Cosmological Mysteries

Dark Matter and Structure formation in the Universe

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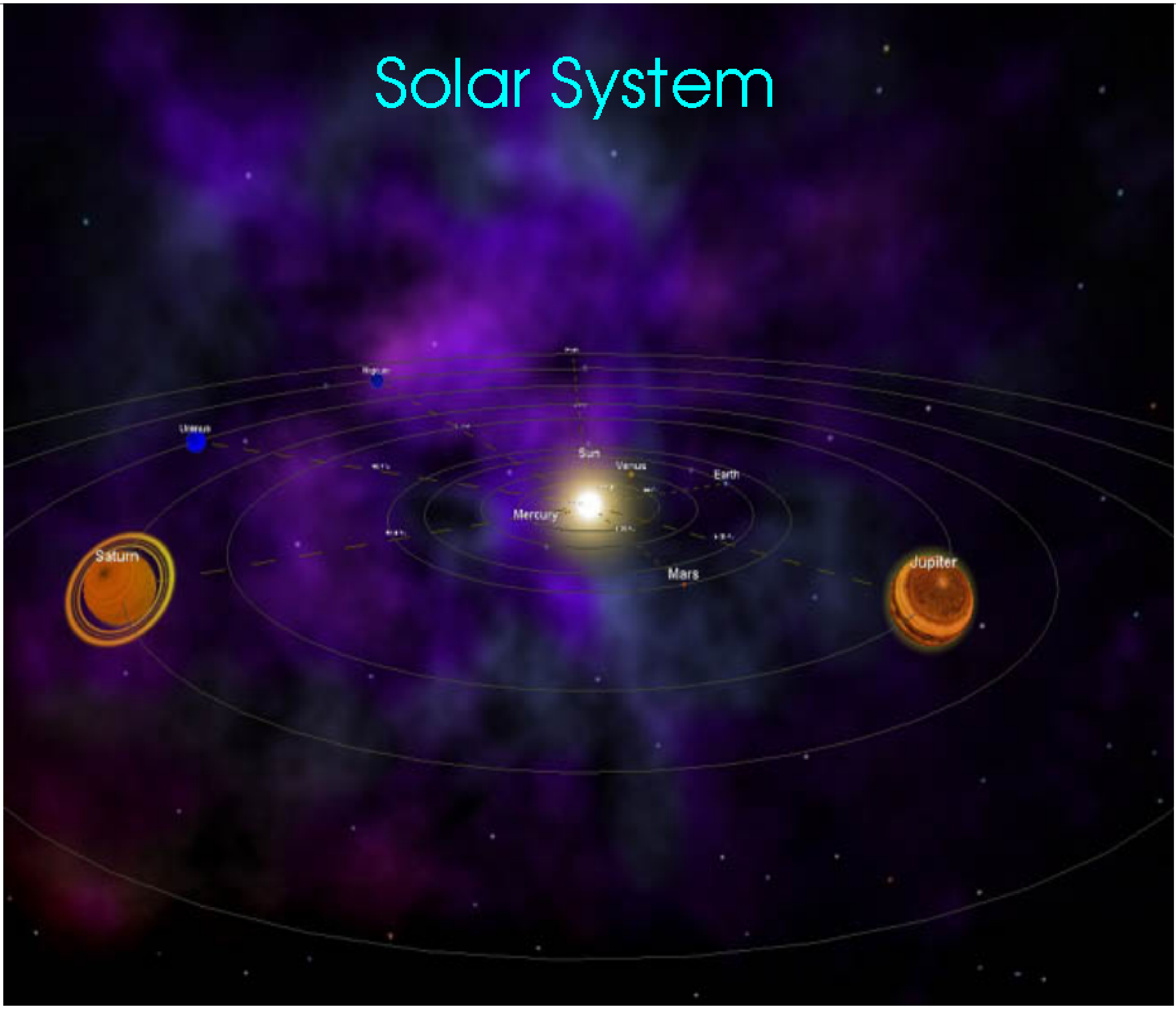
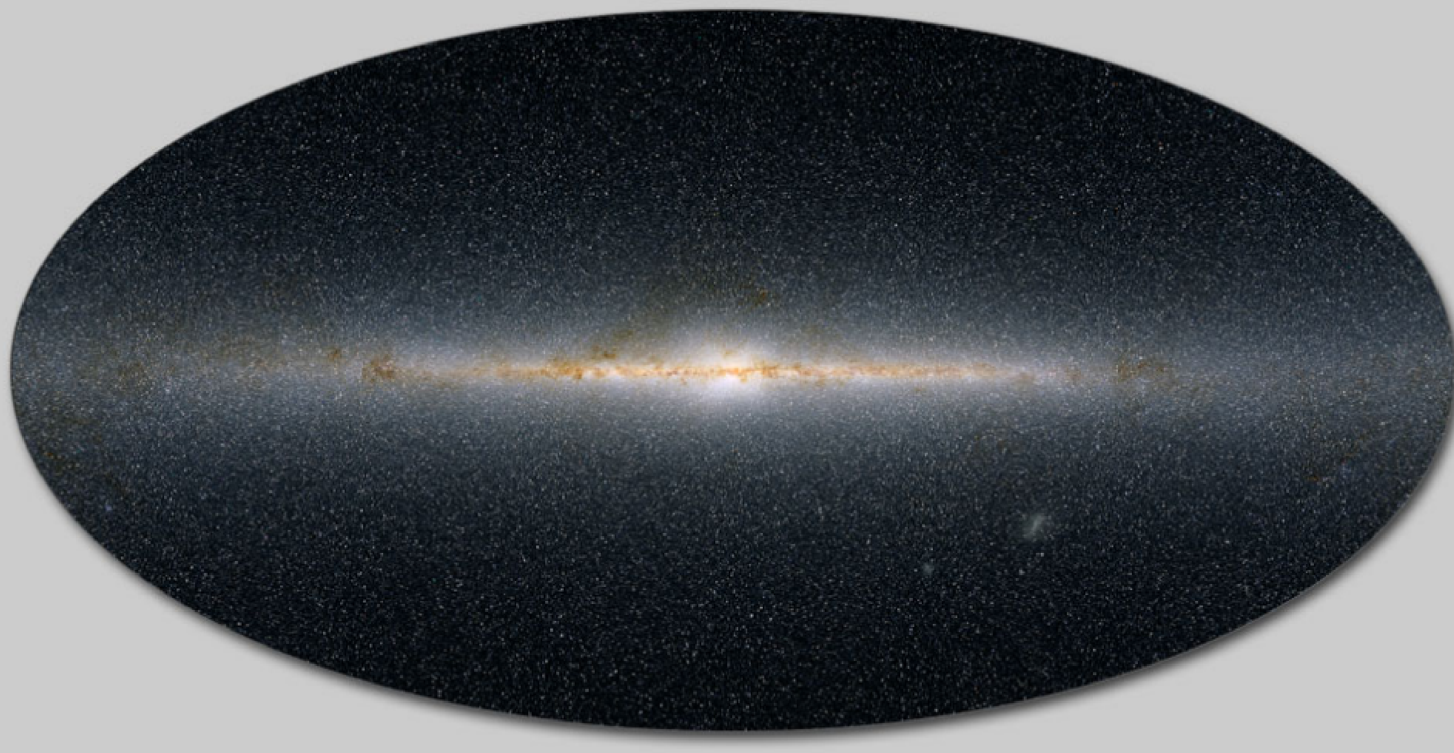
http://astro.uchicago.edu/~andrey/talks/mysteries

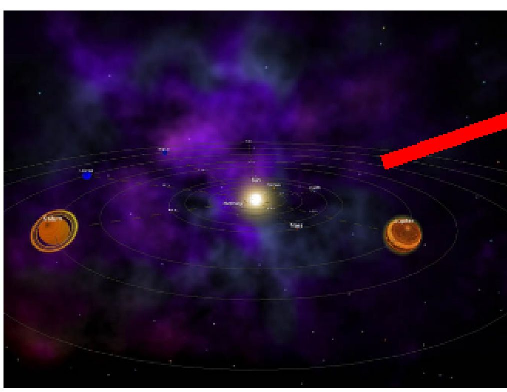

Solar System
Sun
Venus
Earth
Mercury
Saturn
Mars
Jupiter

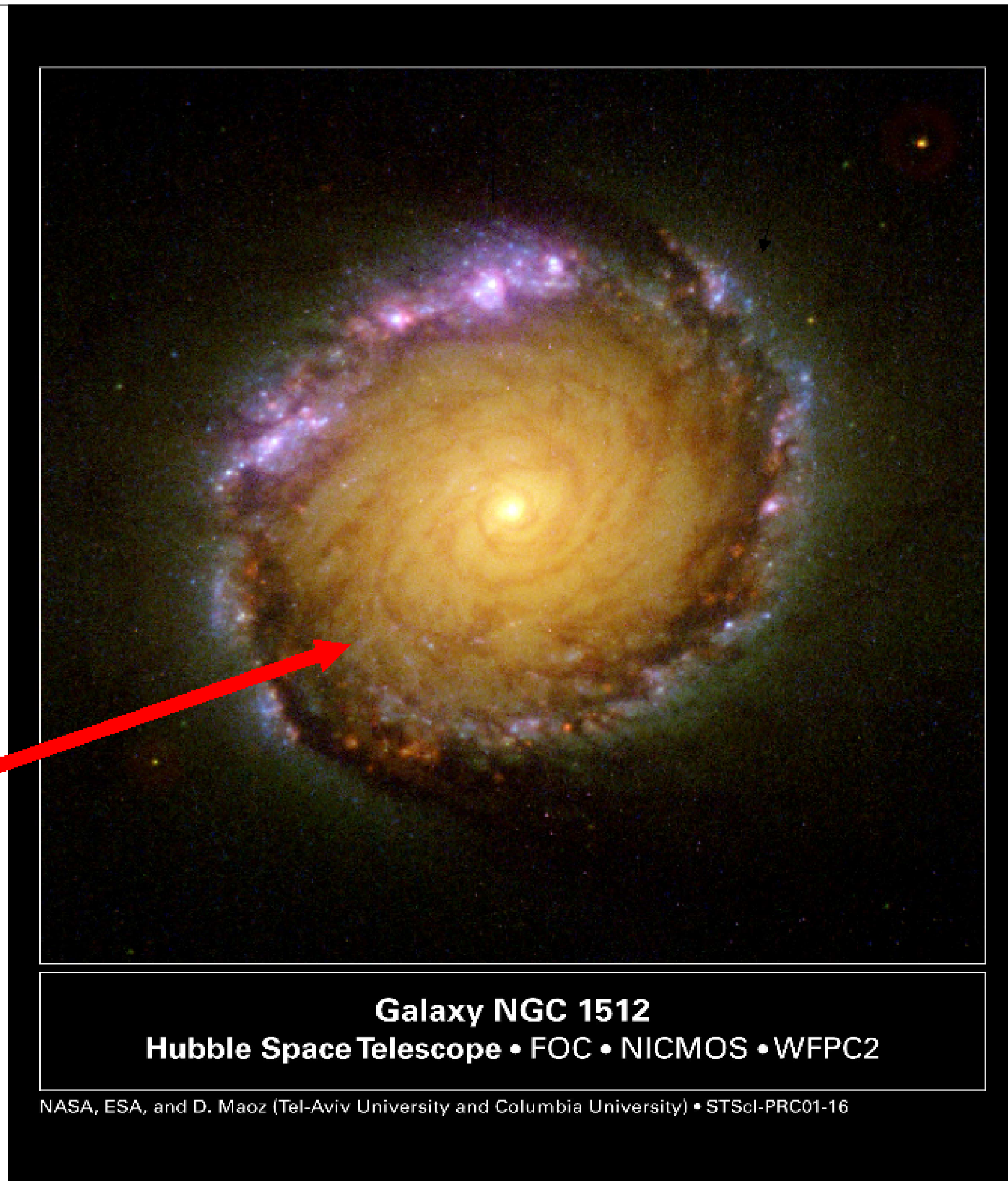
2MASS Showcase



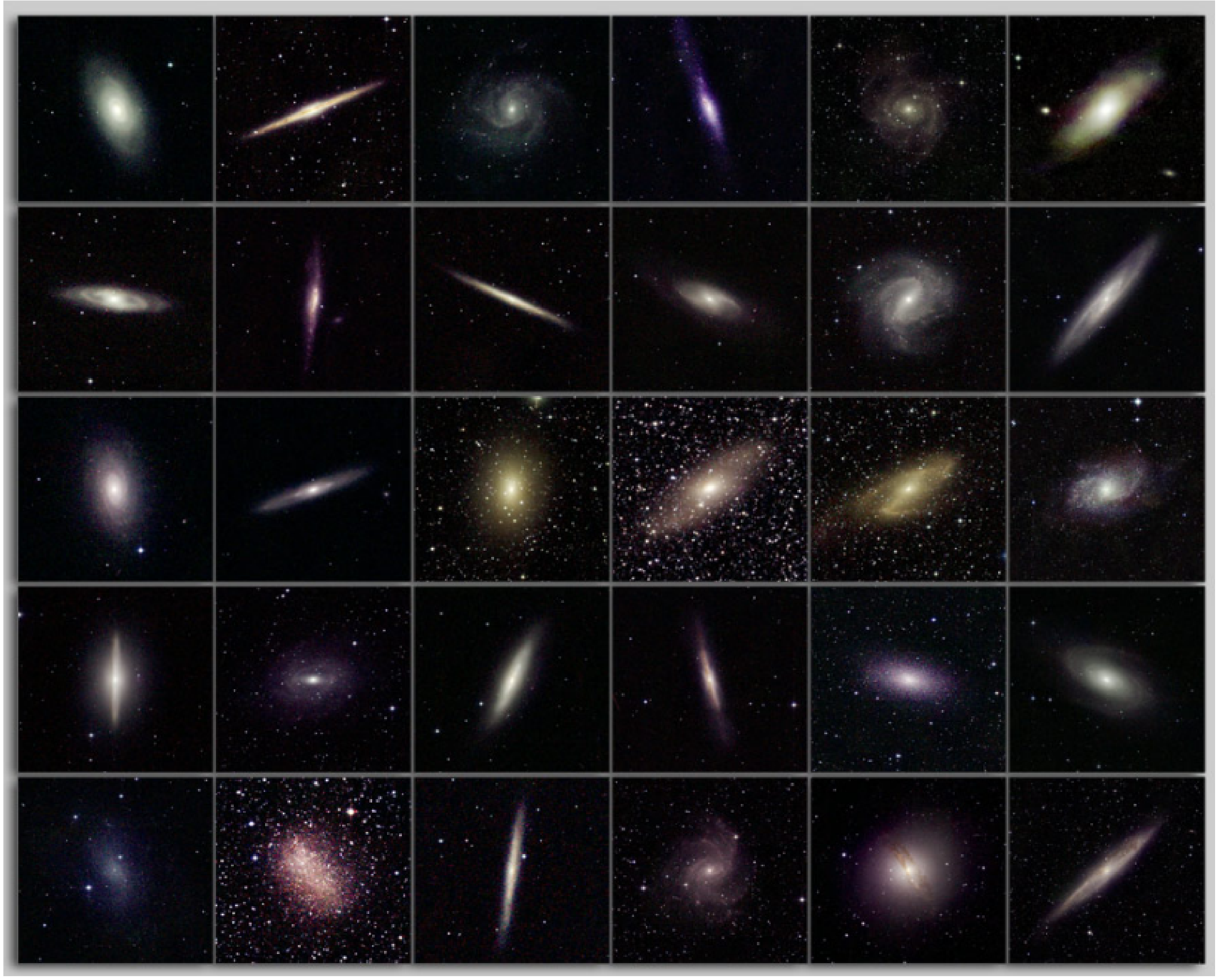
The Infrared Milky Way This map of the infrared sky includes the light of a half billion stars

