large-scale structure of the universe and dark matter

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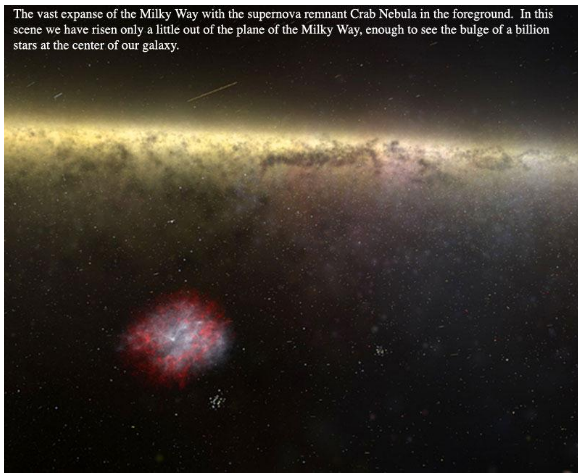
Structures in the nearby universe

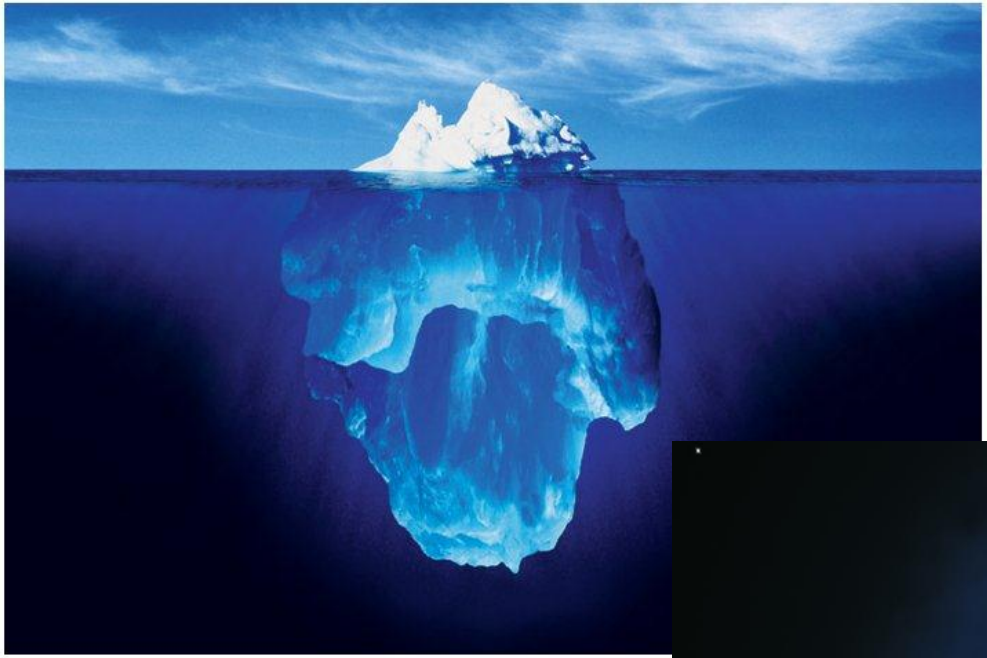
In the last twenty years the region of the Local Supercluster was extensively mapped by Brent Tully and collaborators using redshifts of 21cm line from HI in nearby galaxies and optical spectra



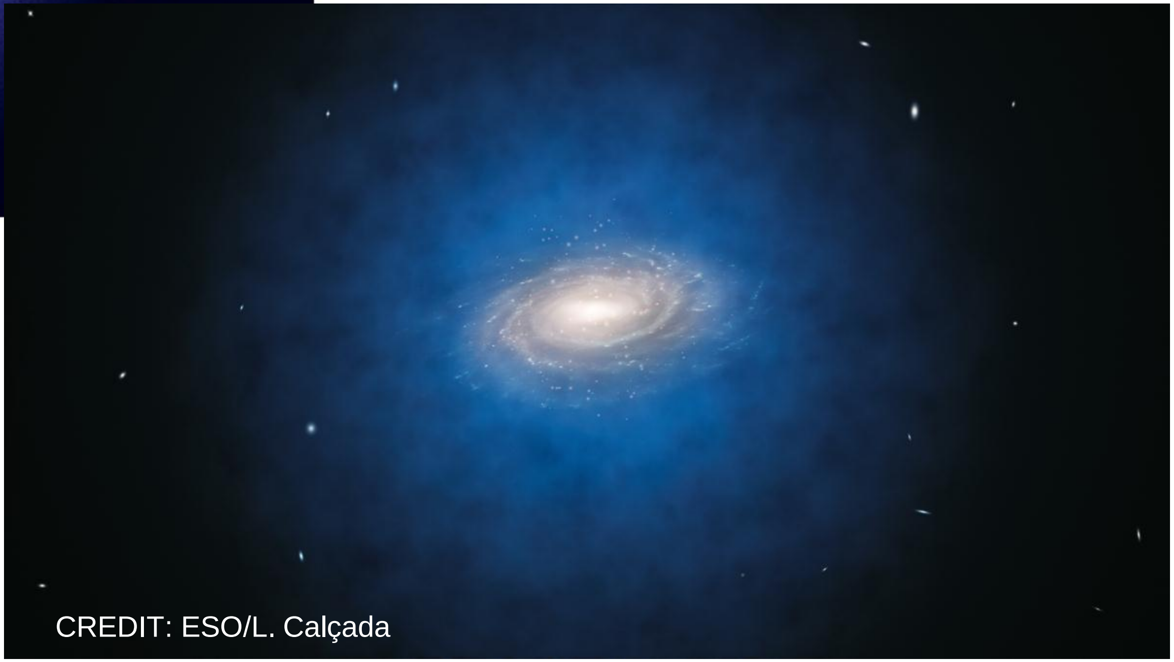
Images, animation, data can be found in Brent Tully's excellent page
http://www.ifa.hawaii.edu/~tully/outreach/

~30,000 galaxies from the Tully's galaxy catalog can be visualized online in a browser using file
http://www.ifa.hawaii.edu/~tully/galaxies.wrl
and Cortona3D VRML viewer from http://www.cortona3d.com/Products/Viewer/Cortona-3D-Viewer.aspx
and are available for visualization and manipulation in the Digital Universe
http://www.haydenplanetarium.org/universe/duguide/exgg_tully.php

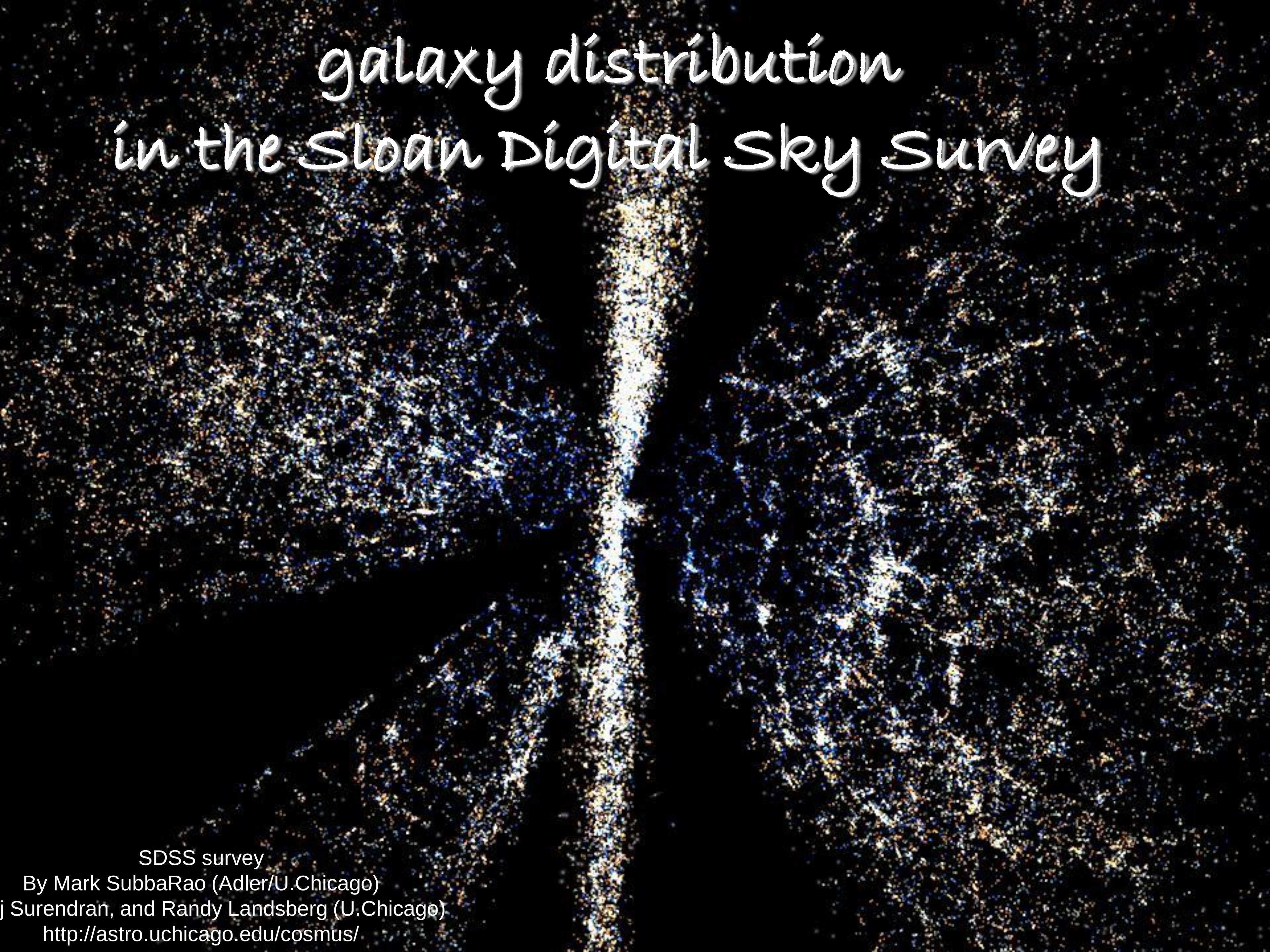
There is ample observational evidence (and theoretical prejudice) that luminous parts of galaxies are only the tip of the iceberg



