large-scale structure of the universe and dark matter

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Discovering our place in the universe

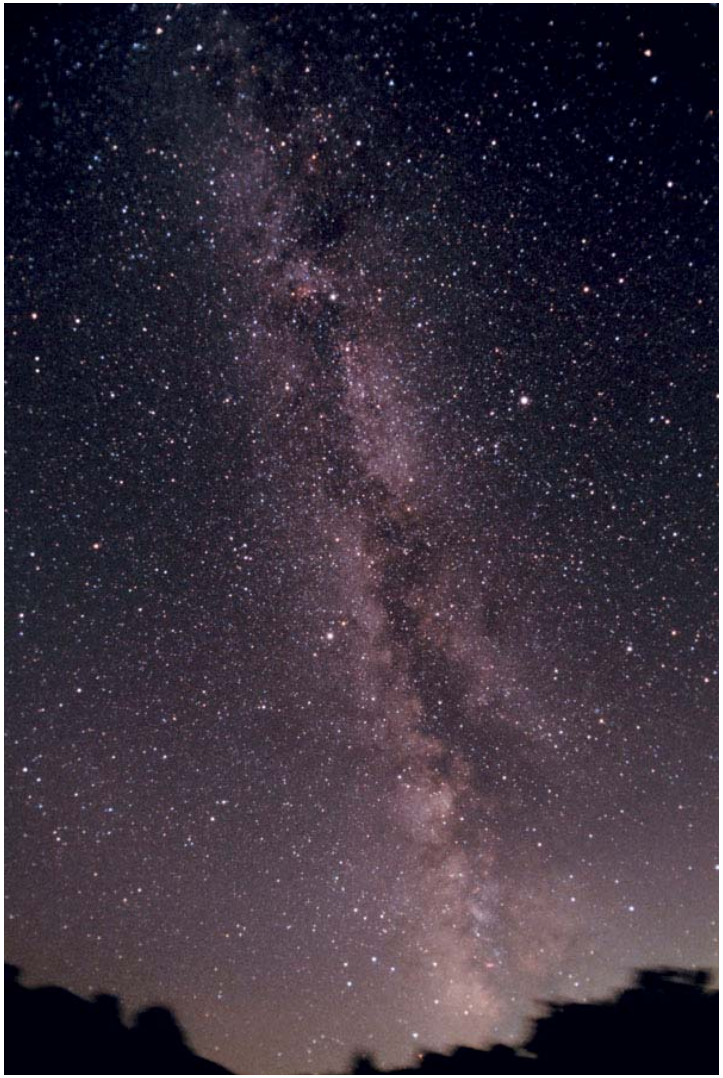


Image of the Milky Way in the region (taken at a dark site in Ohio)

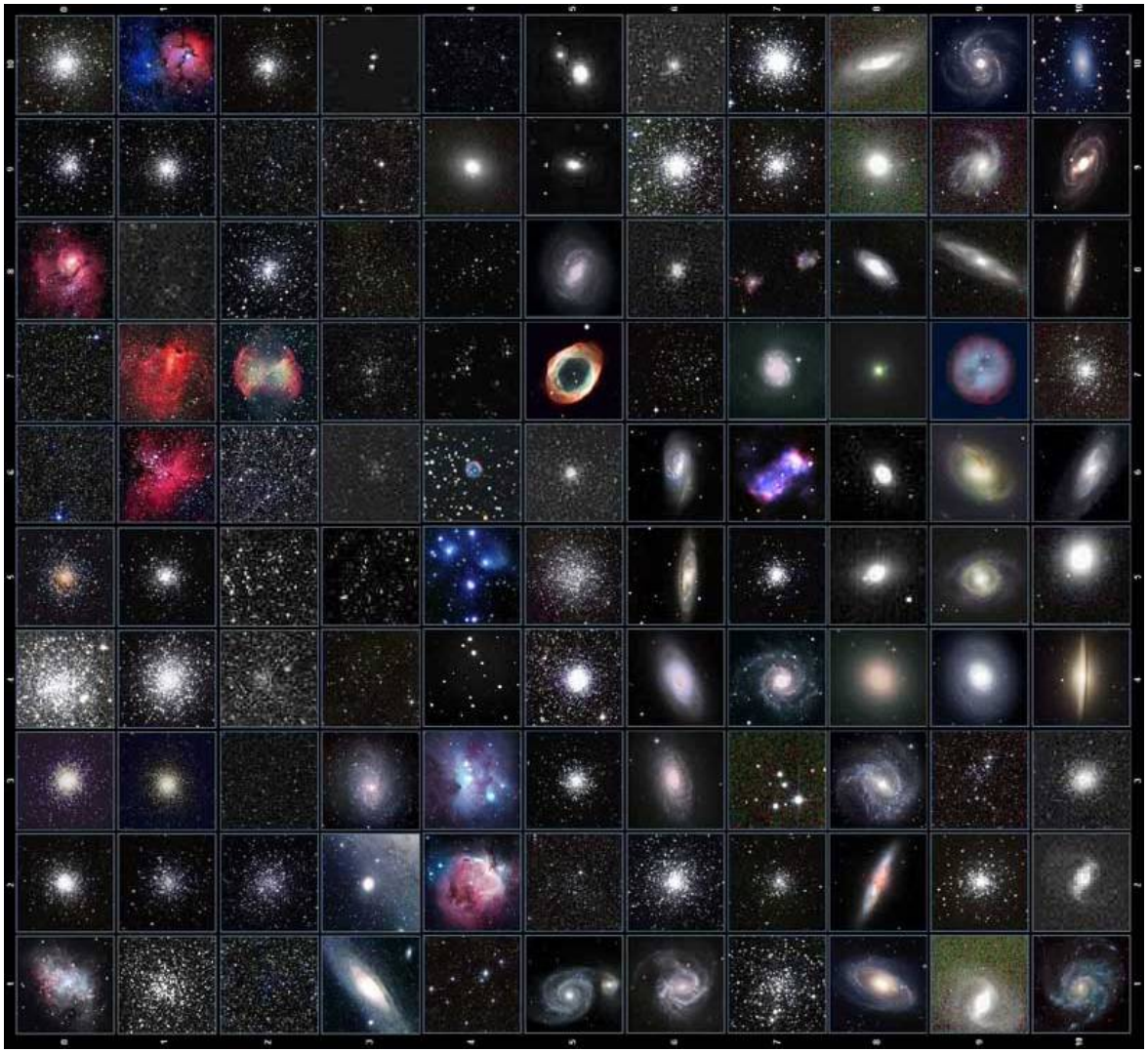
Early 17th century. **Galileo Galilei** used telescope to show that the Milky Way can be resolved into myriads of very faint stars; this suggested that stars were at different distances and that these distances were humongous;

1750. **Thomas Wright** and **Immanuel Kant** – idea that all visible stars are distributed in a flat slab, what we now call the Milky Way galaxy. The Universe of stars has shape; does it also have an edge?!

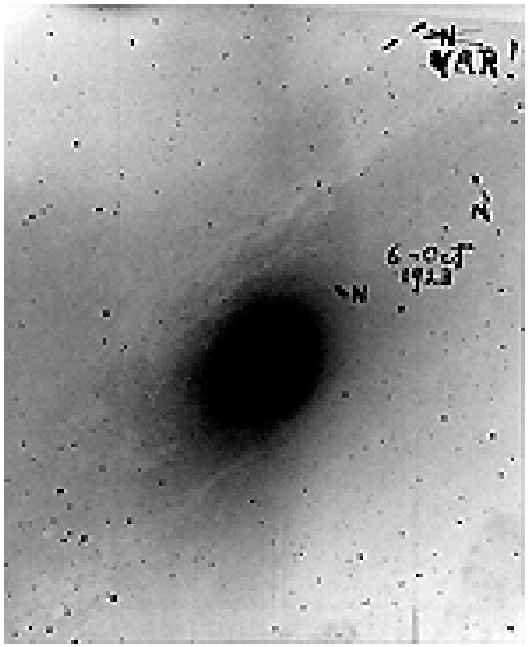
1785. English astronomer **William Herschel** presented an attempt to map the distribution of stars in our galaxy by counting number of stars in different patches of the sky. *Herschel concluded that our Sun and planets are located near the center of the Galaxy*

Discovery of external Universe

1774. Charles Messier publishes catalog of nebulae (or clouds, which he viewed as nuisance in his hunt for comets).



Edwin Hubble
1889-1953
A U.Chicago alum!
(PhD in Astronomy, 1917)

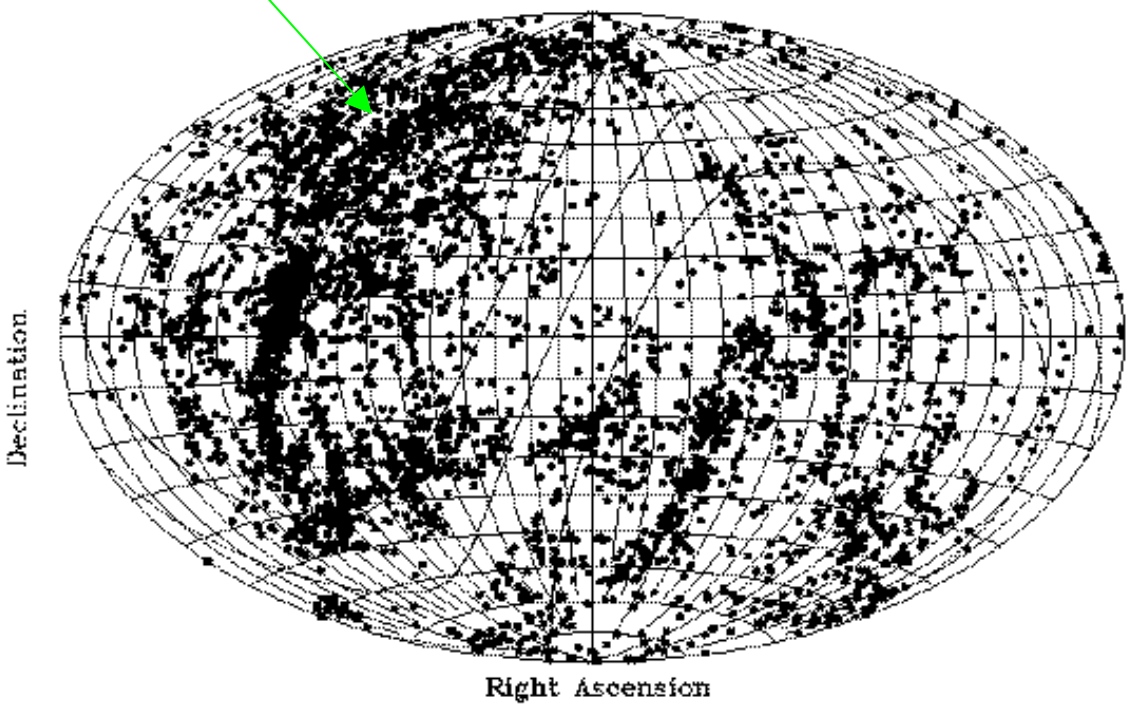


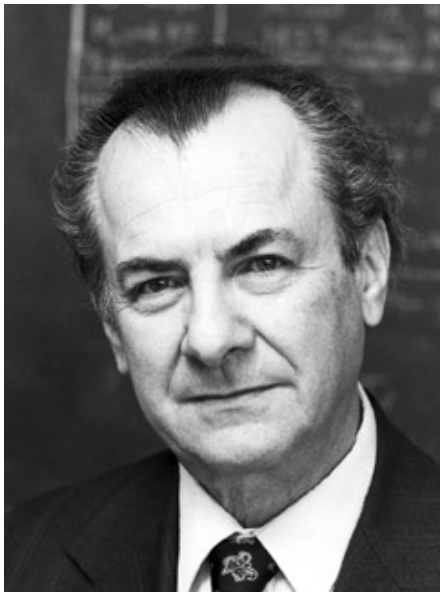
1924. Hubble announced discovery of a Cepheid in the Andromeda spiral nebula.

Using the period-luminosity relation for Cepheids, discovered by Henrietta Leavitt in 1912, Hubble measured distance to the Andromeda, showing once and for all that it was far outside the Milky Way (it is slightly more than 2 million light years away from us

The Local Supercluster (aka the Virgo supercluster)