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

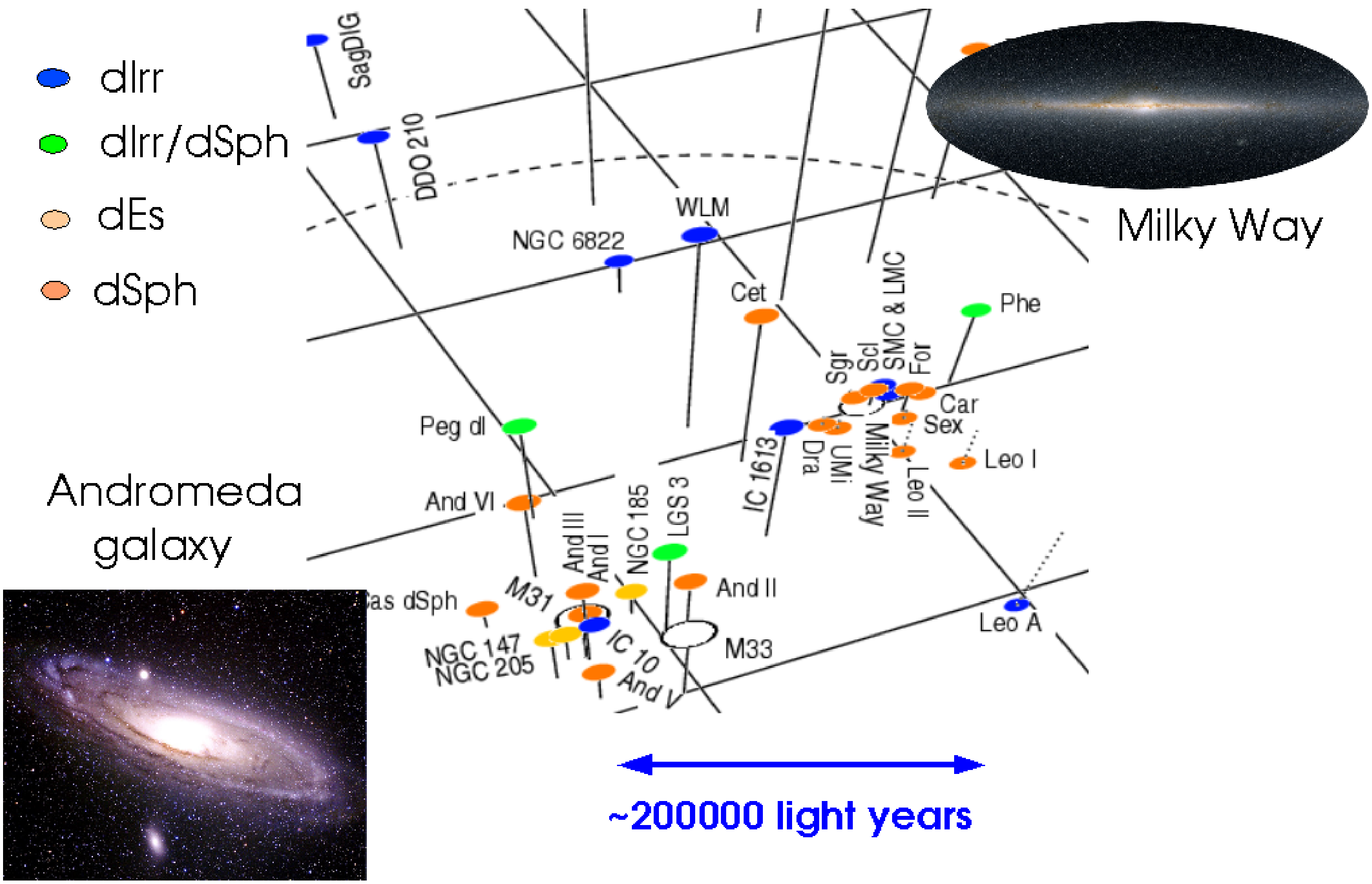



Galaxy NGC 1512
Hubble Space Telescope • FOC • NICMOS • WFPC2
NASA, ESA, and D. Maoz (Tel-Aviv University and Columbia University) • STScI-PRC01-16

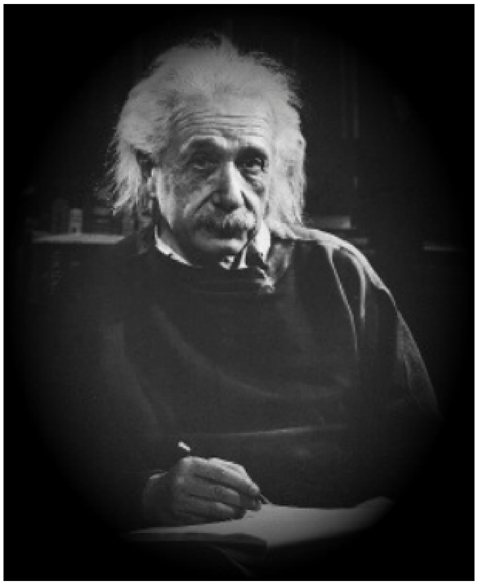
Galaxies come in different shapes and sizes



The Local Group



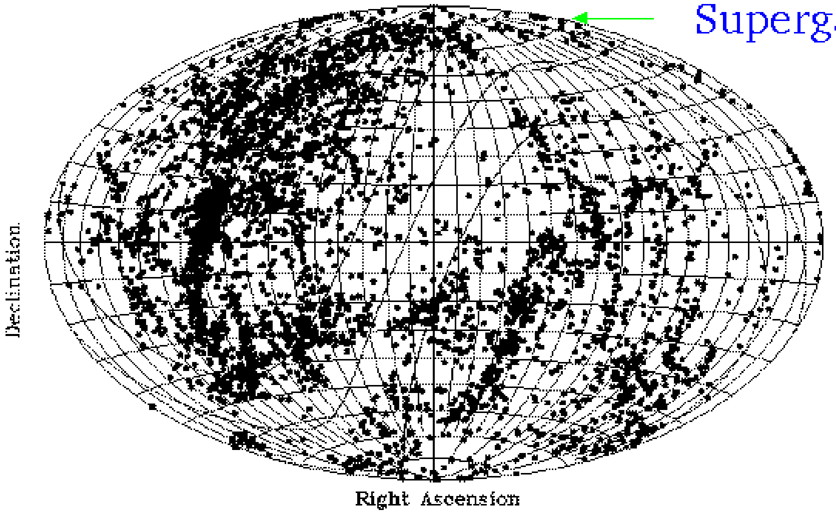
Einstein's Cosmological Principle:



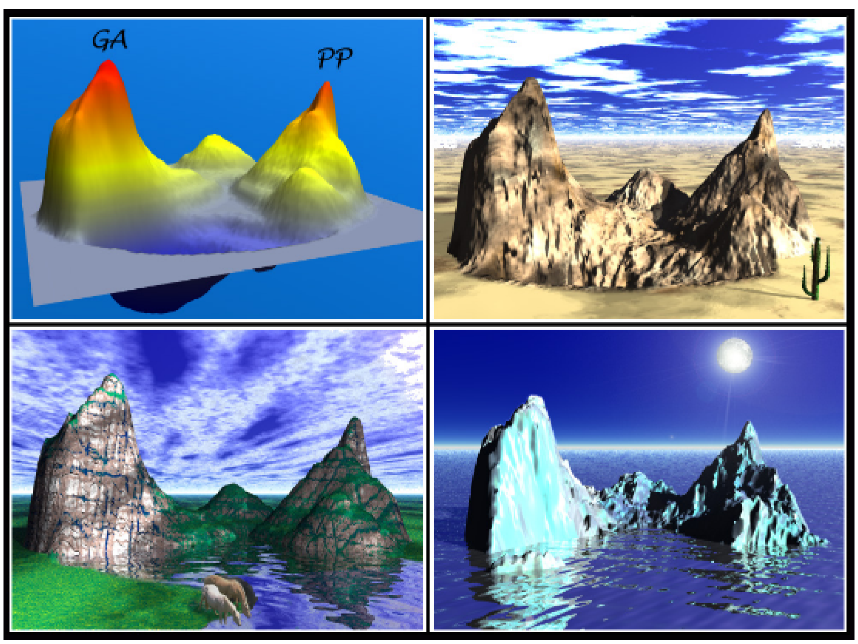
Albert Einstein
(1878- 1955)

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)

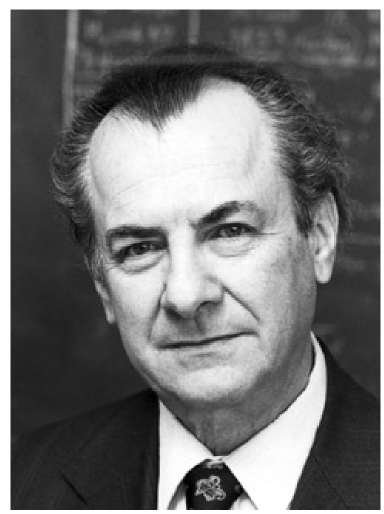
Is distribution of galaxies in space consistent with this?



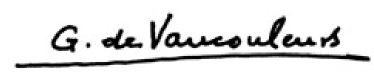
Supergalactic plane



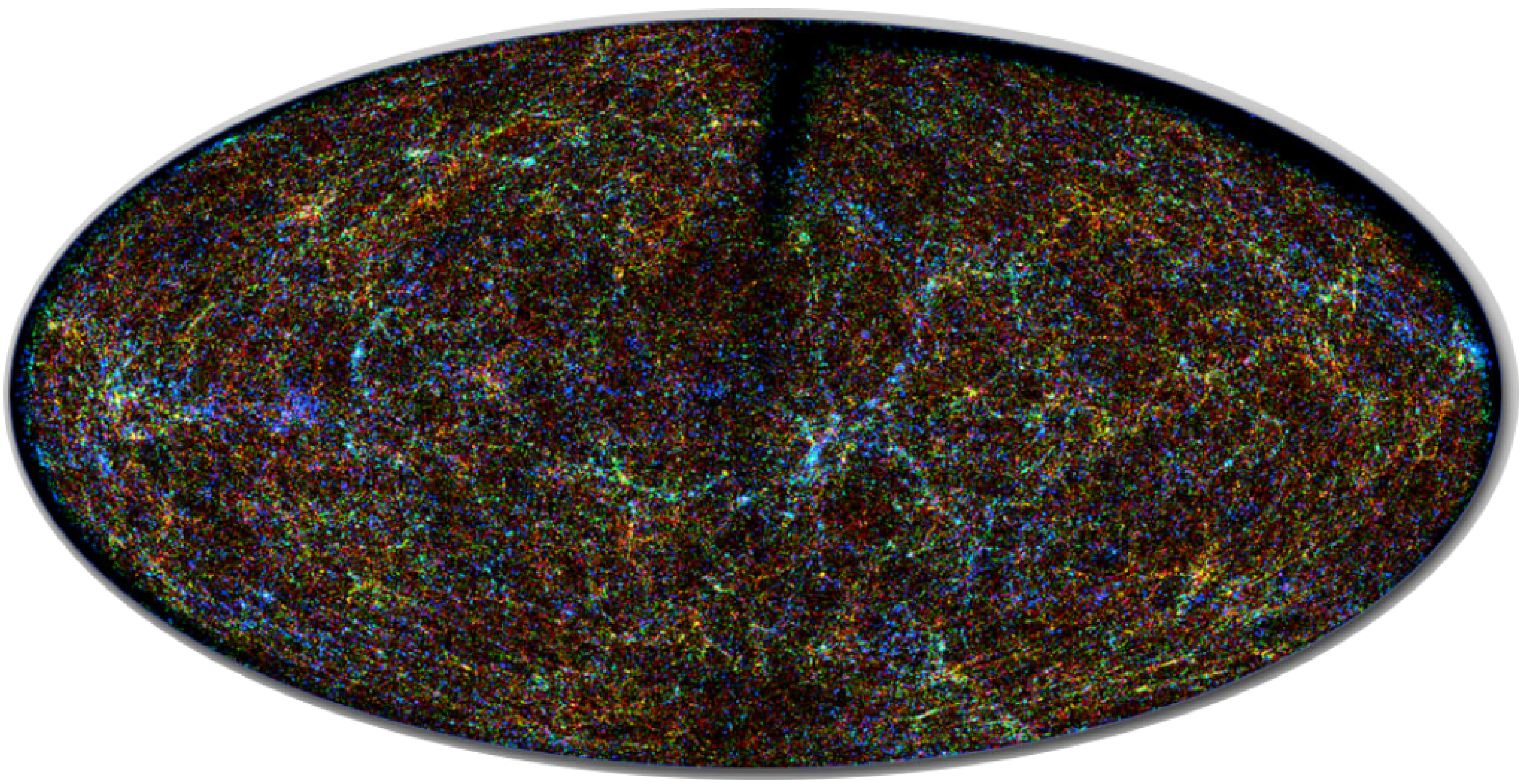
The Local Supercluster



Gerard de Vaucouleurs
1918- 1995

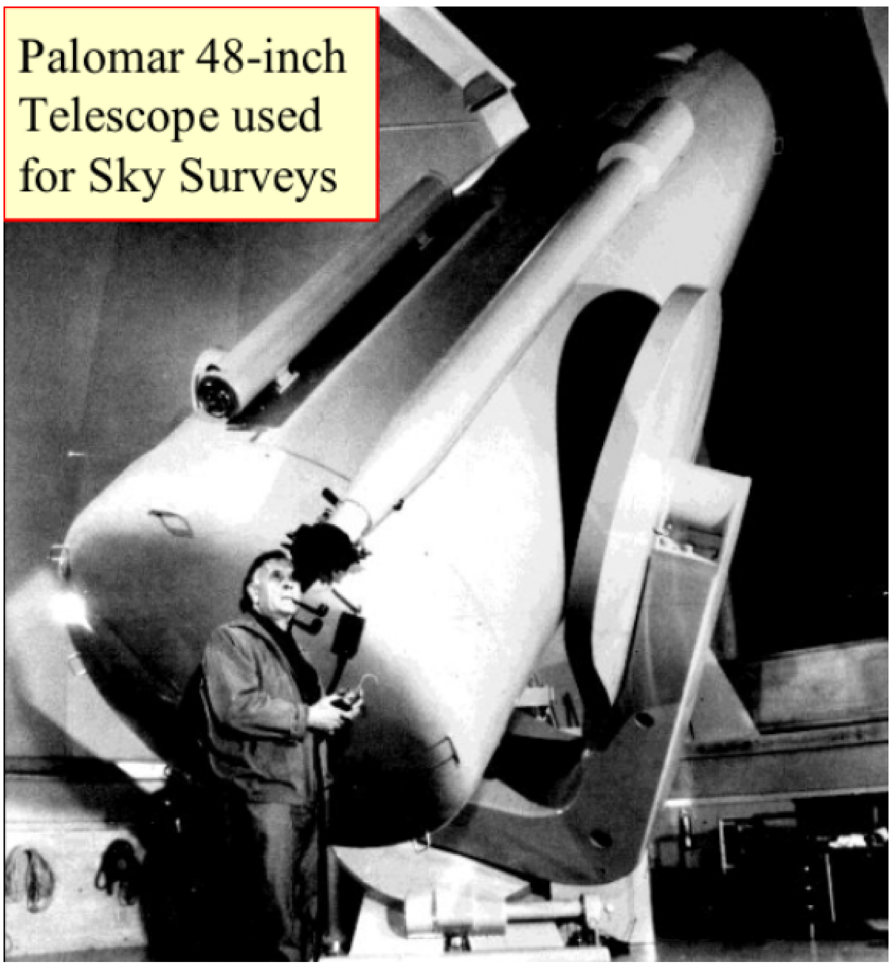


Sky Distribution of Galaxies



From 2D to 3D:

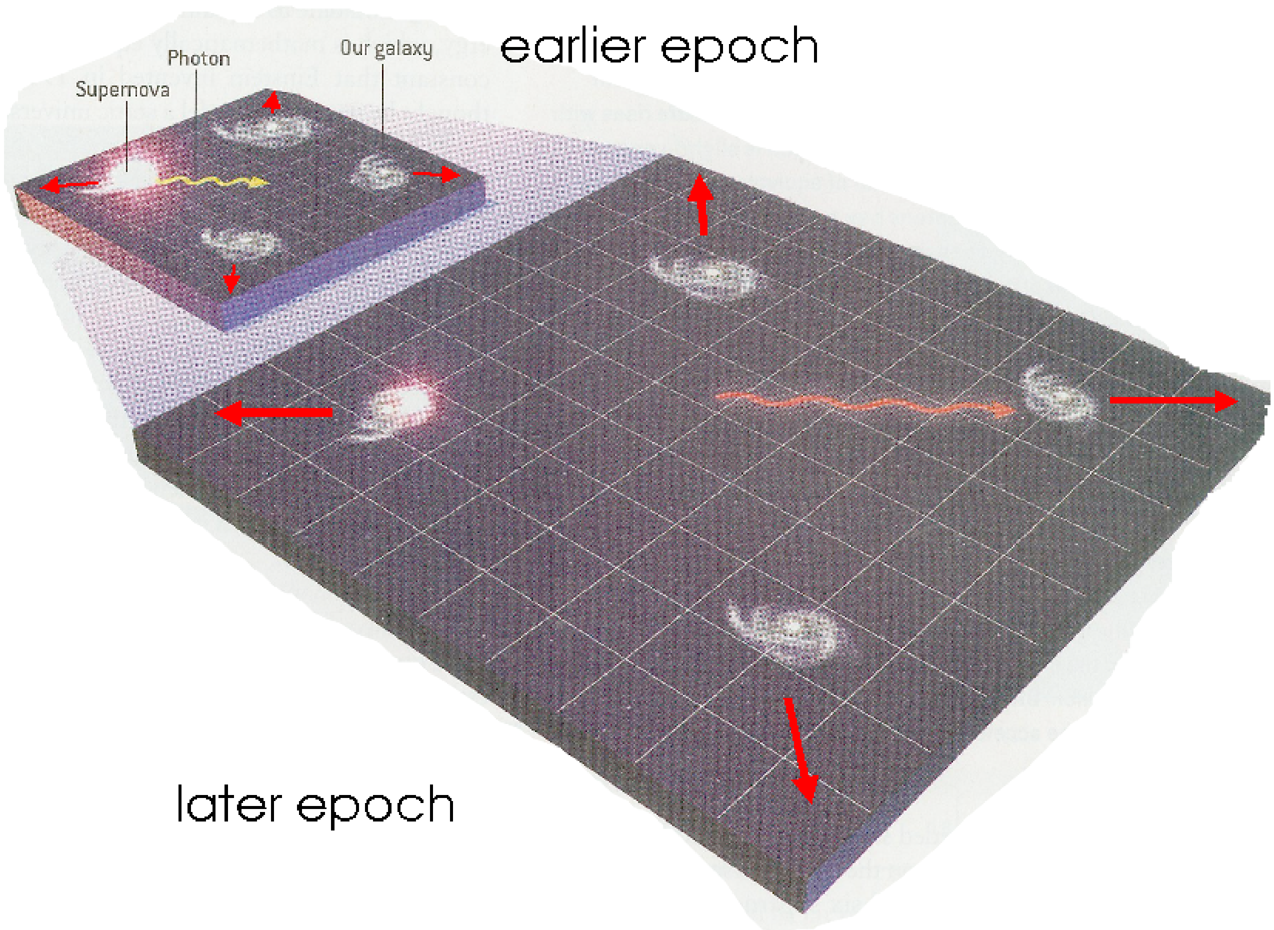
using expansion of the Universe to map it