Stars in galaxies are embedded in extended dark matter "halos"

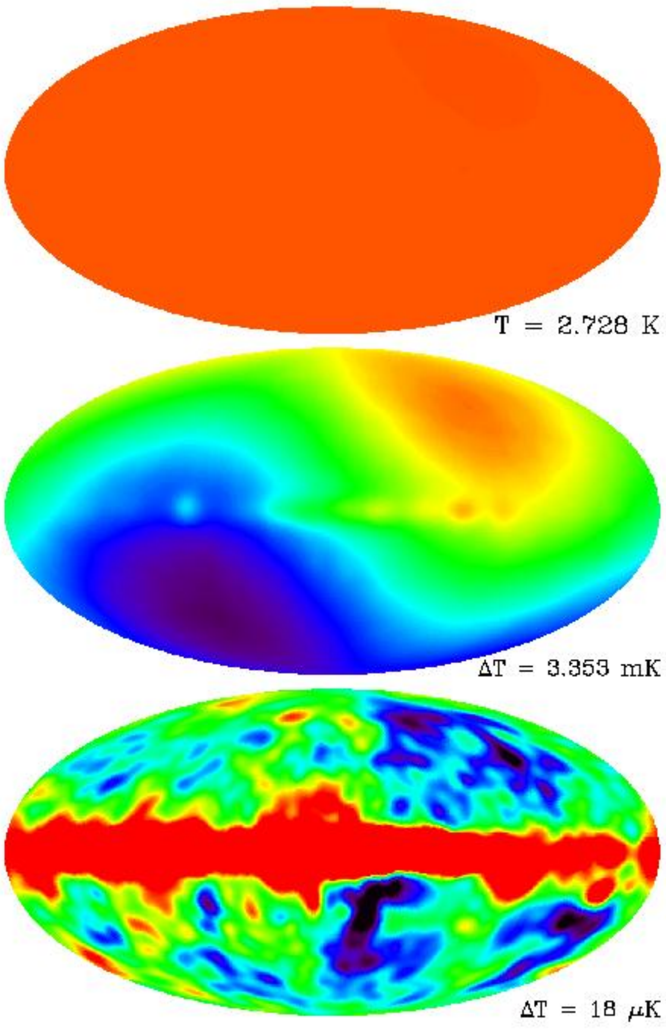


galaxy distribution in the Sloan Digital Sky Survey

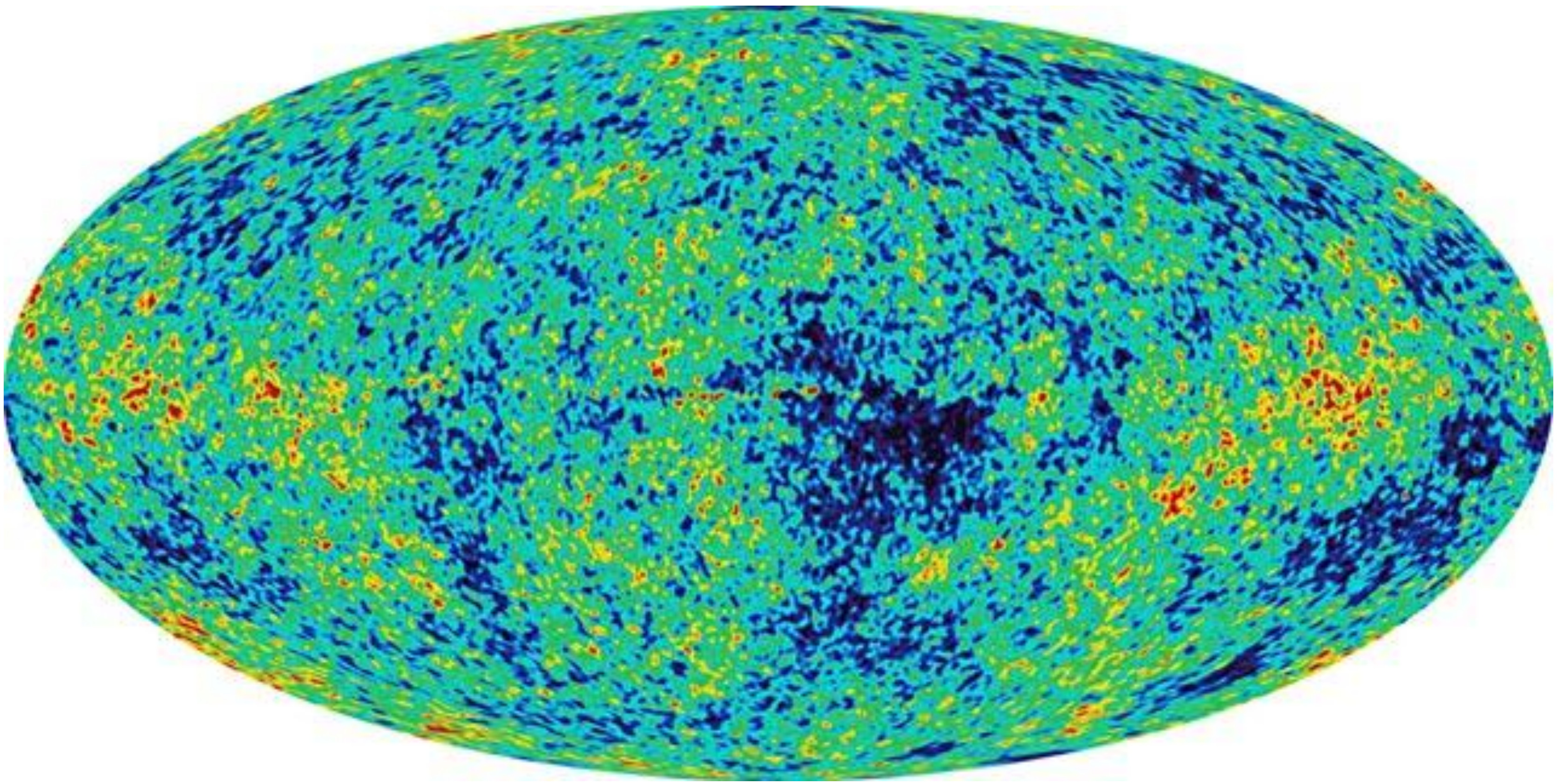


SDSS survey
By Mark SubbaRao (Adler/U.Chicago)
j Surendran, and Randy Landsberg (U.Chicago)
http://astro.uchicago.edu/cosmus/

The seeds of observed large-scale structures in the cosmic microwave background as observed by the COBE satellite in 1992



Tiny perturbations in the cosmic microwave background temperature observed with the WMAP satellite over the last decade