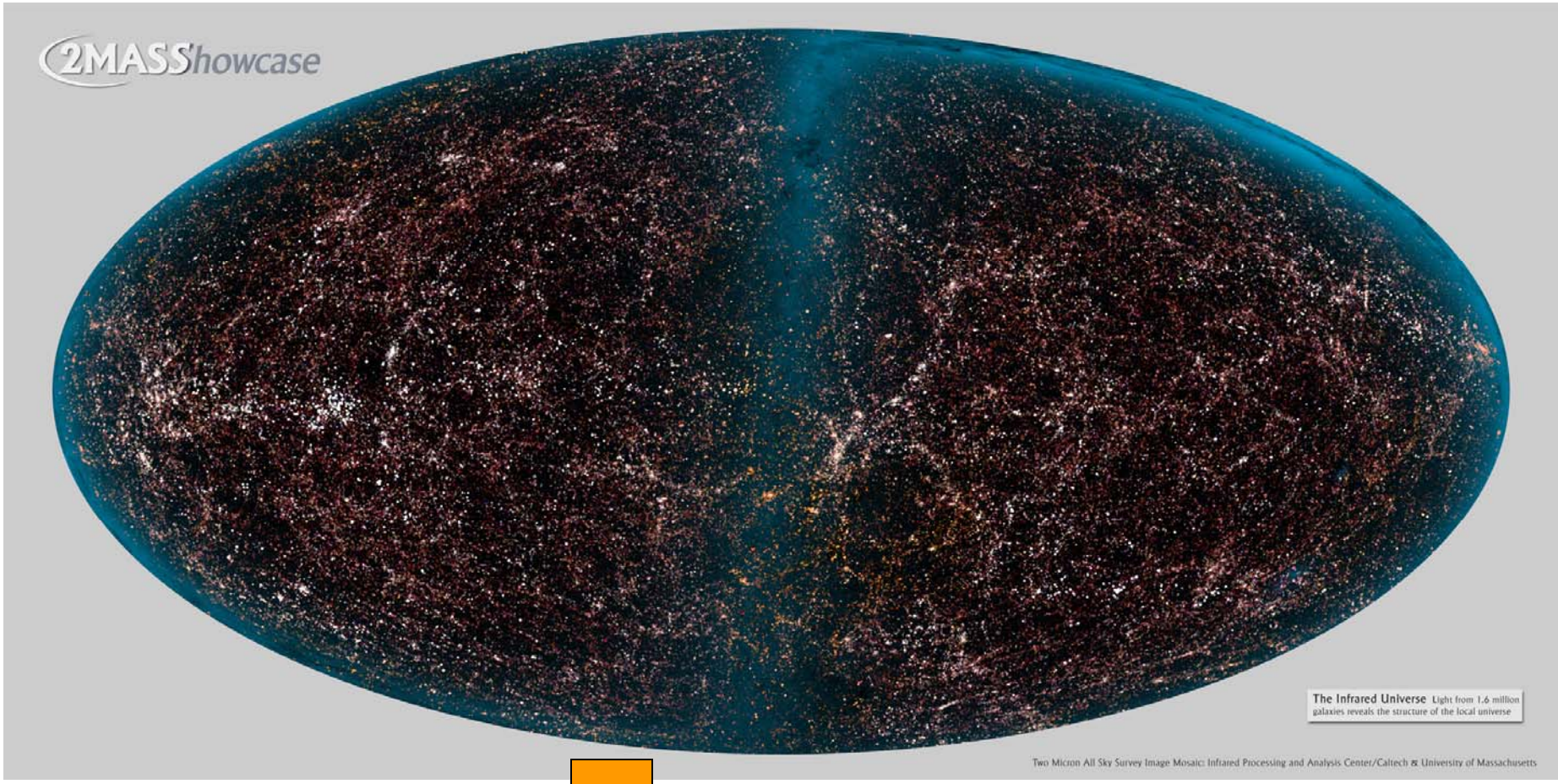
Supergalactic plane on the sky





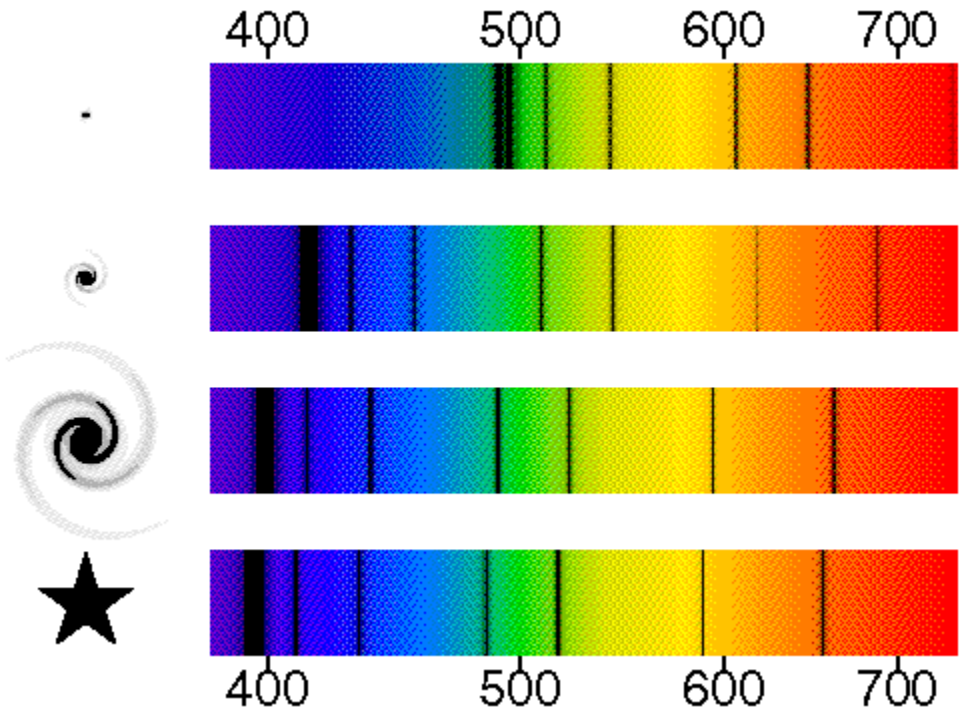
Gerard de Vaucouleurs
1918-1995

Distribution of ~2 million "nearby" galaxies on the sky



R I V U X G

Redshift and blueshift



wavelength in nanometers (10^{-9} m)

$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}},$$

Ignoring relativistic effects

$$z \approx \frac{v}{c}$$

z can be measured from an observed spectrum if we know what the lines are and which wavelength they should correspond to *at rest*

Motion away from us will shift lines to longer wavelengths (redward) and result in ***redshift***
Motion towards us will shift lines to shorter wavelength (blueward) and result in ***blueshift***

Some nearby galaxies (for example, Andromeda) have blueshifted spectra (moving towards us), but a vast majority of galaxies have redshifted spectra.

Edwin Hubble observing at the 100-inch telescope at Mount Wilson

1910s – **Vesto Slipher** measured spectral shifts of spiral nebulae. Most showed redward shift to longer (redder) wavelengths (hence, the name redshift).

1924-1929. **Hubble** and **Milton Humason**, measured spectra for dozens of galaxies. They also measured distances – using the Cepheids when possible or the bright stars called supergiants for more distant galaxies (not as accurate as Cepheid distances).

appearance the spectrum is very much like spectra of the Milky Way clouds in Sagittarius and Cygnus, and is also similar to spectra of binary stars of the W Ursae Majoris type, where the widening and depth of the lines are affected by the rapid rotation of the stars involved.

The wide shallow absorption lines observed in the spectrum of N. G. C. 7619 have been noticed in the spectra of other extra-galactic nebulae, and may be due to a dispersion in velocity and a blending of the spectral types of the many stars which presumably exist in the central parts of these nebulae. The lack of depth in the absorption lines seems to be more pronounced among the smaller and fainter nebulae, and in N. G. C. 7619 the absorption is very weak.

It is hoped that velocities of more of these interesting objects will soon be available.

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a K term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sought in a correlation between apparent radial velocities and distances, but so far the results have not been convincing. The present paper is a re-examination of the question, based on only those nebular distances which are believed to be fairly reliable.

Distances of extra-galactic nebulae depend ultimately upon the application of absolute-luminosity criteria to involved stars whose types can be recognized. These include, among others, Cepheid variables, novae, and blue stars involved in emission nebulosity. Numerical values depend upon the zero point of the period-luminosity relation among Cepheids, the other criteria merely check the order of the distances. This method is restricted to the few nebulae which are well resolved by existing instruments. A study of these nebulae, together with those in which any stars at all can be recognized, indicates the probability of an approximately uniform upper limit to the absolute luminosity of stars, in the late-type spirals and irregular nebulae at least, of the order of M (photographic) = -6.3.[1] The apparent luminosities of the brightest stars in such nebulae are thus criteria which, although rough and to be applied with caution,

The paper that revolutionized cosmology

1929. Hubble published his first paper showing correlation between recession velocity and distance to the galaxy

"A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae"

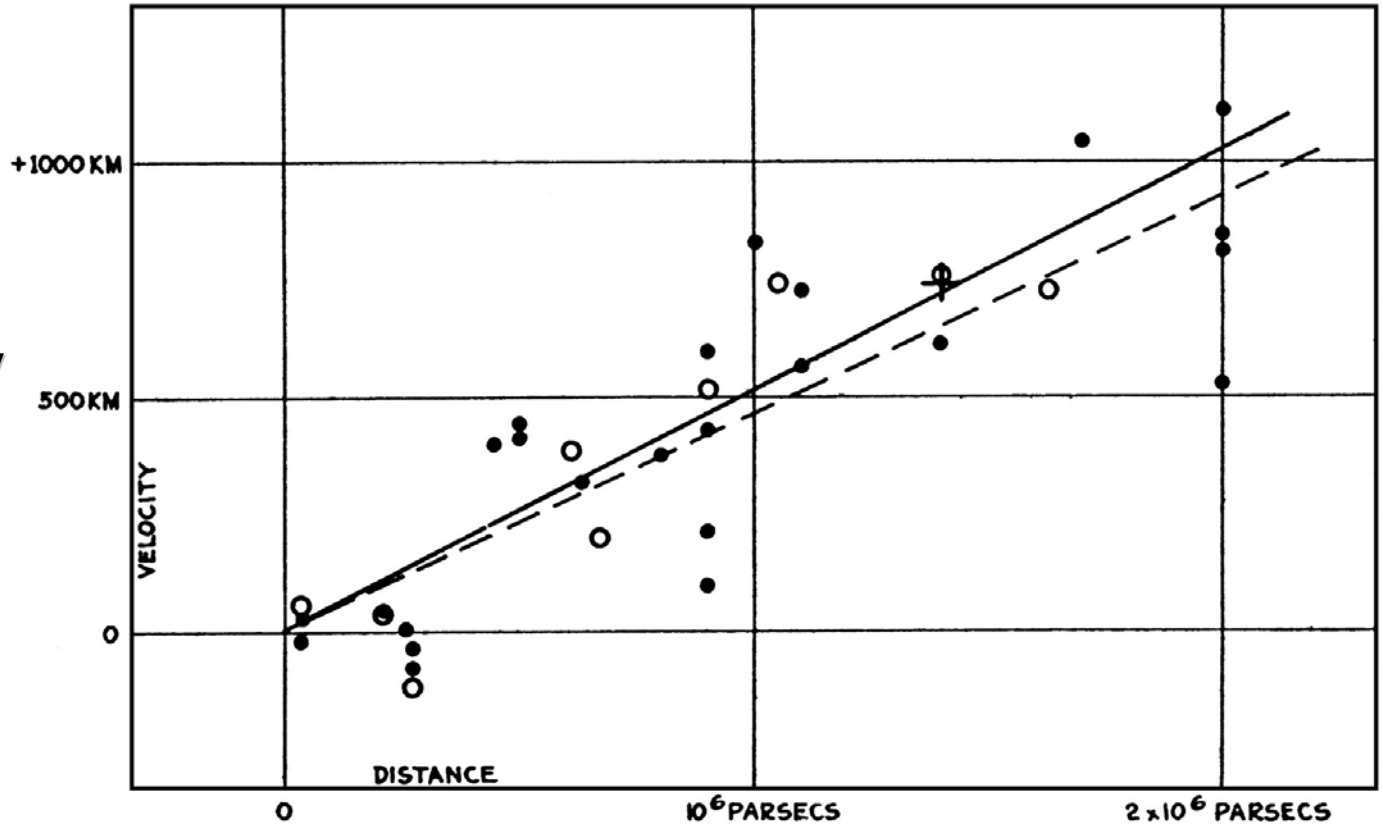
6 pages, 1 table, 1 figure

A figure from the paper – what's now called the *"Hubble diagram"* showing relation between recession velocity and distance to the galaxy

Hubble law: *velocity* = *H* times *distance*
where *H* is a constant now called the *Hubble constant*

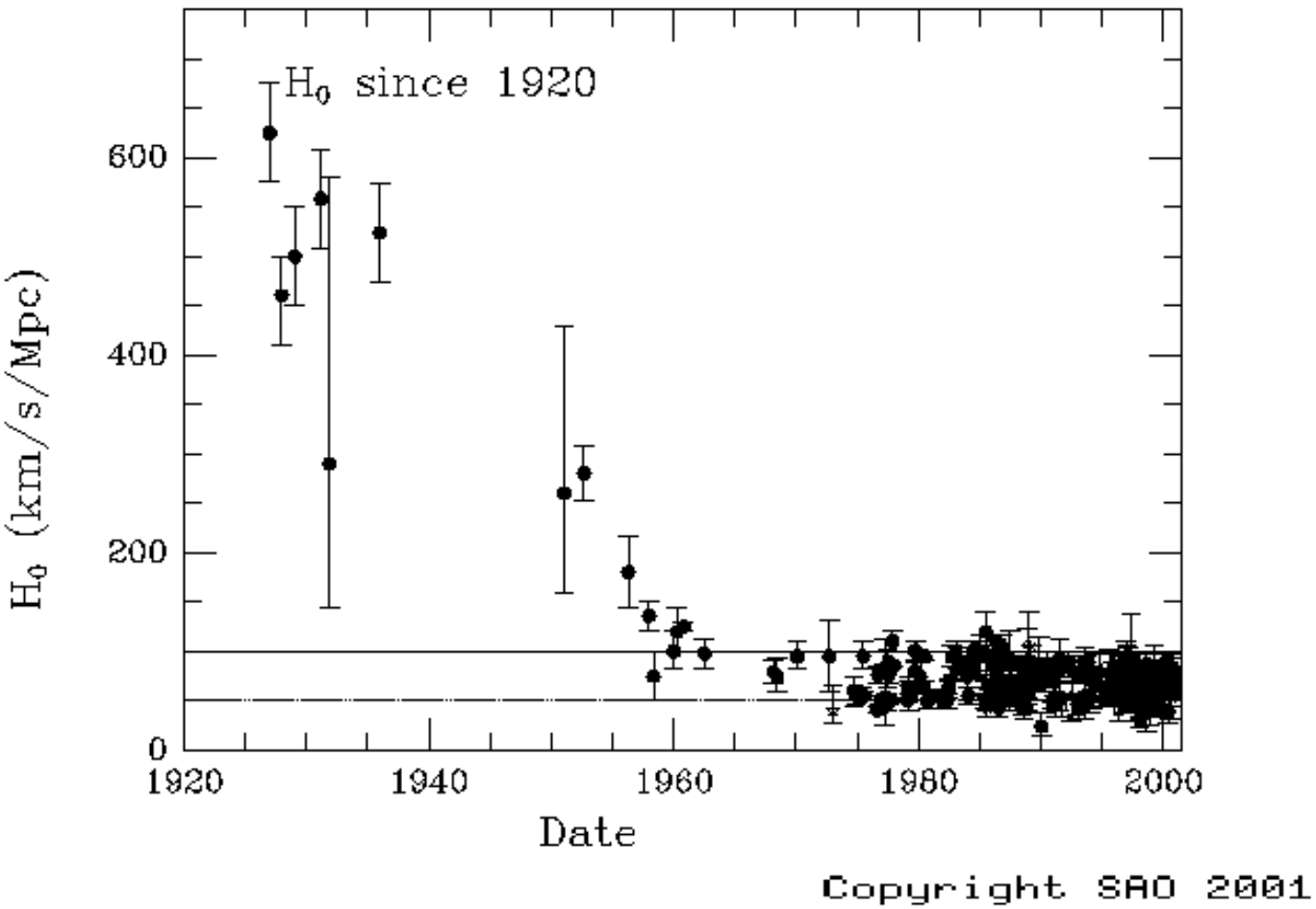
Hubble estimated *H* to be ~500 km/s/Mpc –
about 7 times larger than current measurements indicate

Velocity inferred from galaxy spectrum in km/s



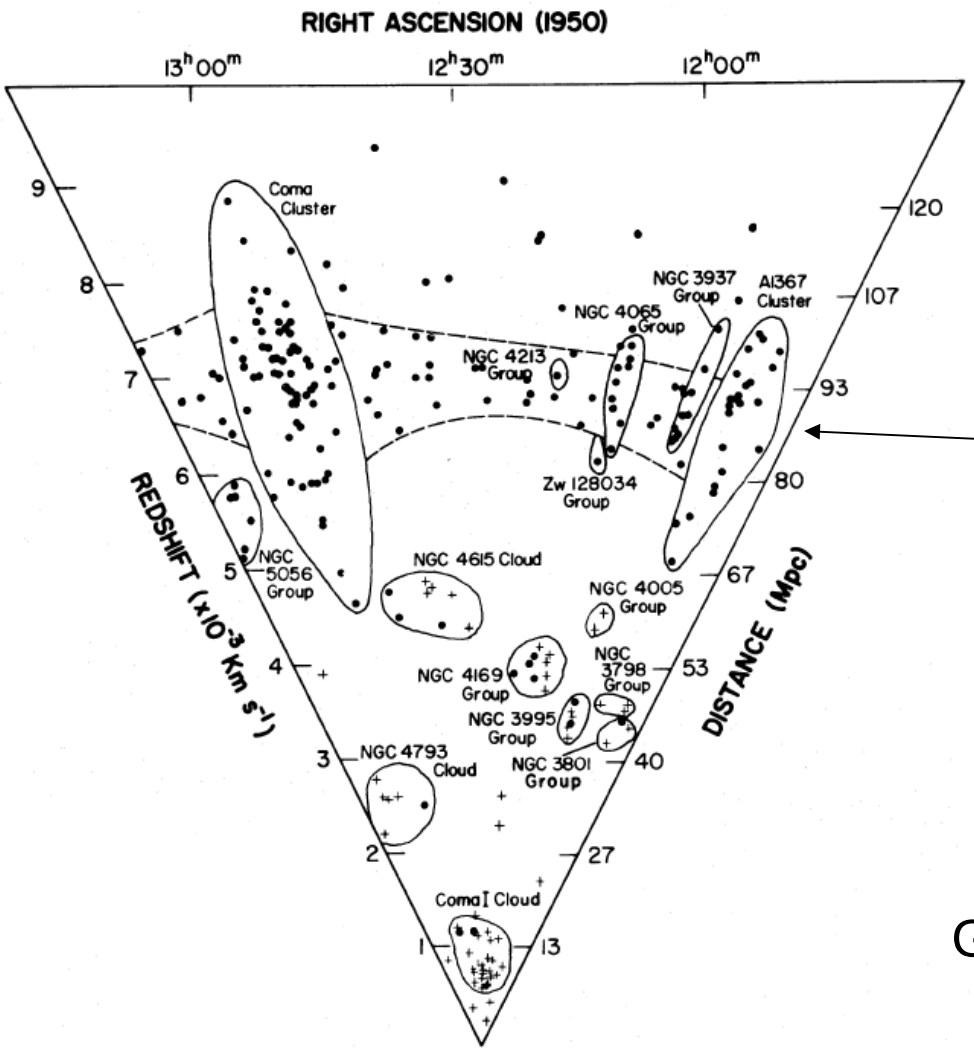
Distance in parsecs (1 parsec = 3.26 light years, 1 million parsecs = Megaparsec or Mpc)

