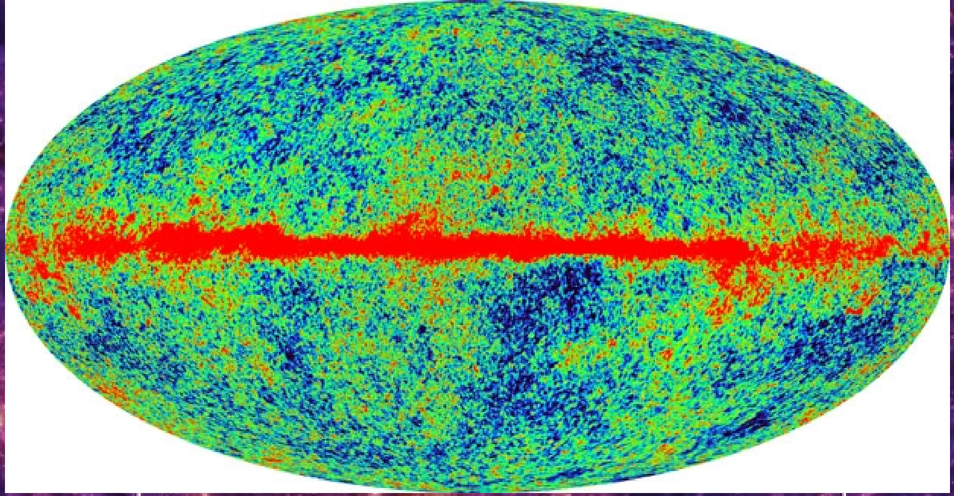
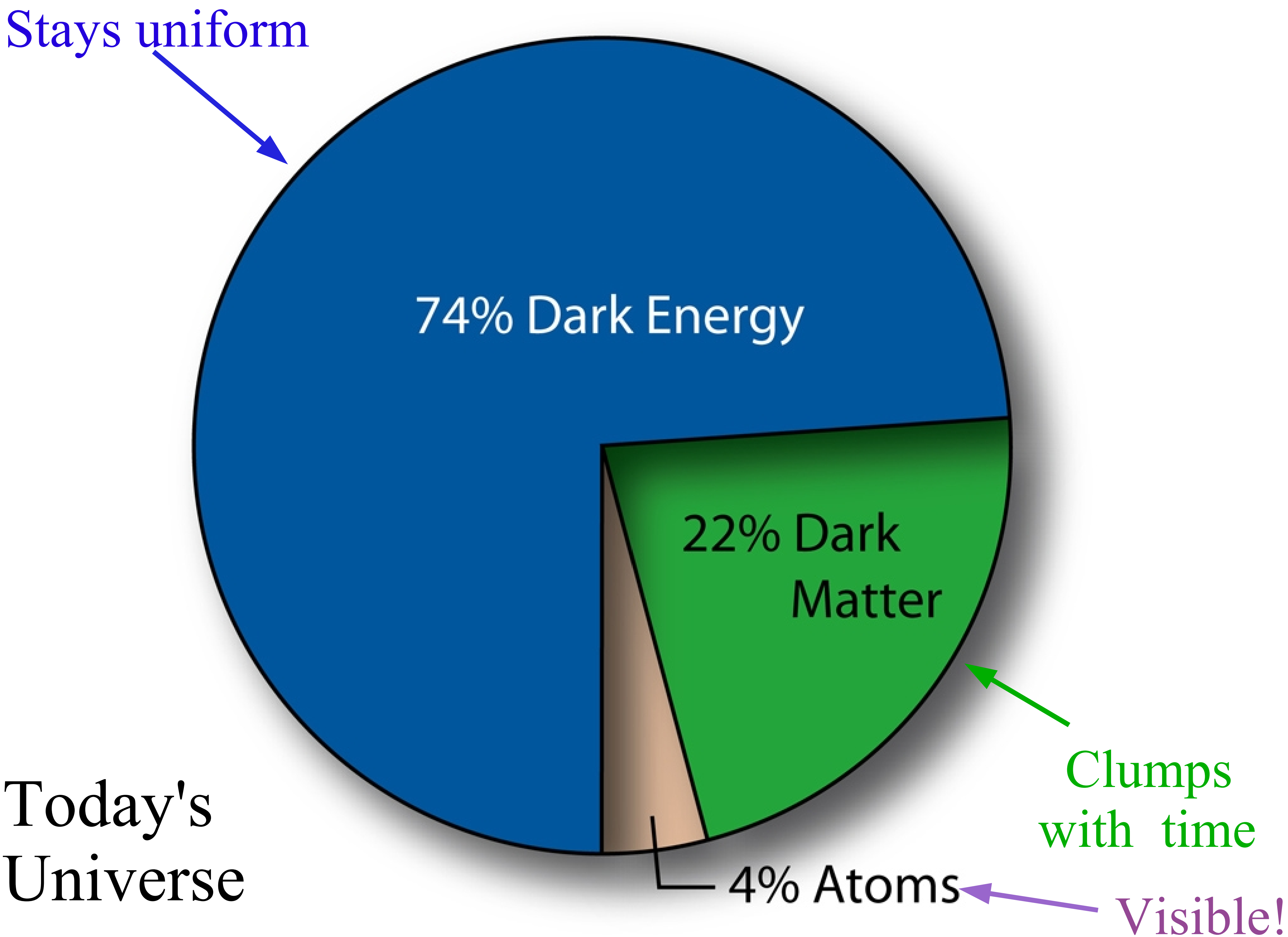
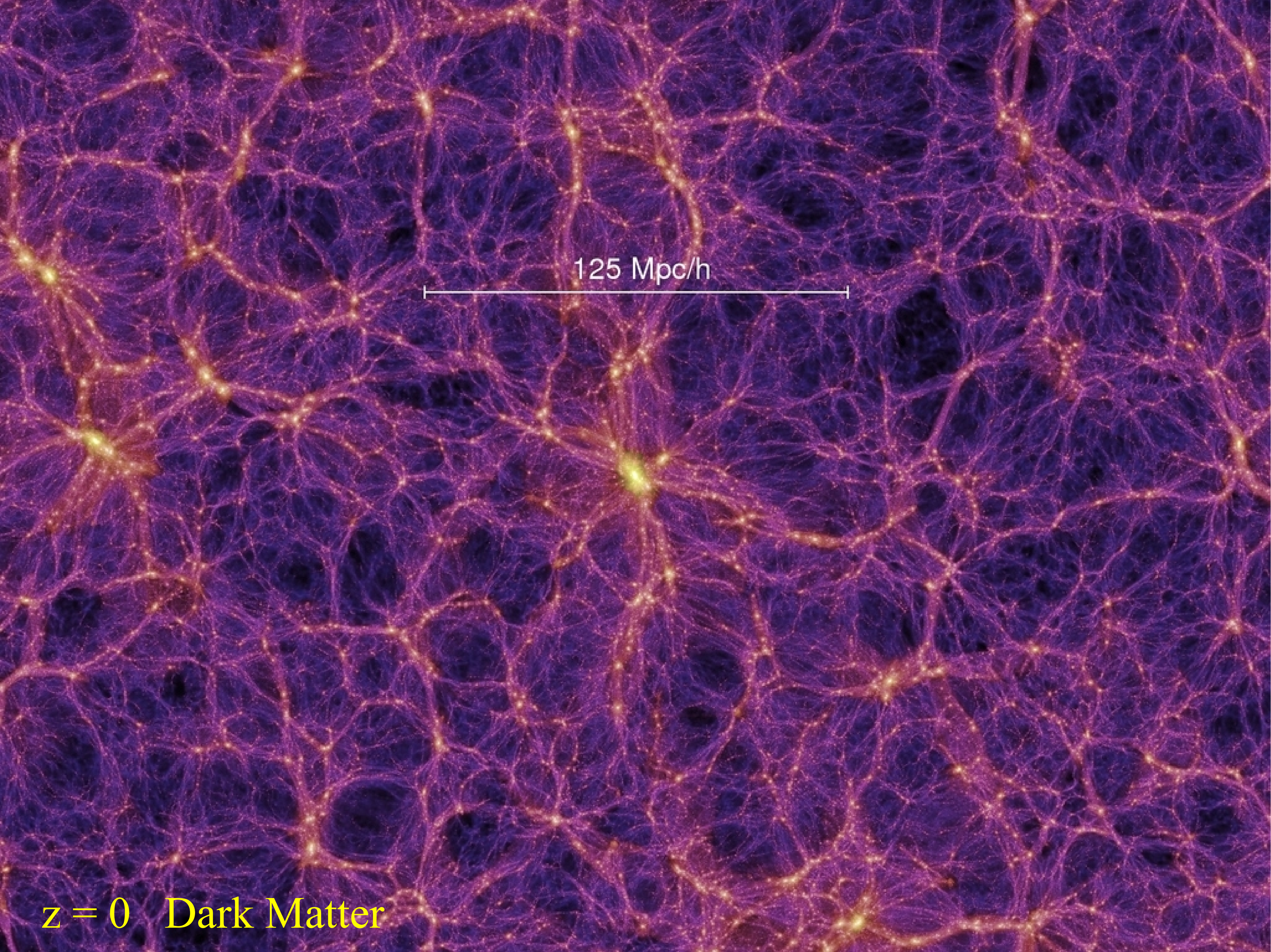