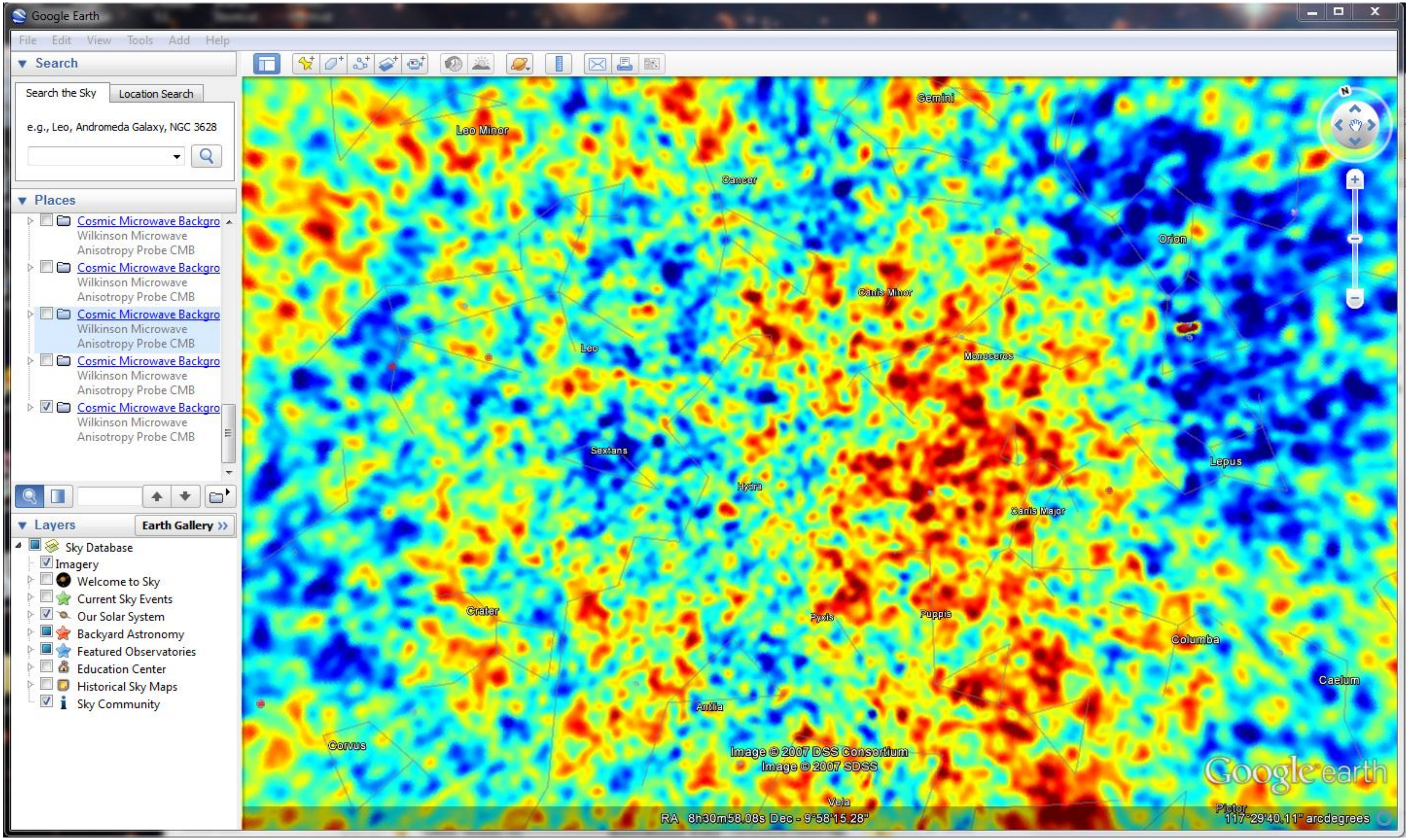


http://map.gsfc.nasa.gov/

CMB (WMAP data) in Google Sky

http://www.google.com/earth/index.html

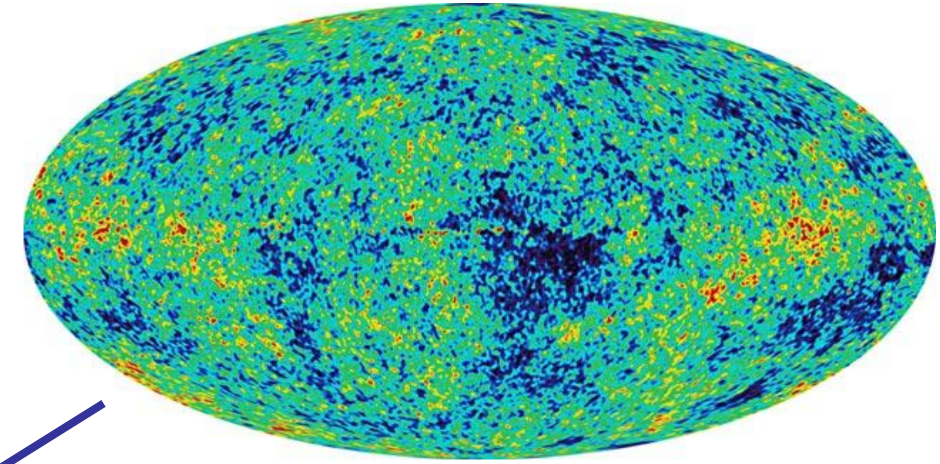
http://lambda.gsfc.nasa.gov/product/map/dr4/google_sky/7year/

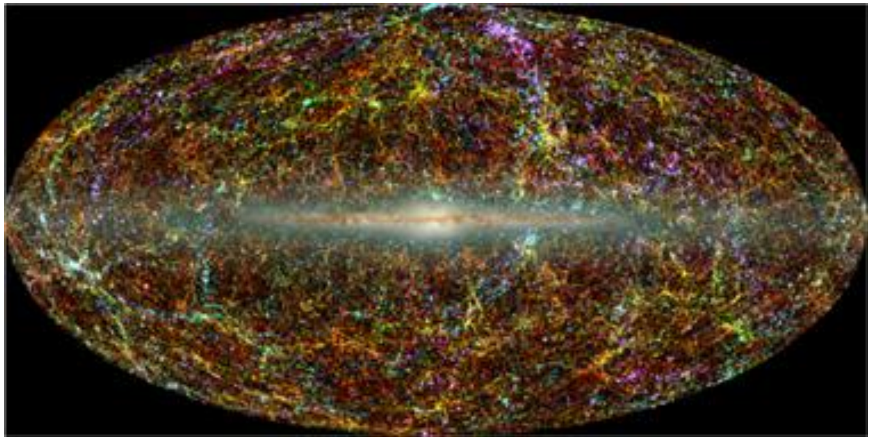


Formation of structures from quantum fluctuations

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)

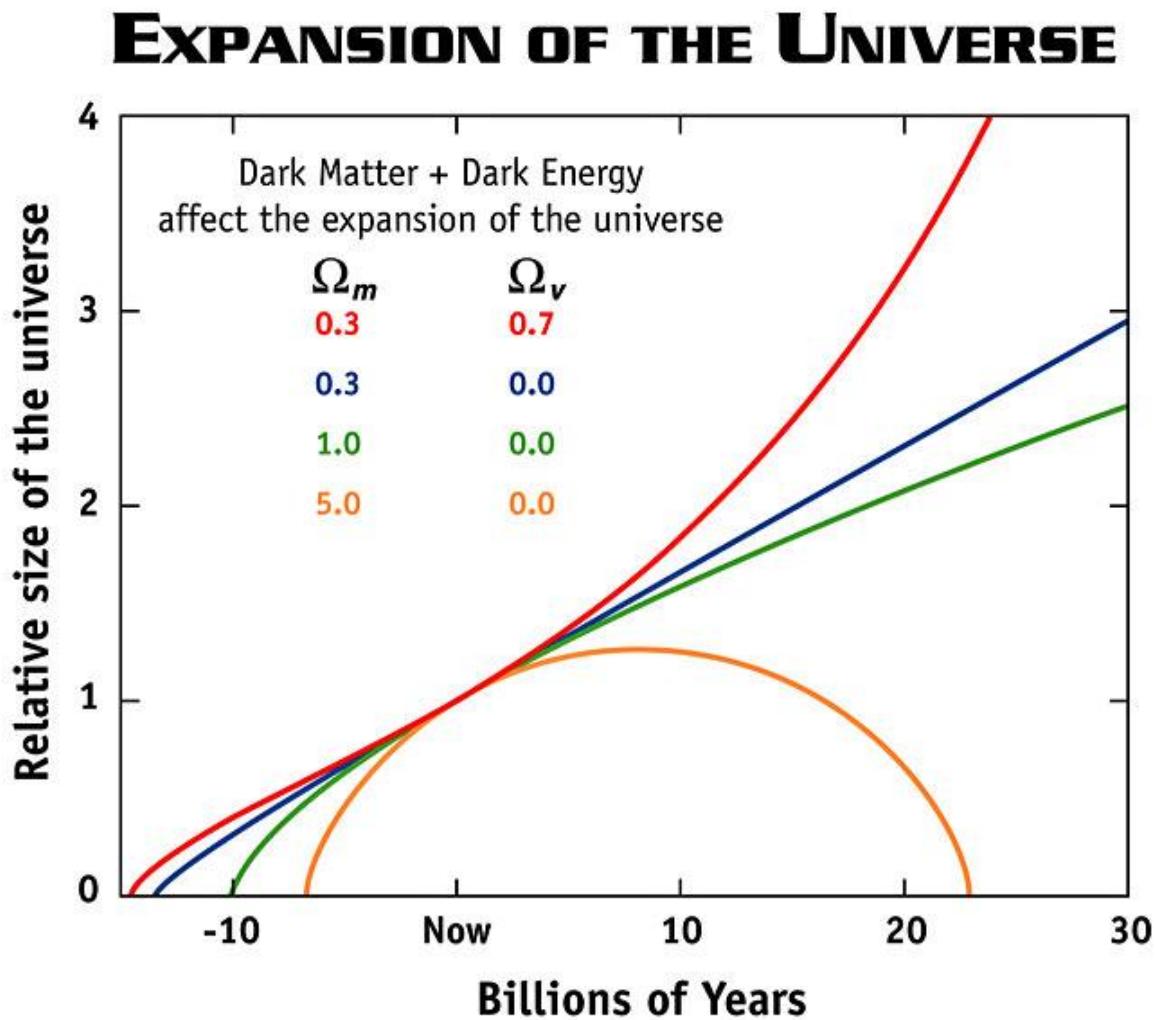




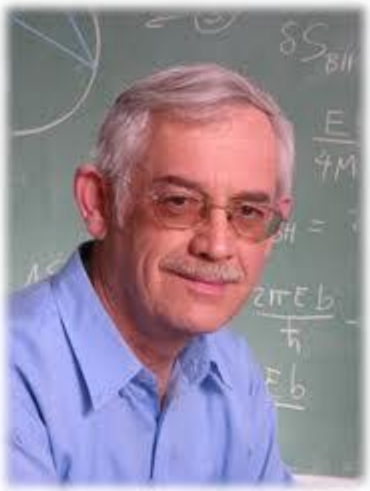
galaxies, clusters, superclusters

Large-scale structure and dark matter

Dark matter is required to explain how amplitude of fluctuations grows so quickly in the 13.5 billion years in the evolution of the universe



A caveat: modified gravity models may change the picture



In 2004 Jacob Bekenstein presented a new theory of gravity called TeVeS (TensorVectorScalar). The overall expansion of the universe in such model is almost identical to the standard model based on Einstein's General Relativity. Structure formation can in principle be fast enough without dark matter