Hubble constant measurements: the history



http://cfa-www.harvard.edu/~huchra/hubble/

mapping 3d distribution of galaxies



in the 1970s – structures around nearby rich clusters were surveyed painstakingly measuring recession velocity from individual galaxy observations

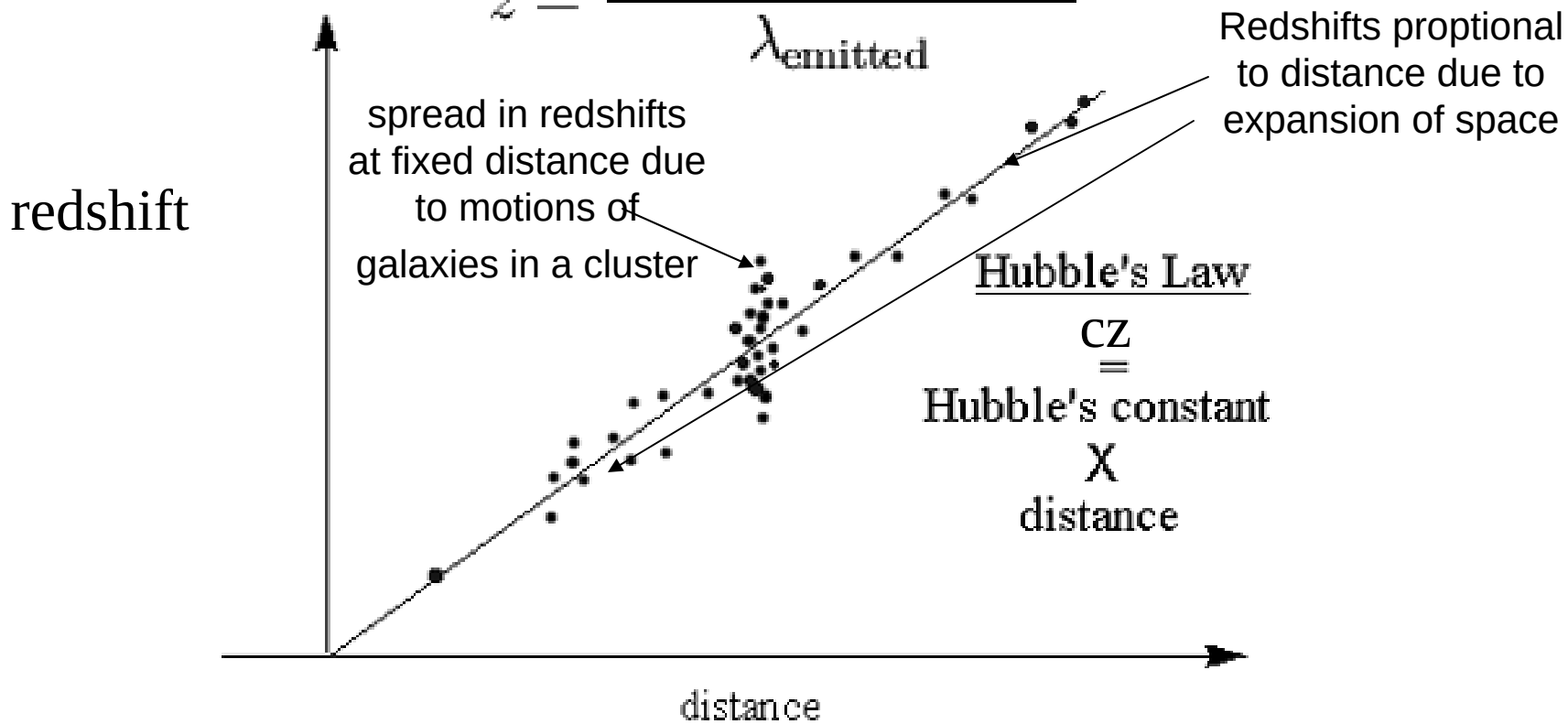
~100 Mpc scale

"The Coma Supercluster"
Gregory & Thompson 1978
ApJ 222, 784

Galaxy redshifts can be due to both their physical motion with respect to us and due to cosmological redshift

motions of galaxies in clusters and filaments create a “finger-of-God” effect: appearance that clusters are elongated in the direction towards us

$$z = \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}}$$



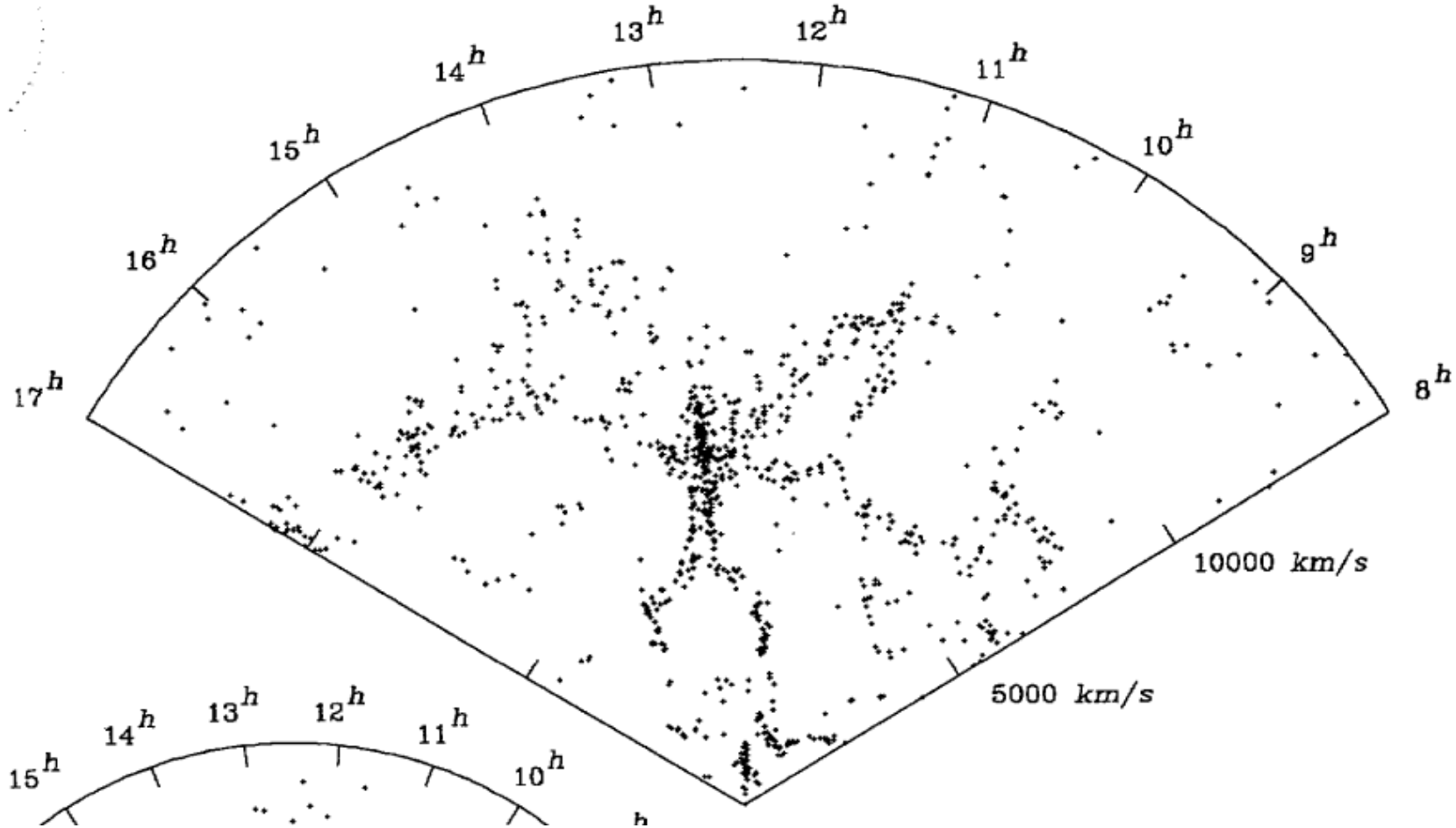
in the late 70s – early 80s
CfA1 and CfA2 surveys using novel techniques
to measure spectra of multiple galaxies

THE ASTROPHYSICAL JOURNAL, 302:L1–L5, 1986 March 1

A SLICE OF THE UNIVERSE[1]

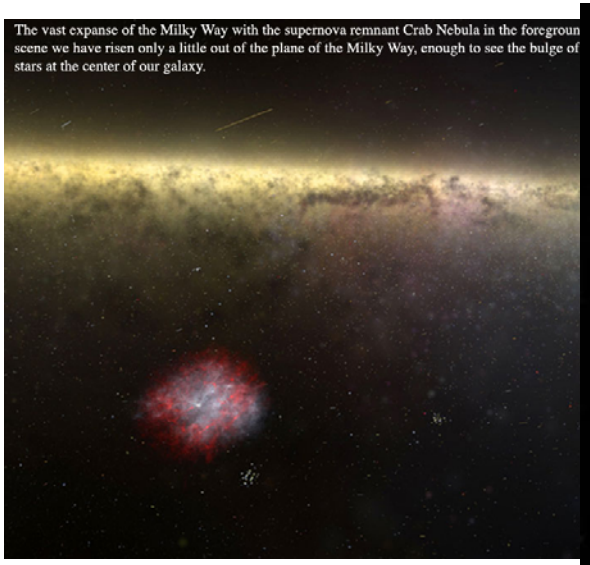
VALÉRIE DE LAPPARENT,[2,3] MARGARET J. GELLER,[2] AND JOHN P. HUCHRA[2]
Received 1985 November 12; accepted 1985 December 5

Vol. 302

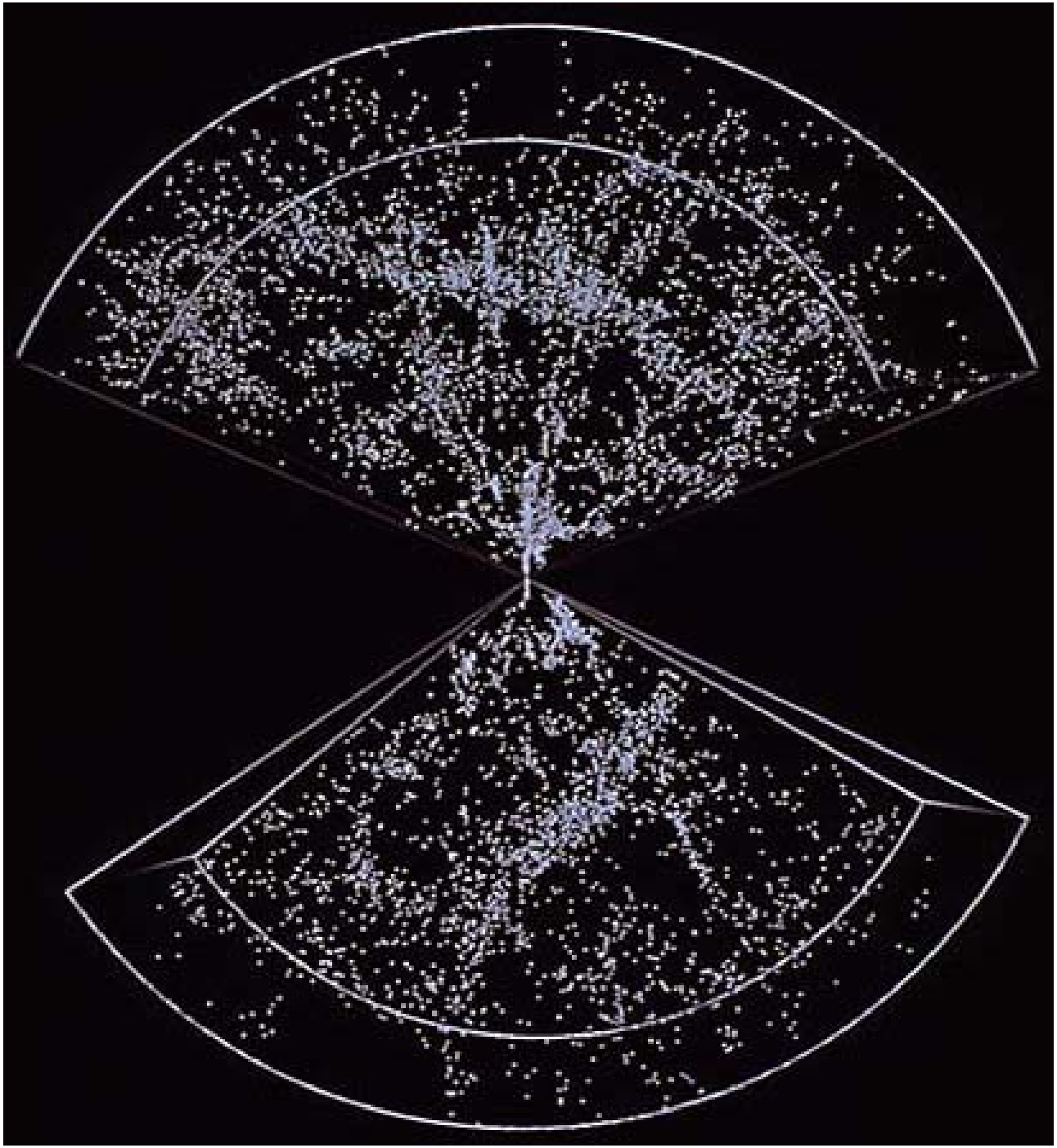


Structures in the neaby Universe:
from the Milky Way to the Local Supercluster

In the last twenty years the region of the Local Supercluster was extensively mapped by Brent Tully and collaborators using redshifts of 21cm line from HI in nearby galaxies and optical spectra