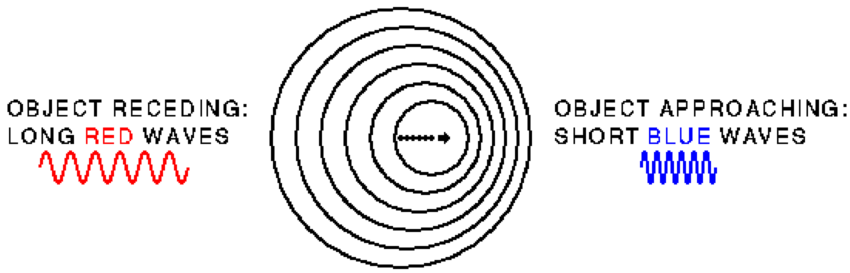
Edwin Hubble
(1889- 1953)

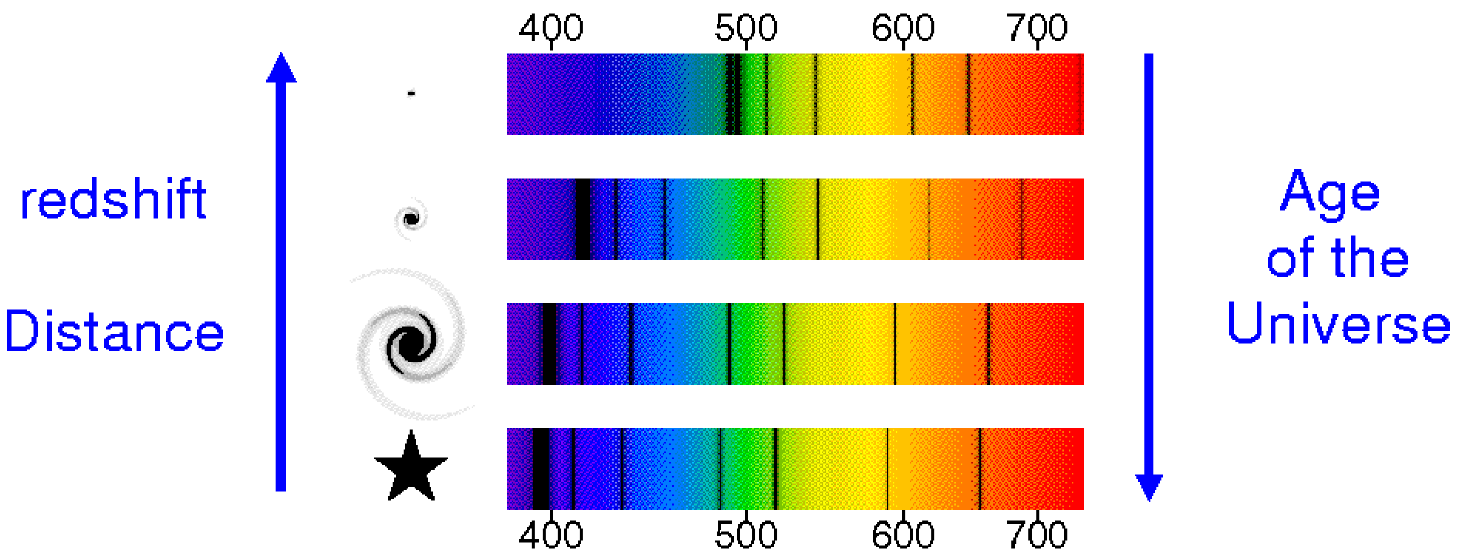
U.Chicago alum!
(PhD, 1917)

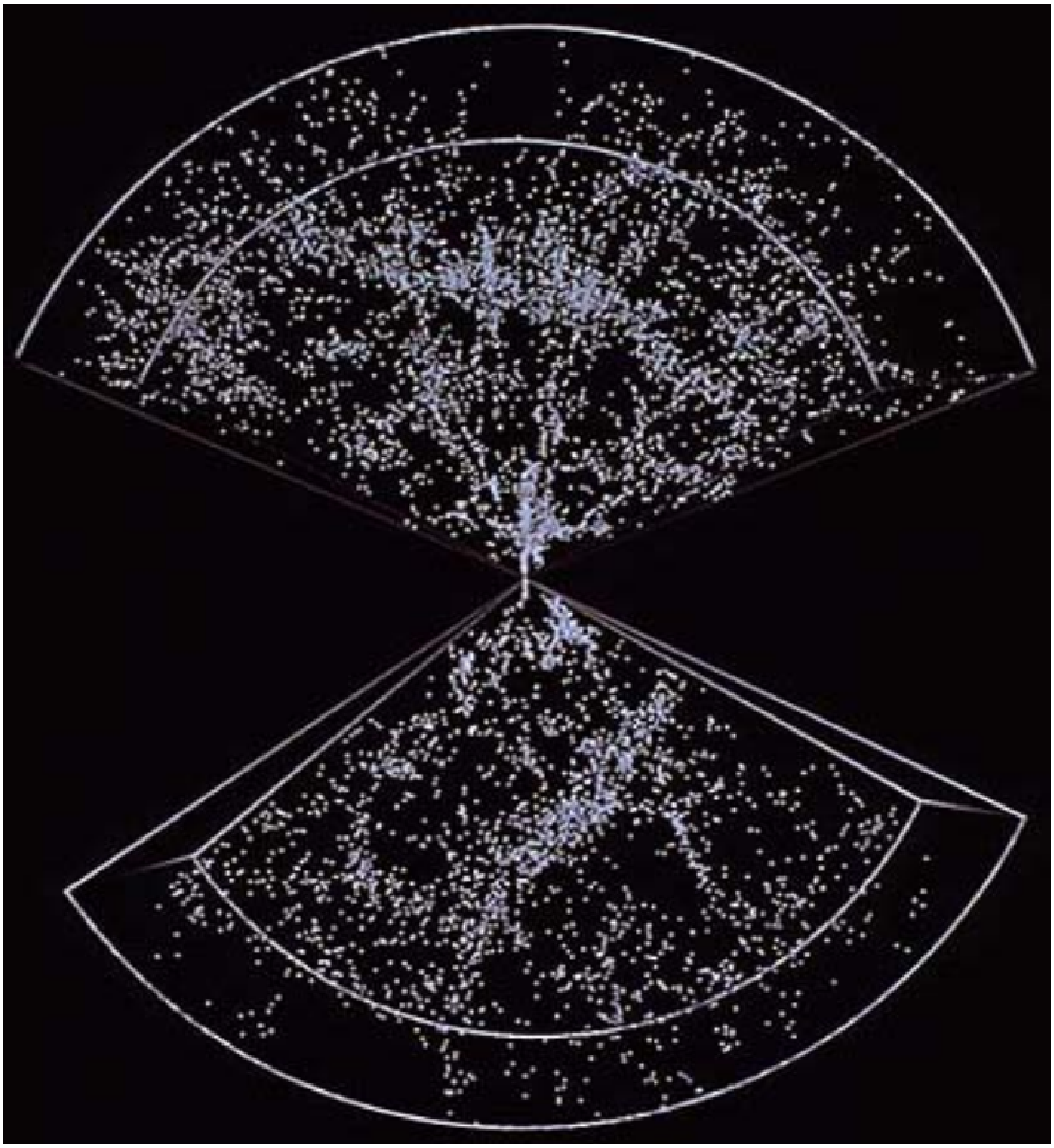
Expansion of space



Cosmological Redshift
as a measure of distance and time





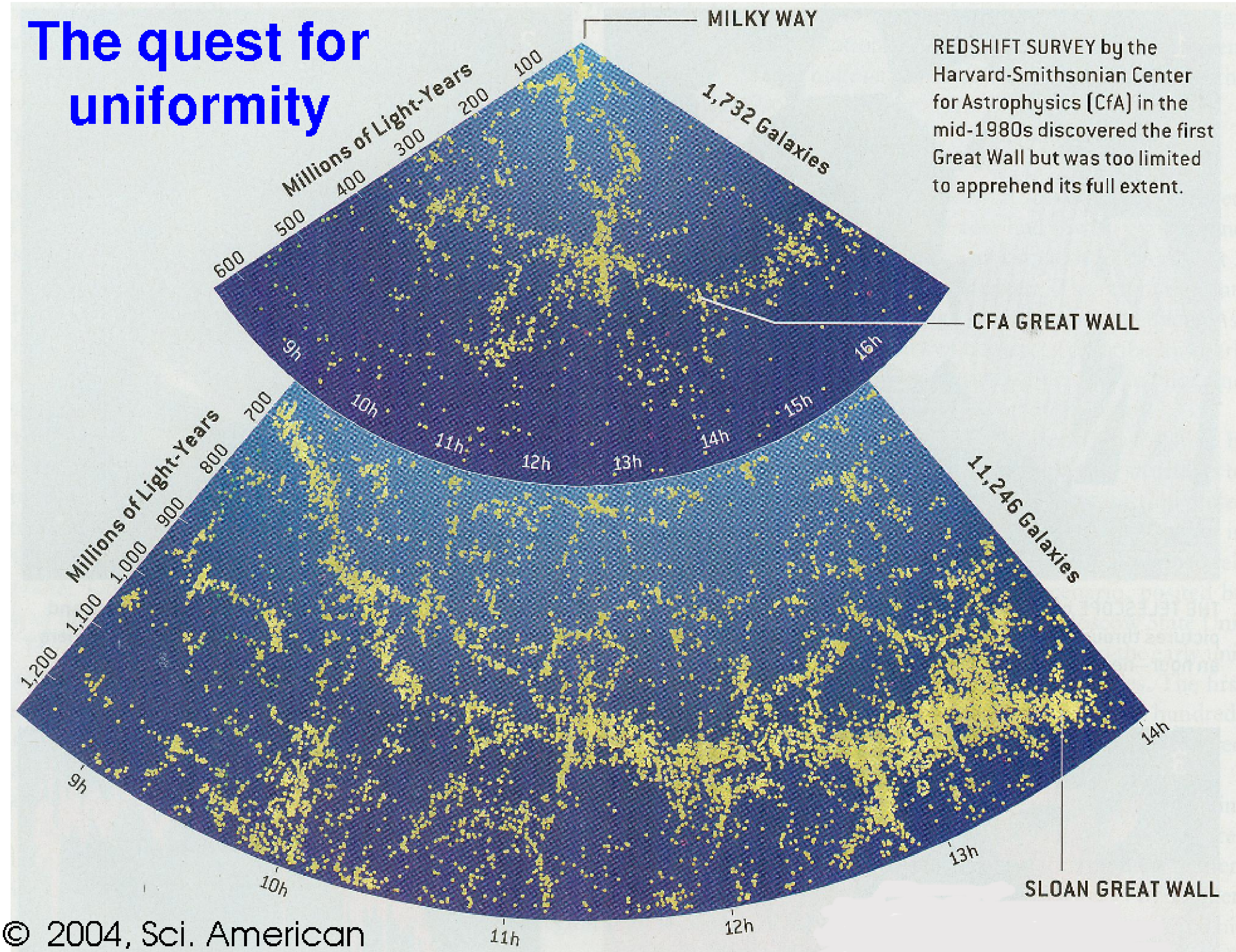


Large- scale distribution of galaxies

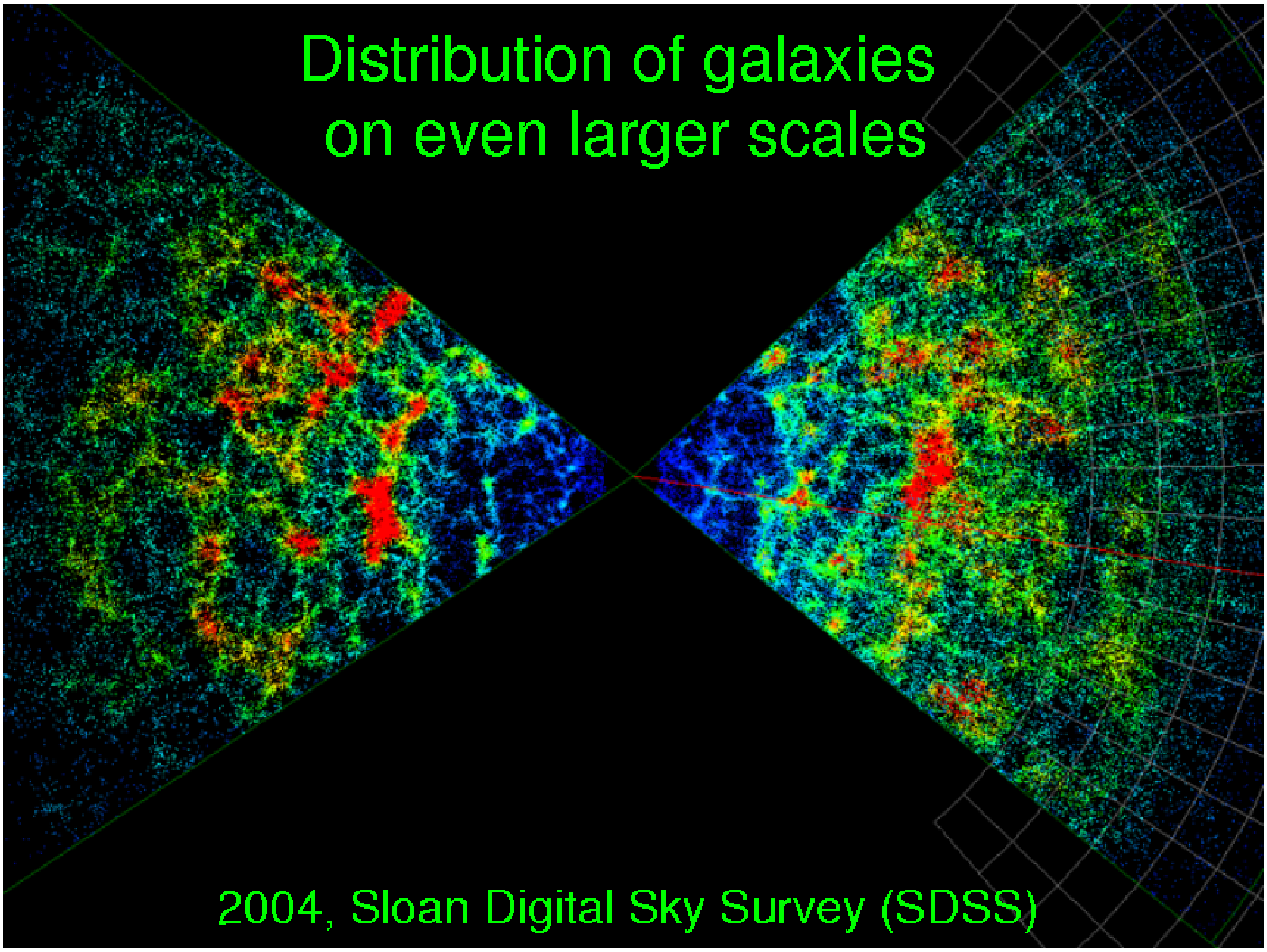
at distances less than 300 million light years