IOP A website from the Institute of Physics

physicsworld.com

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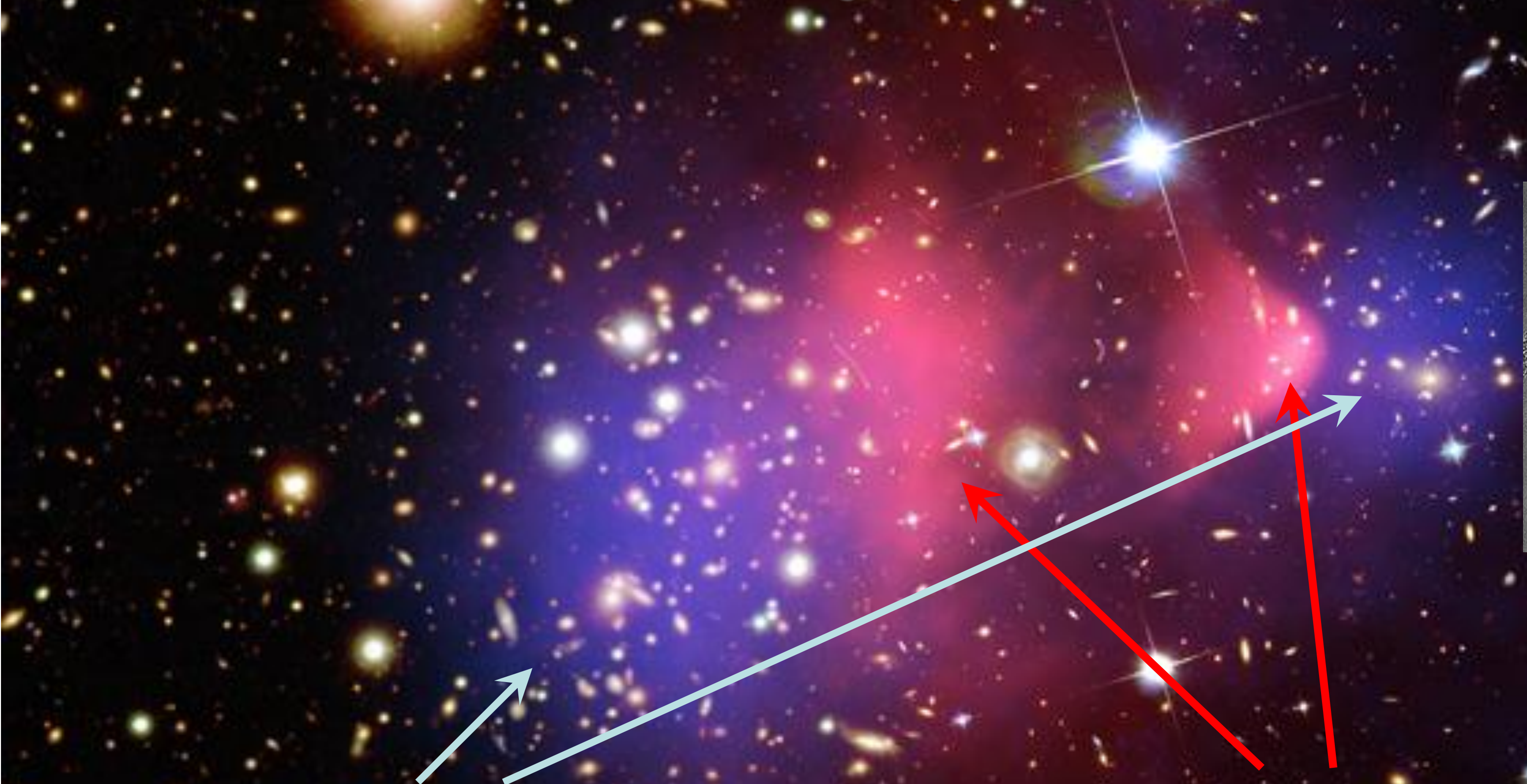
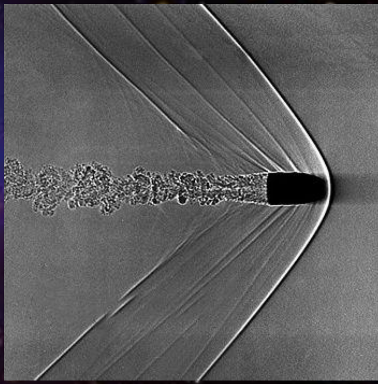
Cosmic structure explained without dark matter

Dec 18, 2006

An alternative to Einstein's theory of general relativity called "TeVeS" could describe the formation of cosmic structure without requiring the existence of dark matter, say physicists in the US (*Phys. Rev. Lett.* **97** 2006).

merging "Bullet" cluster [Clowe et al. 2006] shows that
1. gravitationally dominant mass component (responsible for lensing – blue) is displaced from the hot gas – the dominant baryonic mass component,
implying that some other dark mass dominates gravity
and that some sort of dark matter would be required even in the modified gravity models



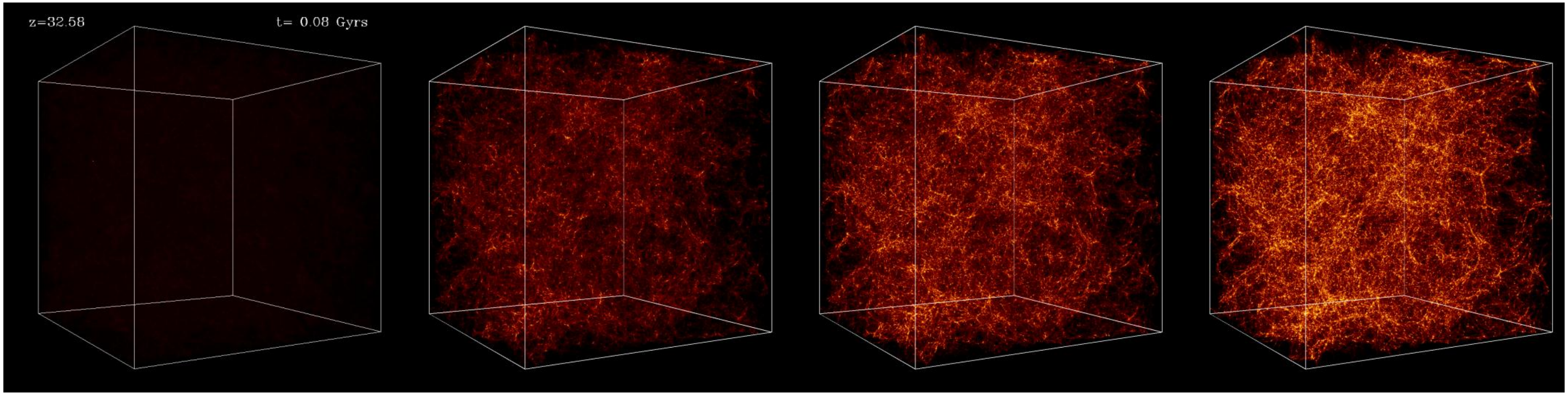


blue glow *= dark matter density from weak lensing analysis of faint background galaxies in the optical HST image*

Red/pink glow *= X-ray emission of the hot intracluster gas, as observed by the Chandra satellite*

So how do structures form in these models?

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 to resort to computer simulations.

Computer simulations of structure formation

"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

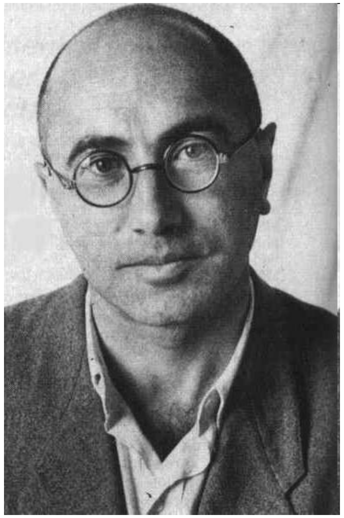
- ***assume a cosmological model*** *(a set of parameters that determine expansion of the universe) and properties of dark matter particles (i.e., hot, warm, cold, weakly interacting or strongly interacting)*
- *these assumptions determine* ***initial conditions*** *– a random realization of a density field that is consistent with observations of cosmic microwave background. The initial conditions are set after some hundred million years after the Big Bang, when perturbation amplitude is still small*
- *initial* ***density field is evolved in time*** *until present day epoch (or even into the future) using computer code that calculates relevant forces (e.g., gravity) that act on matter parcels in a box with periodic boundary conditions.*

Evolution of structures depends on properties of dark matter particles

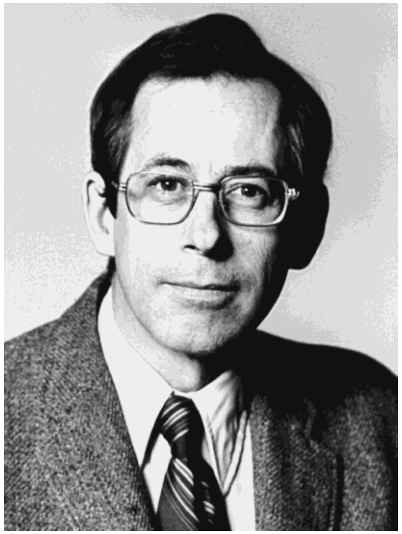
such as…

- ***their mass and velocity in the early universe*** *– generic classes of hot, warm, and cold dark matter particles are considered in models*
- ***strength of interactions between dark matter particles*** *– generic classes of weakly interacting and strongly interacting dark matter are considered*

the standard model of structure formation is based on <u>w</u>eakly <u>i</u>nteracting <u>m</u>assive (i.e., cold) <u>p</u>articles (WIMPS), a.k.a. <u>c</u>old <u>d</u>ark <u>m</u>atter (CDM)



Yakov Zel'dovich

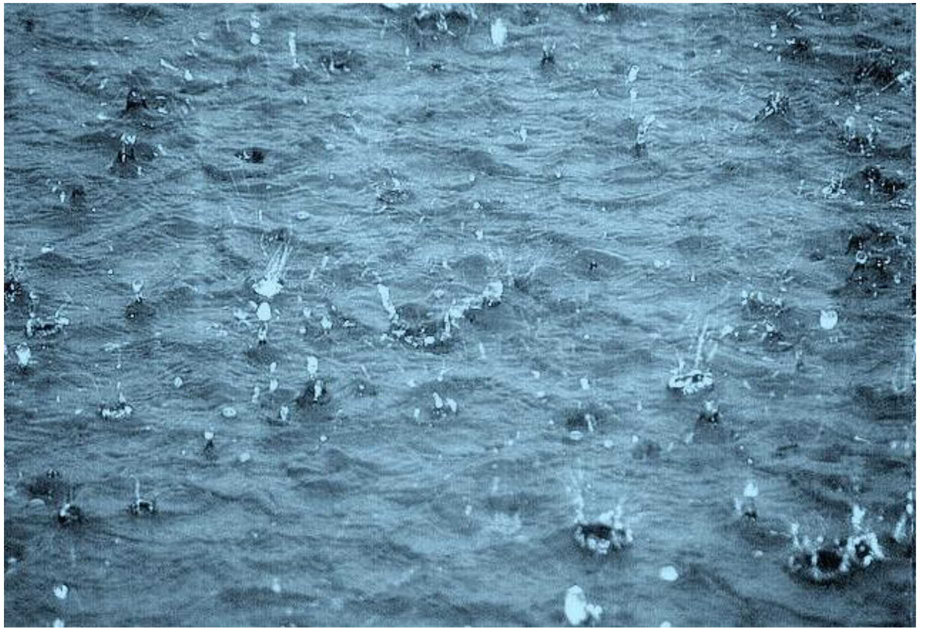


Jim Peebles

Mass and velocity of dark matter in the early universe determine the smallest scale on which perturbations survive