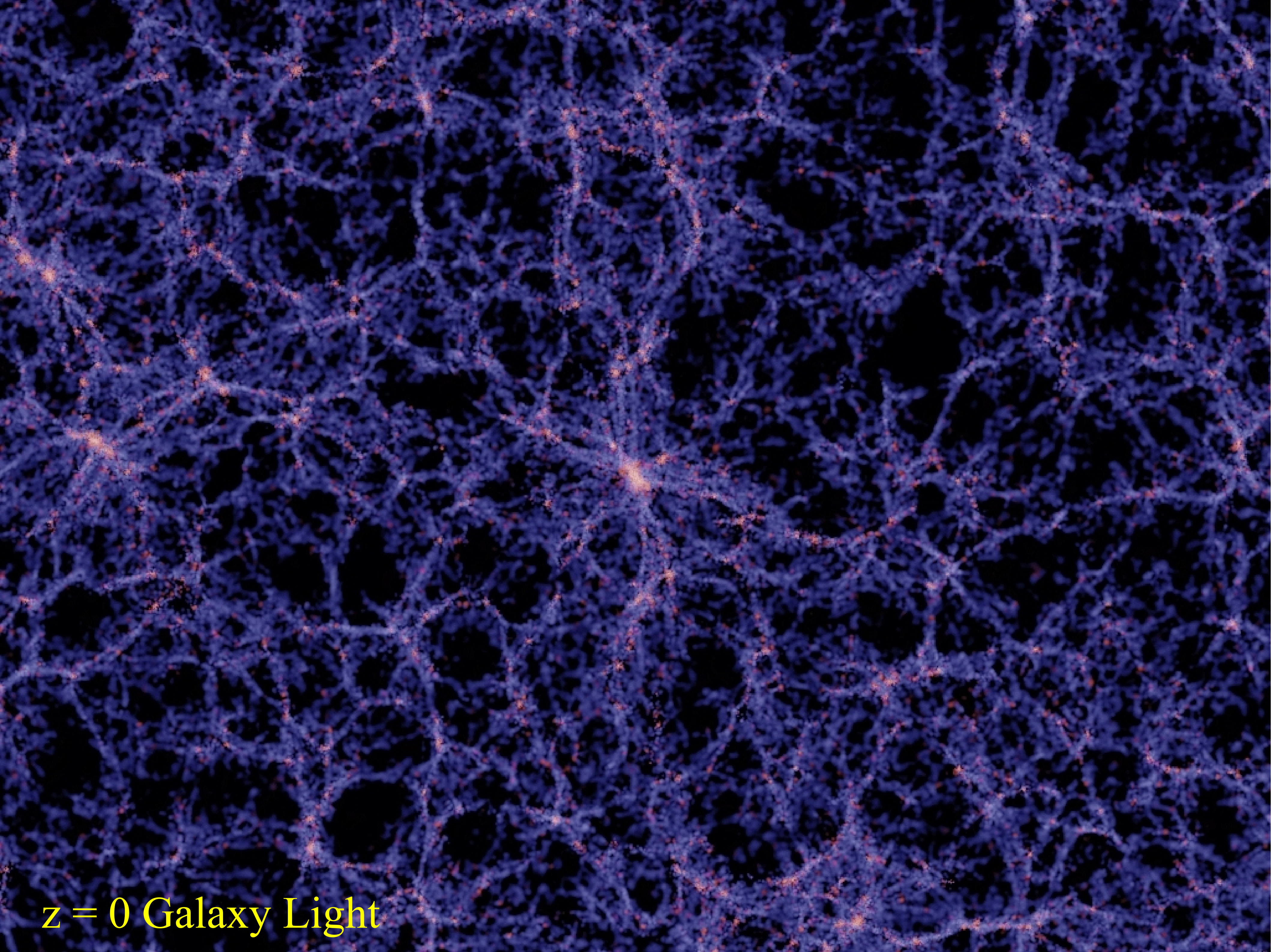
LRZ
November 2007

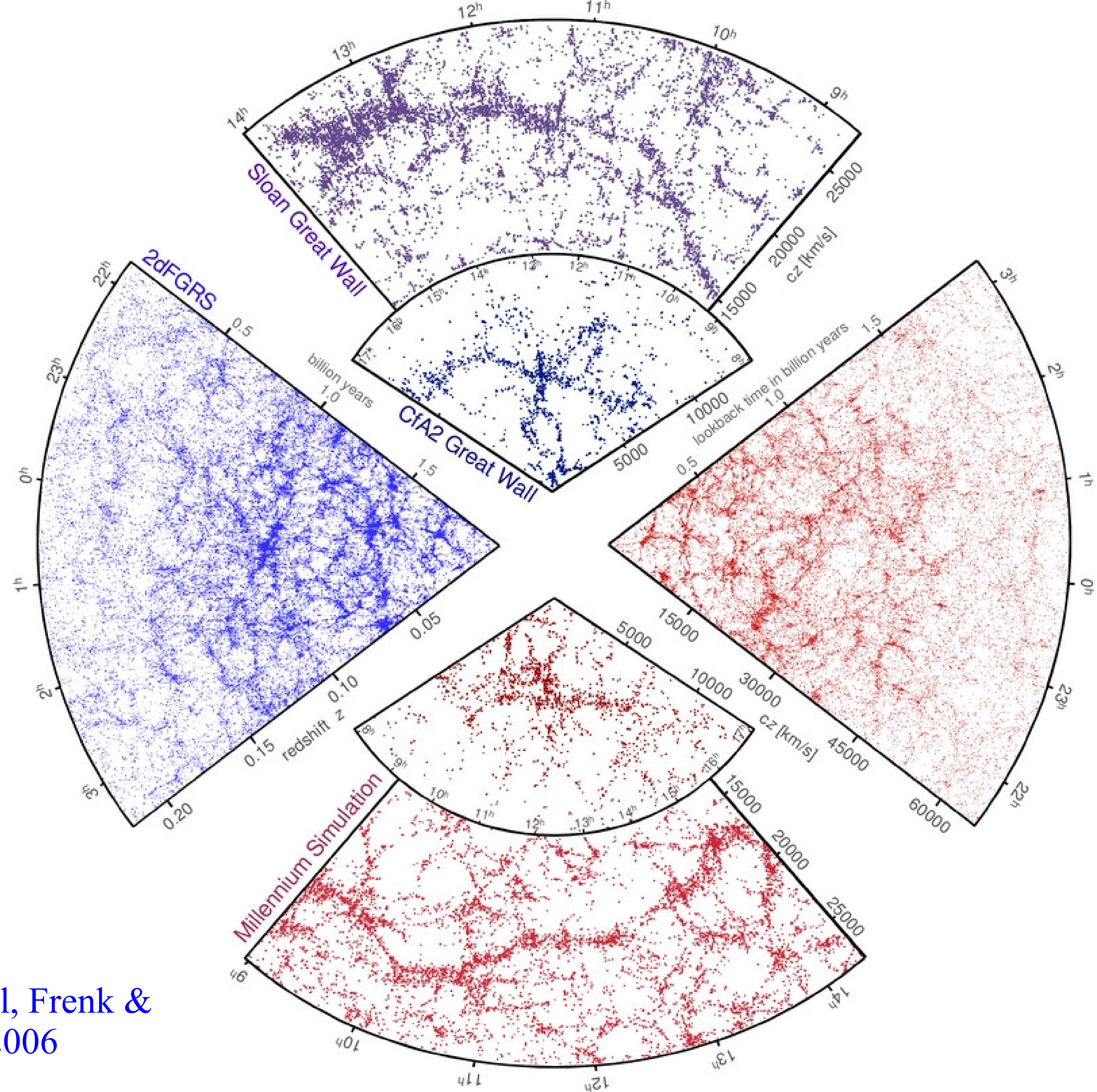
The Aquarius Project: Cold Dark Matter under a Numerical Microscope