CfA galaxy survey 1980- 1990

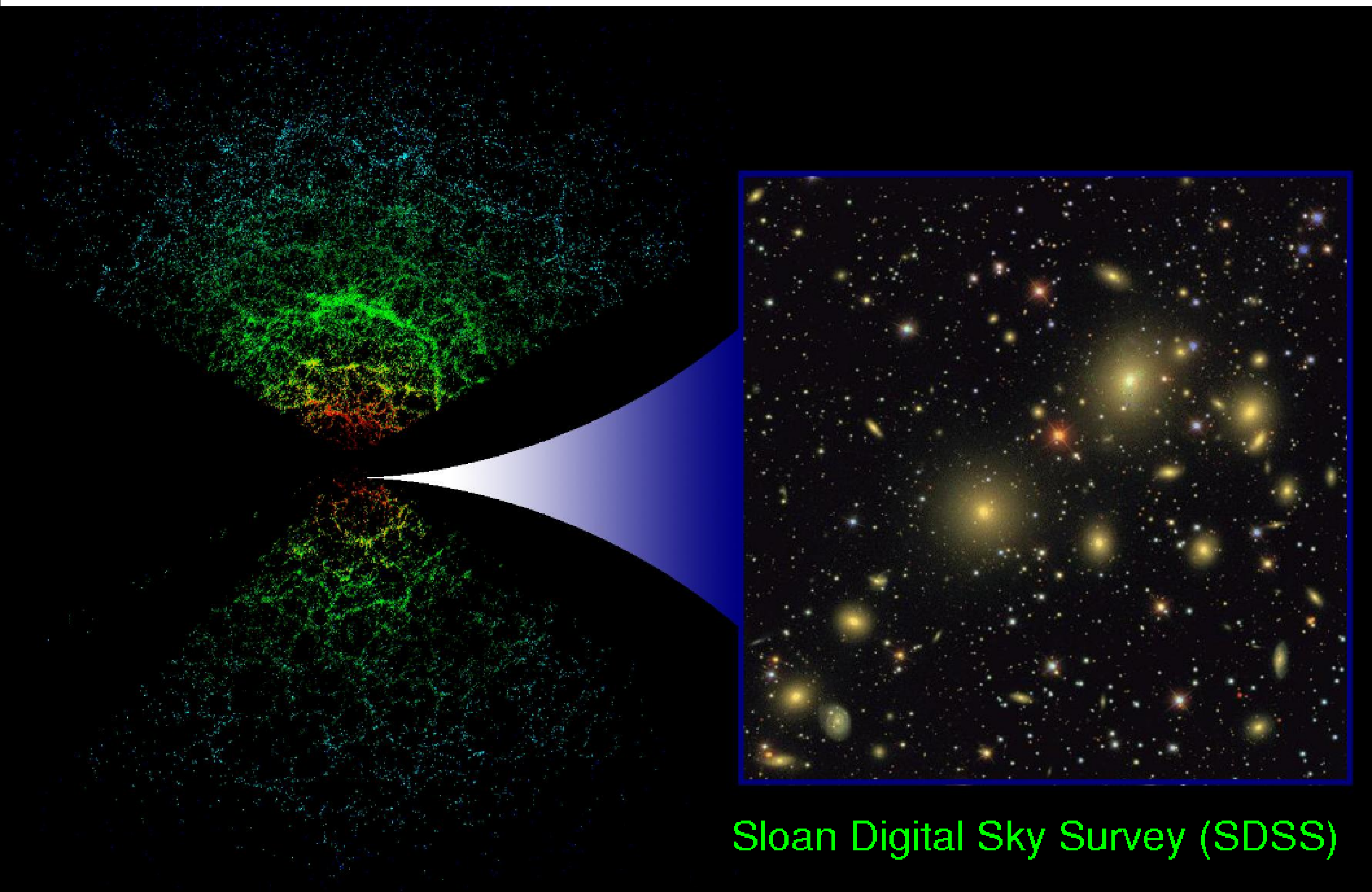
The quest for uniformity



The end of greatness...

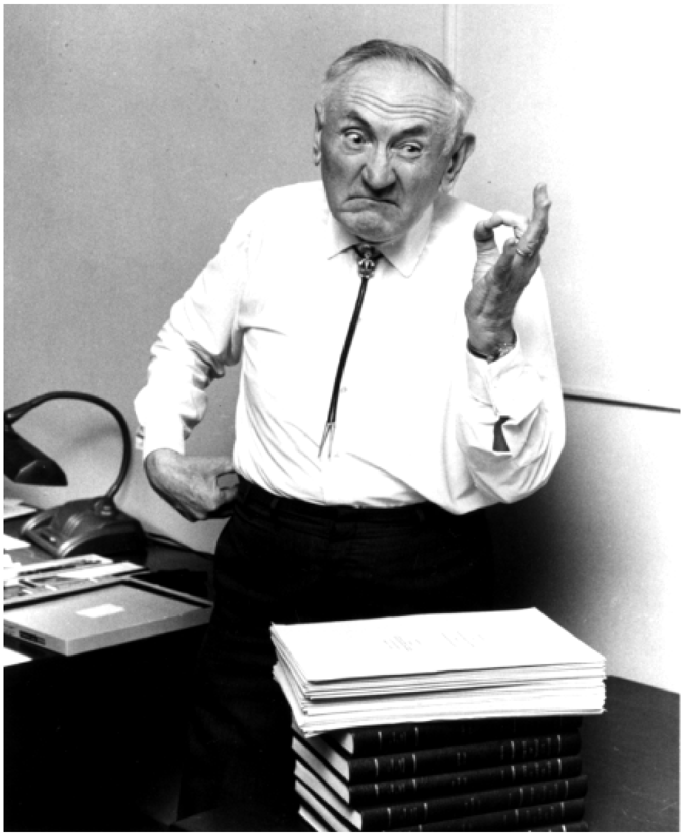


Back to the "small" scales: galaxy clusters

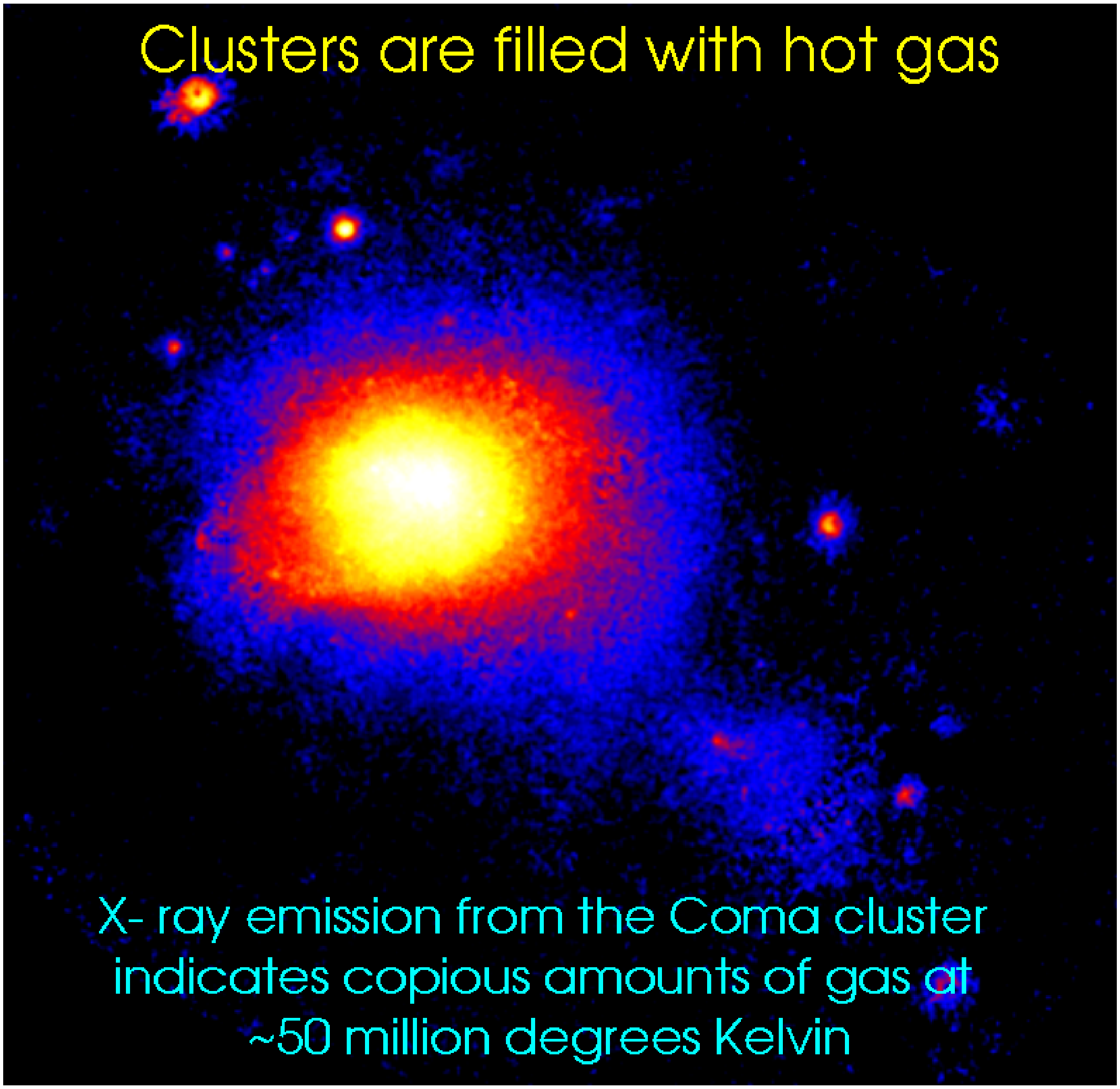


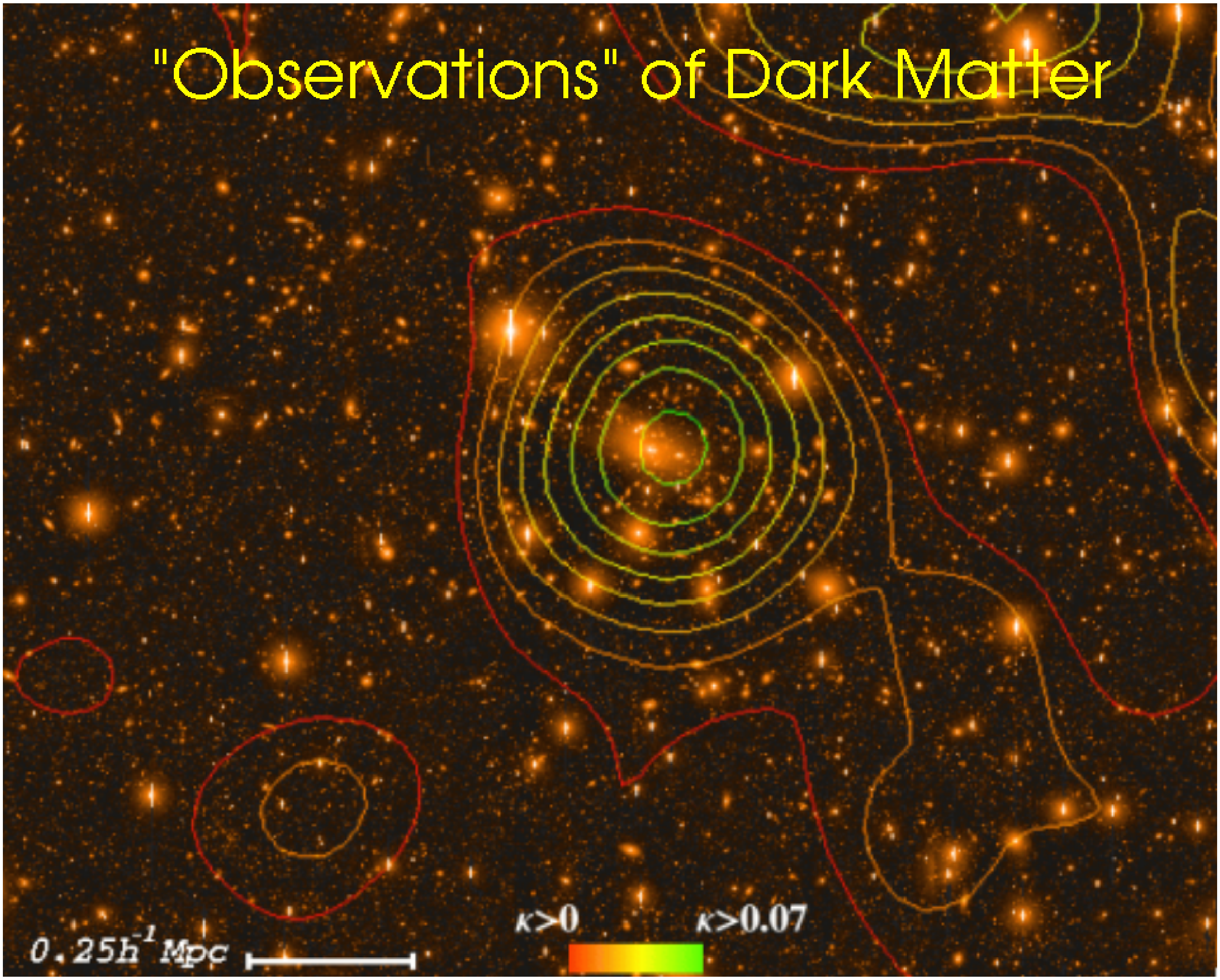

Perseus cluster:
`Constellation' of galaxies

Clusters and Dark Matter



Fritz Zwicky
(1898- 1978)


Clusters are filled with hot gas
X- ray emission from the Coma cluster
indicates copious amounts of gas at
~50 million degrees Kelvin


"Observations" of Dark Matter
0.25h-1 Mpc
κ>0
κ>0.07

(Some of)
The Current Cosmological Mysteries

- Is the Universe full of weird dark matter? Or, even weirder, dark energy?

  the answer appears to be YES. how we know? what is Dark Matter? what is Dark Energy

- How did it all begin? How did the structures form?

  understanding how the structures, and galaxies in particular, form is critical to understanding the origins of everything we see around us, including the intelligent life

- How do we find out?

  a variety of new observations, sophisticated computer modeling using modern supercomputers

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!