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

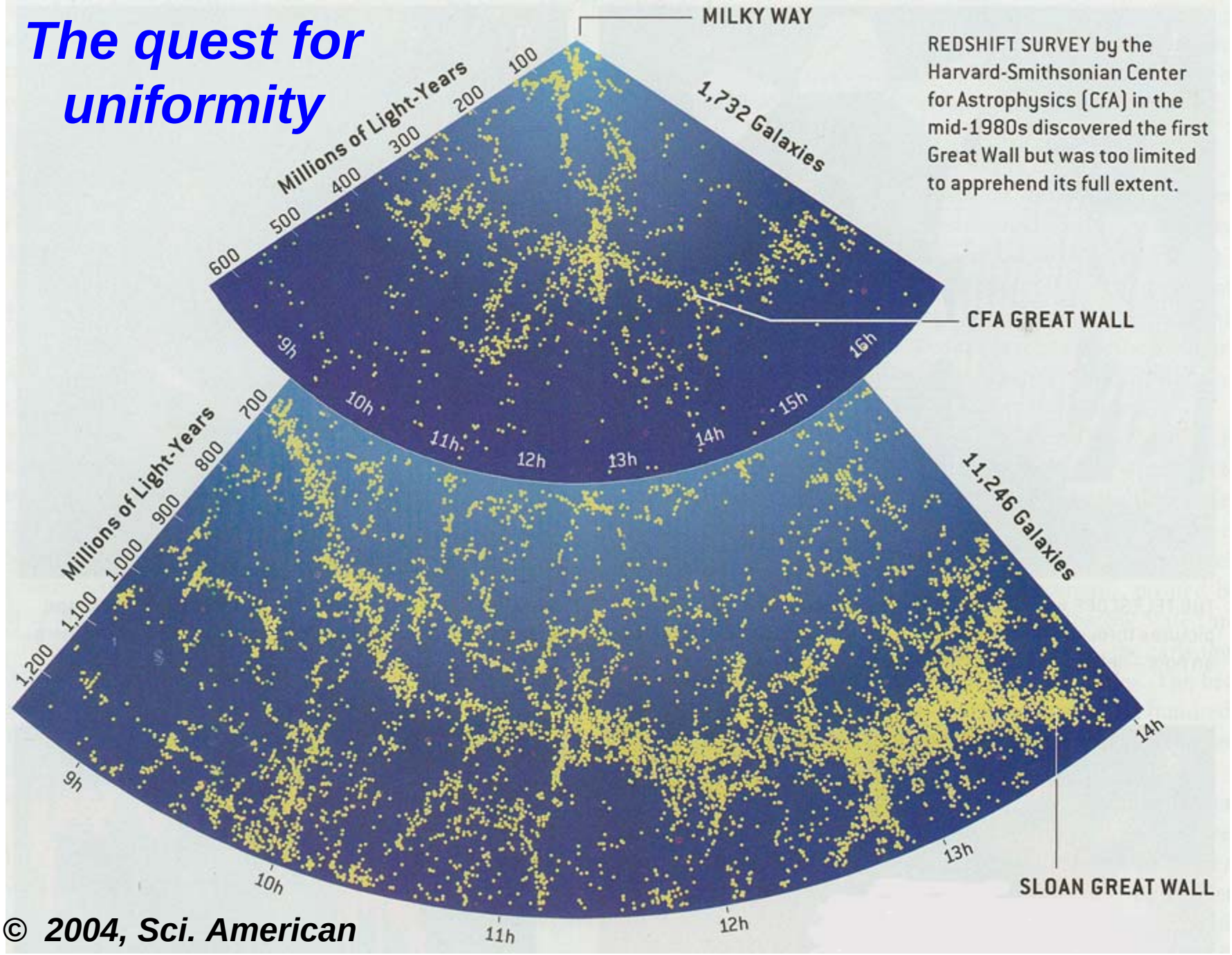


Large-scale distribution of galaxies

at distances less than [300 million light years]

CfA galaxy survey 1980-1990

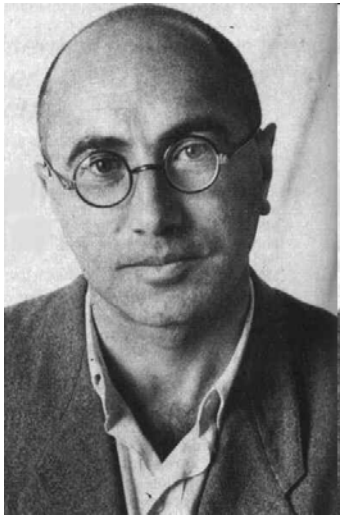
The quest for uniformity



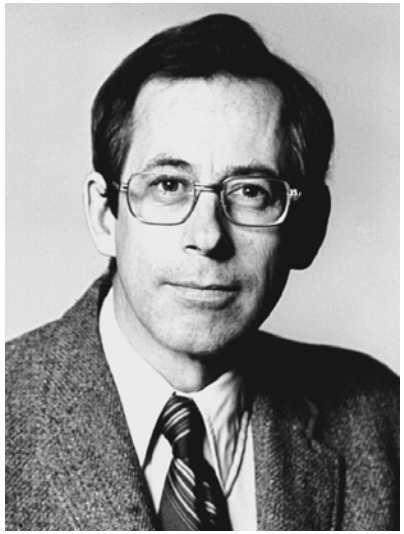

The end of greatness...
SDSS survey
By Mark SubbaRao (Adler/U.Chicago)
j Surendran, and Randy Landsberg (U.Chicago)
http://astro.uchicago.edu/cosmus/

Even before observers have discovered and quantified the cosmic web, in the 1970s and 1980s theorists have developed two competing models of how structures in the universe form

- ***Hot Dark Matter (HDM, a.k.a. "top-down scenario")*** *– the model assumes that only perturbations on largest scales existed in the early universe. Such perturbations collapse into pancakes, filaments and clusters. Filaments and pancakes then fragment into galaxies.*
- ***Cold Dark Matter (CDM, a.k.a. "bottom-up" or "hierarchical" scenario)****. Perturbations exist on all scales and their amplitude increases with decreasing scale.*



Yakov Zel'dovich

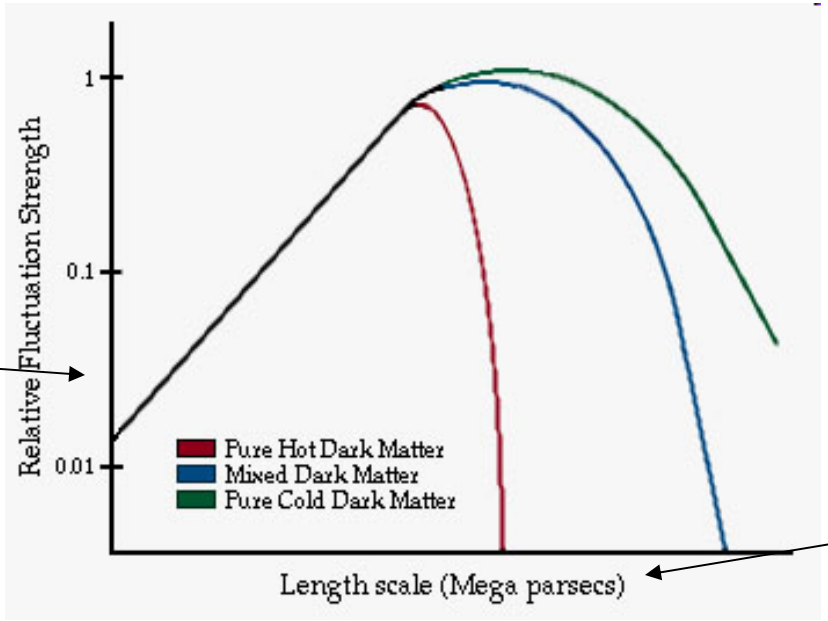


Jim Peebles

density perturbations in
Hot Dark Matter model

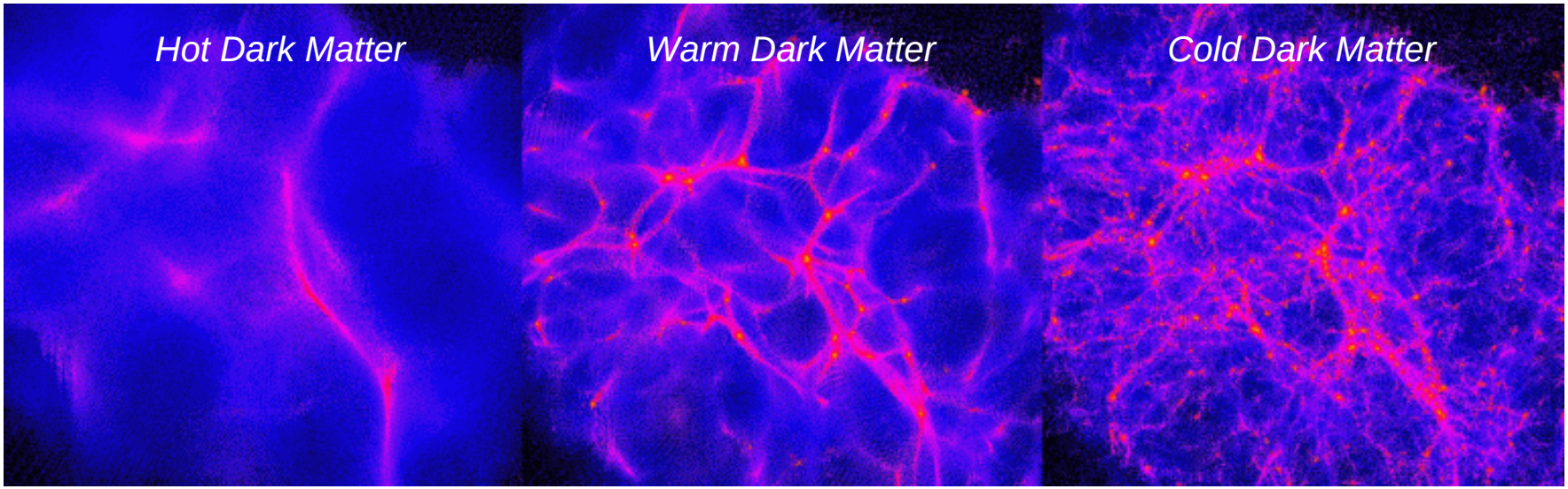
density perturbations in
Cold Dark Matter model

y-axis
typical relative amplitude
of perturbations



x-axis:
size of perturbations

example of structures forming in the Hot, Warm, and Cold dark matter scenarios:



http://www.itp.uzh.ch/research_groups/astrophysics/pictures.html

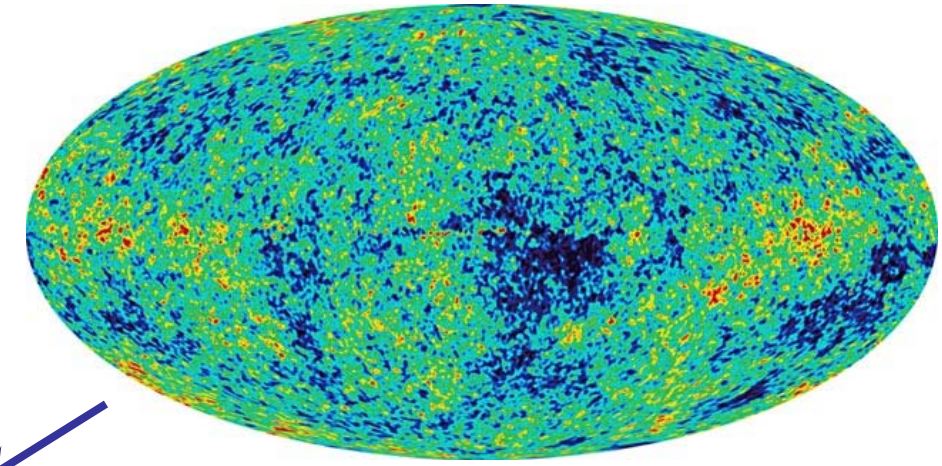
The Hot and Cold Dark Matter structure formation scenarios are different in what they assume about properties of the main dark matter particle

- ***Hot Dark Matter*** *– the model assumes that dark matter particles were "hot" during early stages of evolution of the universe so that they did not feel any initial density perturbations and were streaming out of them. A leading candidate for such dark matter particle was neutrino.*
- ***Cold Dark Matter*** *– the model assumes that dark matter particles were sufficiently cold so they could assemble in the initial overdense regions allowing them to grow in amplitude with time. An example of such dark matter particle are WIMPs, predicted in supersymmetry theories. CDM scenarios based on particle physics were developed in the early 1980s by a number of researchers.*
- *Initial fluctuations for both types of models were postulated. However, in the early 1980s the inflation model of the early universe presented a beautiful hypothesis for the quantum origin of fluctuations in the universe.*

Formation of structures from quantum fluctuations

Quantum fluctuations of energy before and during inflation

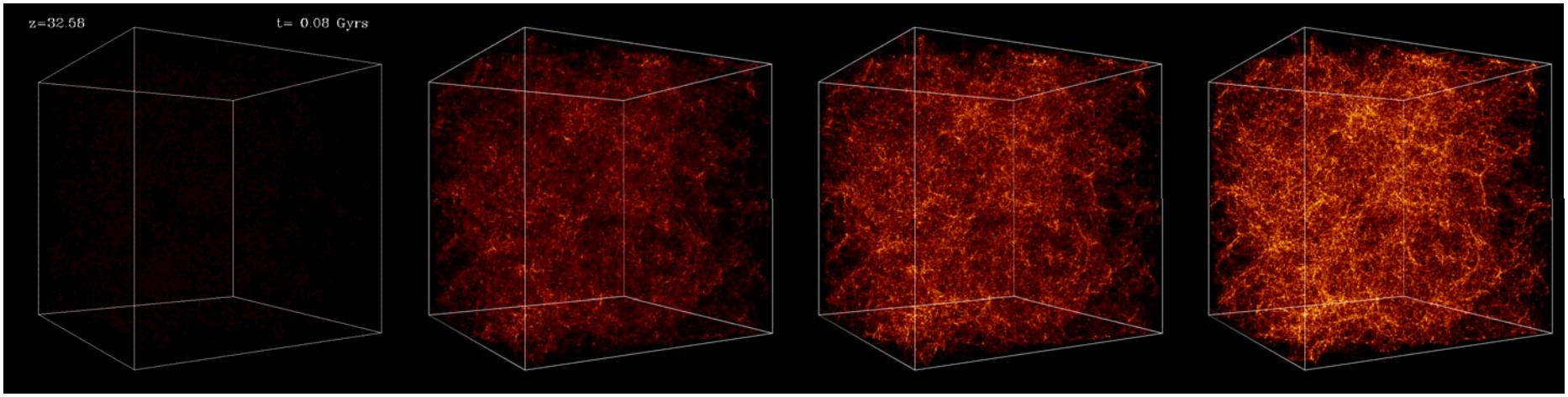
Small inhomogeneities in density and temperature of primordial plasma, manifested in temperature fluctuations of the CMB (discovered by the COBE satellite in 1992; -> Nobel prize in 2006)



galaxies, clusters, superclusters

So how do structures form in the CDM cosmology?

In the beginning when fluctuations are small, the evolution of density perturbations is relatively simple, they simply grow as time goes and all perturbations grow at the same rate: the evolution is akin to a picture developing on a photo negative…



As the amplitude of perturbations grows, the evolution becomes more and more complicated because gravity leads to nonlinear and chaotic processes (think about how difficult it is to predict evolution of all planetary bodies in the solar system over many periods of time). To describe such evolution, we need computer simulations.

simulation

SECOND EDITION 1989

Pronunciation Spellings Etymology Quotations Date chart

1. a. The action or practice of simulating, with intent to deceive; false pretence, deceitful profession.

1340 *Ayenb.* 23 And þerof wexeþ uele zennes, ase ariȝthalf; þet is to wytene: lozengerie, simulacion. **c1400** *Rom. Rose* 7230 He nys no full good championn That dredith such similacioun. **1412-20** LYDG. *Chron. Troy* IV. 4504 Amonge hem silfe to bringe in tresoun, Feyned trouþe and symulacioun. **1542** UDALL *Erasm. Apoph.* 170 He..did with mutual simulacion on his partie cover & kepe secrete the colorable dooyng of the saied feloe. **1577** tr. *Bullinger's Decades* (1592) 319 This precept doth commaunde vs..that..wee doe our neighbor harme..neither by simulation nor dissimulation. **1611** SPEED *Hist. Gt. Brit.* VI. (1632) 114 His nature relishing too much of the Punick craft and simulation. **1692** SOUTH *Serm.* (1697) I. 525 A Deceiving by Actions, Gestures, or Behaviour, is called Simulation, or Hypocrisie. **1711** STEELE *Tatler* No. 213 ¶1 Simulation is a Pretence of what is not, and Dissimulation a Concealment of what is. **1788** WESLEY *Wks.* (1872) VII. 43 Simulation is the seeming to be what we are not; dissimulation, the seeming not to be what we are. **1836** LANDOR *Pericles & Aspasia* Wks. 1846 II. 379, I wish he were as pious as you are: occasionally he appears so. I attacked him on his simulation. **1872** SHIPLEY *Gloss. Eccl. Terms* 71 Fraud.., whether it consists in simulation or dissimulation.

b. Tendency to assume a form resembling that of something else; unconscious imitation.

1870 MARCH *Anglo-Saxon Gram.* 28 *Simulation.* The feigning a connection with words of similar sound is an important fact in English and other modern languages: asparagus > sparrow-grass.