Volker Springel, Simon White & the Virgo Consortium
Max Planck Institute for Astrophysics

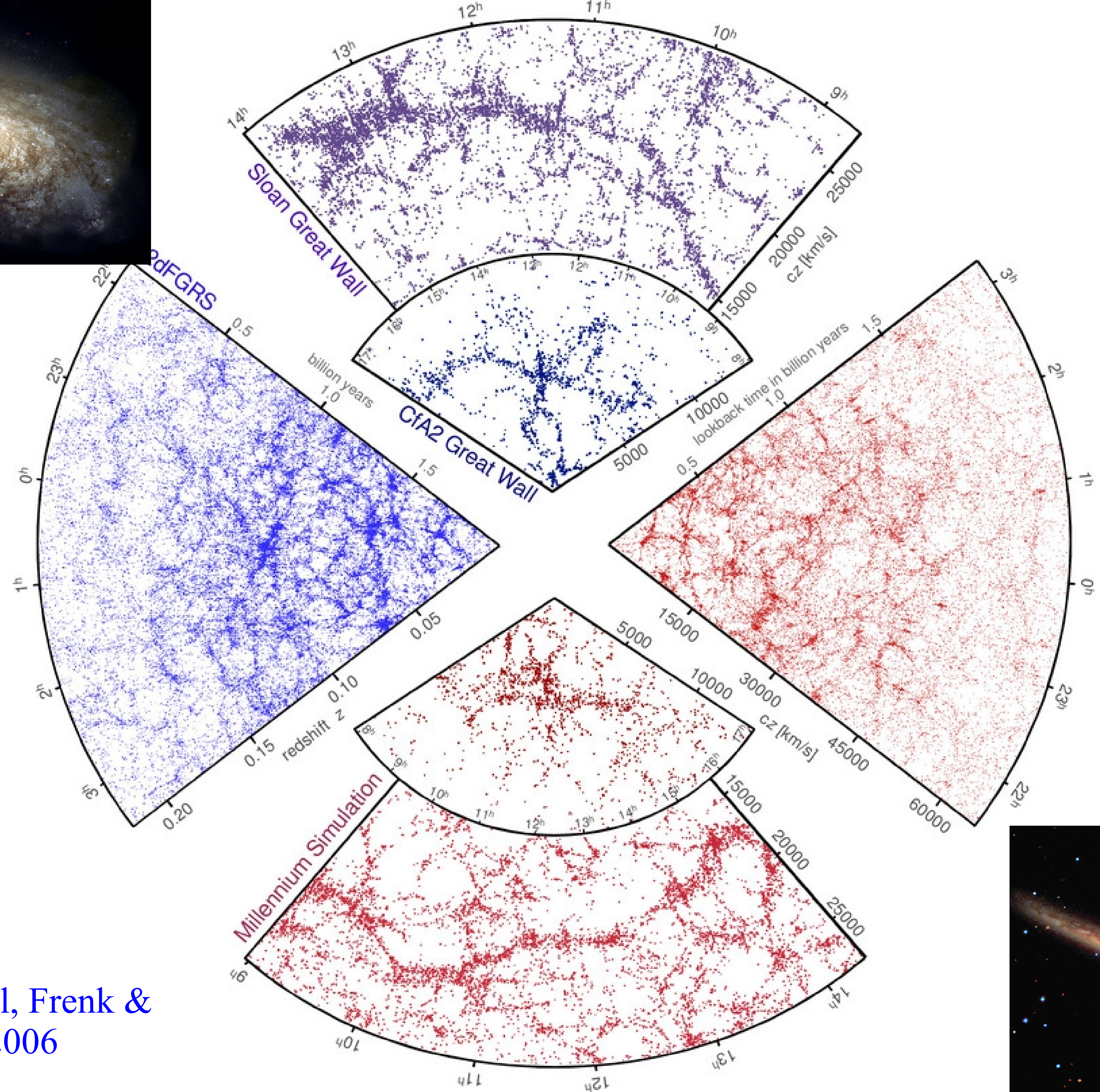

Stays uniform
74% Dark Energy
22% Dark Matter
4% Atoms
Clumps with time
Visible!
Today's Universe

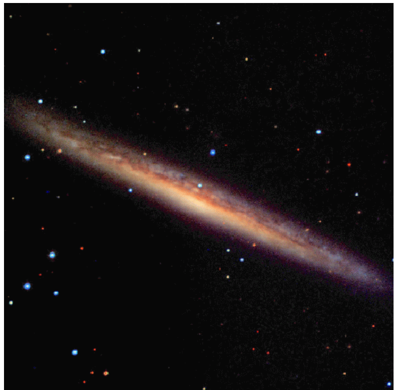

125 Mpc/h
z = 0 Dark Matter


z = 0 Galaxy Light



Springel, Frenk & White 2006





Springel, Frenk & White 2006

Visualizing Darkness

- Uniformity, filamentarity, hierarchy – it all depends on scale

- The smooth becomes rough with the passing of time

- The Milky Way hums with memories of its past

Scientific issues for Aquarius

- Central structure of the Milky Way's halo
  -- Dark Matter annihilation radiation

- Abundance and structure of substructures
  -- Relation to observed dwarf satellite galaxies
  -- Annihilation radiation from dwarfs

- Assembly history of the Milky Way
  -- Origin of various stellar components of the Milky Way