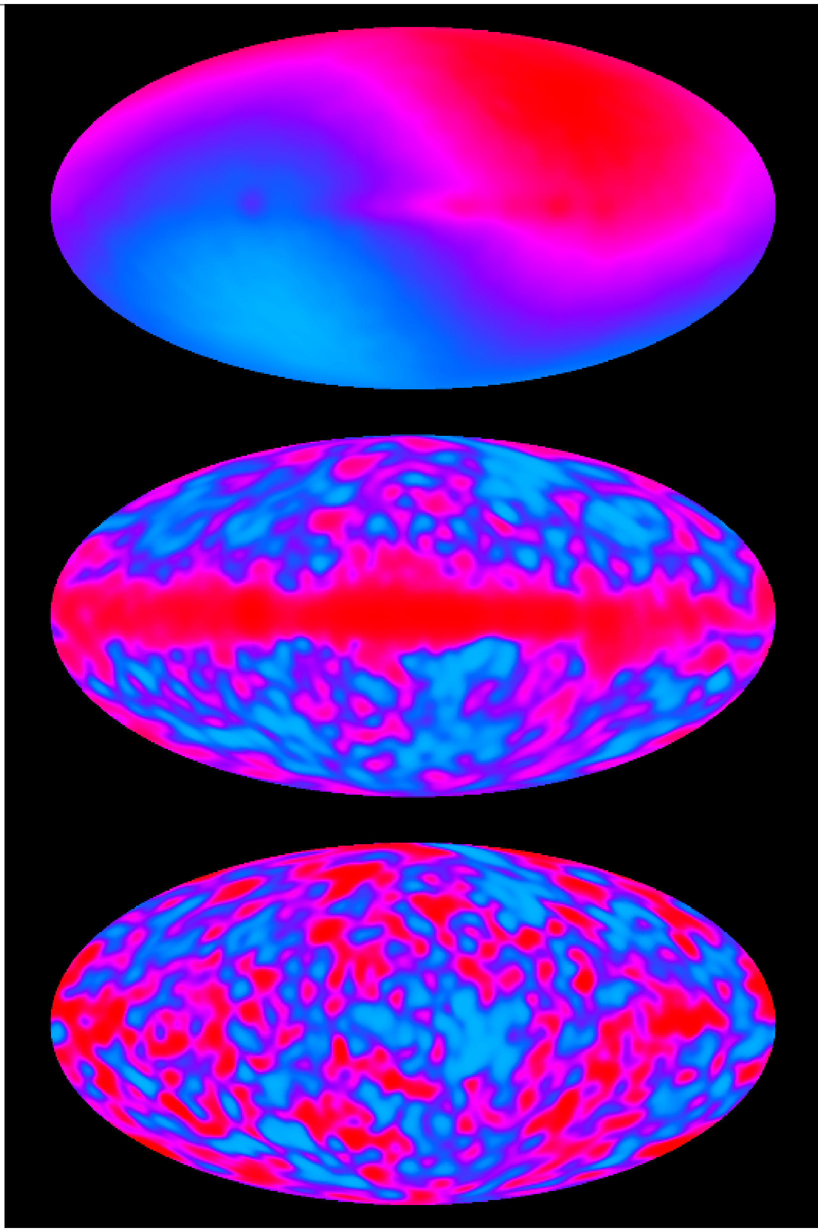
- ☐ Large- scale structure of the Universe

  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

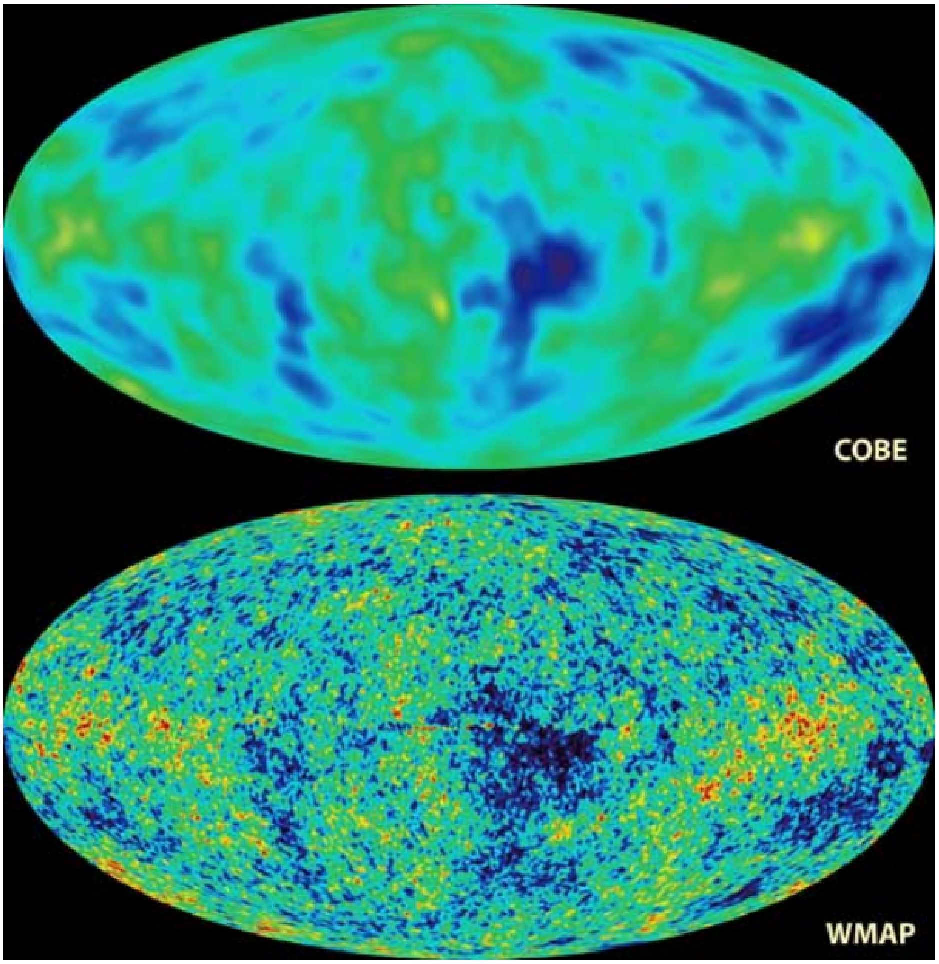
- ☐ Standard rulers (systems with known intrinsic size)

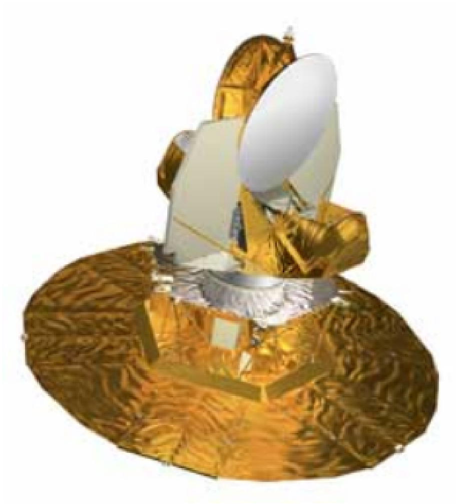


Cosmic Microwave Background Temperature Fluctuations

COsmic Background Explorer (COBE) satellite

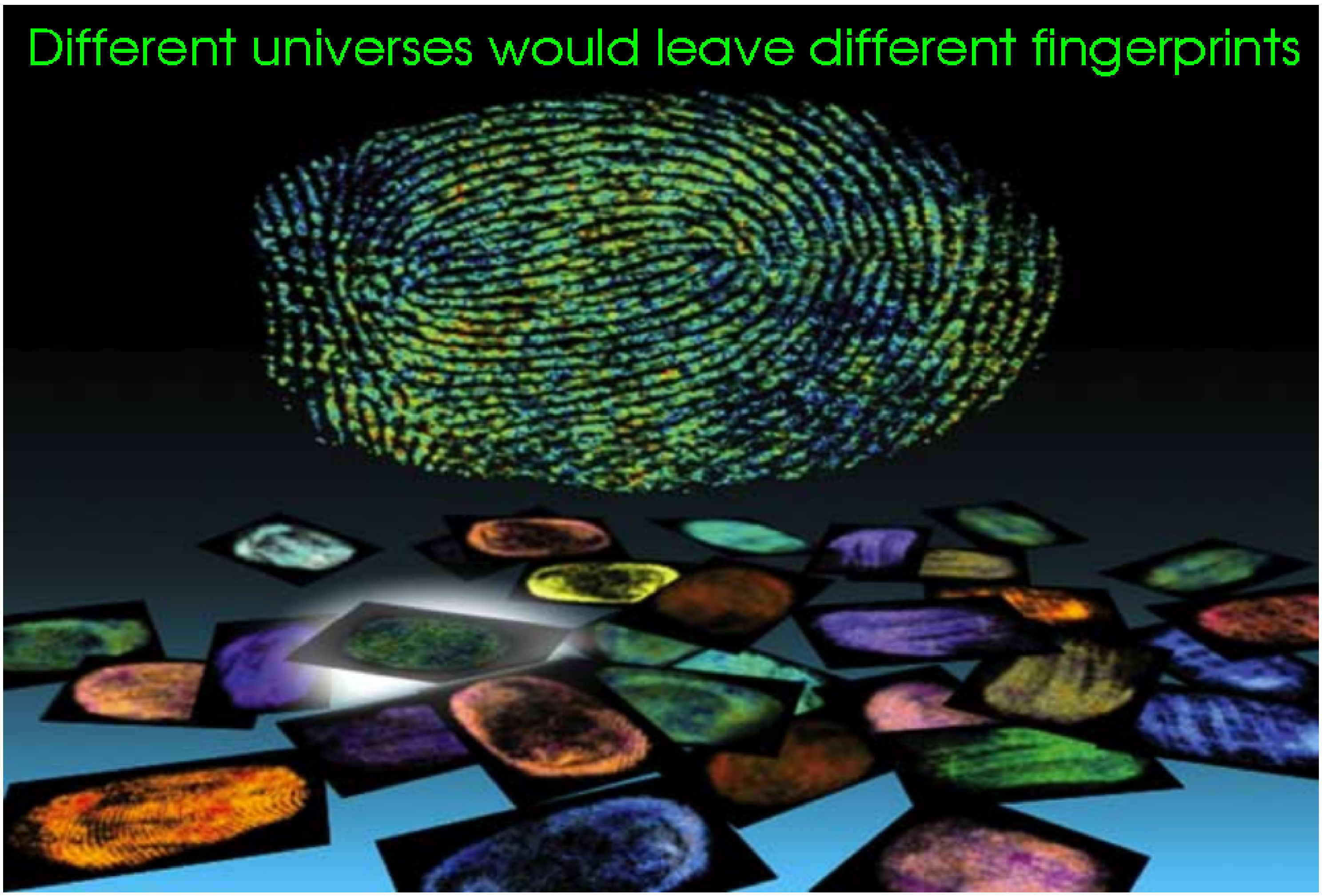
version 2003



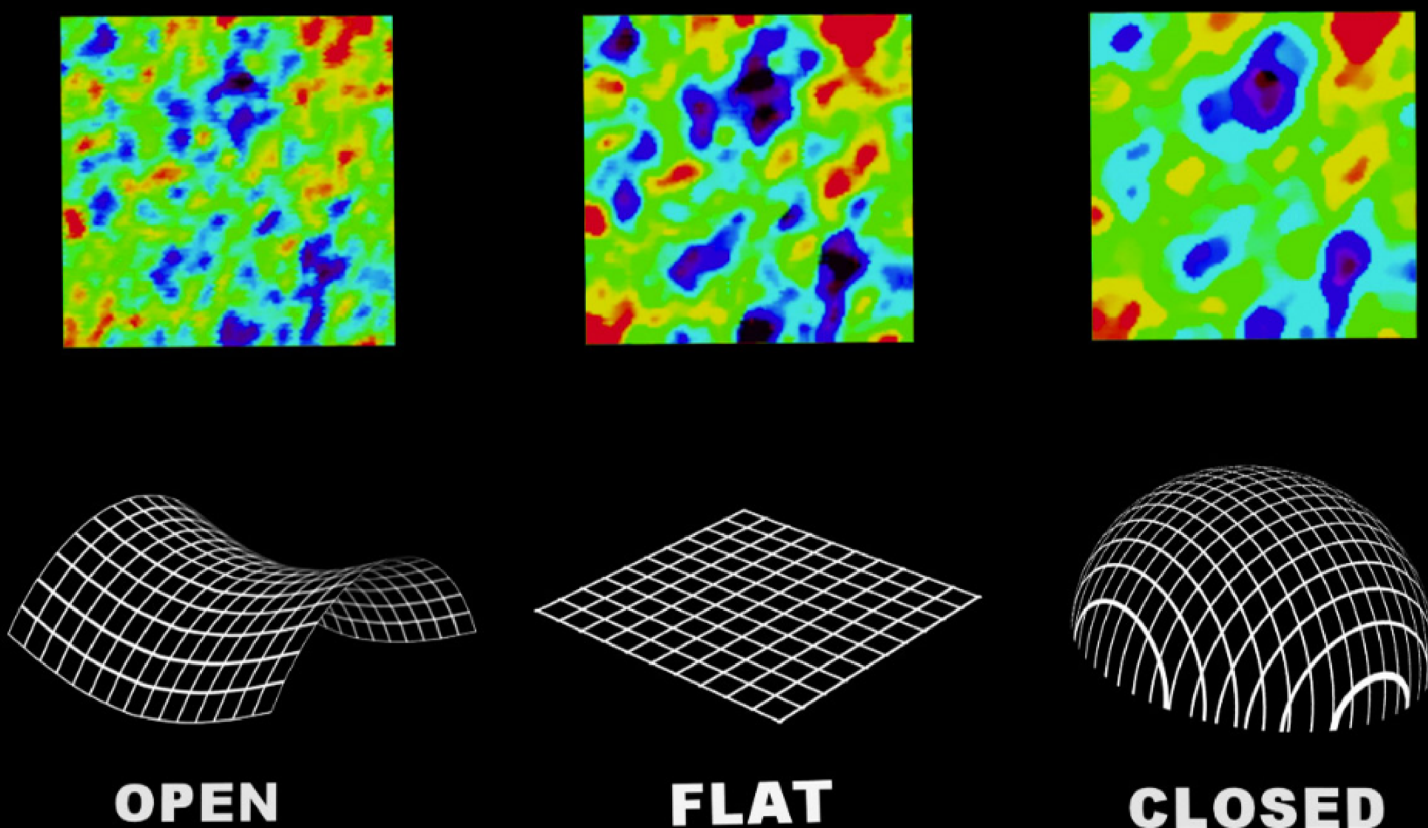


Wilkinson
Microwave Anistoropy
Probe
(WMAP)
satellite

What do we learn?

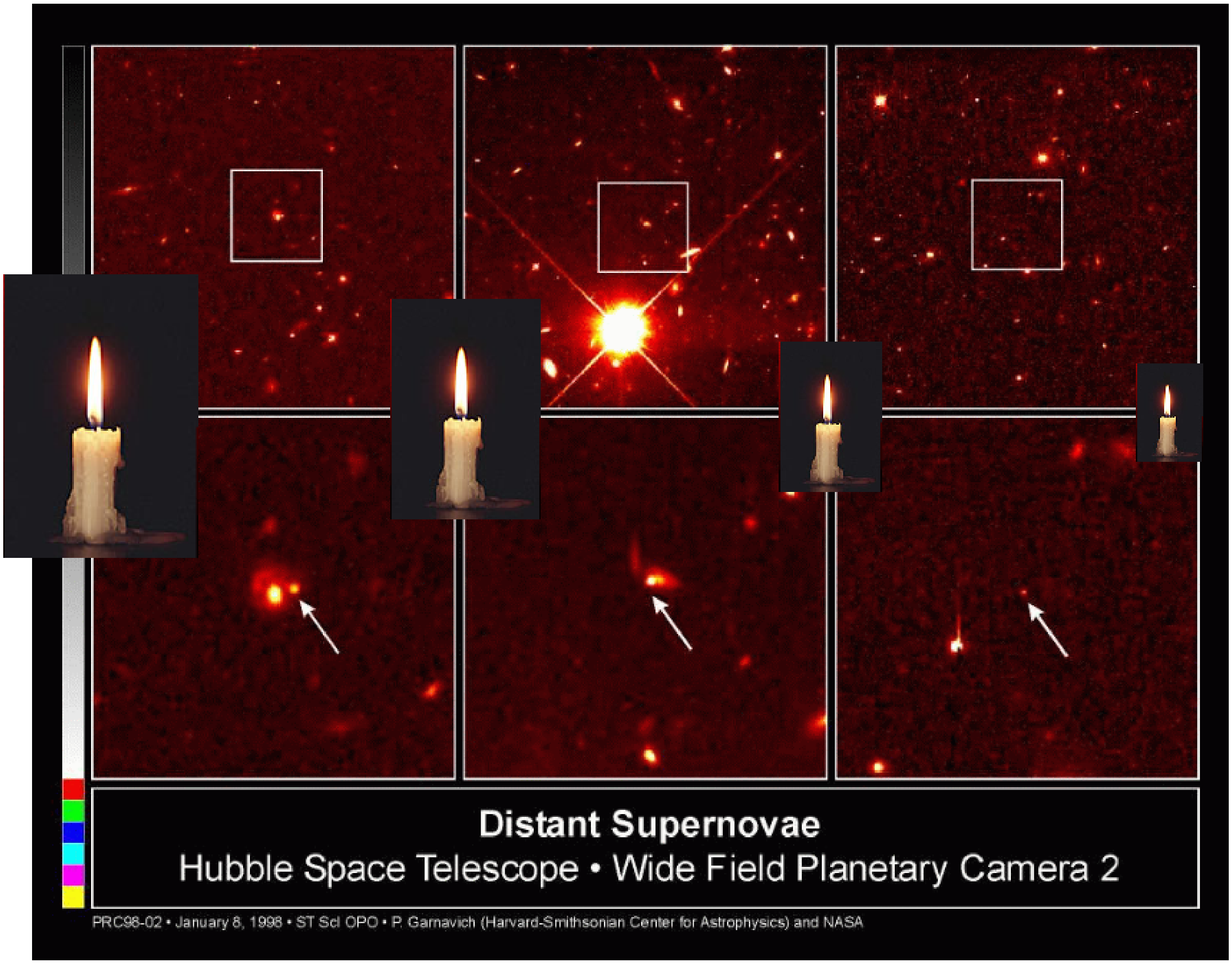


GEOMETRY OF THE UNIVERSE

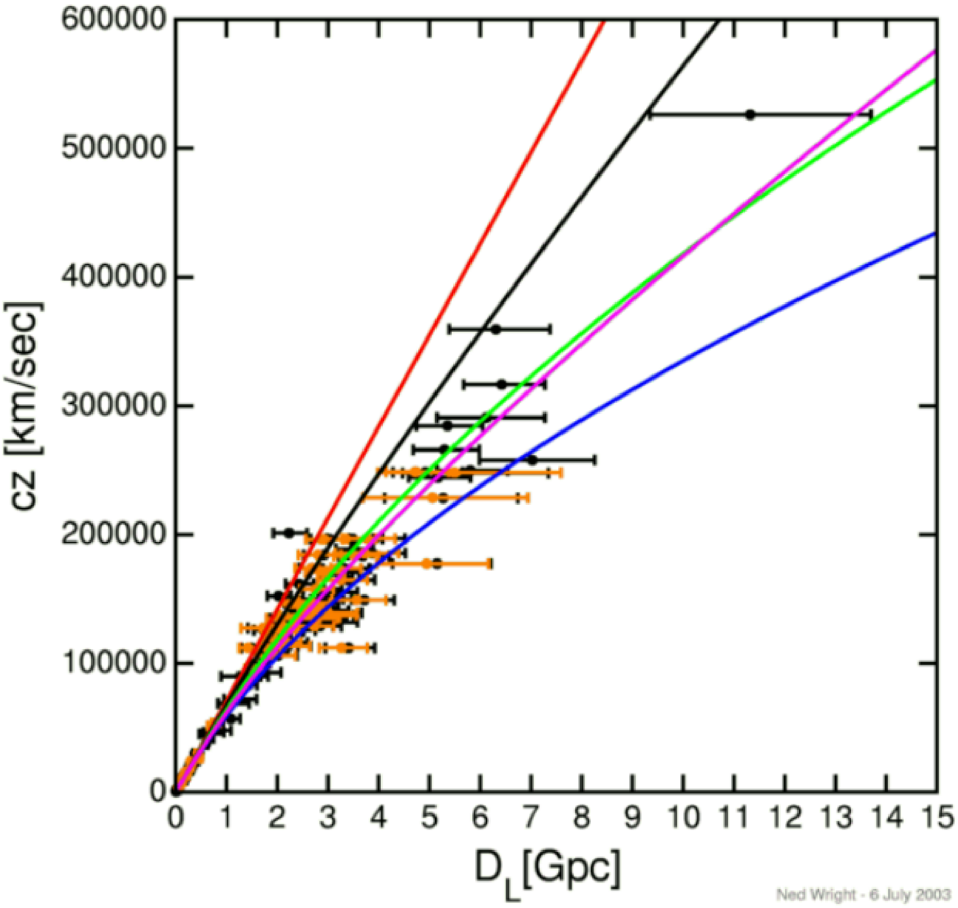


Universes with different amounts of matter would distort the CMB radiation by different amounts