2. A false assumption or display, a surface resemblance or imitation, *of* something.

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simulation (scientific method)

computer simulation

Simulations of future climate change *from the article* global warming (Earth science)

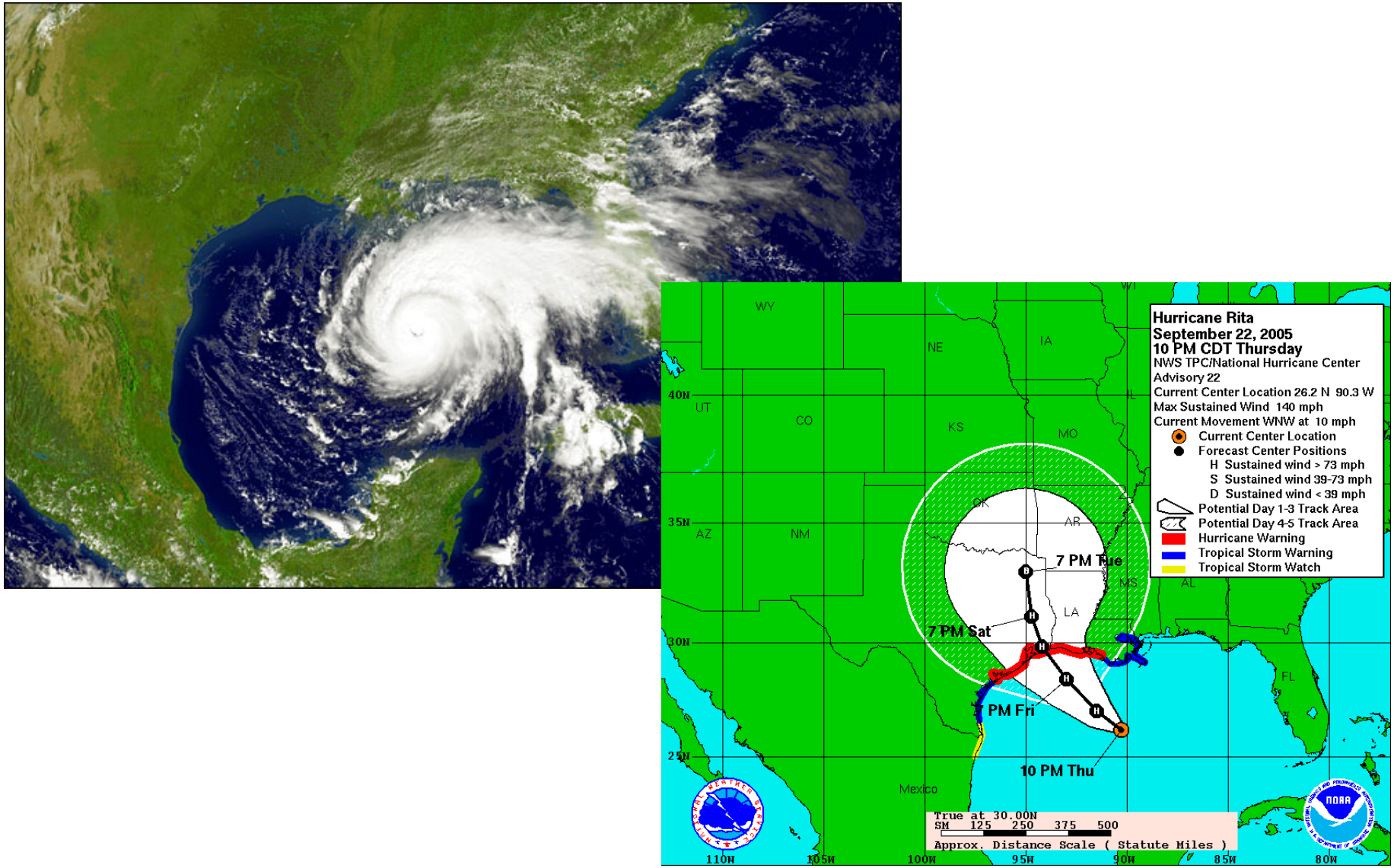
artificial life (computer simulation)

Strong AI, applied AI, and cognitive simulation *from the article* artificial intelligence (AI)

ARTICLE *from the* Encyclopædia Britannica

computer simulation, the use of a computer to represent the dynamic responses of one system by the behaviour of another system modeled after it. A **simulation** uses a mathematical description, or model, of a real system in the form of a computer program. This model is composed of equations that duplicate the functional relationships within the real system. When the program is run, the resulting mathematical dynamics form an analog of the behaviour of the real system, with the results presented in the form of data. A **simulation** can also take the form of a computer-graphics image that represents dynamic ... *(100 of 362 words)*

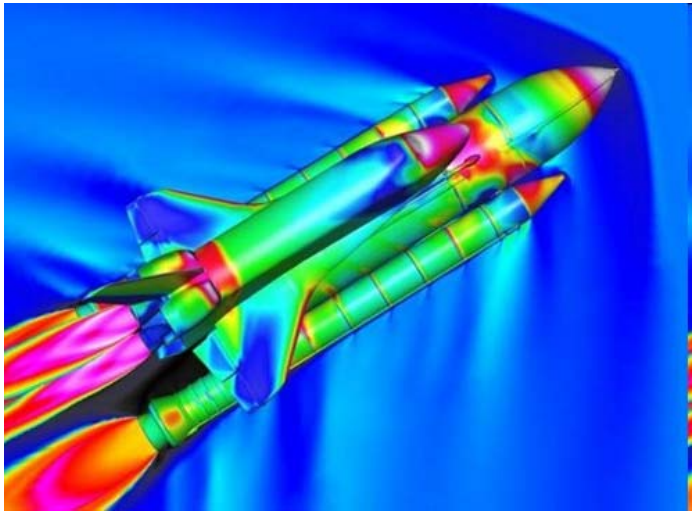
You use results of computer simulations daily (whenever you check weather forecast)



computer simulations of structure formation:

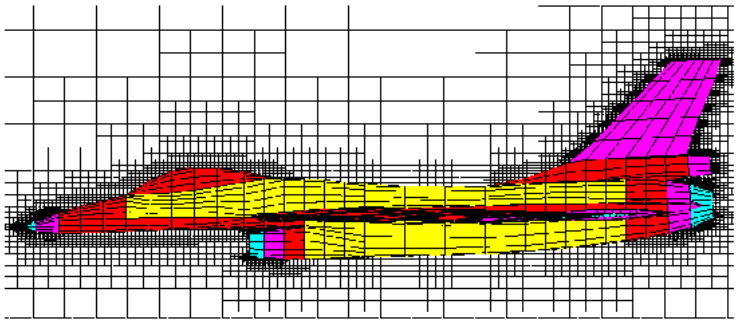
- *Gravity is the king*

  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)*

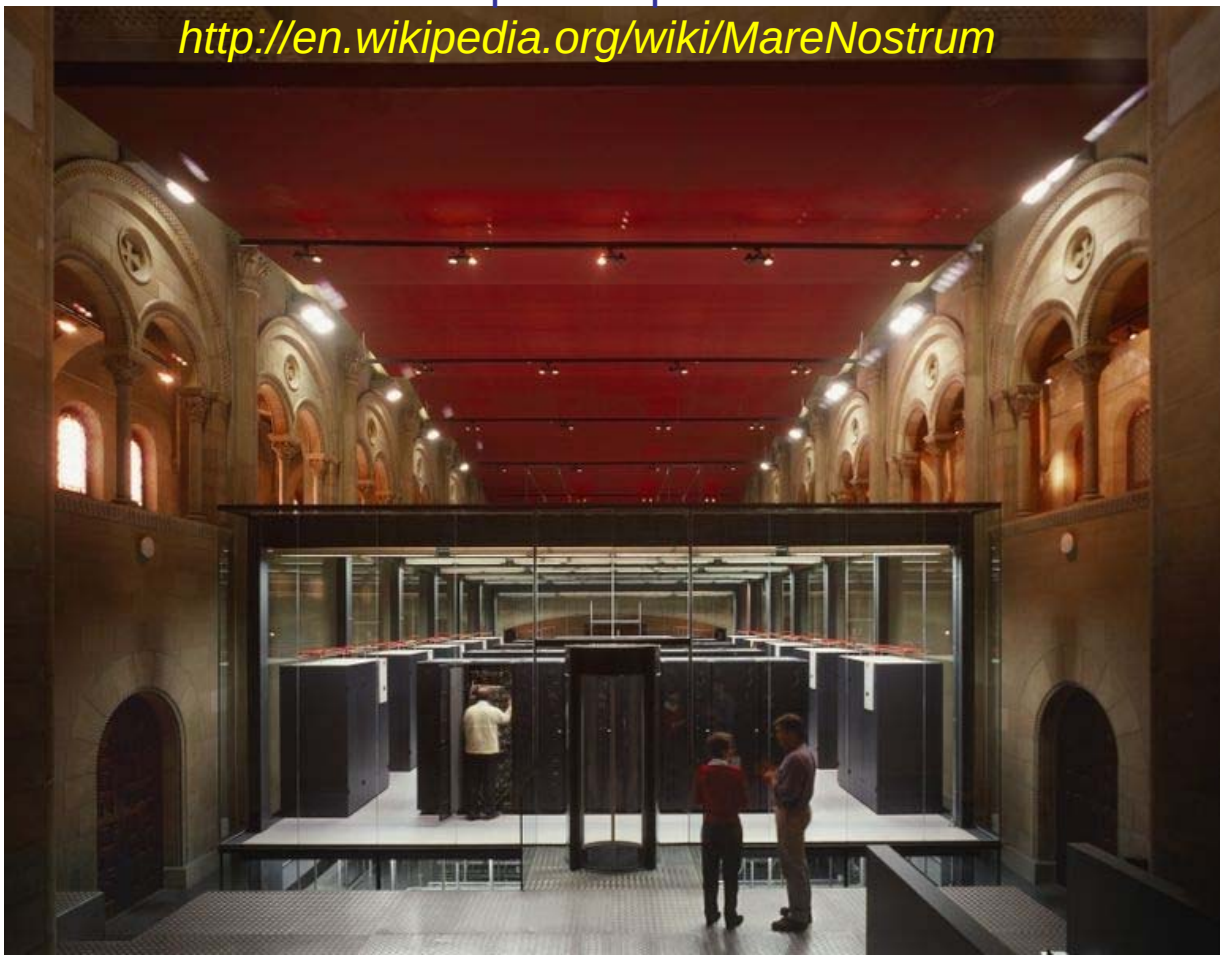
"An intellect (aka the Laplace demon), which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes."

Pierre-Simon Laplace

Modern Day Laplace Demon

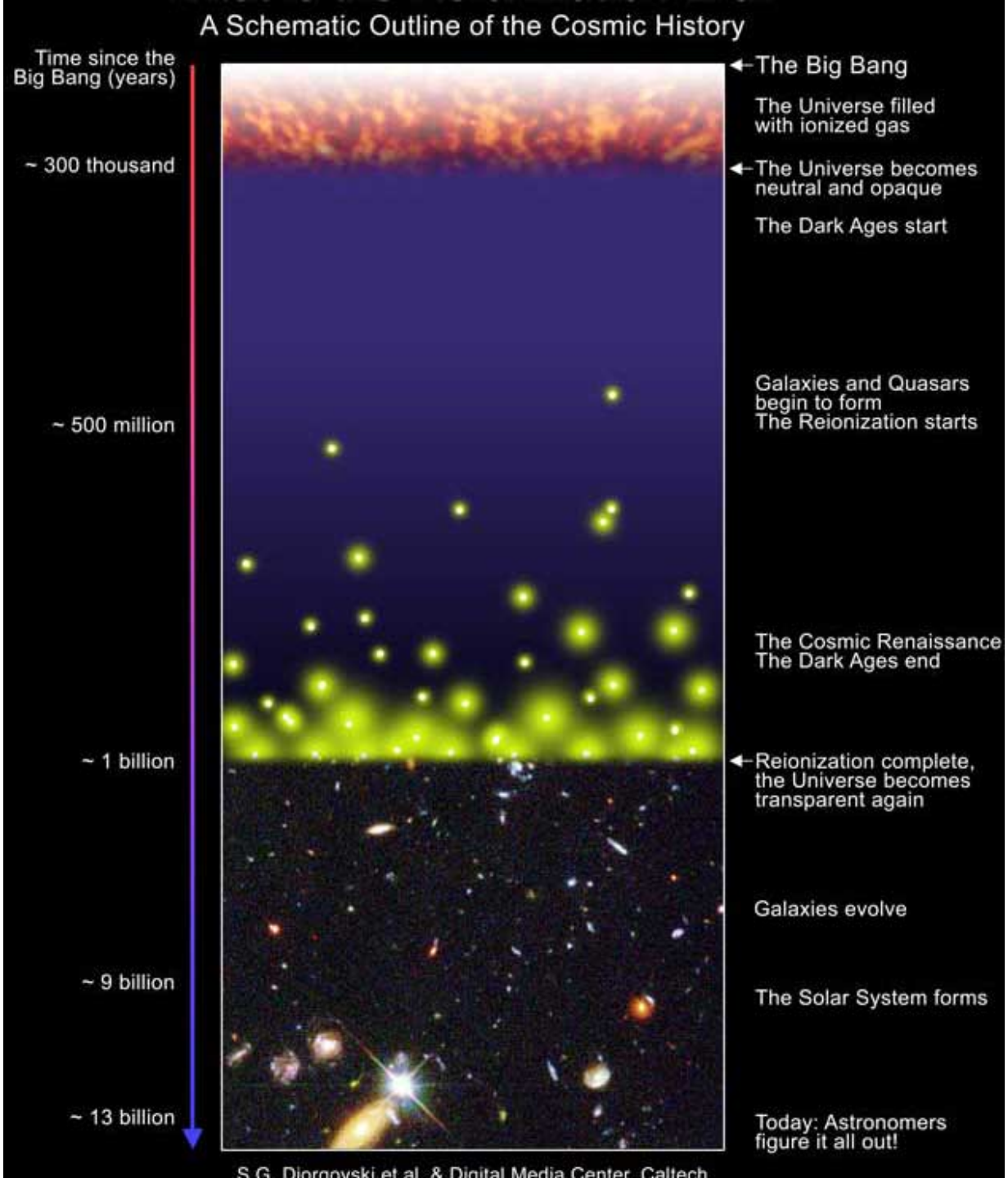
MareNostrum supercomputer in Barcelona

http://en.wikipedia.org/wiki/MareNostrum

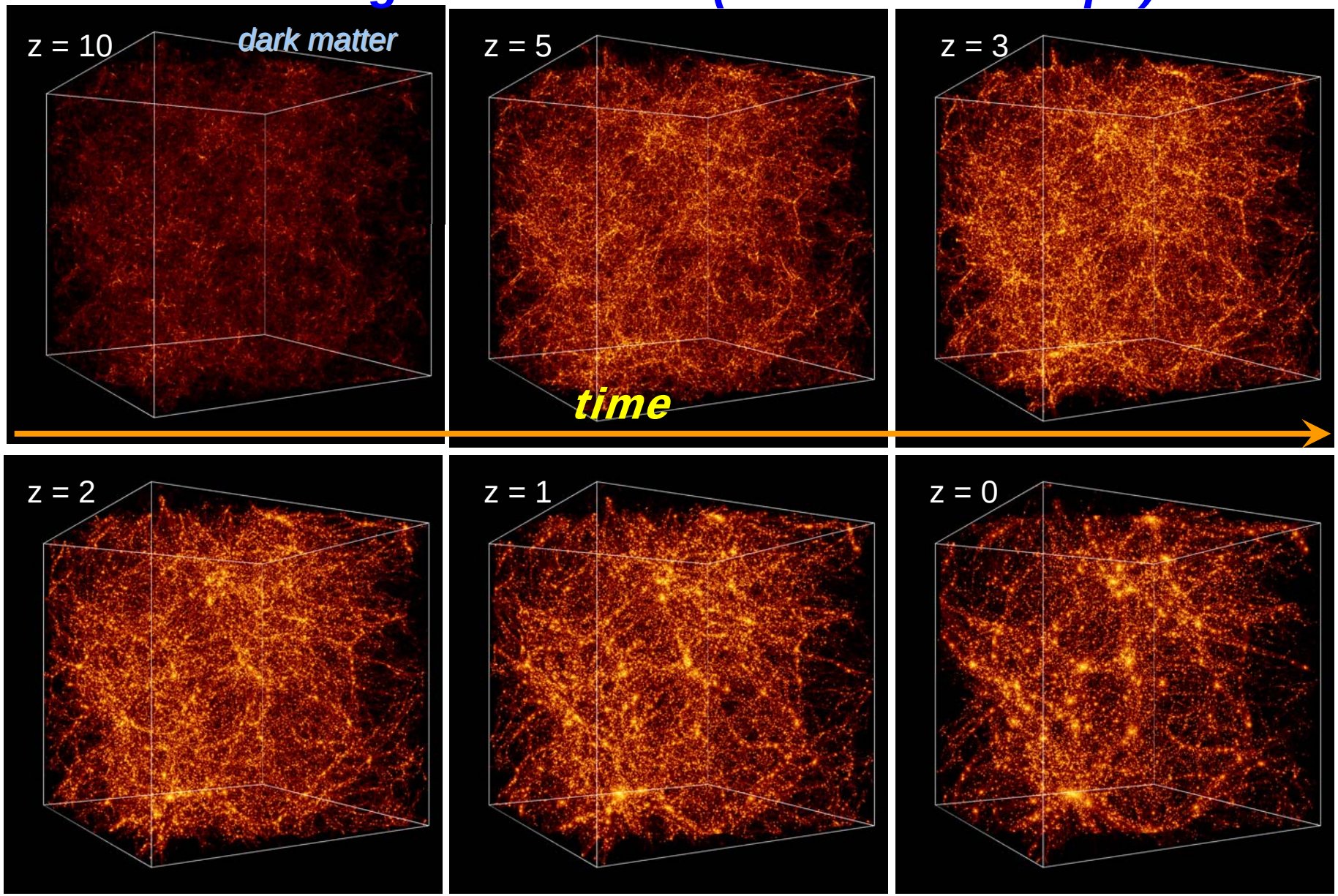


The list of 500 most powerful supercomputers in the world:
http://www.top500.org/site/2540

