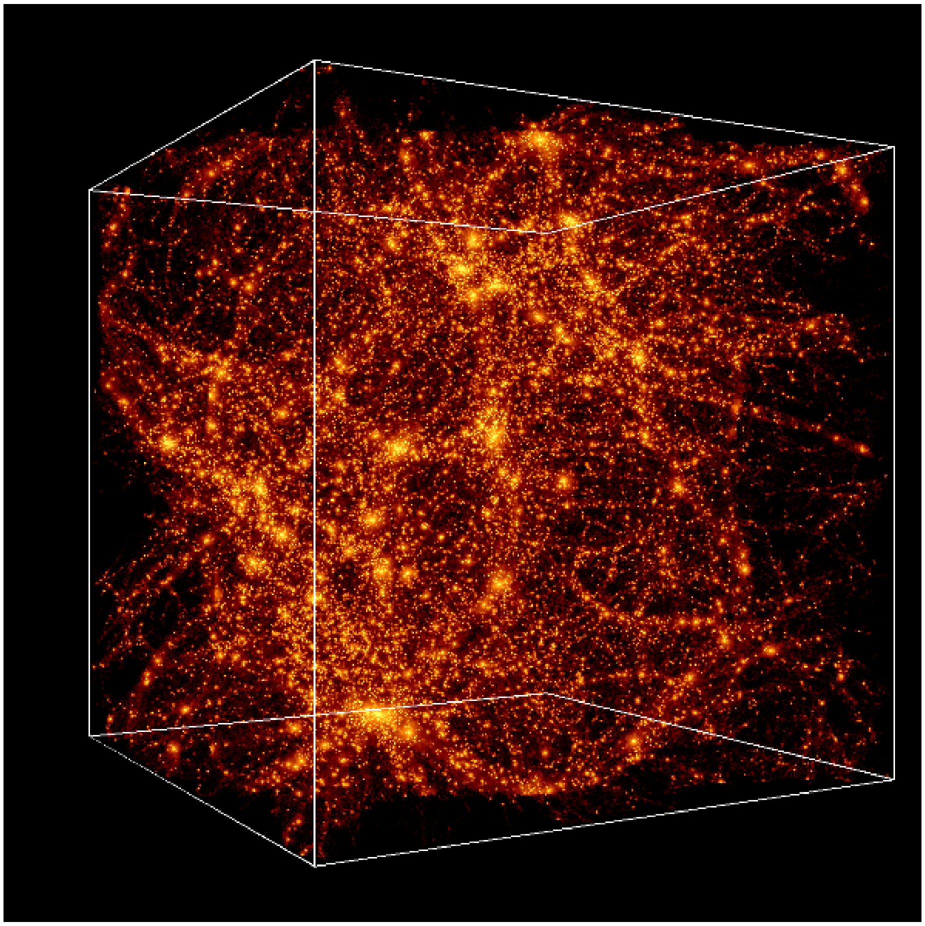
Universe in a Box: modelling formation of structures