density perturbations in
Hot Dark Matter model

density perturbations in
Cold Dark Matter model



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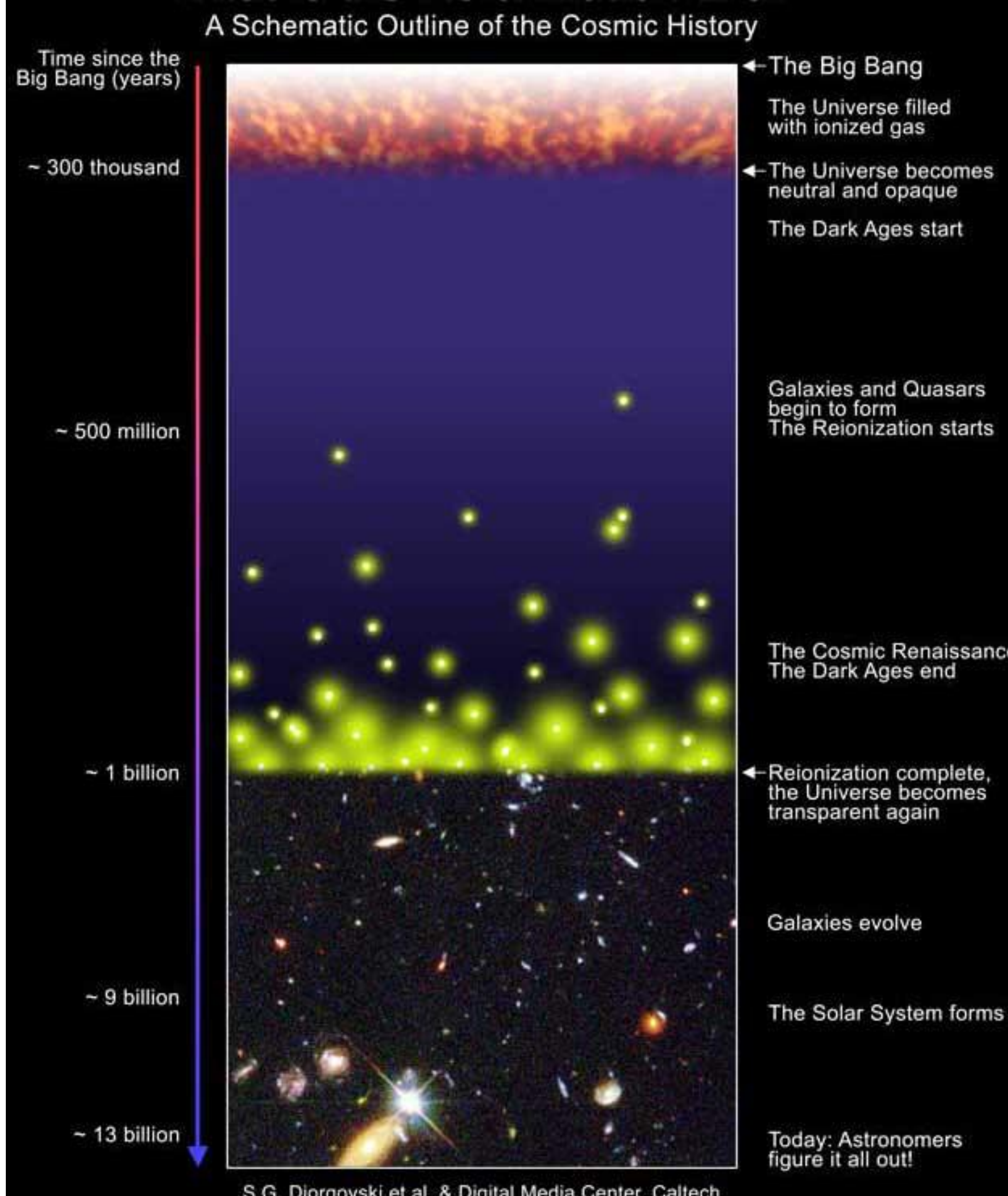
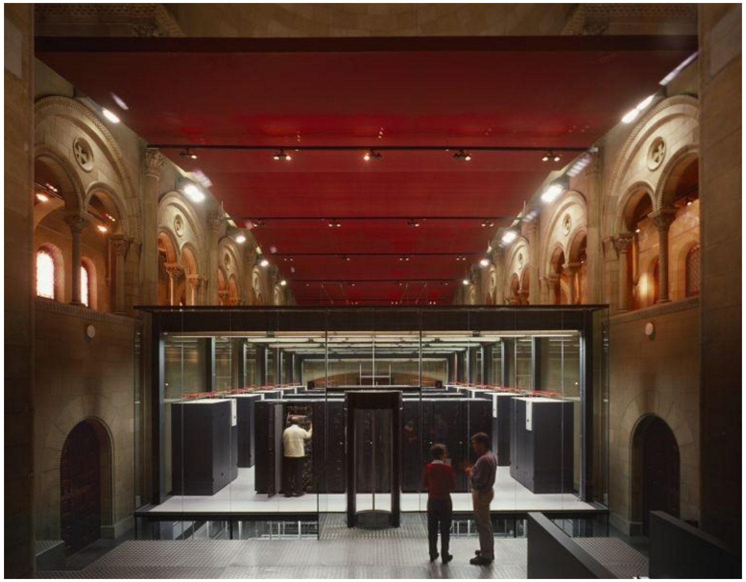
Cosmological simulations of structure formation start around here



Modern Day Laplace Demons

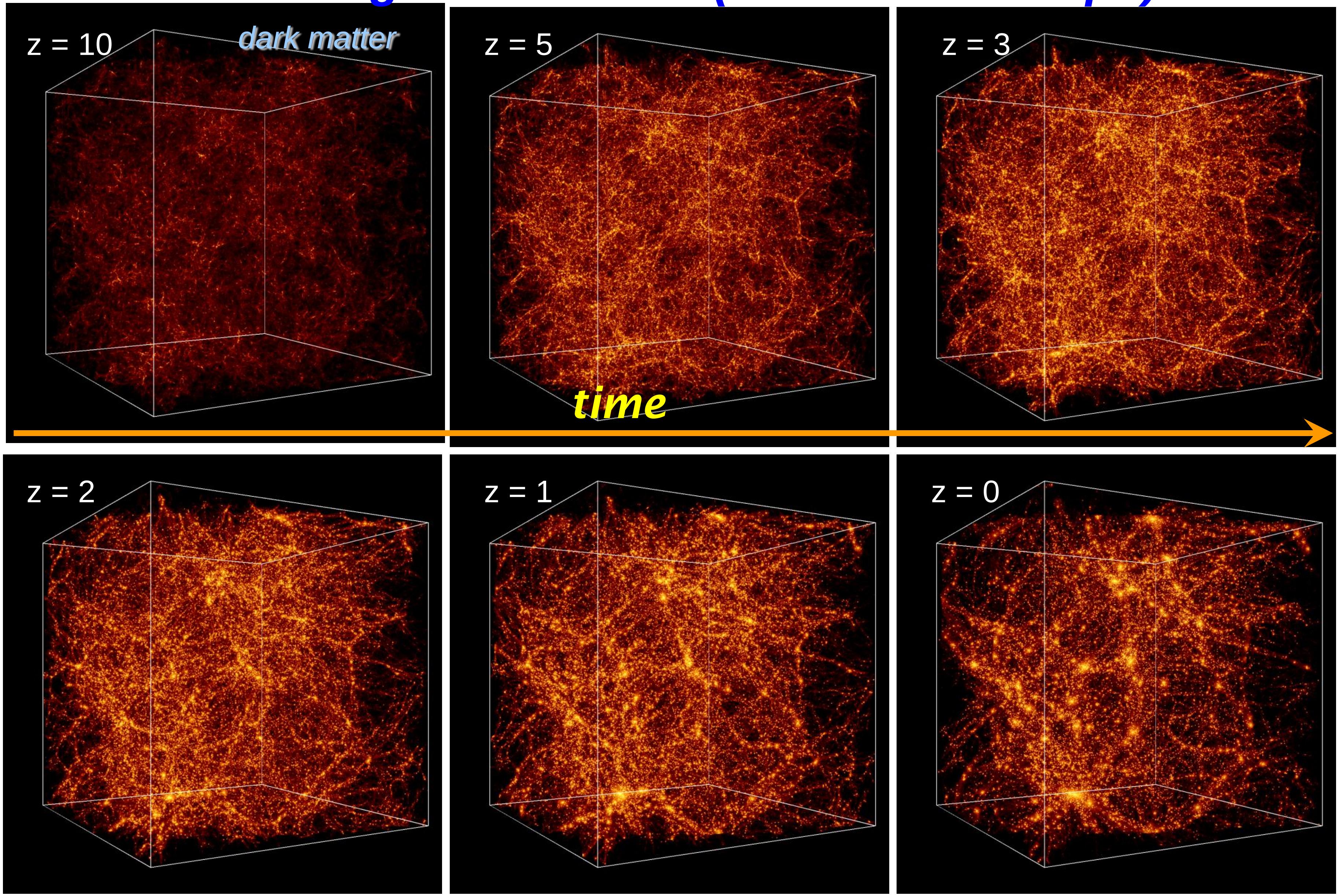
MareNostrum supercomputer in Barcelona
http://en.wikipedia.org/wiki/MareNostrum