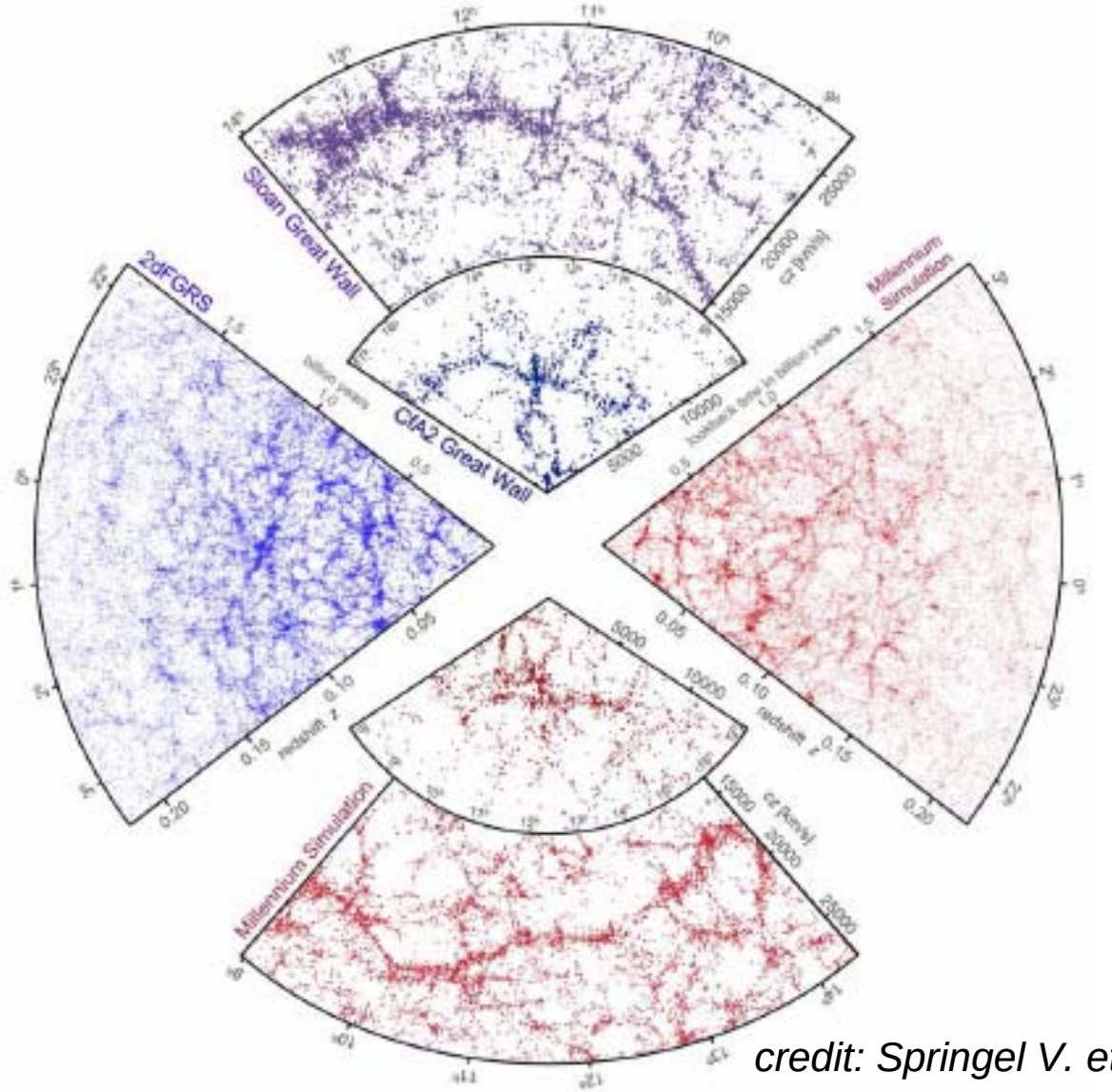
Cosmological simulations of structure formation start around here →



evolution of large-scale structure in a CDM model with cosmological constant (box size=100 Mpc)



computer simulations vs. the real Universe

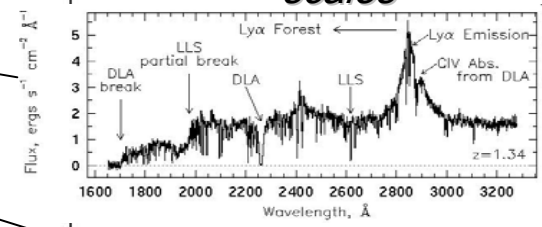


credit: Springel V. et al. 2005, Nature

Cold Dark Matter paradigm of structure formation

- *kinematically cold, almost collisionless dark matter (83% by mass)*
- *ordinary matter (aka "the baryons", 17% by mass)*
- *Gaussian and nearly scale free primordial density fluctuations*
- *standard gravity in expanding FRW universe*

distribution of neutral hydrogen in quasar spectra on small scales



rms fluctuations of density field averaged on a given scale (extrapolated to z=0 using linear theory)

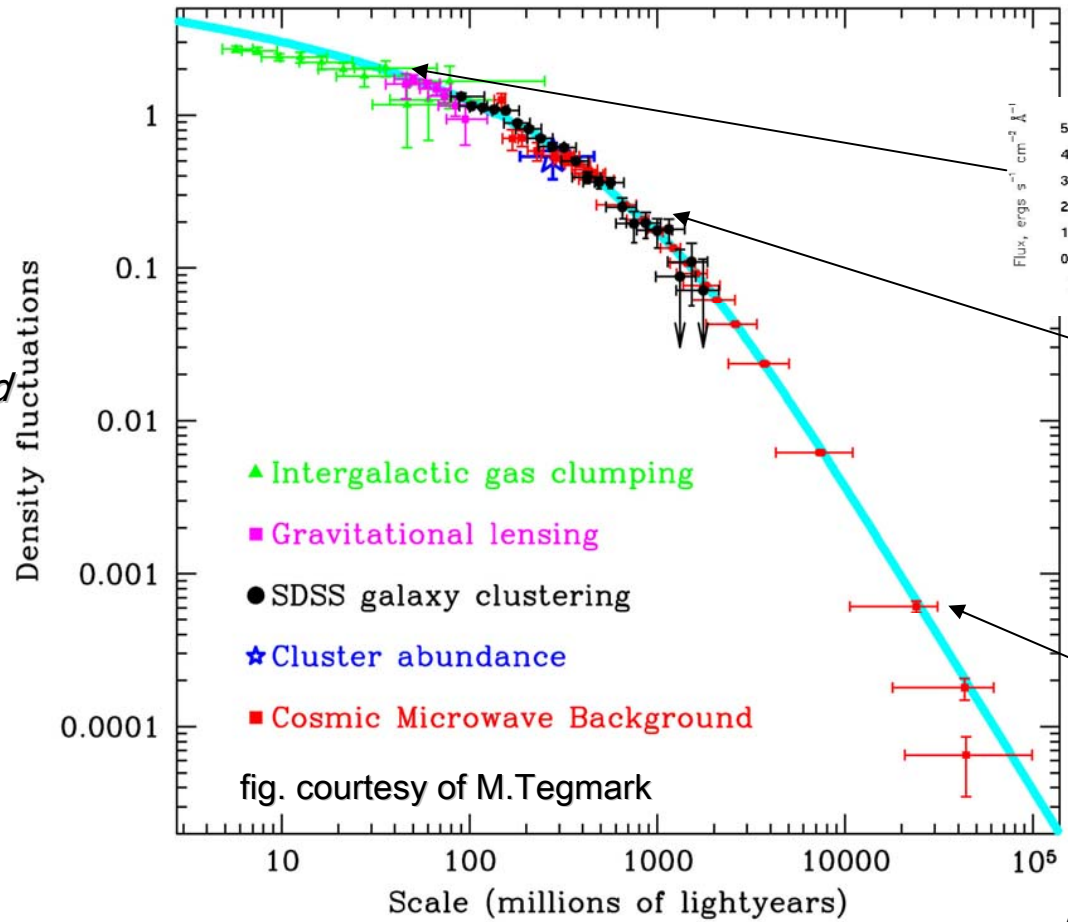
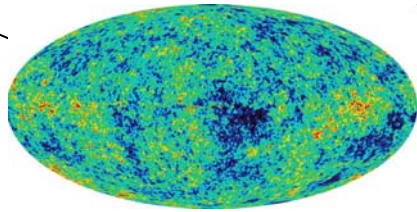