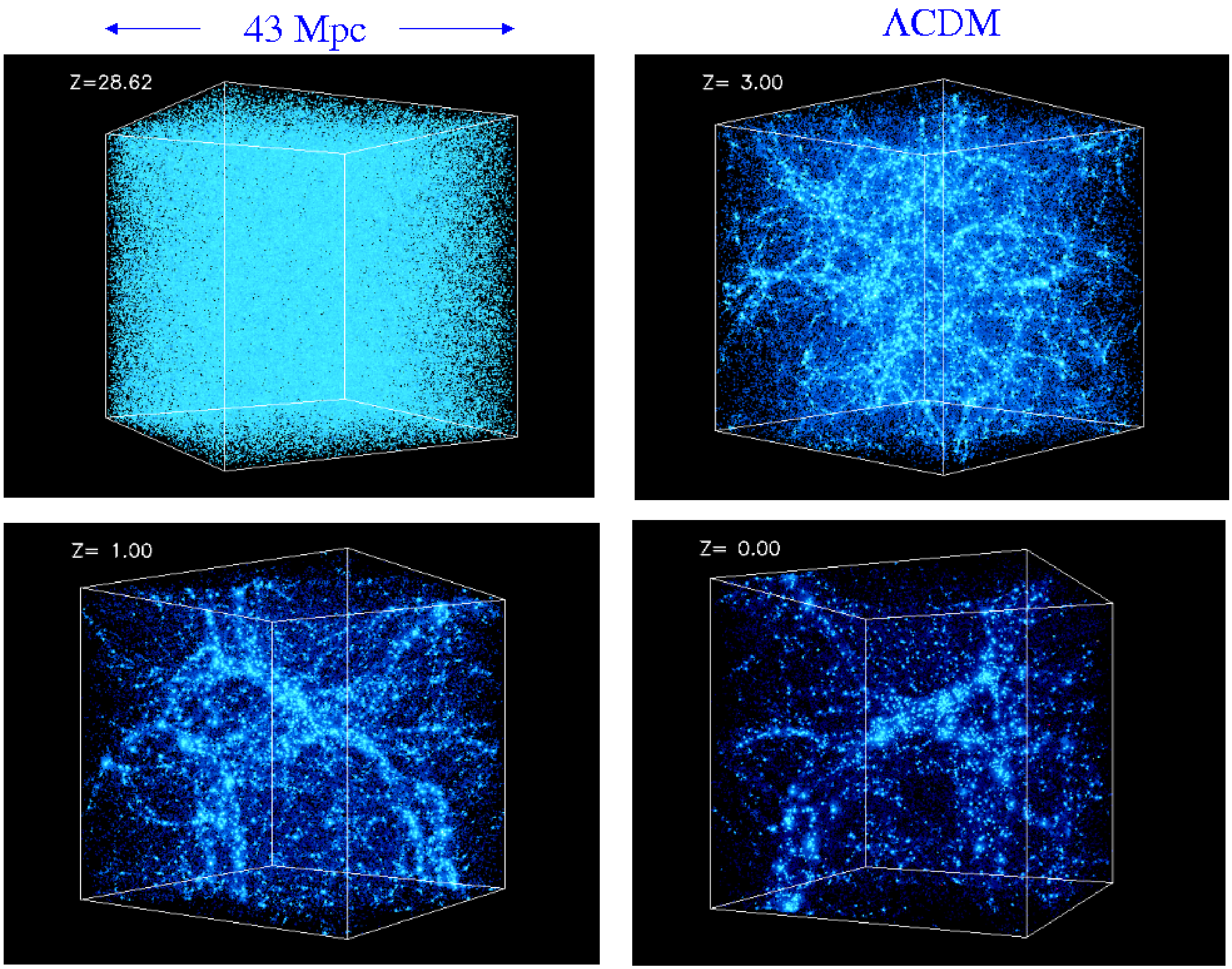
redshift = 1;   7.7 billion years ago