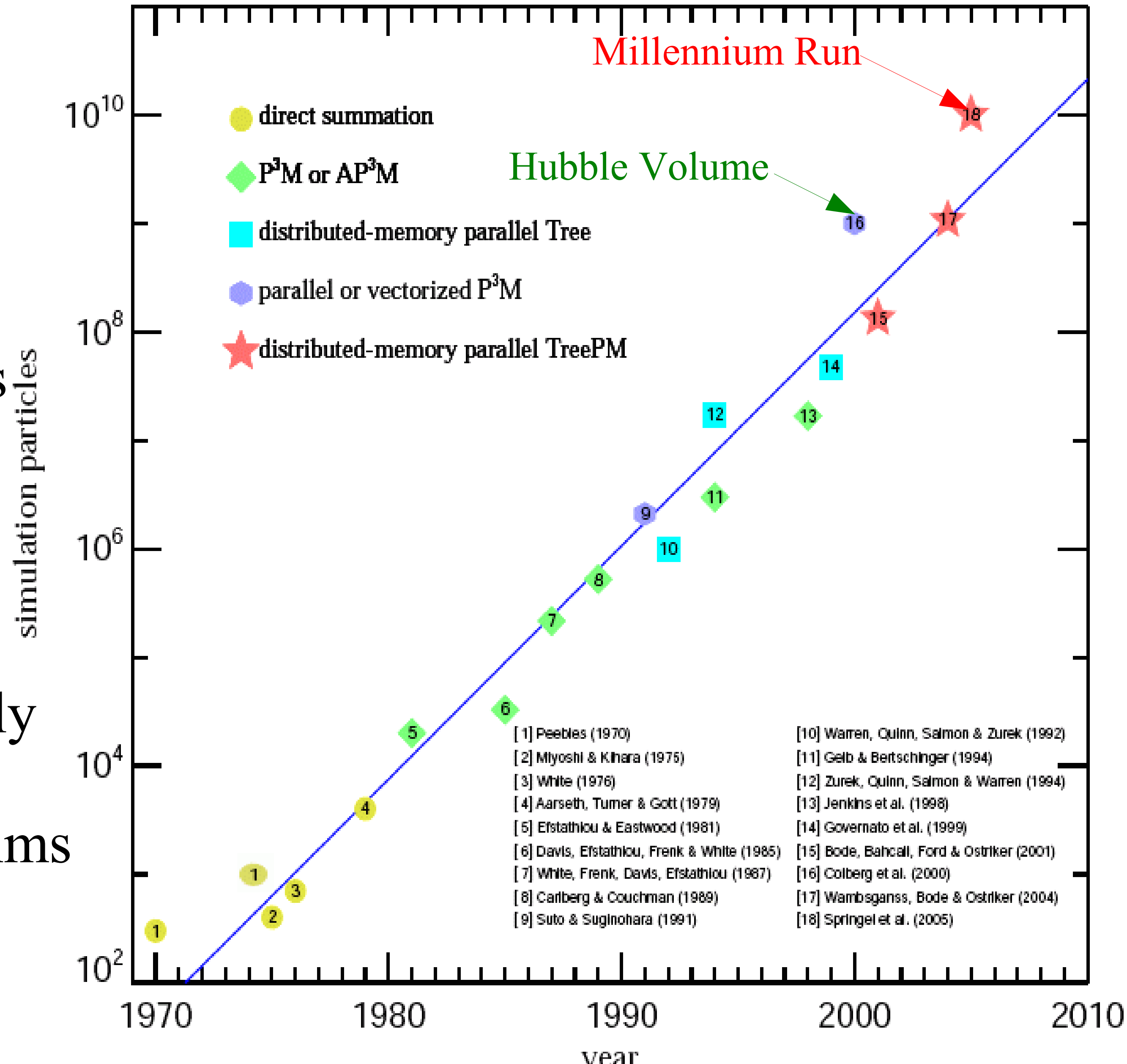
Numerical issues for Aquarius

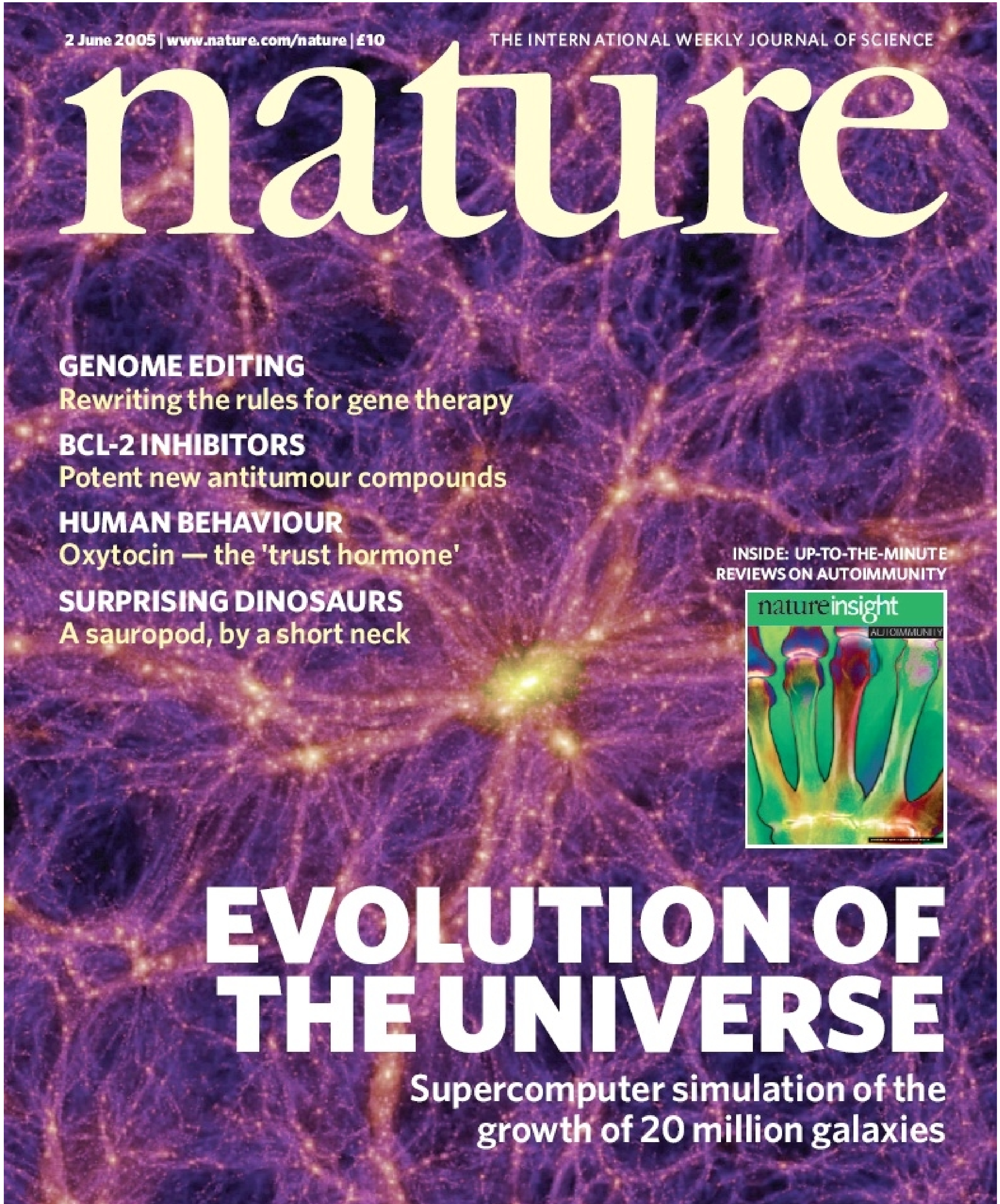
- Very large dynamic range required
  - -- 10^6 in linear scale, mass density
  - -- 10^3 in time-scale
  - -- $> 10^{12}$ in mass
- Distribution of load for parallel execution
  - -- Final system has a single centre of concentration
  - → no simple decomposition into equivalent spatial domains
- Need to store system state at frequent interval
  - -- 40 Tbyte of stored data for later post-processing