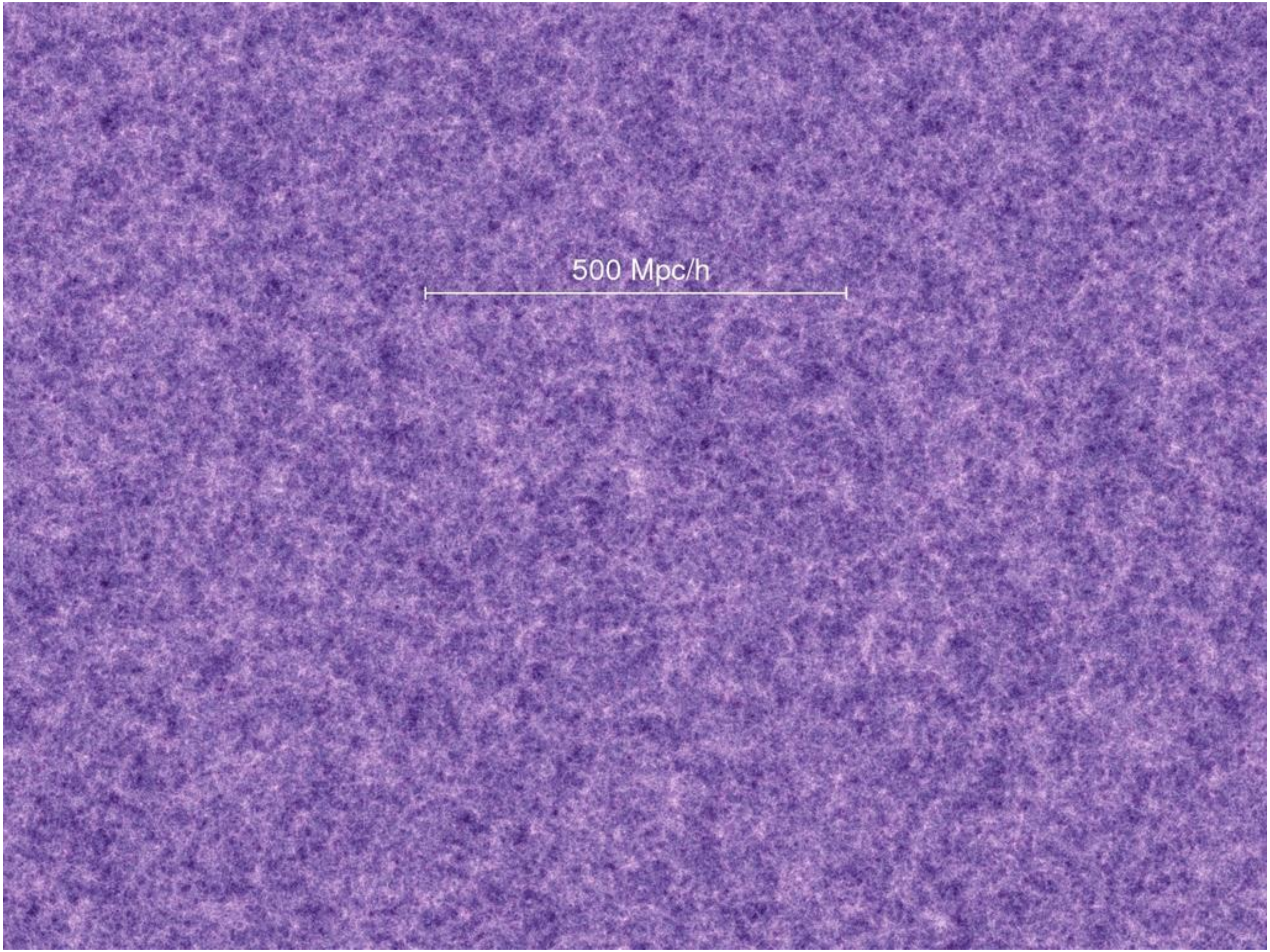
Mira Blue Gene Q petascale machine
at the Argonne National Lab
https://www.alcf.anl.gov/mira

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

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

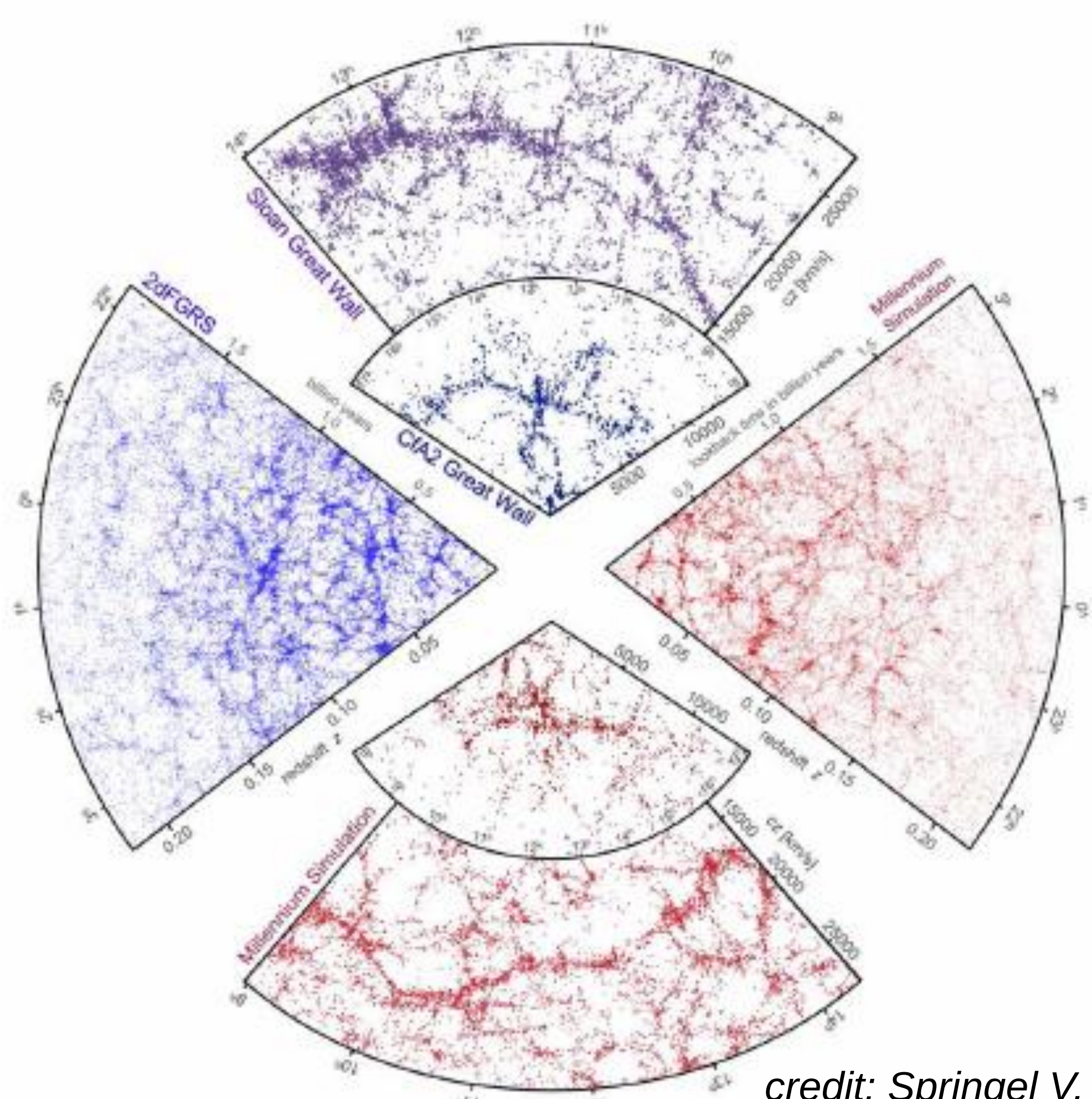


On 100 Mpc things get boring…



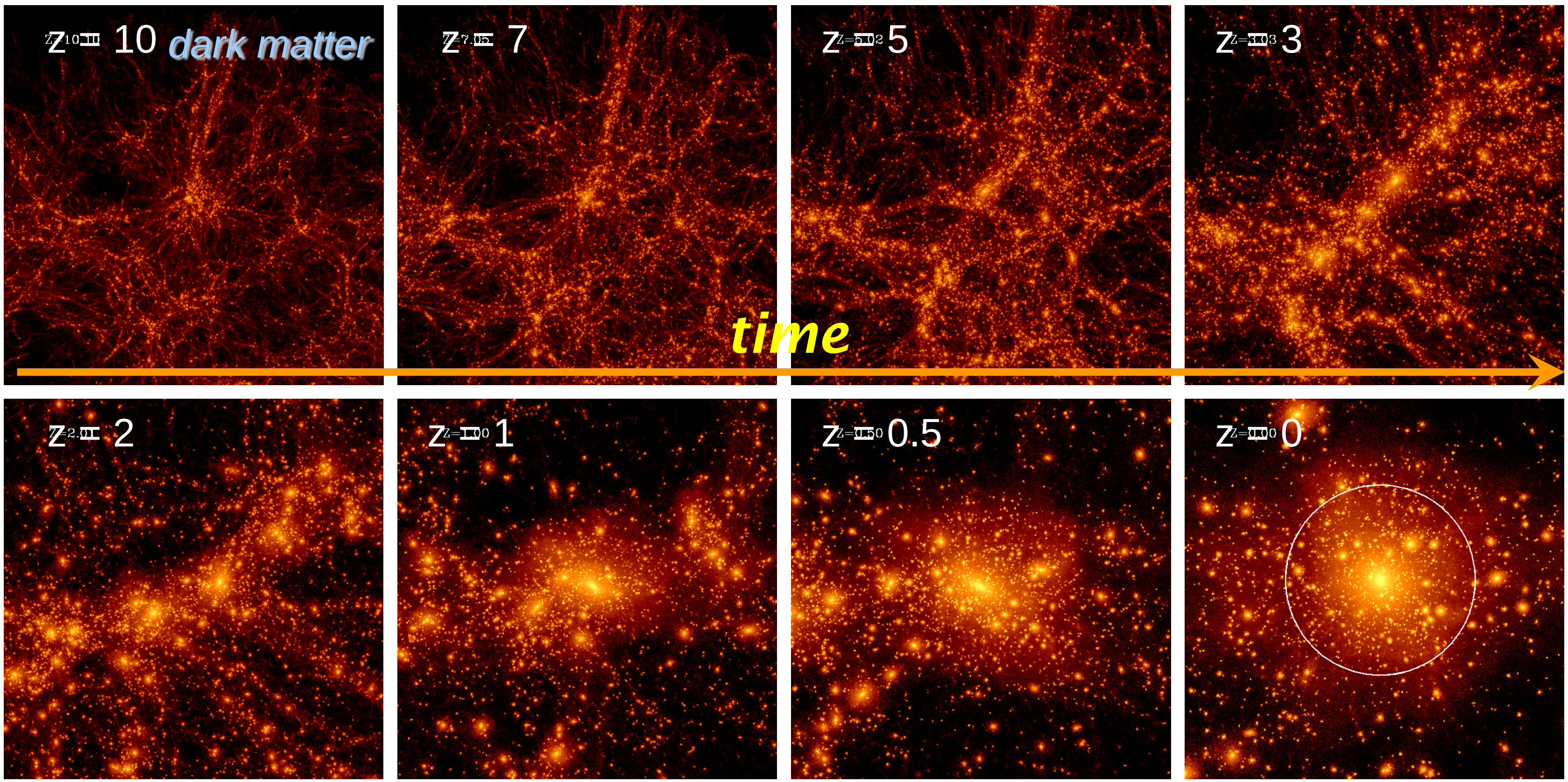
http://www.mpa-garching.mpg.de/galform/virgo/millennium/