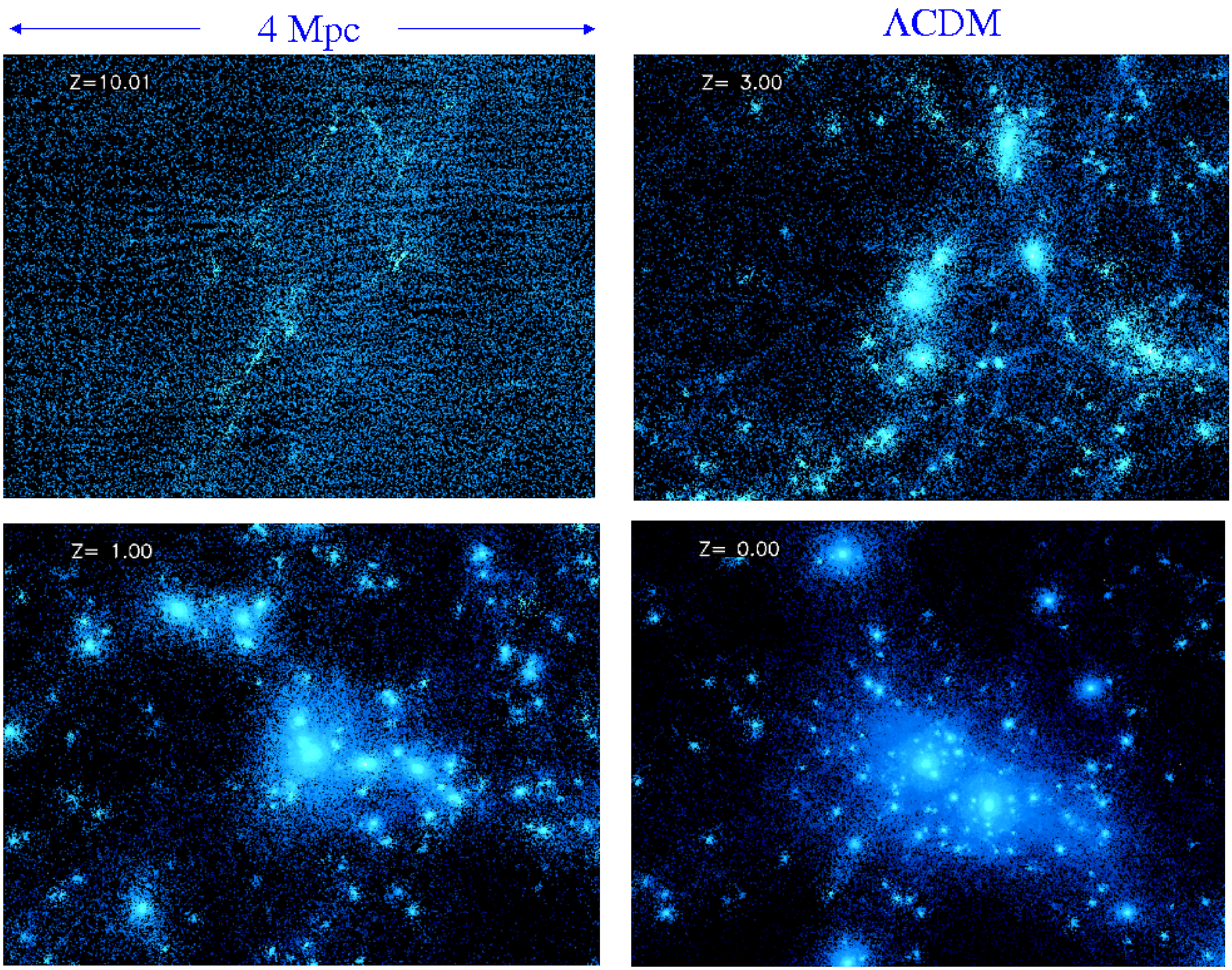
Universe in a Box: modelling formation of structures