Moore's Law for Cosmological N-body Simulations

Springel et al 2005

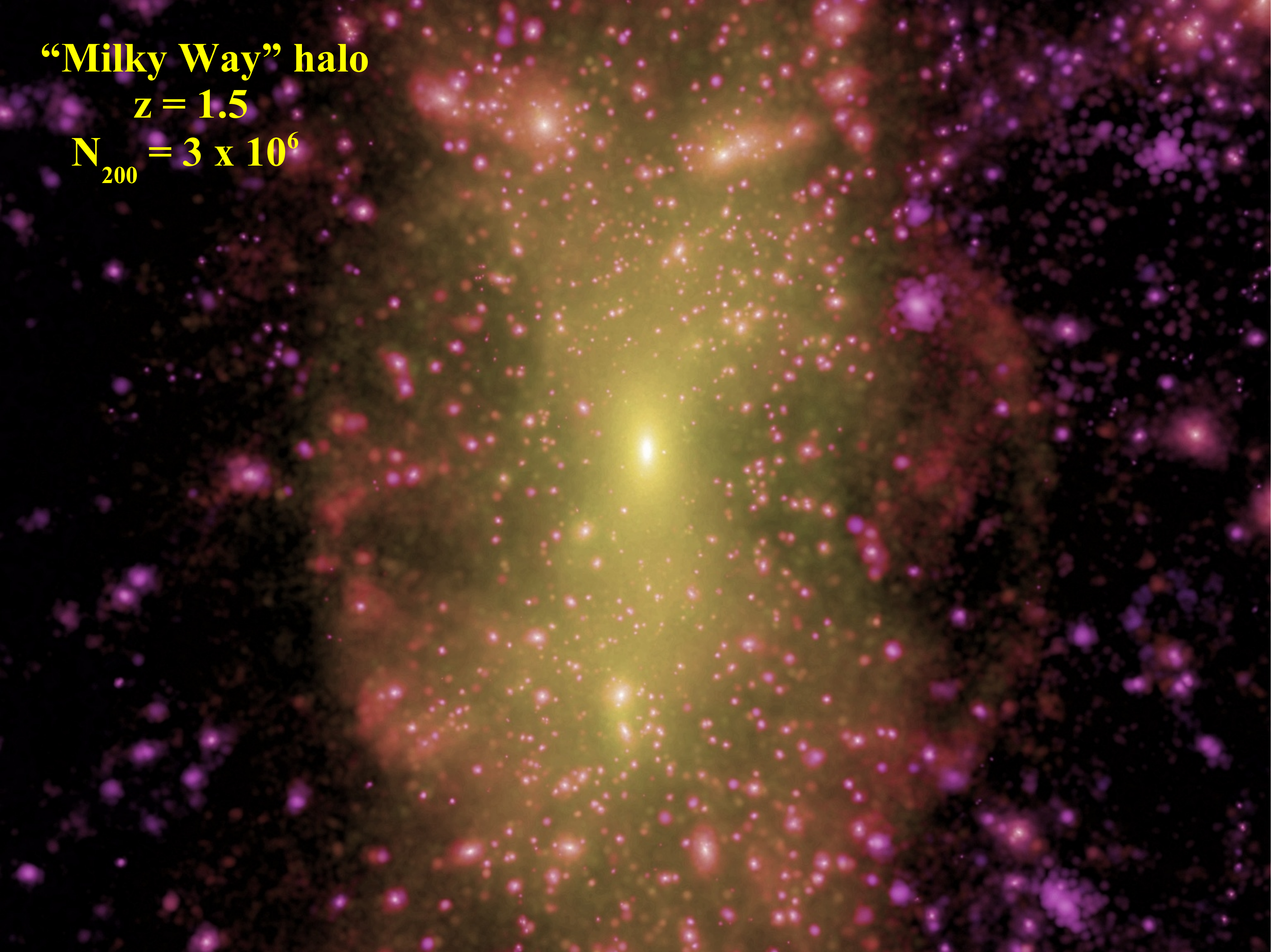
- Computers double their speed every 18 months
- A naive N-body force calculation needs N^2 op's
- Simulations double their size every 16.5 months
- Progress has been roughly equally due to hardware and to improved algorithms




2 June 2005 | www.nature.com/nature | £10
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
nature
GENOME EDITING
Rewriting the rules for gene therapy
BCL-2 INHIBITORS
Potent new antitumour compounds
HUMAN BEHAVIOUR
Oxytocin — the 'trust hormone'
SURPRISING DINOSAURS
A sauropod, by a short neck
INSIDE: UP-TO-THE-MINUTE
REVIEWS ON AUTOIMMUNITY
natureinsight
AUTOIMMUNITY
EVOLUTION OF
THE UNIVERSE
Supercomputer simulation of the
growth of 20 million galaxies

Name	$N_{\rm tot}$	$N_{\rm FoF}$	Mass resolution	Spatial resolution	$N_{\rm cpu}$
C02-400^3	19.170.765	5.546.052	$2.49 \times 10^5\, h^{-1}\mathrm{M}_\odot$	$250\, h^{-1}\mathrm{pc}$	64
C02-800^3	168.320.279	44.049.741	$1.67 \times 10^5\, h^{-1}\mathrm{M}_\odot$	$88\, h^{-1}\mathrm{pc}$	256
C02-1200^3	606.866.170	157.239.052	$1.00 \times 10^4\, h^{-1}\mathrm{M}_\odot$	$48\, h^{-1}\mathrm{pc}$	256
C02-2400^3	4.397.586.154	~1.258.000.000	$1.25 \times 10^3\, h^{-1}\mathrm{M}_\odot$	$15\, h^{-1}\mathrm{pc}$	1024

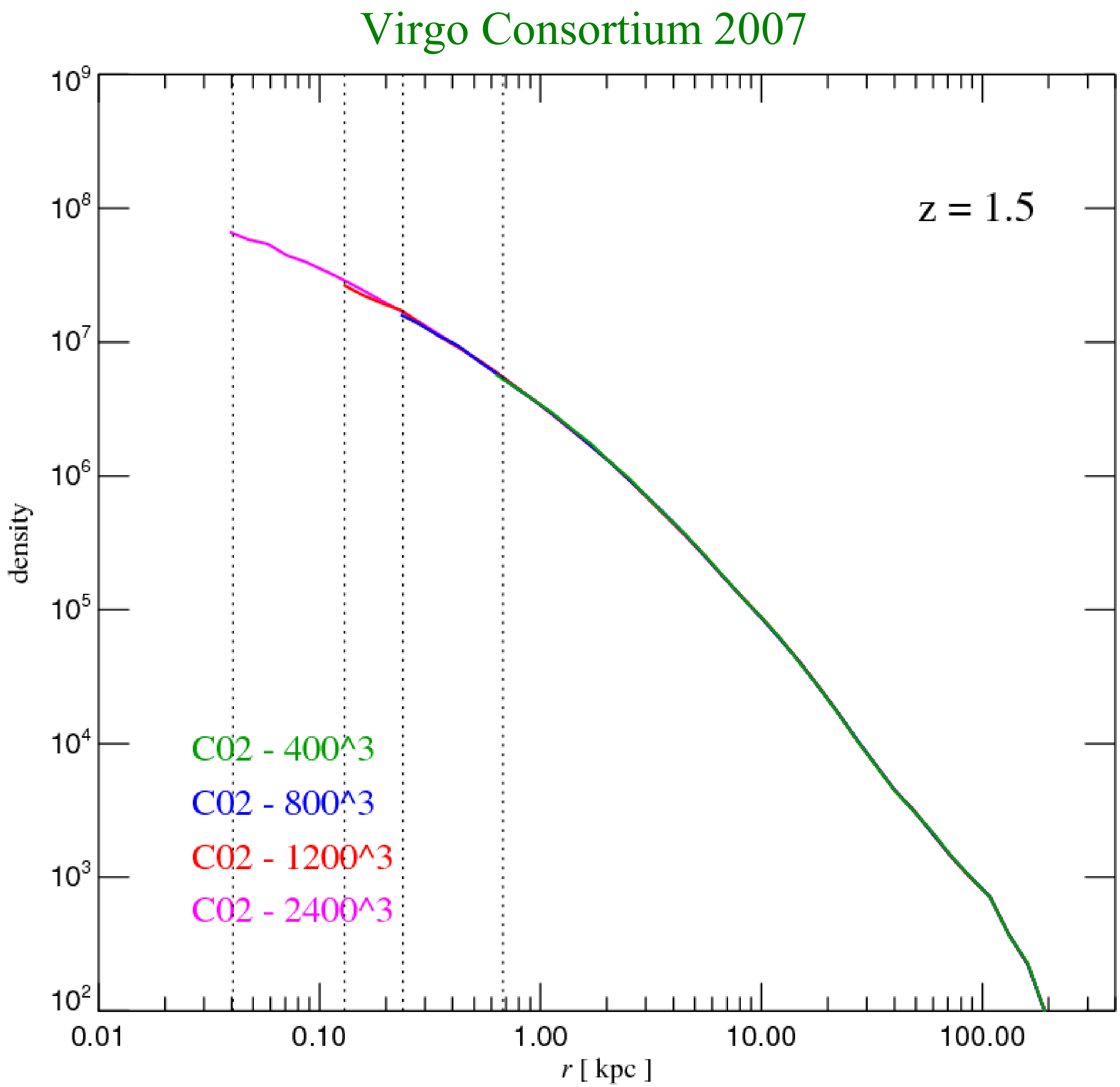
C02-2400^3 will require 4,000,000 processor-hours on HLRB-2 and produce 40 Tbytes of stored output