High redshift supernovae type Ia



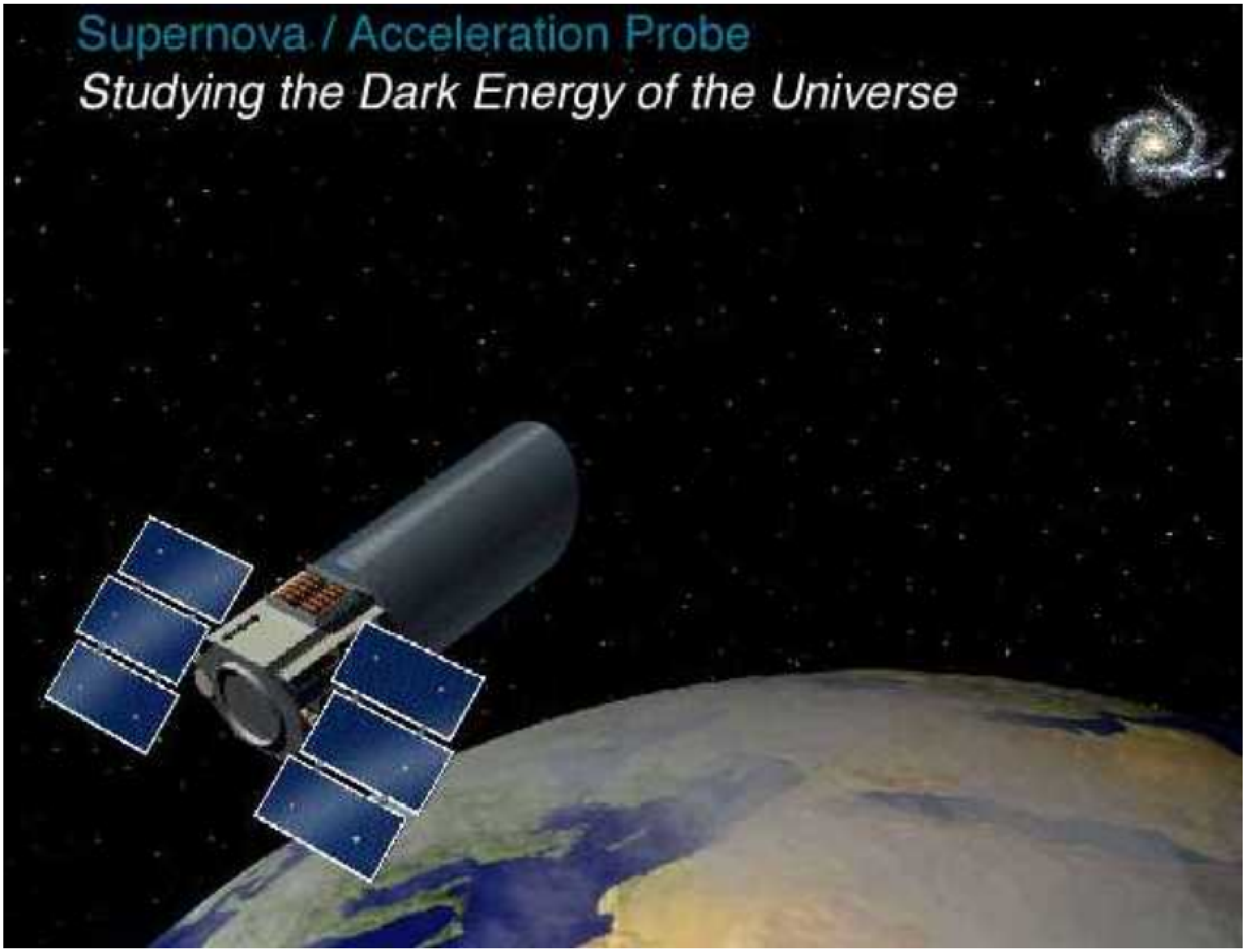
The accelerating Universe!



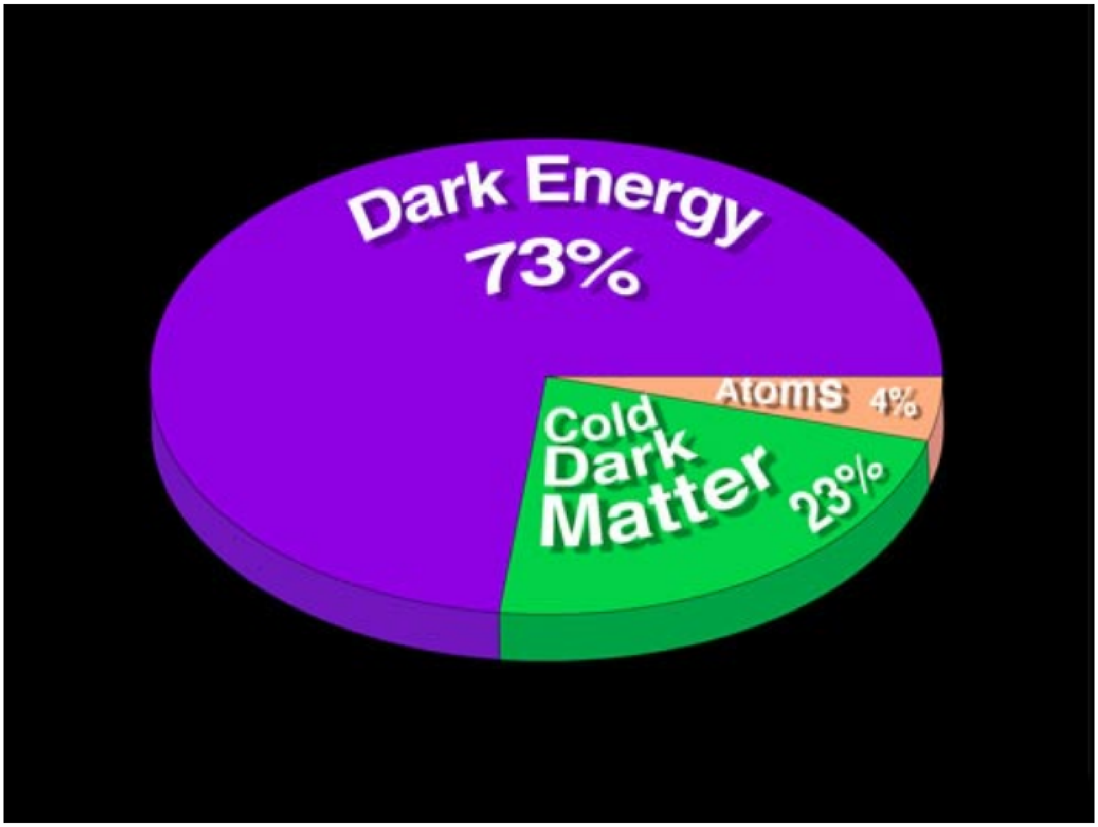
recession velocity (in km/sec)

distance from the Earth (in billions of parsecs)

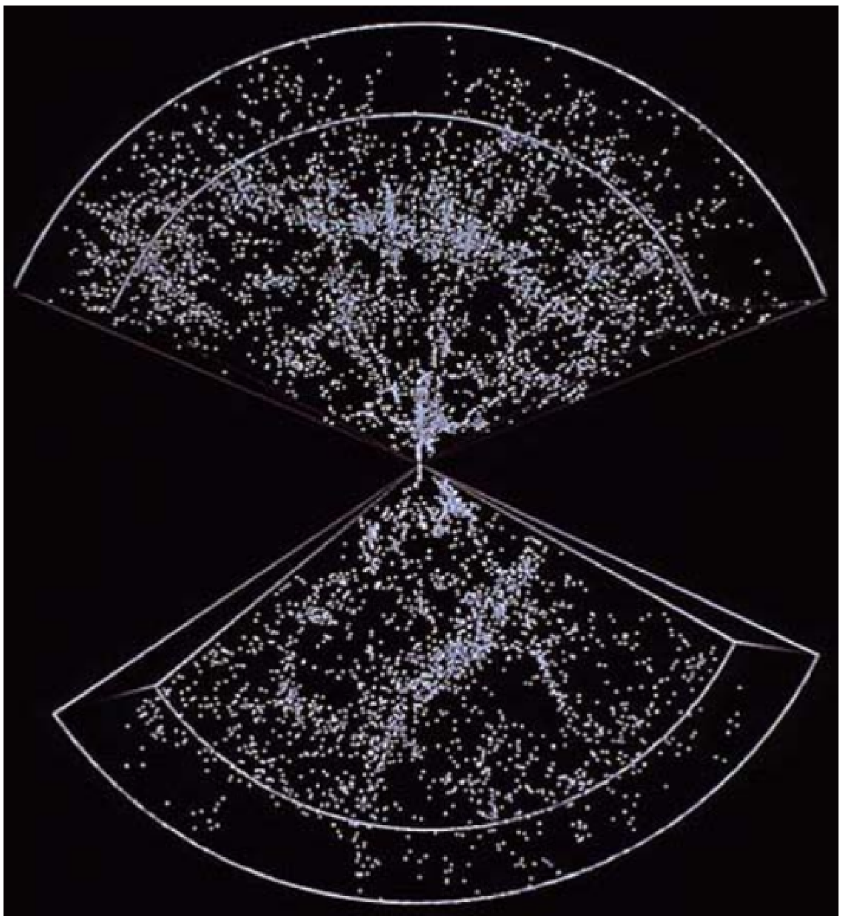
The proposed SNAP satellite



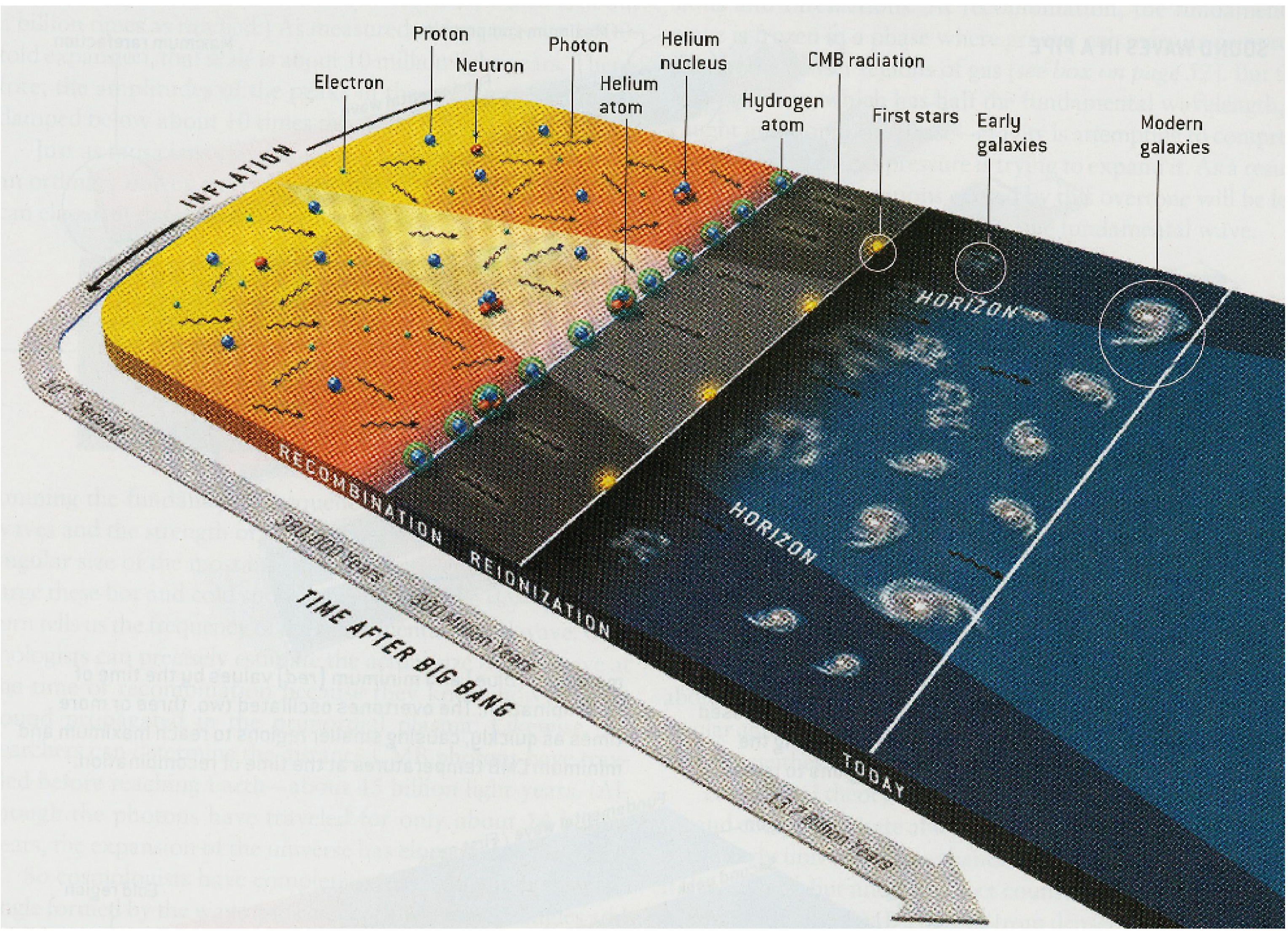
Cosmic Pie



Towards a coherent picture: modeling structure formation in the Universe



A Brief History of the Universe



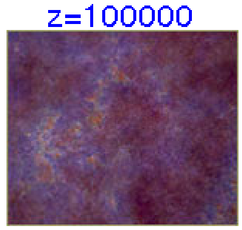
Formation of structures

Big Bang

$z=10^{66}$

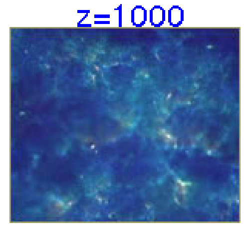
First particles
form

Light elements
(H, He, Li)
form
z=100000



Universe becomes
neutral

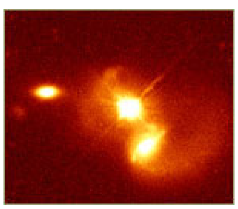
z=1000



First stars form
Universe is reionized
z~10

Galaxies form

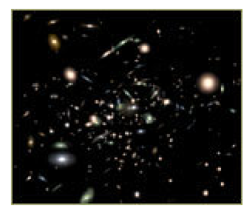
z~1- 5



Solar system
forms
z~0.4

Present day

z=0



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

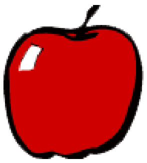
  these predictions are used to set up initial conditions of the simulations

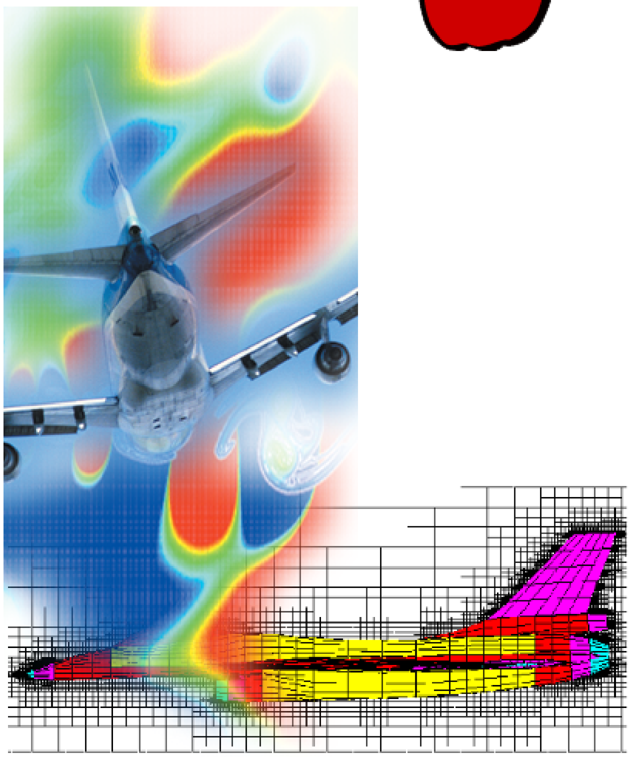
- Simple analytic predictions are accurate only while inhomogeneities are small (<10% fluctuations with respect to the mean density of the Universe)

  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?