fig. courtesy of M.Tegmark

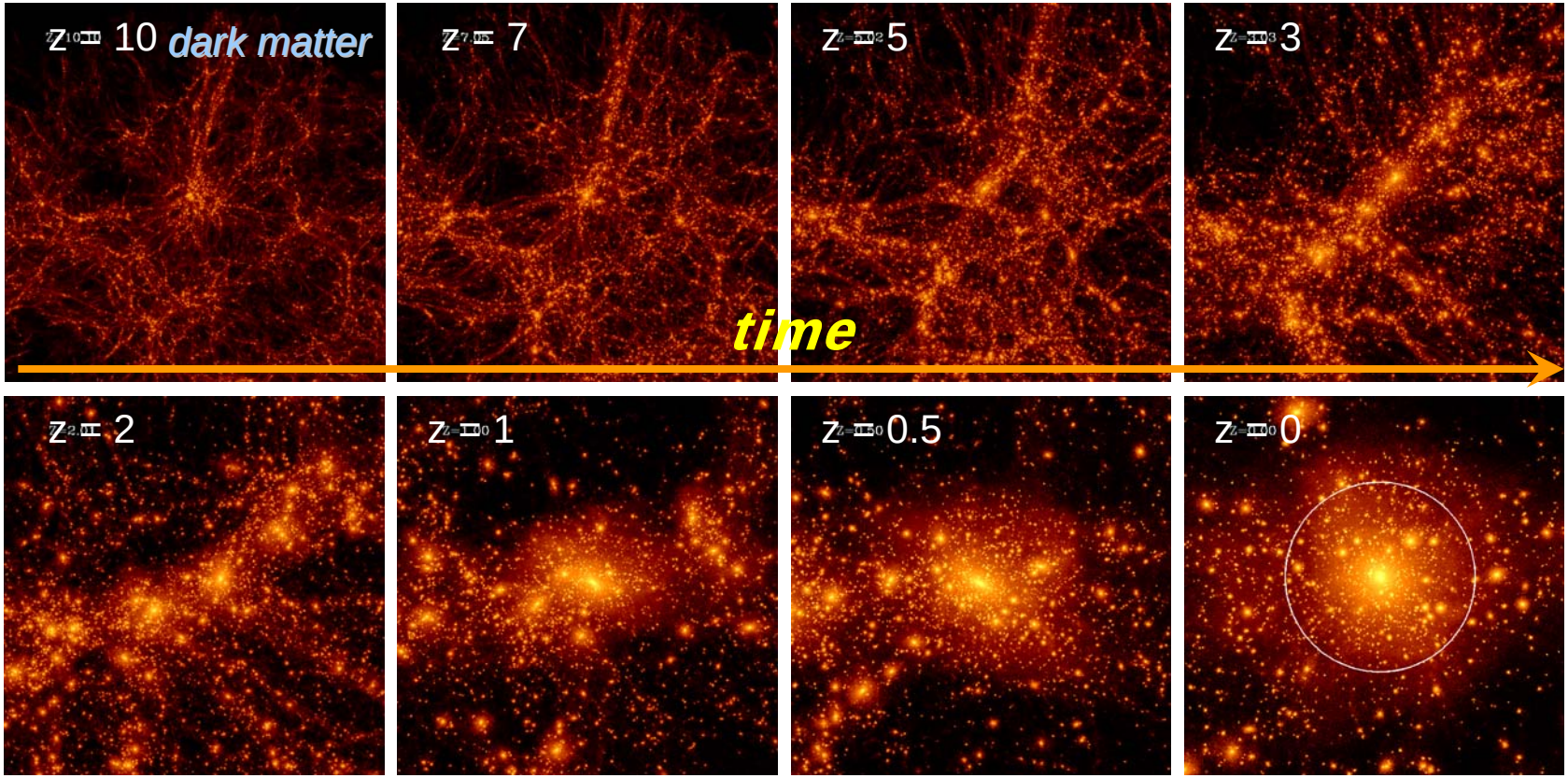
averaging scale

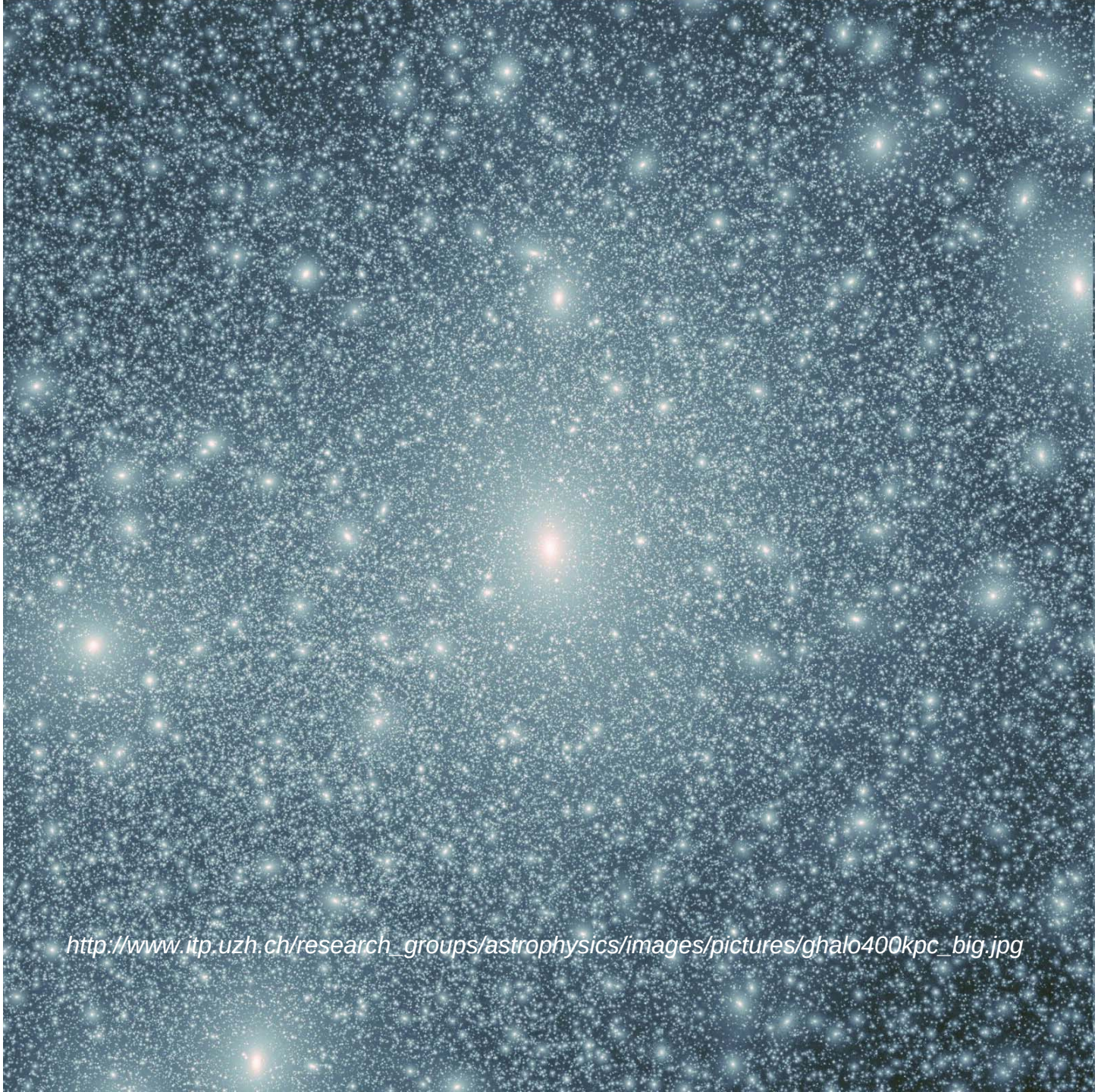
clustering of galaxies



Anisotropies In the cosmic microwave background temperature

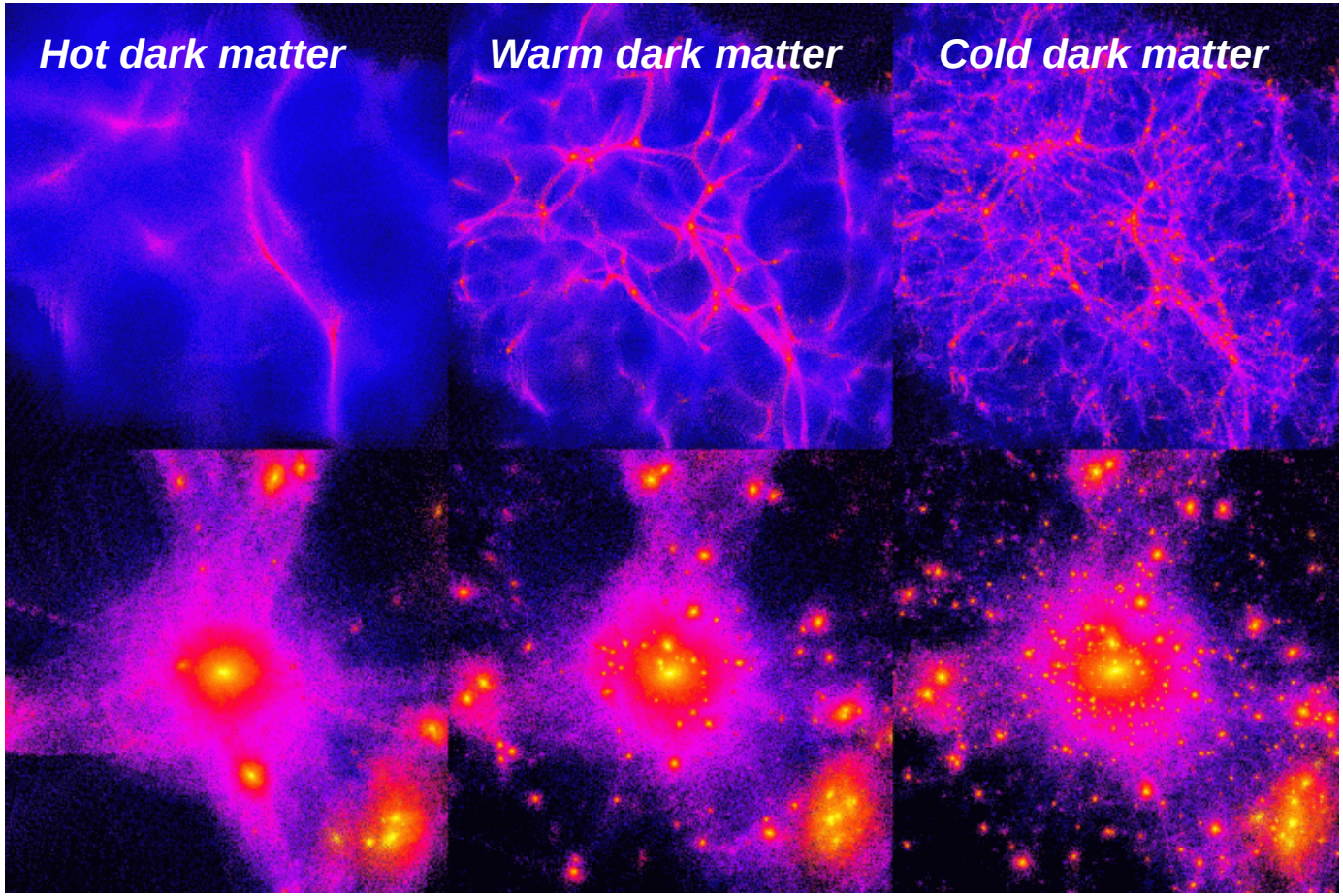
Hierarchical Formation of halos in CDM model




http://www.itp.uzh.ch/research_groups/astrophysics/images/pictures/ghalo400kpc_big.jpg

Details of structure formation

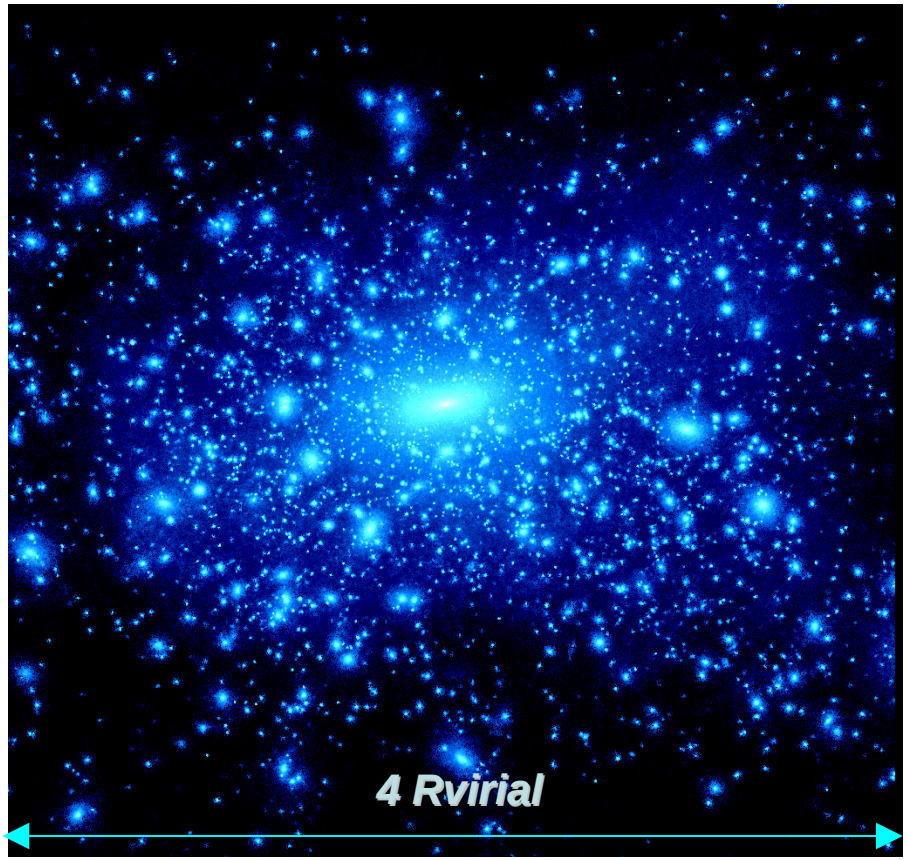
Depends on how cold the dark matter is



Credit: Ben Moore http://www.nbody.net

Dark matter distribution in CDM halos is approximately self-similar (i.e., halos of different mass look similar when rescaled to the same size)

z=0 dark matter distribution in a cluster-sized ($3x10^{14}$ Msun) and a Milky Way-sized ($2x10^{12}$ Msun) objects formed in the ΛCDM universe (brightness and color reflect log of the local matter density)



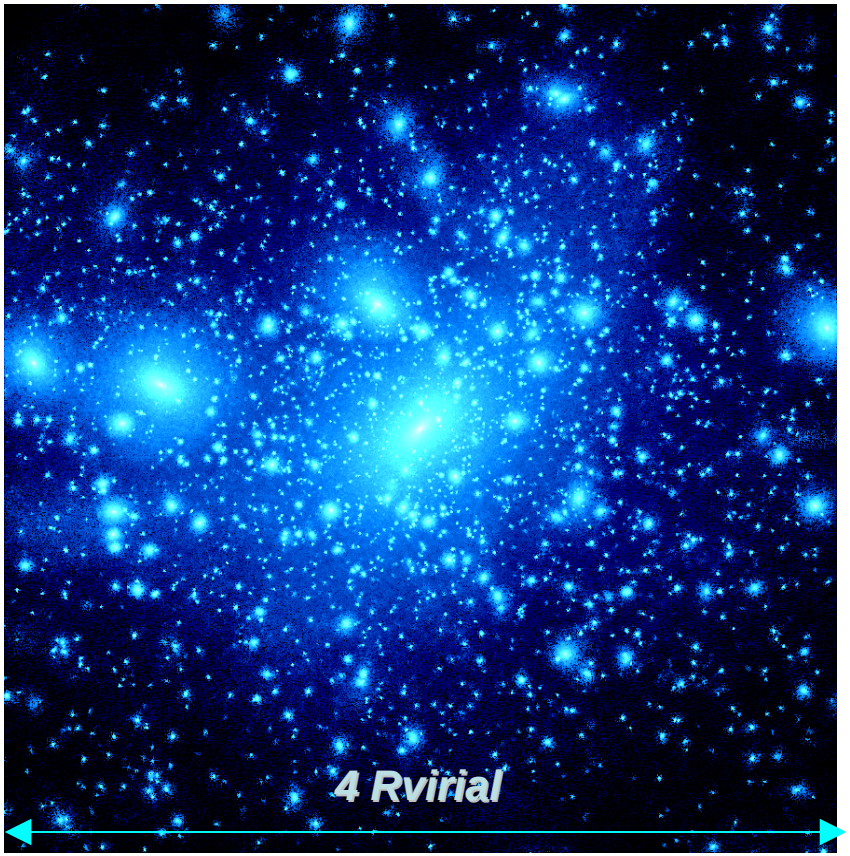


fig. from Kravtsov '09 (http://arxiv.org/abs/0906.3295)

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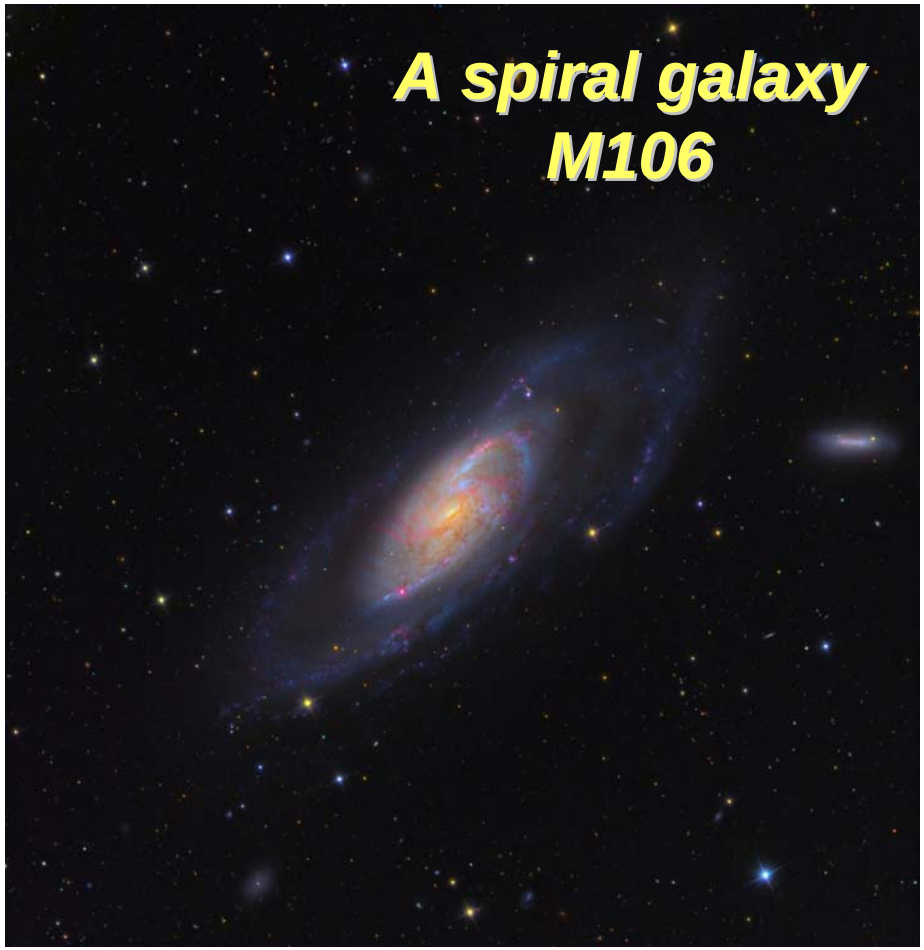
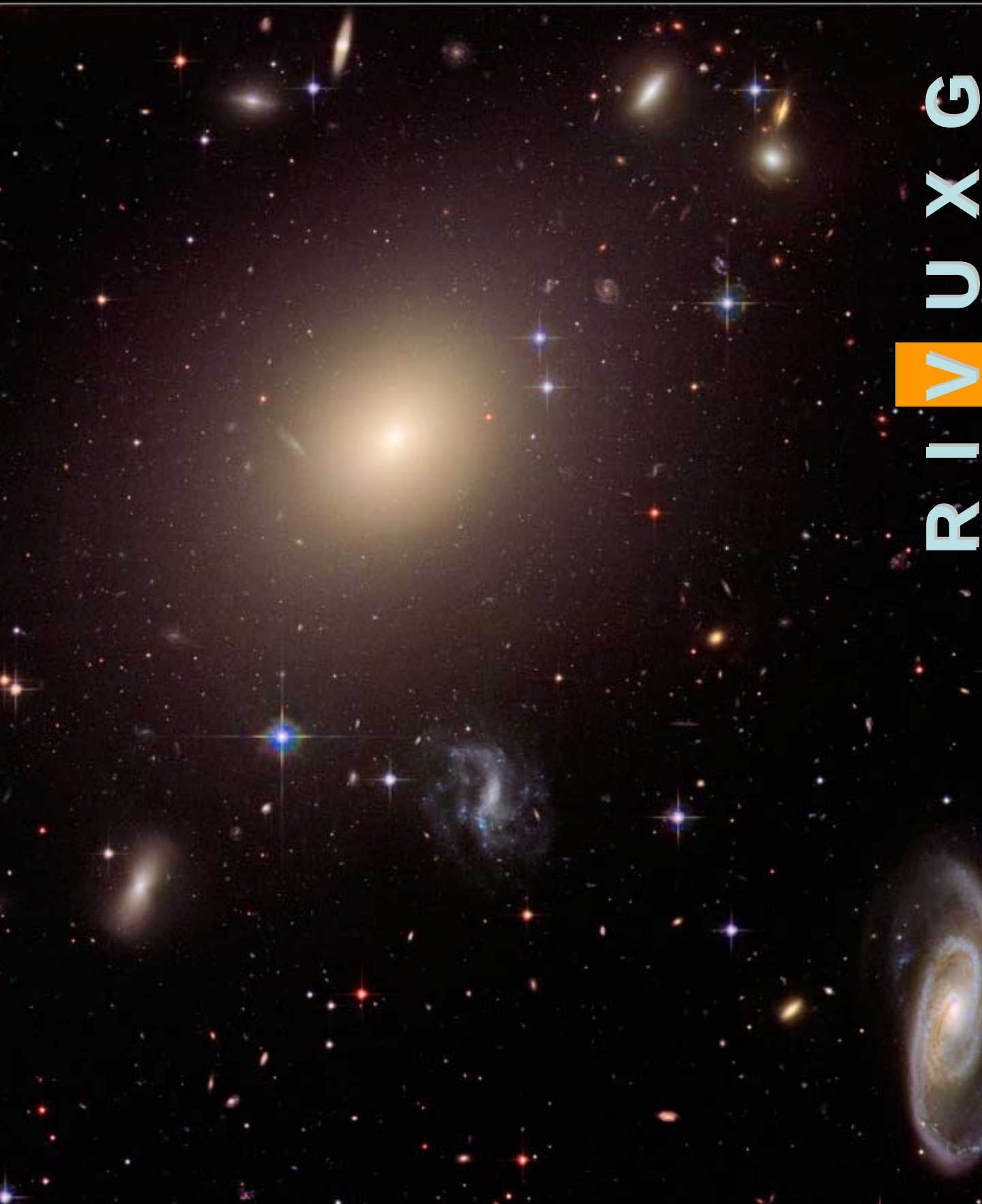
distribution of ordinary luminous matter in and around galaxy and galaxy cluster (manifestly not self-similar)