Computer simulations vs. real universe



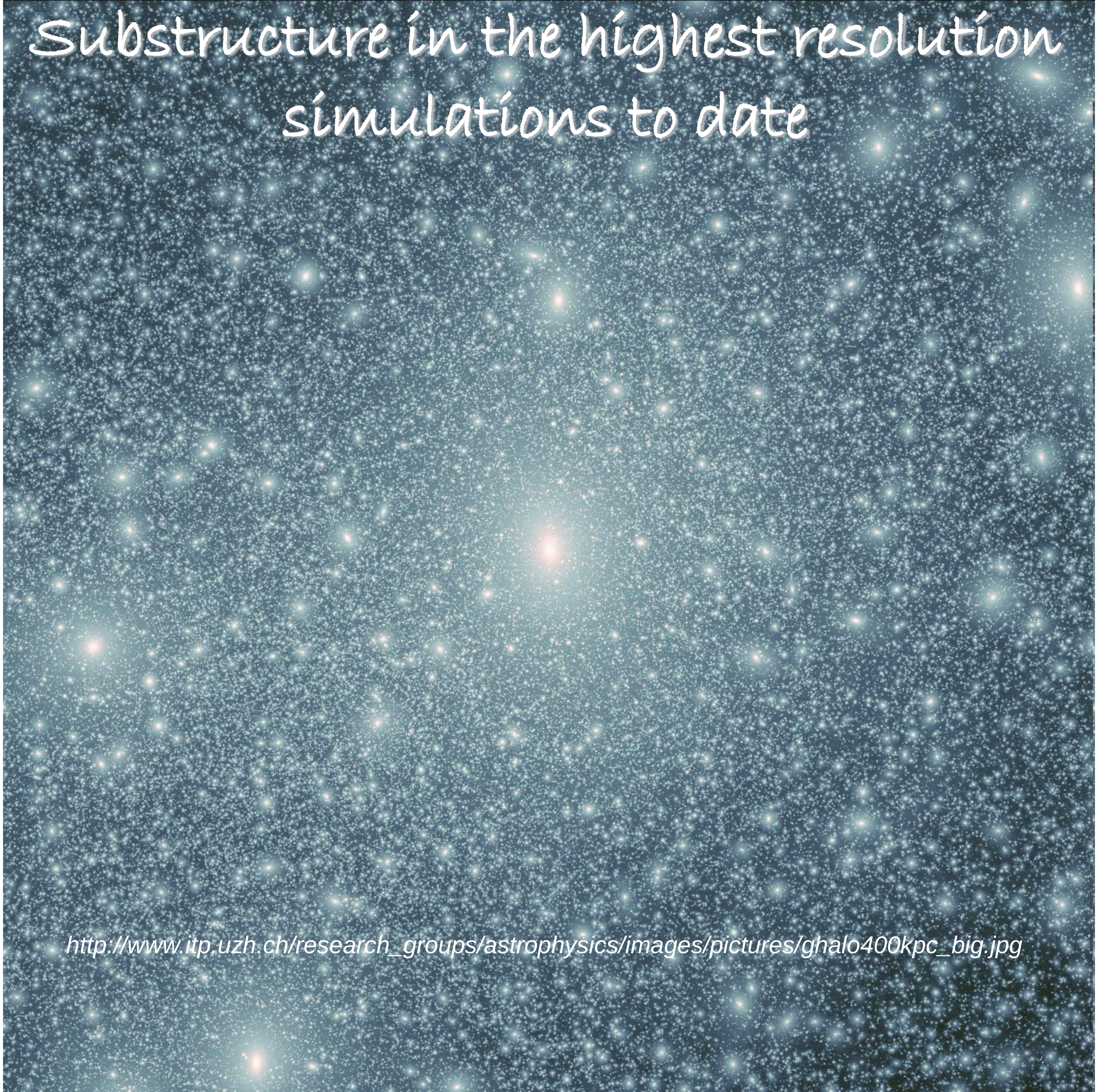
credit: Springel V. et al. 2005, Nature

Hierarchical Formation of halos in the cold dark matter model



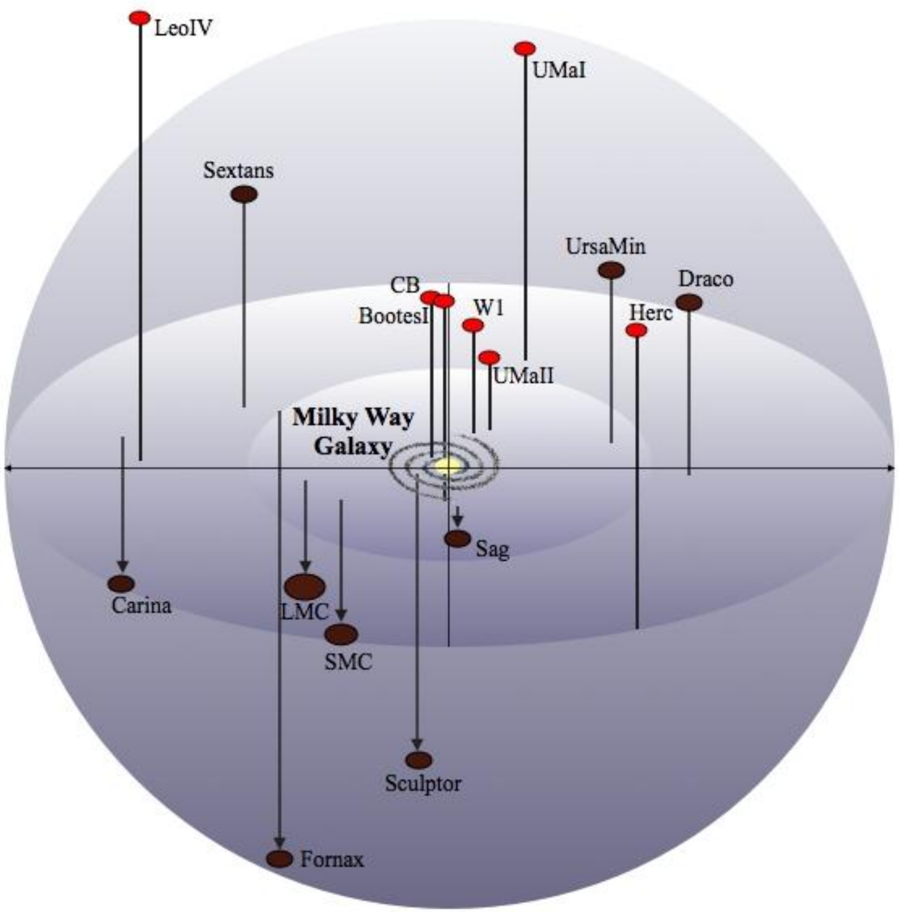
characteristic features: bottom-up build-up of structures and presence of large amount of "substructures" in the forming objects

Substructure in the highest resolution simulations to date

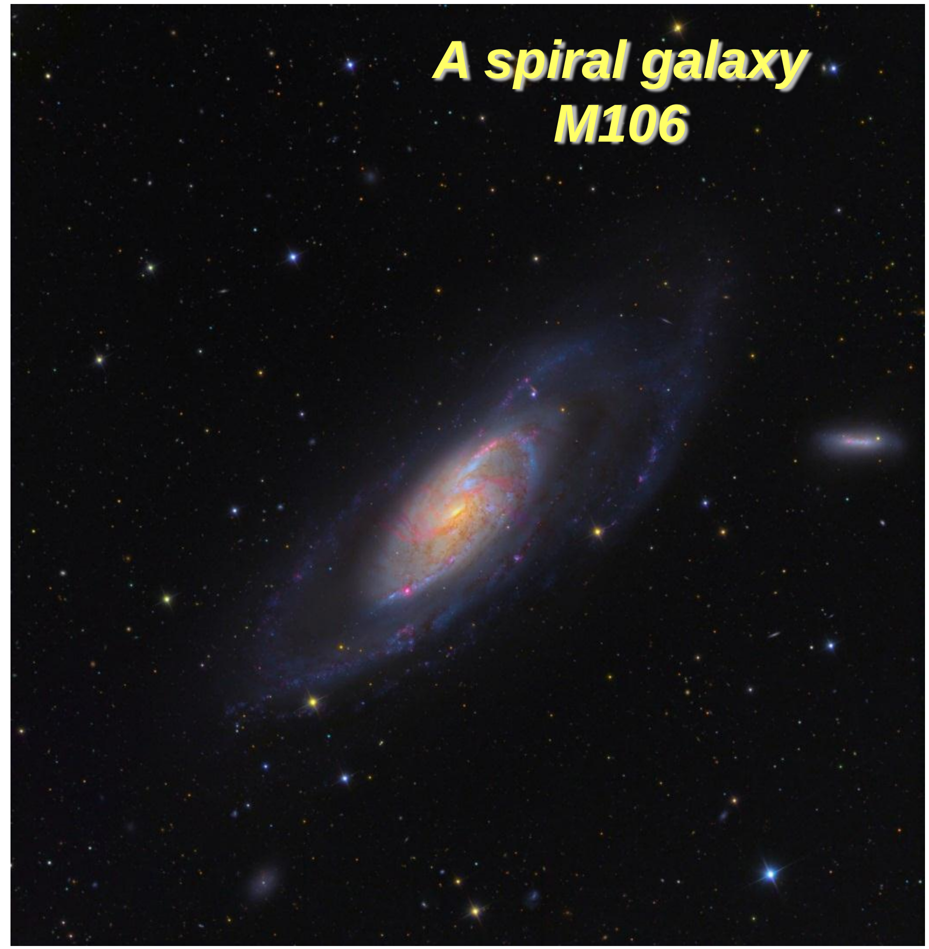


http://www.itp.uzh.ch/research_groups/astrophysics/images/pictures/ghalo400kpc_big.jpg