“Milky Way” halo
z = 1.5
N200 = 3 x 10^6


"Milky Way" halo
z = 1.5
N_{200} = 94 x 10^6

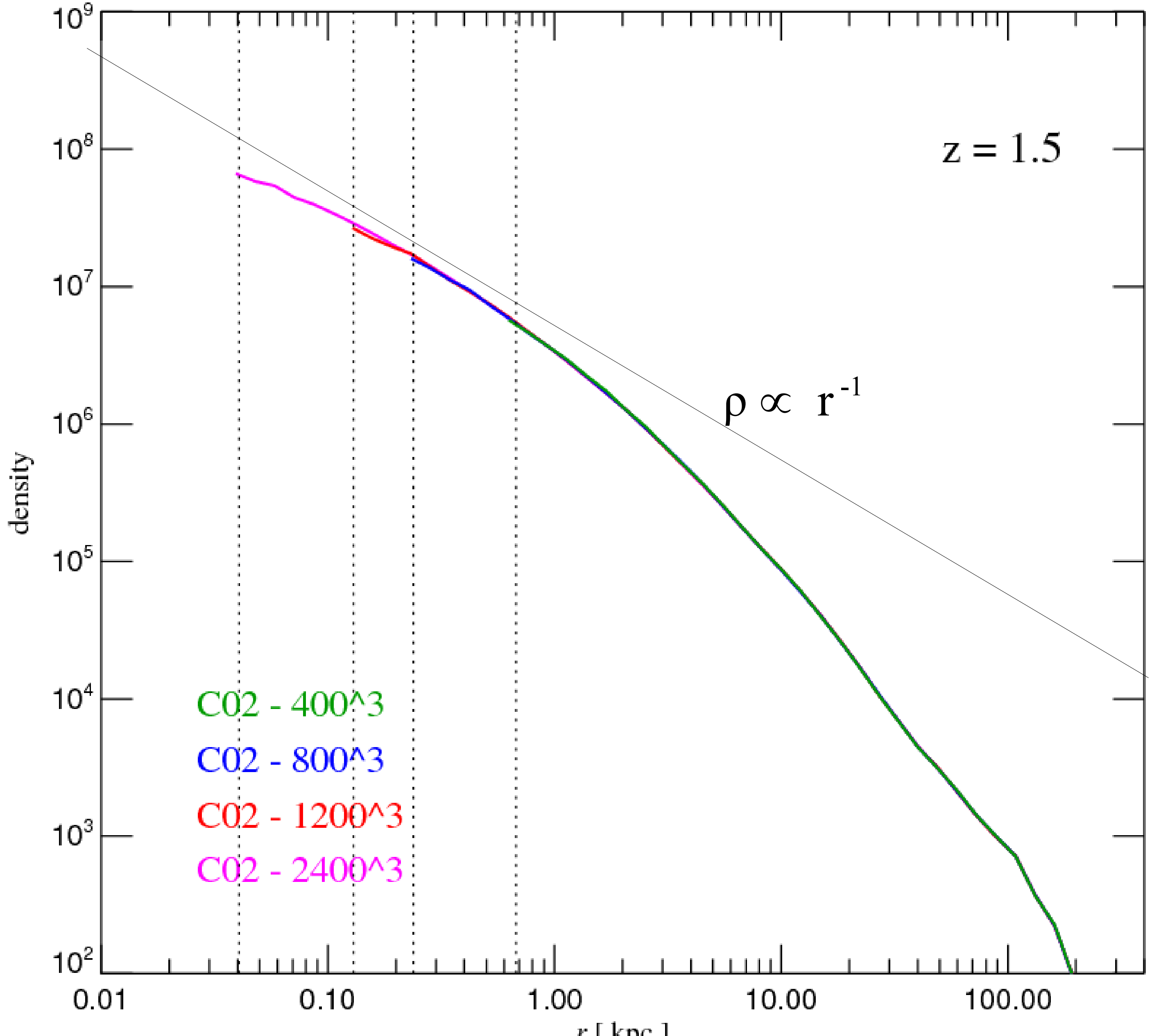

"Milky Way" halo
z = 1.5
N200 = 750 x 10^6

How well do density profiles converge?



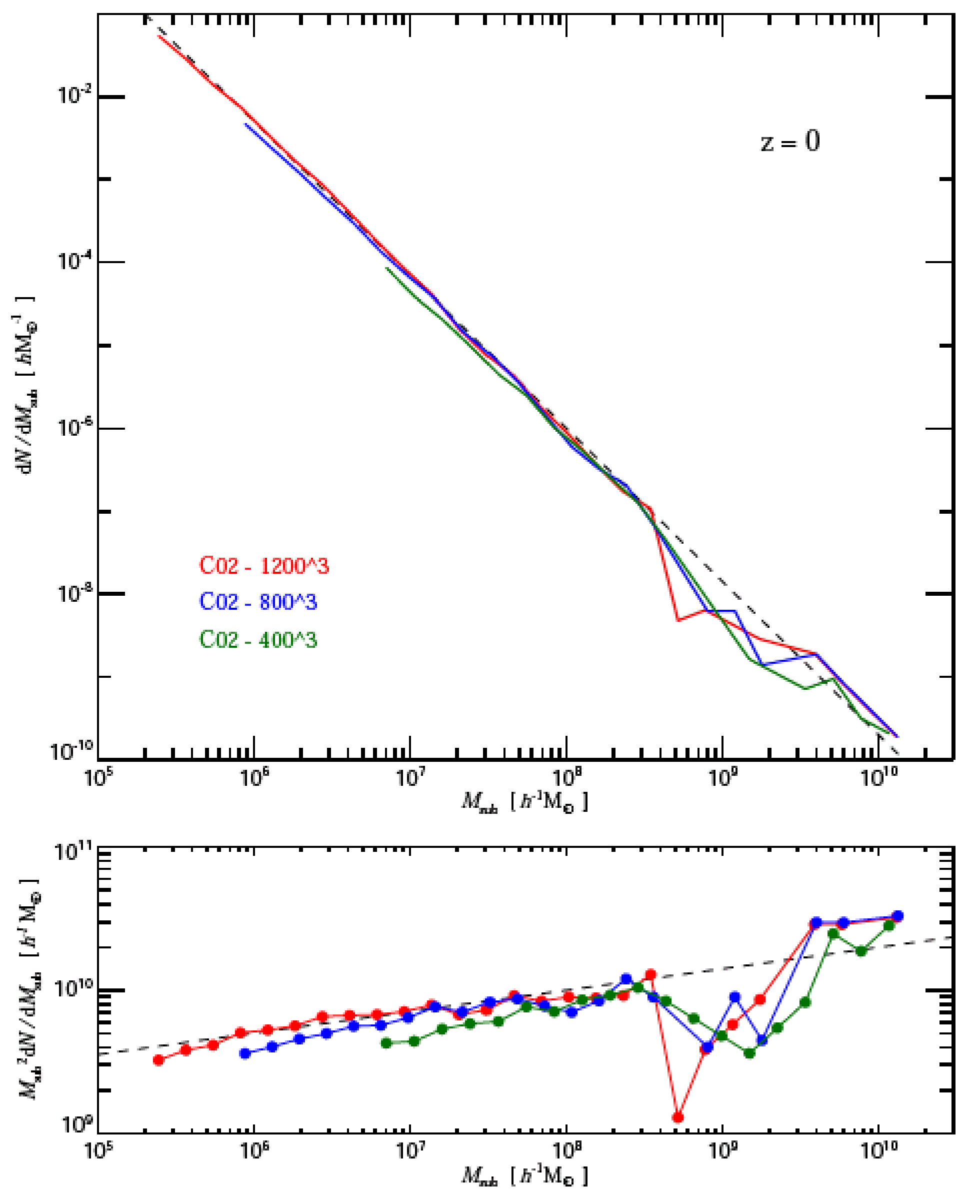
How well do density profiles converge?