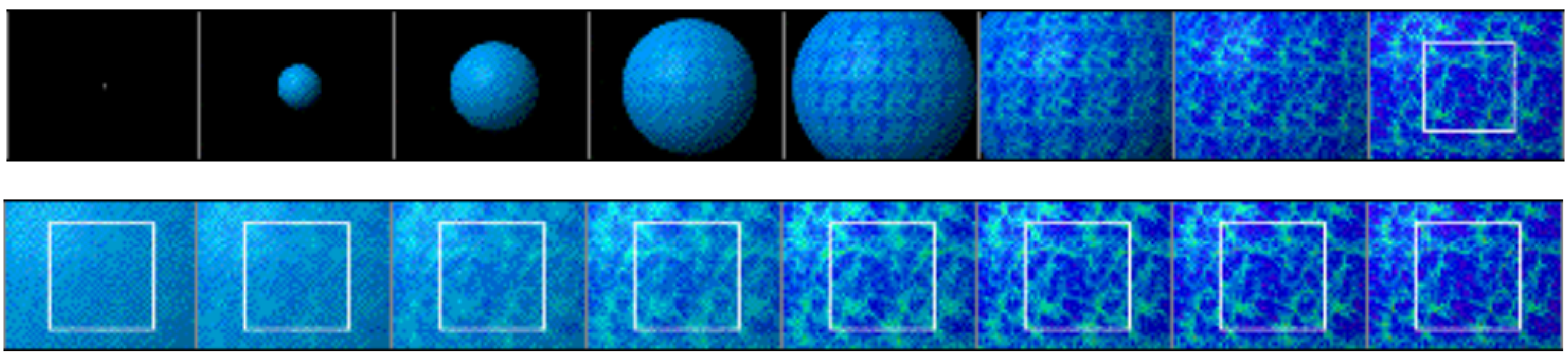
- Gravity is the king

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

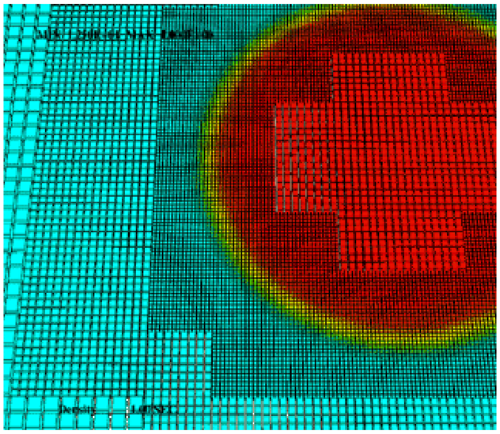
- Other forces may need to be included depending on the composition of the Universe and scales considered

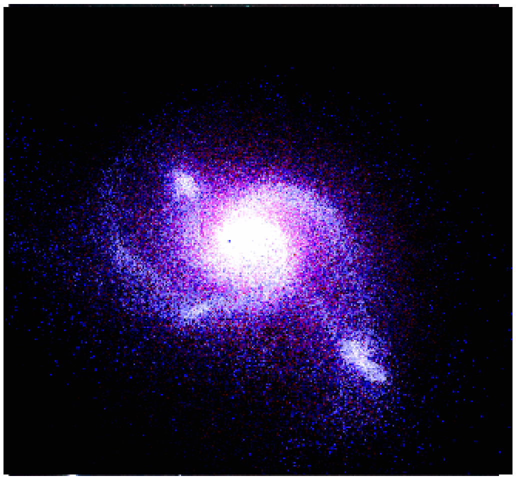
  ordinary matter, the baryons, experiences pressure forces if compressed to sufficiently high densities. these "hydrodynamic" forces are included in simulations that include baryons

We all live in



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

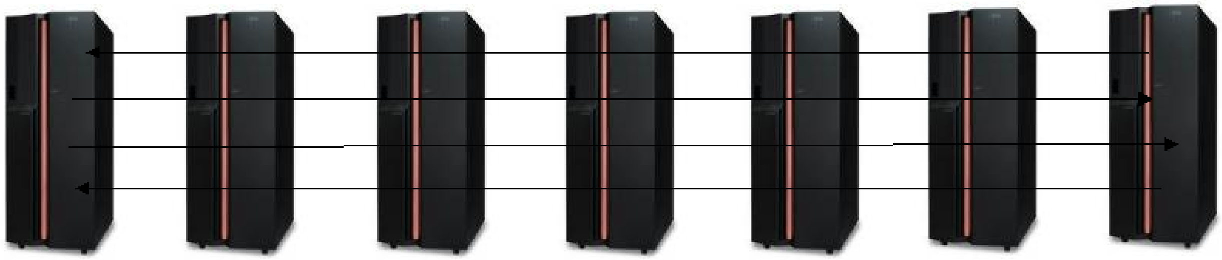
- - - - > need to discretize

Hardware

Supercomputers at National Centers and Labs

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

www.ncsa.uiuc.edu



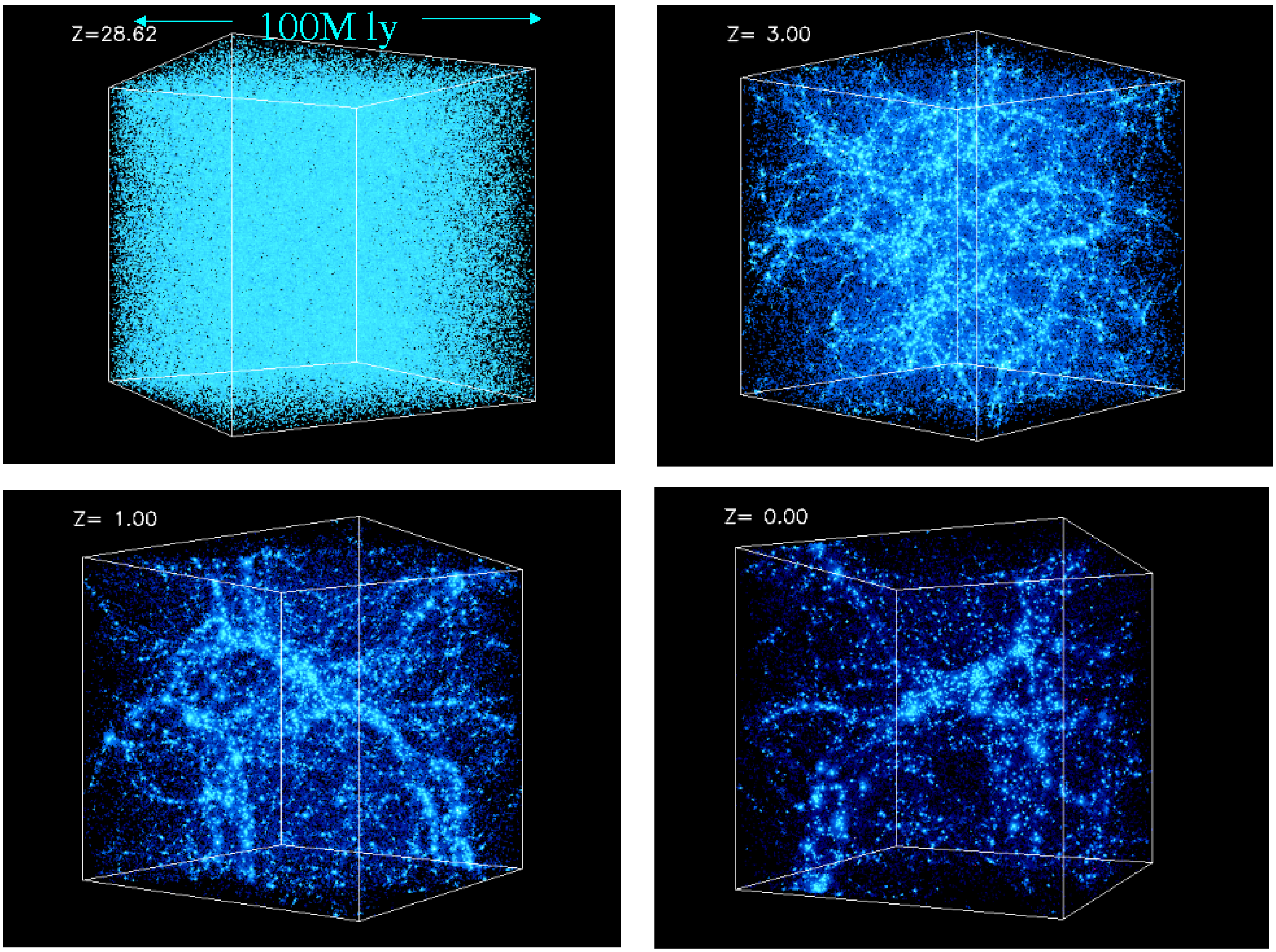
Lots and lots of storage...

Many Many Lines of Software

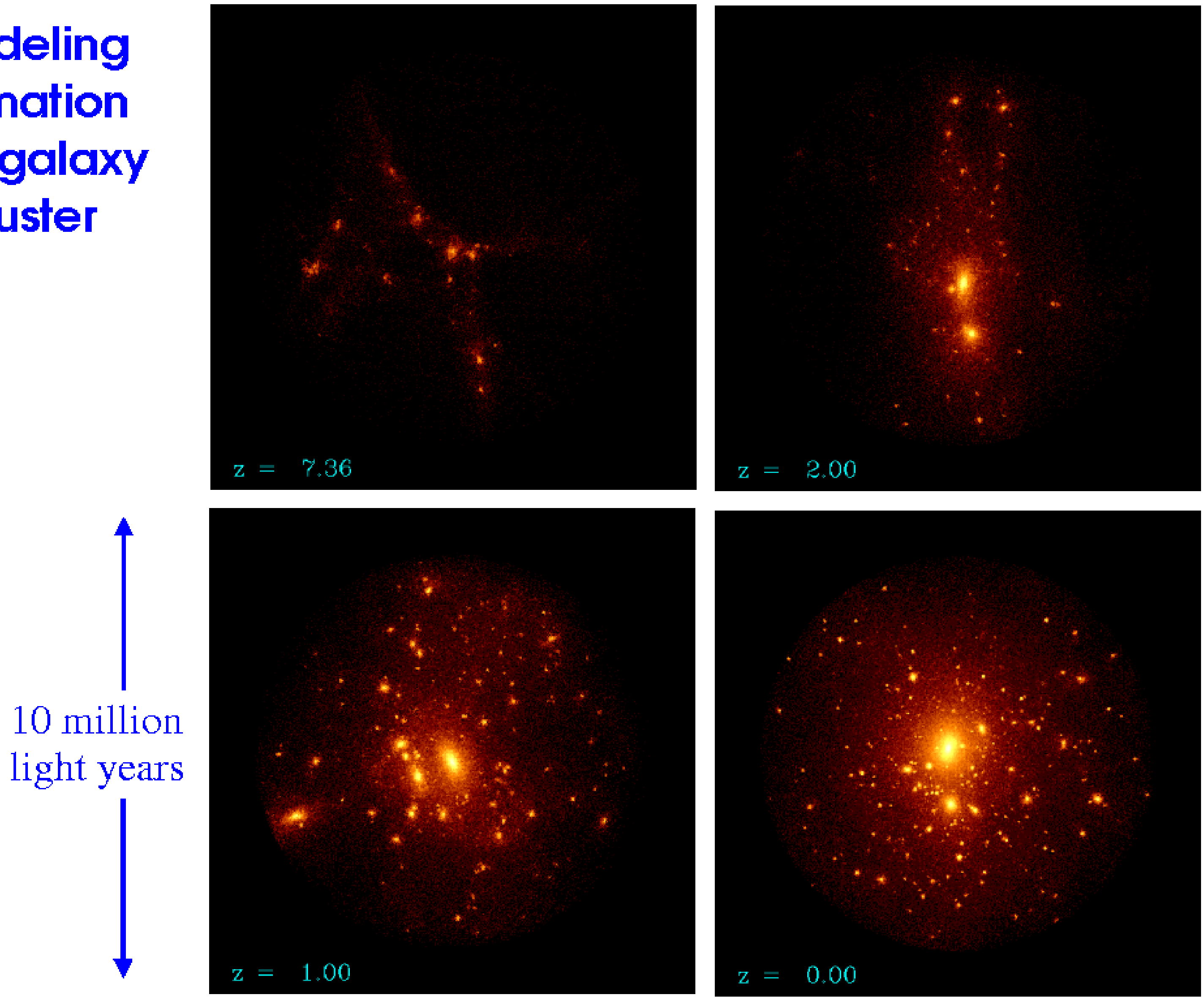
```
c     --------------------------------
      subroutine Split ( Level , mtot )
c     --------------------------------
c
c     purpose: splits cells marked to split
c
c     input  : Level - level to process
c     output : mtot  - # of cells just split
c
#     include "a_def.h"
      include 'a_tree.h'
      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

       Bad news !!!

      if ( dev .gt. eps ) then
        write(*,'(1x,''Riemann_1 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)
        gam_s  = ind_r * (str(5) - stl(5)) + stl(5)
```

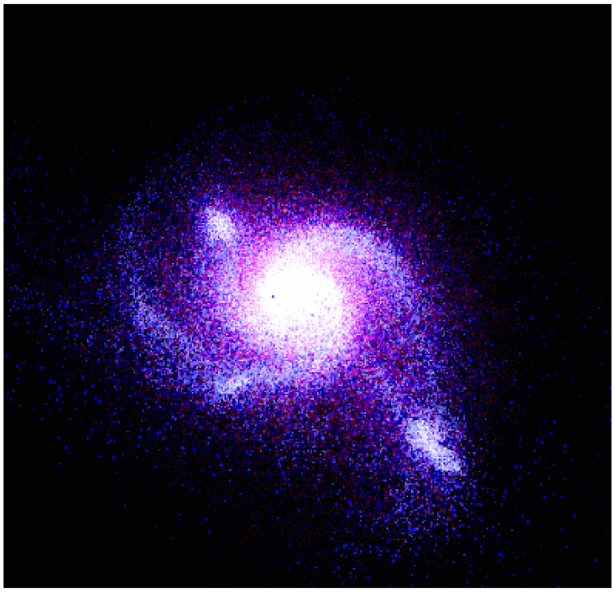
Universe in a box: formation of a filament