redshift = 0;   today

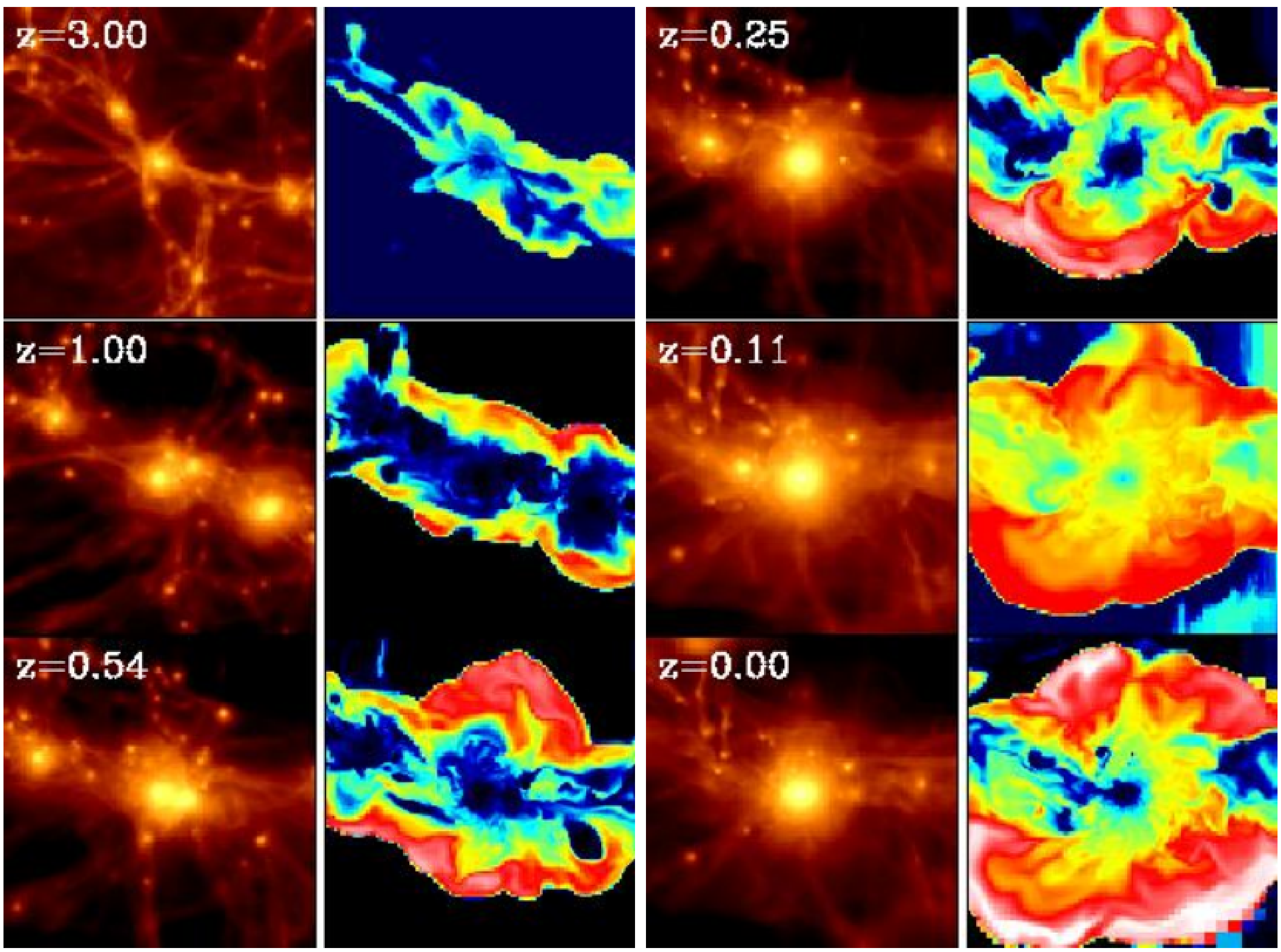




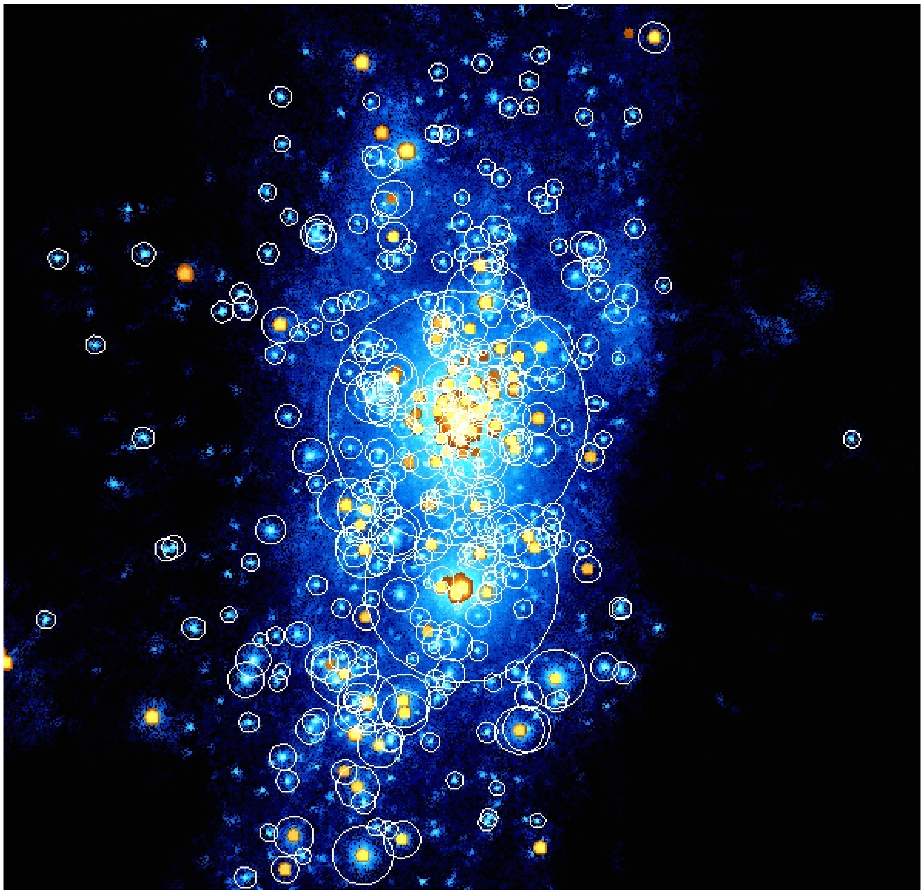
43 Mpc
ΛCDM
Z=28.62
Z= 3.00
Z= 1.00
Z= 0.00