Virgo Consortium 2007



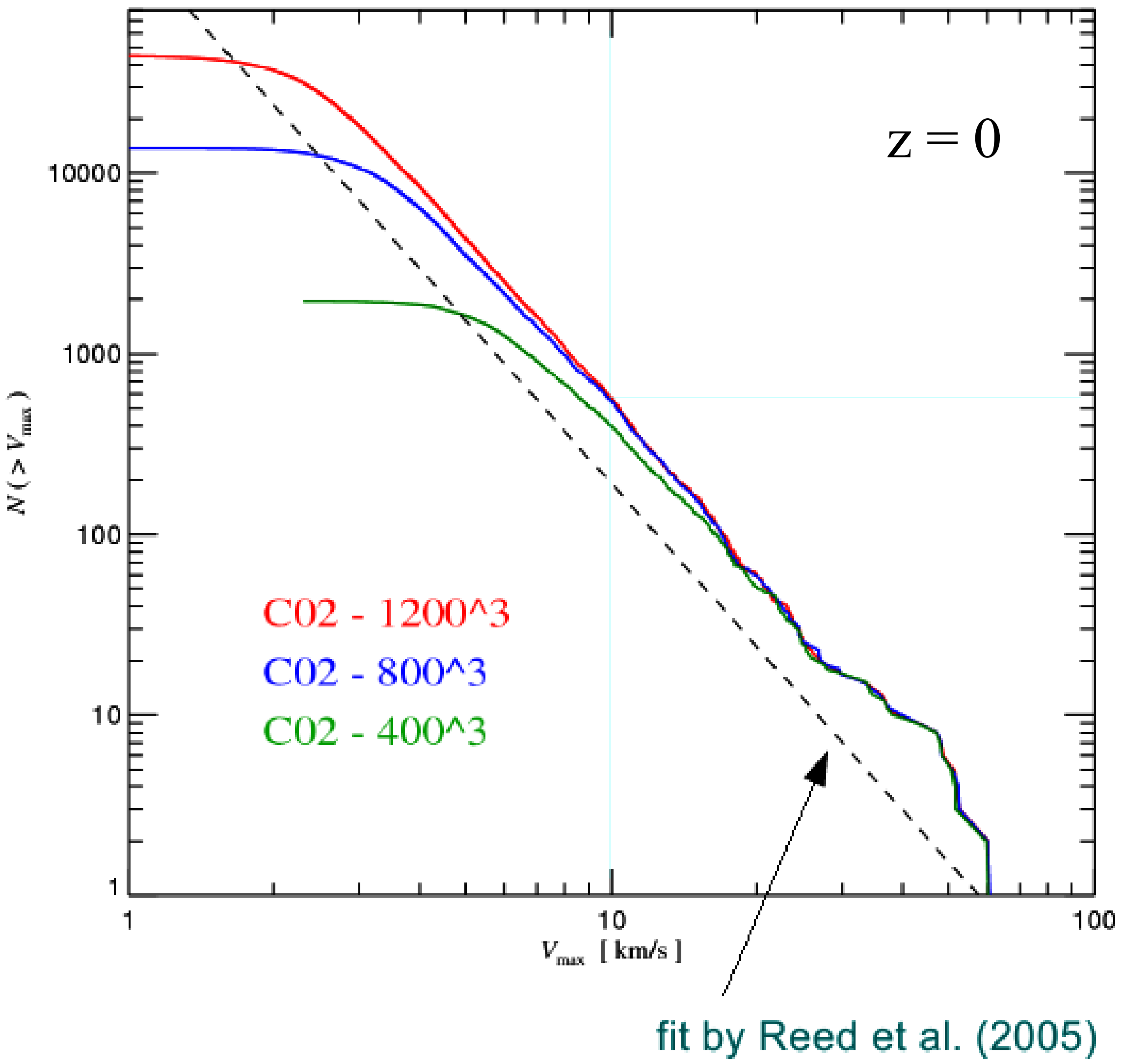
How well does substructure converge?

Virgo Consortium 2007

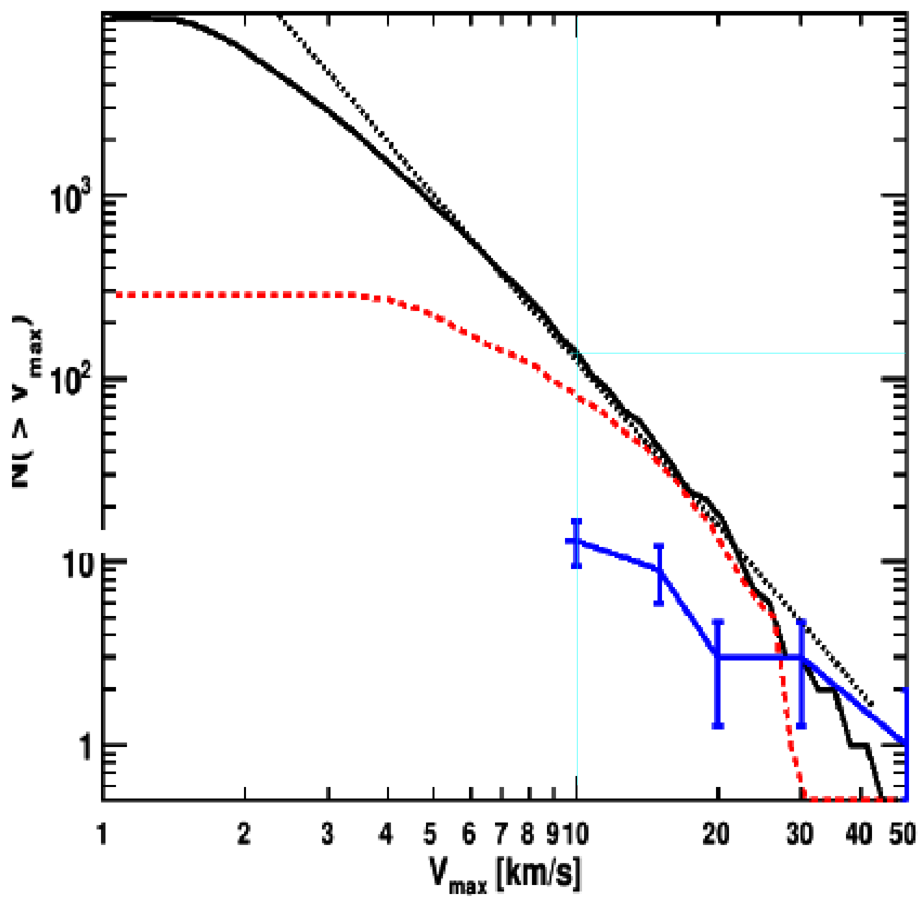


How well does substructure converge?