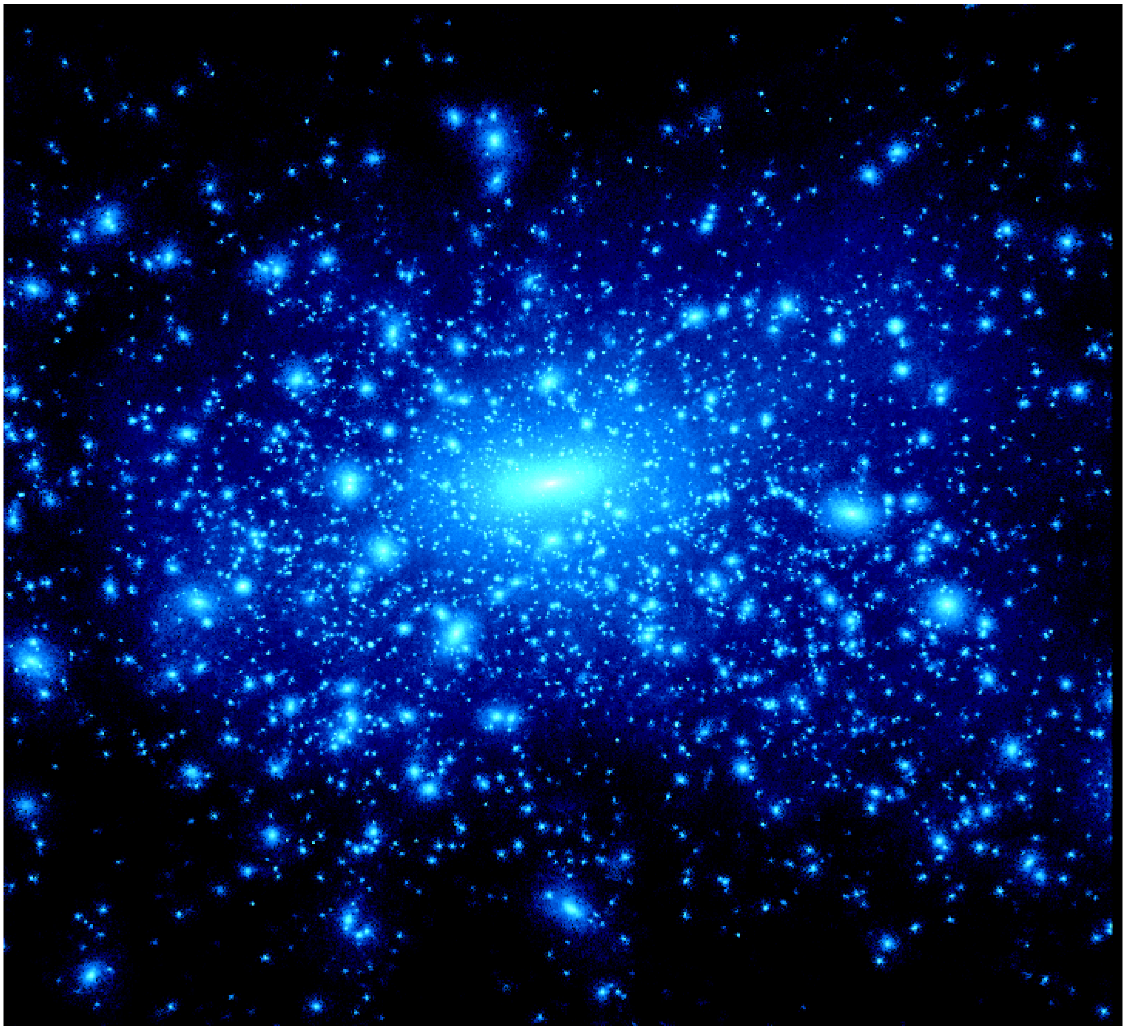
modeling formation of a galaxy cluster



Towards simulating realistic galaxies

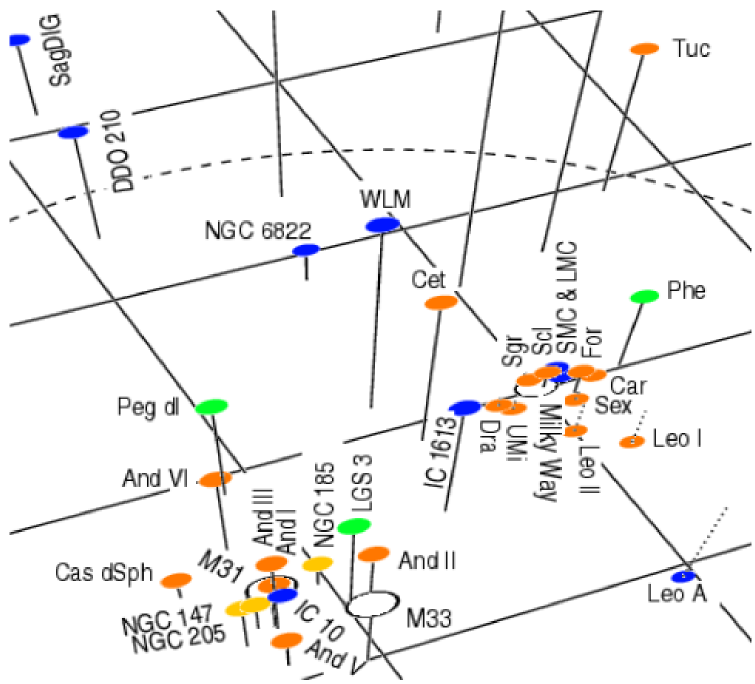


A cluster or a galaxy?

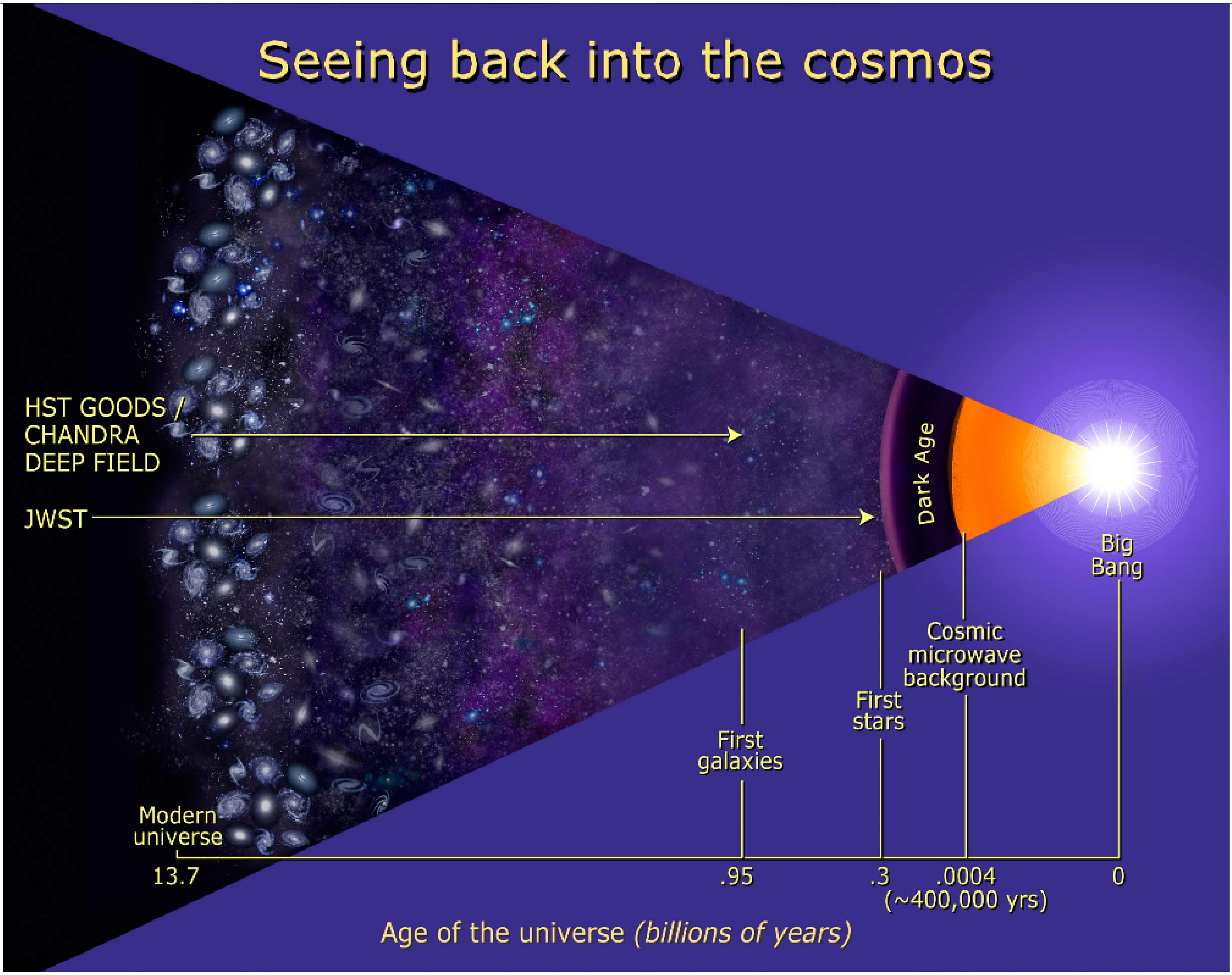


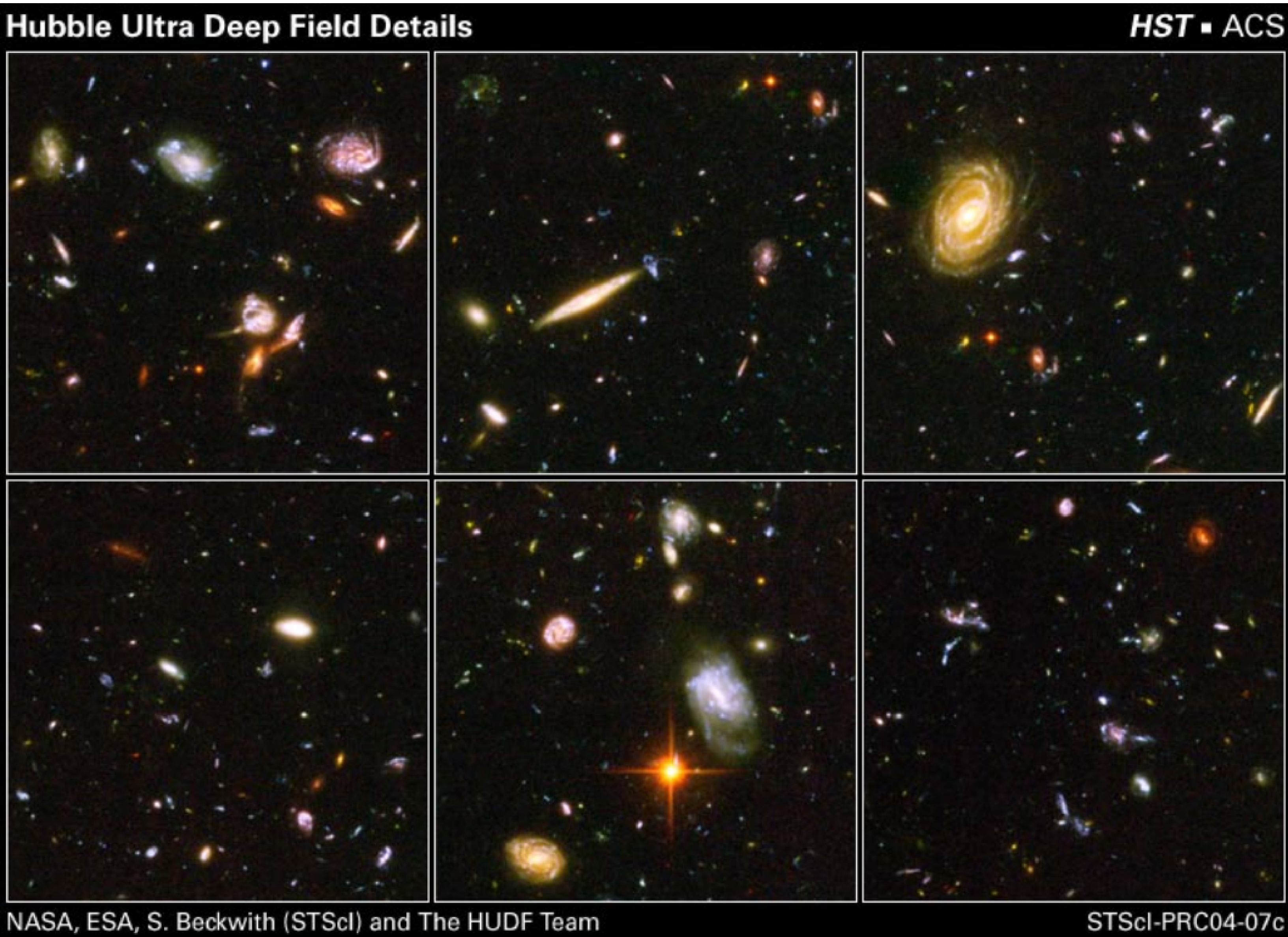
Modeling the Local Group

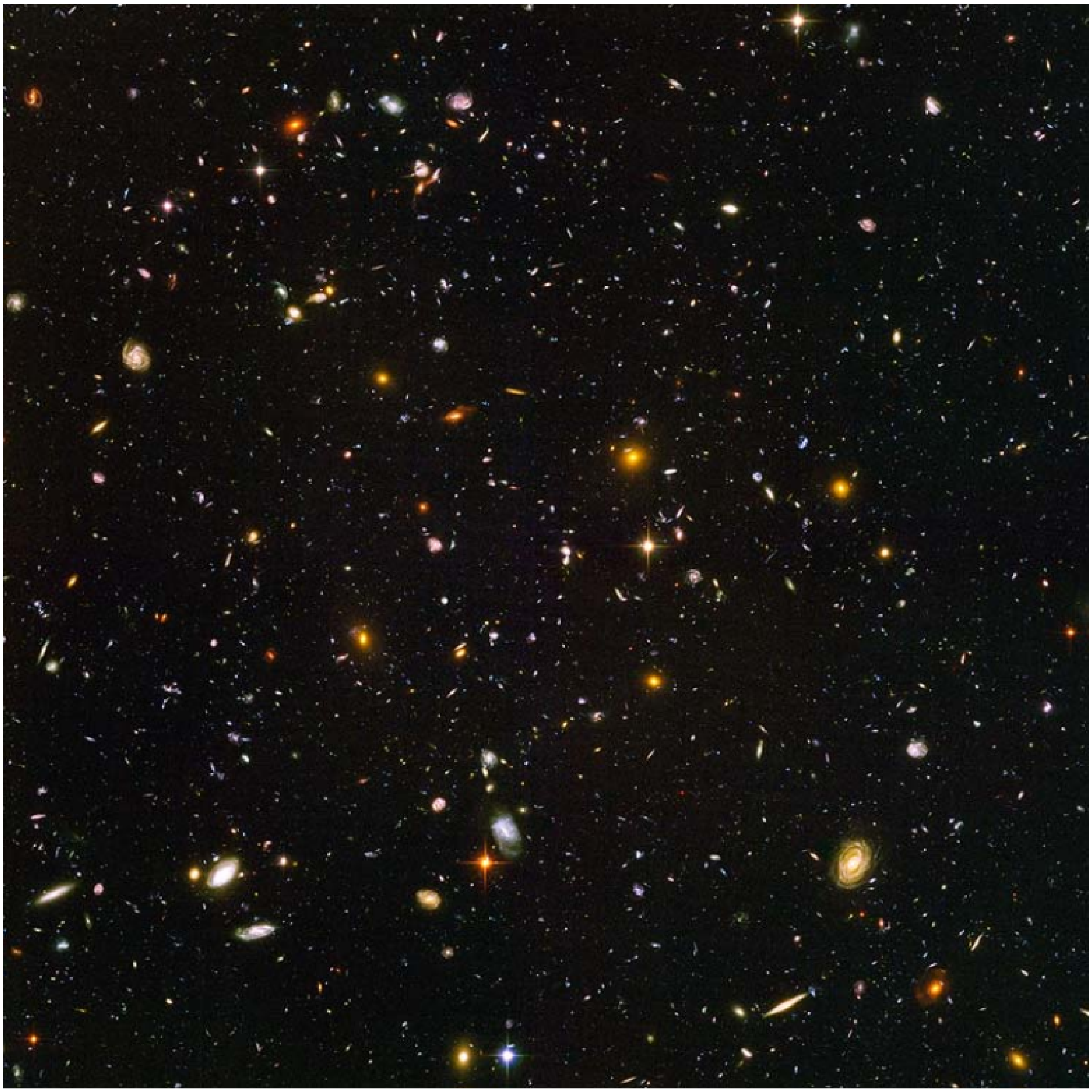
computer simulation



The Local Group


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)*


Hubble Ultra Deep Field Details
HST ▪ ACS
NASA, ESA, S. Beckwith (STScI) and The HUDF Team
STScI-PRC04-07c



Additional Reading

Slides of this talk:
http://astro.uchicago.edu/~andrey/talks/mysteries

Animations:
http://cfcp.uchicago.edu/lss

Scientific American, February 2004

The Elegant Universe by Brian Greene, Norton, 2003

The Extravagant Universe by Robert Kirshner, 2002

Voyage to the Great Attractor by Alan Dressler, 1994

Map of the Universe:
www.astro.princeton.edu/~mjuric/universe

Wilkinson Microwave Anisotropy Probe:
map.gsfc.nasa.gov