Galaxy ESO 325-G004 in the Abell Cluster S0740



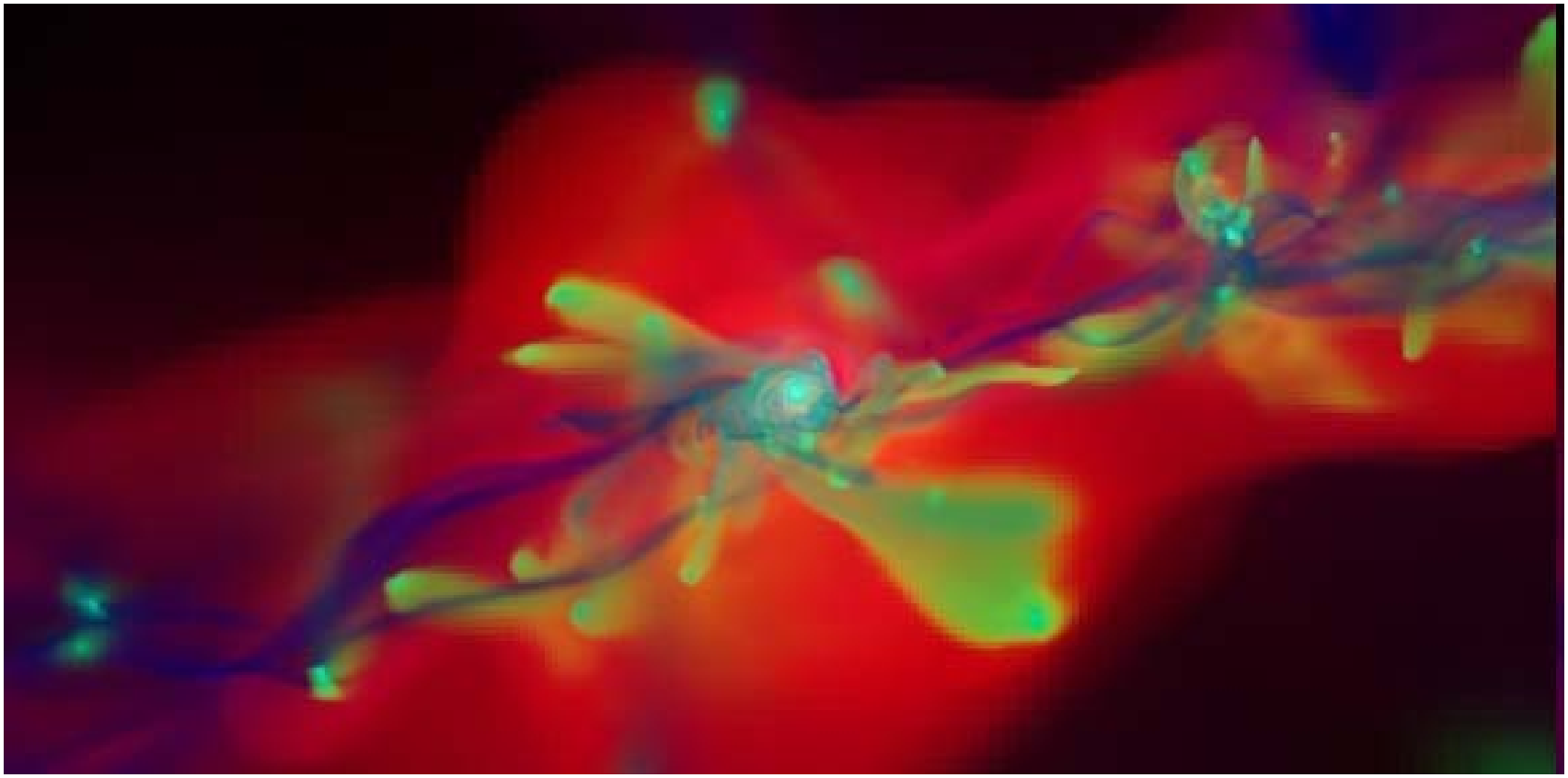
RIVUXG

Most of nearby galaxies have are almost pure disks and have very small or no bulge

http://www.astrofoto.es/Galeria/2008/ngc7331caha/ngc7331caha_en.html

http://www.starshadows.com/gallery/display.cfm?imgID=319

The current frontier: formation of galaxies in the CDM model

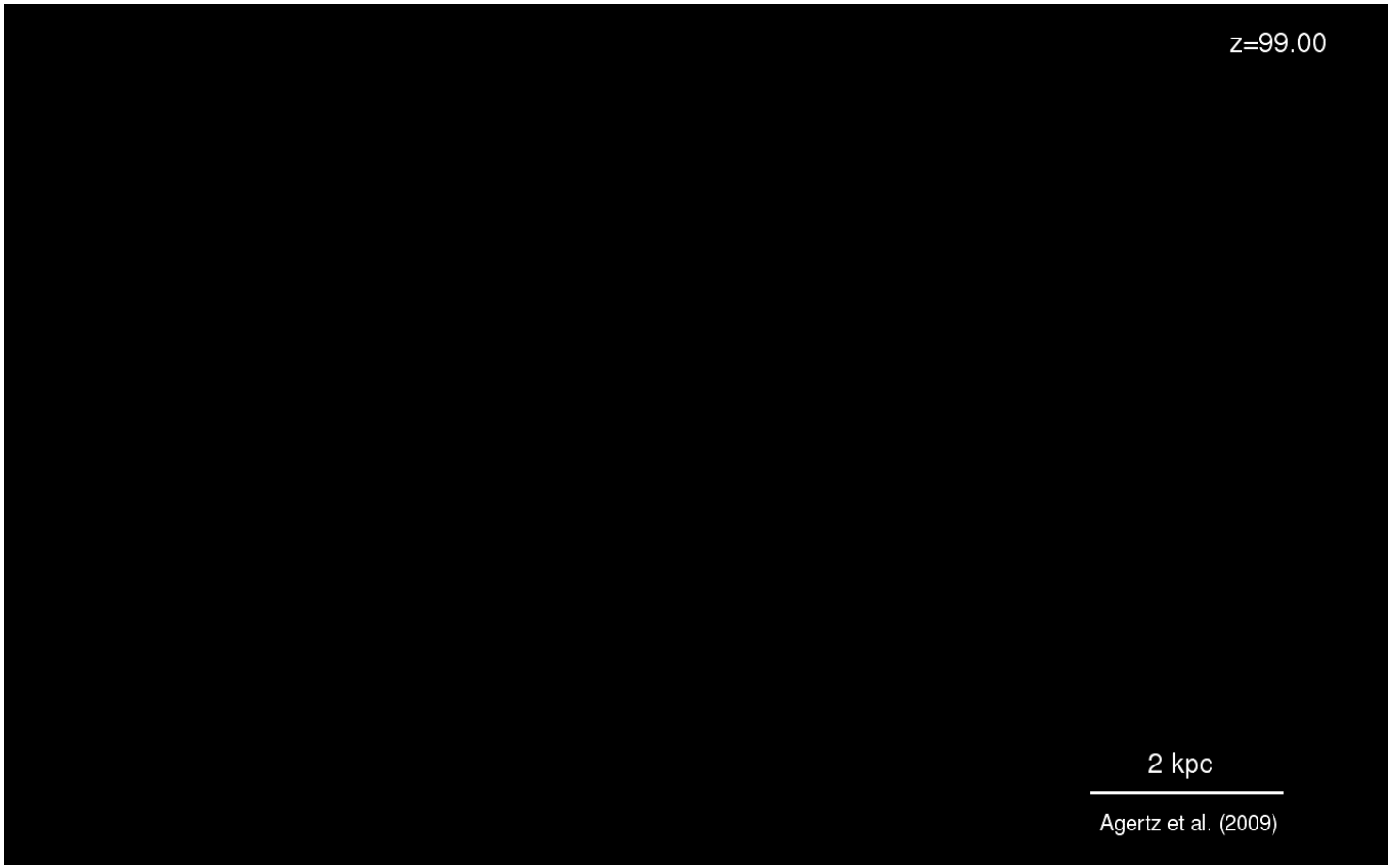


credit: Oscar Agertz (University of Zurich, starting KICP fellow in October)

http://www-theorie.physik.unizh.ch/~agertz/CLUMPS/High_resolution_version_of.html

The current frontier: formation of galaxies in the CDM model

evolution of baryon density (blue), temperature (red), and metallicity (green)



credit: Oscar Agertz (University of Zurich, starting KICP fellow in October)

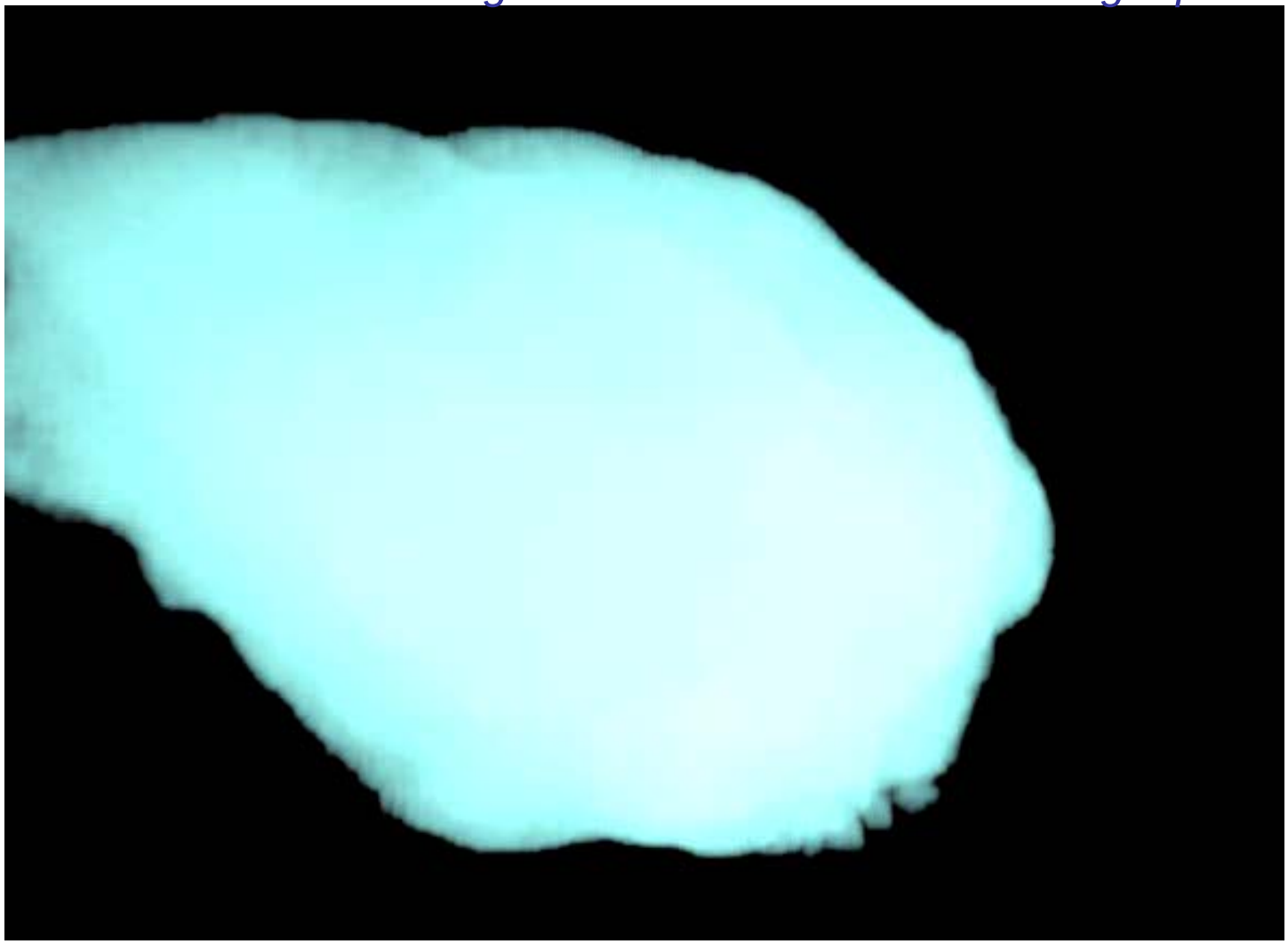
http://www-theorie.physik.unizh.ch/~agertz/CLUMPS/High_resolution_version_of.html

Cutting edge research to cutting edge art

“Galaxies Forming Along Filaments, Like Droplets Along the Strands of a Spider’s Web” – sculpture by the Argentine artist Tomas Saraceno (2009).

hierarchical galaxy formation

cyan/blue haze=gas, dots=stellar particles (with color indicating age)
the size of the region shown is about 1 comoving Mpc



credit: Fabio Governato and collaborators (http://www-hpcc.astro.washington.edu)

Take home points

- *Over the last 30 years a **highly successful Cold Dark Matter paradigm of structure formation** has been developed.*

- *In this paradigm **structures are seeded by tiny quantum perturbations** in the earliest stages of evolution of the universe, which were then stretched during inflationary expansion to cosmological scales.*

- *How the perturbations evolve during subsequent stages of evolution of the universe depends on what matter is made of. **We cannot explain the wealth of observational data on galaxies and structures they form at different redshifts without invoking dark matter.***

- ***The entirety of empirical evidence is best explained, if most of matter in the universe is in the form of "Cold Dark Matter"** – dark matter particles, which moved sufficiently slowly during early stages of evolution of the universe as to not to erase all perturbations on observable scales.*

- *The model can explain large-scale distribution of galaxies with amazing accuracy. Tests of this model on galactic scales are ongoing. Attempts to discover dark matter and identify dark matter particles will be one of the most exciting science stories of the next decade!*