Virgo Consortium 2007

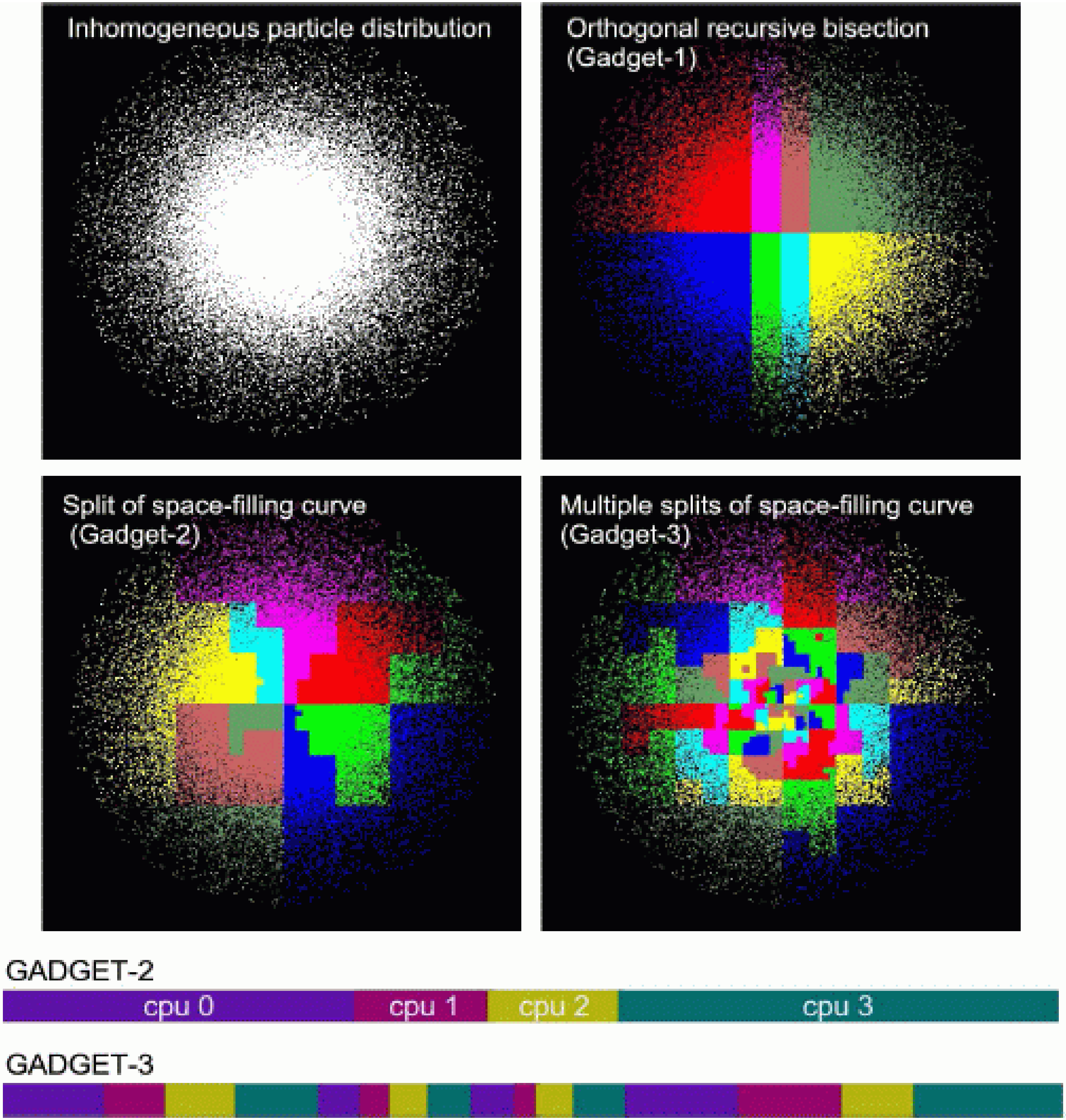


Diemand, Kuhlen & Madau (2007)



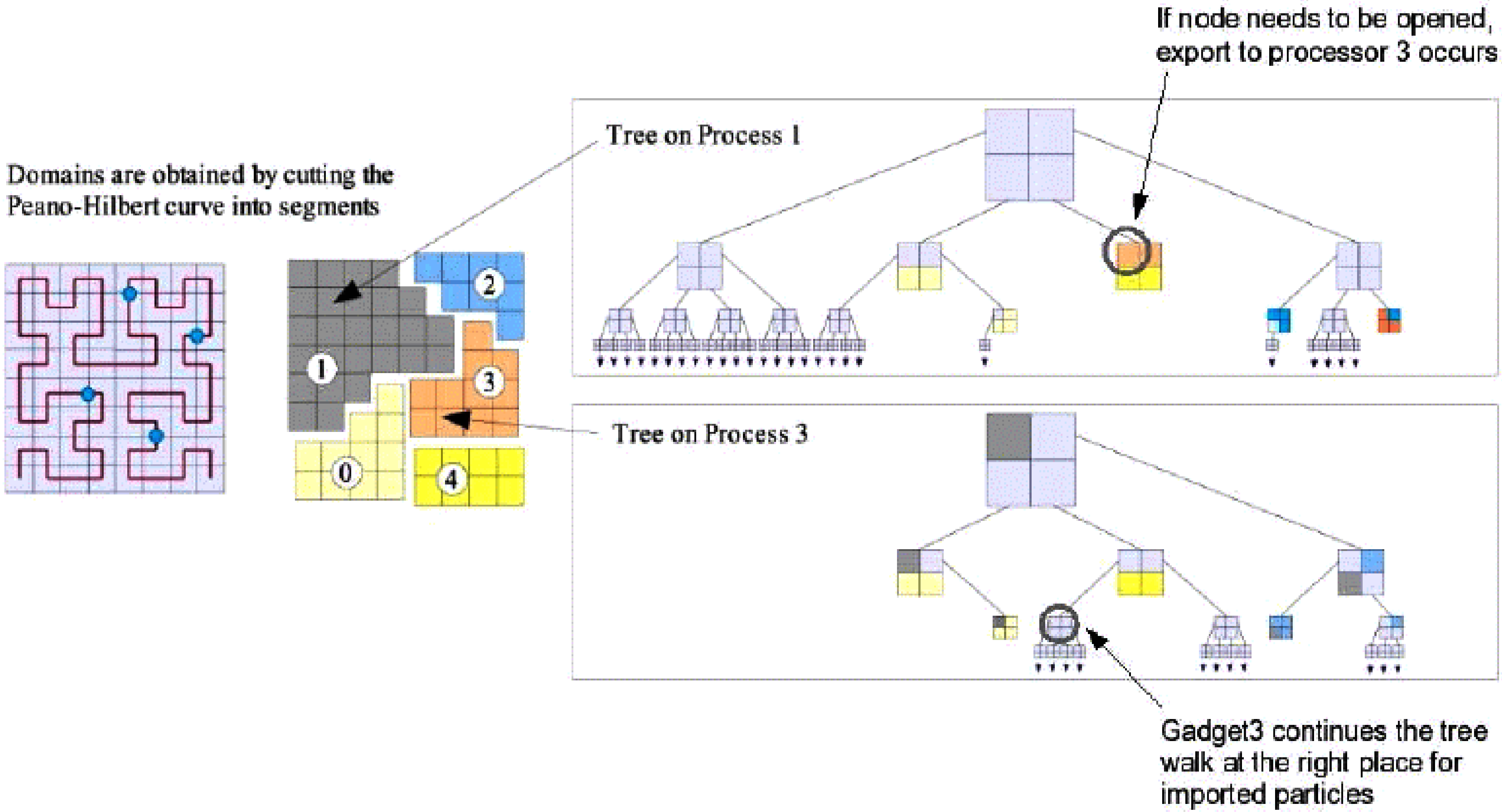
The GADGET-3 production code

- A further development by Volker Springel of the publicly released GADGET-2 code
- ANSI-C and MPI-1.1, using FFTW and GSL
- Input output in native format or HDF5
- Porting to HLRB-2 simple (except for 2 compiler bugs)
- PM—oct-tree Poisson solver
- Flexible and variable individual leap-frog time-stepping
- Domain decomposition based on Peano-Hilbert curve



Inhomogeneous particle distribution
Orthogonal recursive bisection
(Gadget-1)
Split of space-filling curve
(Gadget-2)
Multiple splits of space-filling curve
(Gadget-3)
GADGET-2
cpu 0
cpu 1
cpu 2
cpu 3
GADGET-3

Tree algorithm



The Aquarius Game Plan

- A resolution study using the HLRB-2 halo
- Five more halos studied to resolution 1/8 of the HLRB-2 halo
- Analysis of DM structure and modelling of MW formation by international science groups within the Virgo Consortium (D, UK, NL, USA, J)