4 Mpc
ΛCDM
Z=10.01
Z= 3.00
Z= 1.00
Z= 0.00

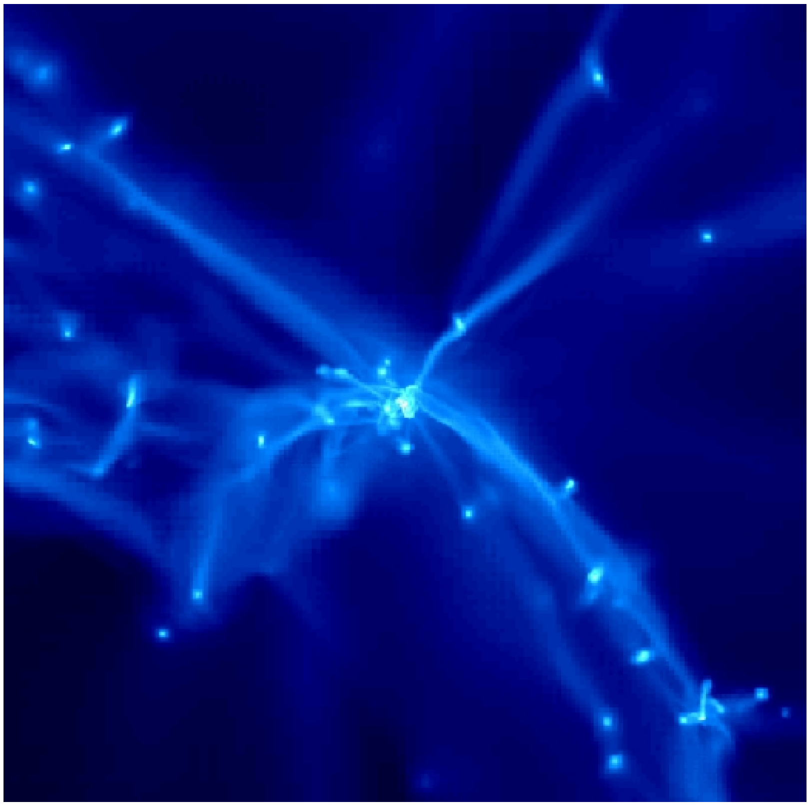
Baryons: sloshing, shocking, cooling

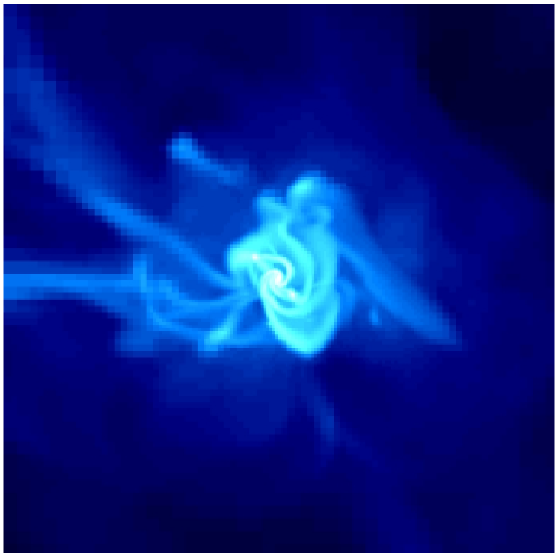


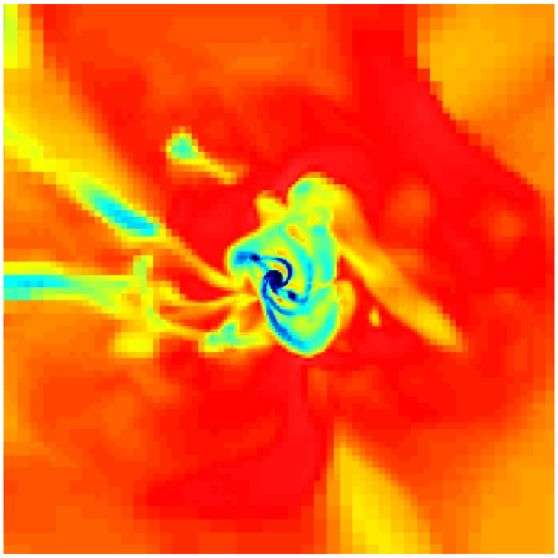
From darkness to light:
the messy physics of galactic kitchen



To model formation of galaxies we need to deal with "gastrophysics"...







Towards simulating realistic galaxies