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

Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08
Supergalactic plane on the sky

The Local Supercluster

Gerard de Vaucouleurs 1918-1995

G. de Vaucouleurs
Galaxies of the Infrared Sky Near and far structures in the local universe are color-coded by galaxy brightness
Large-scale structure of the Universe as seen by the CfA survey
On even larger scales...
(billions of light years)

2dF Galaxy Redshift Survey

106688 Galaxies
Seeing back into the cosmos

HST GOODS / CHANDRA DEEP FIELD

JWST

Modern universe

13.7

Age of the universe (billions of years)

First galaxies

First stars

Cosmic microwave background

Big Bang

Dark Age

0 (~400,000 yrs)
Structures in the Universe
(Very) Brief History

3 min 3x10^5 yrs 5x10^9 yrs

CMB
\gamma

Nucleo-Synthesis
Last Scattering
Galaxy Formation

e
p
n
He

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: $\Omega_i = \rho_i / \rho_{\text{crit}}$

$$\rho_{\text{crit}} = \frac{3H_0^2}{8\pi G} = 1.8788 \times 10^{-29} h^2 \text{ g cm}^{-3}$$
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 Anisotropy Probe (WMAP) satellite results circa February 2003
High redshift supernovae type

Distant Supernovae
Hubble Space Telescope • Wide Field Planetary Camera 2

PRC98-02 • January 8, 1998 • ST ScI CPO • P. Garnavich (Harvard-Smithsonian Center for Astrophysics) and NASA
SNAP satellite proposal

Supernova / Acceleration Probe
Studying the Dark Energy of the Universe
Cosmic Pie

- Dark Energy: 73%
- Cold Dark Matter: 23%
- Atoms: 4%
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)

Lots and lots of storage...
Many Many Lines of Software

subroutine Split ( Level, mtot )

purpose: splits cells marked to split
input : Level - level to process
output : mtot - # of cells just split

include 'a_def.h'
include 'a_tree.h'
include 'a_control.h'

integer mtot, Level
integer idcell
real*8 e_kin, e_ip
real*8 nhvar(nhvar), wvar1, wvar2, wvar3
dimension iPyr(nchild,3) / interpolation pyramid vertices

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 /

else
if ( sta1(1) .gt. eps ) then
  w1l = ( sl * p_1 + b1 ) / ( p_1 + cl )
  w2l = 1 ./sqrt(max(small_R, w1l * stl(1) * (p_1 + stl(3))))
  u1l = stl(2) + ( stl(3) - p_1 ) * w2l
  wlr = ( er * p_1 + br ) / ( p_1 + cr )
  w2r = 1 ./sqrt(max(small_R, wlr * stri(1) * (p_1 + stri(3))))
  url = str(2) + ( p_1 - stri(3) ) * w2r
  p2 = max( small_R, 1.0000001 * p_1 - ( url - u1l )
    * abs( p_1 - p_0 )
    / ( abs( url - ur_0 )
    + abs( u1l - ul_0 )
    + small_R )

  p_0 = p_1
  p_1 = p_2
  ul_0 = u1l
  ur_0 = url
  devi = abs( p2 - p_1 ) / ( p2 + p_1 )
  sta1(1) = devi
  dev = max( dev , devi )
endif
endif

... Warning! The loops below are to be executed SERIALLY

IF ( Level .eq. MinLevel ) THEN
  do icl = 1, ncell10
    if ( vnw1(icl) .gt. vsplit ) then
      ires = iSplitCell ( icl )
      if ( ires .eq. nnil ) then
        mtot = mtot + 1
        icl = i0ctCh(icl)
        v_p = nhvar(3,icl)**2 +
          nhvar(4,icl)**2 +
          nhvar(5,icl)**2
    endif
  enddo
endif

Bad news !!!

if ( dev .gt. eps ) then
  write(*,'(lx,''Kiemann_L solver iteration failure'')')
  stop
endif

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)
qgam_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
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