We do not observe large amounts of substructure in distribution of luminous matter around galaxies

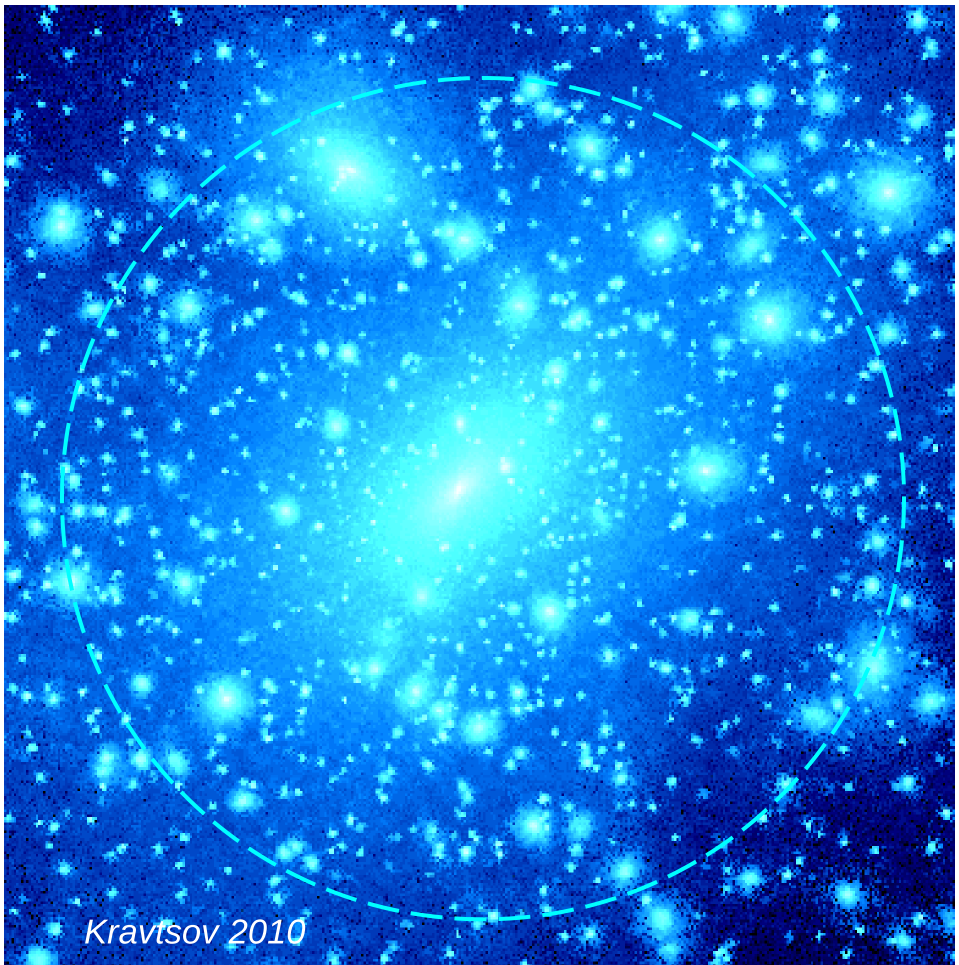


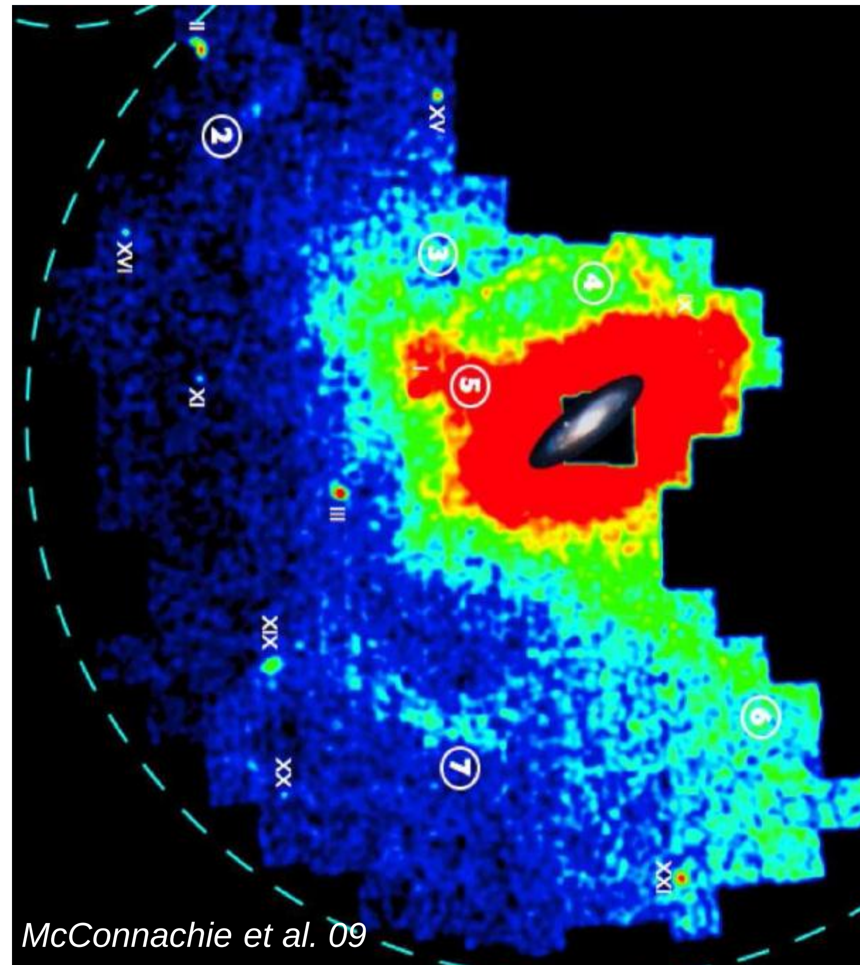
distribution of smaller luminous galaxies around Milky Way



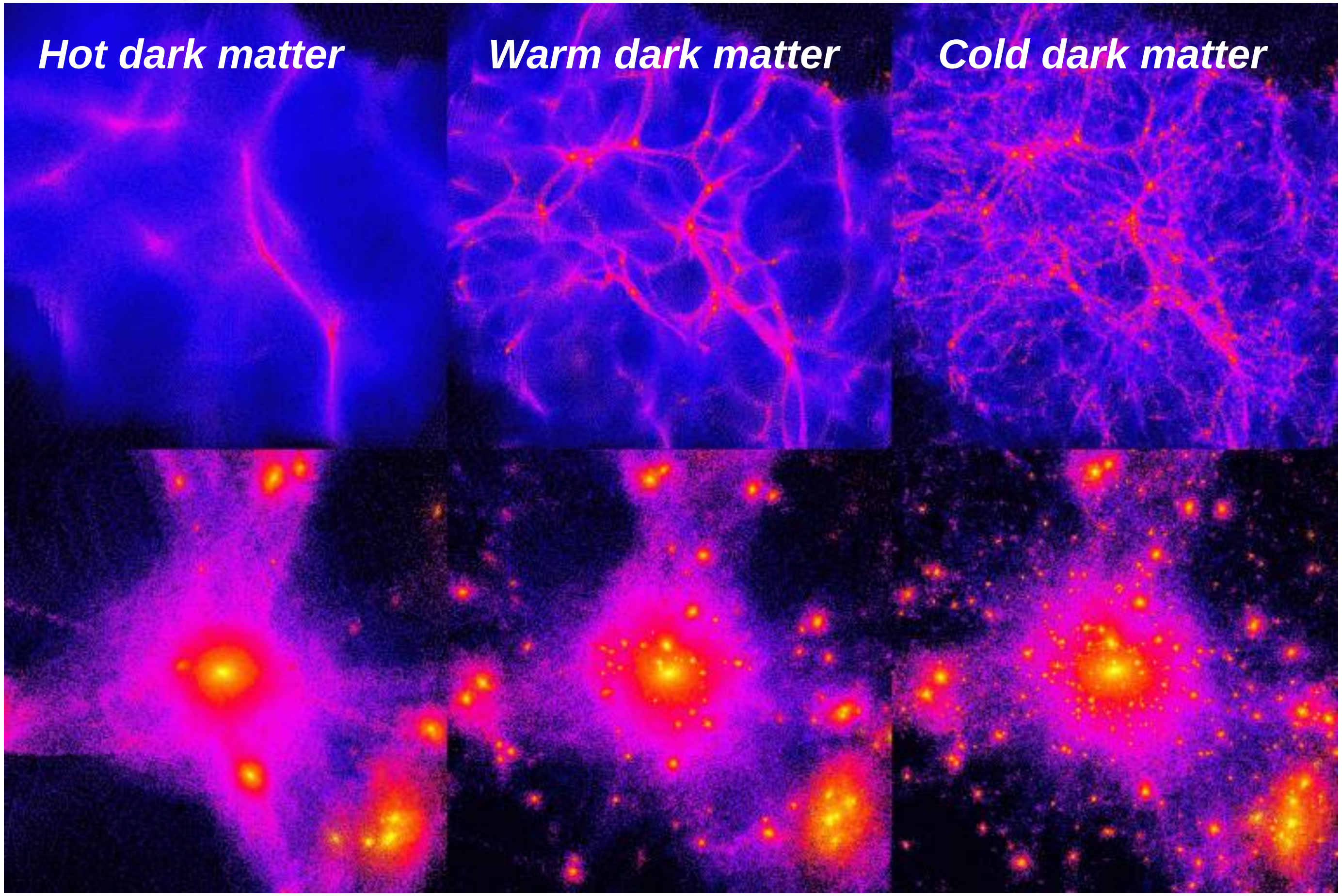
The "substructure problem"

circles show equivalent regions in simulated halo and around M31





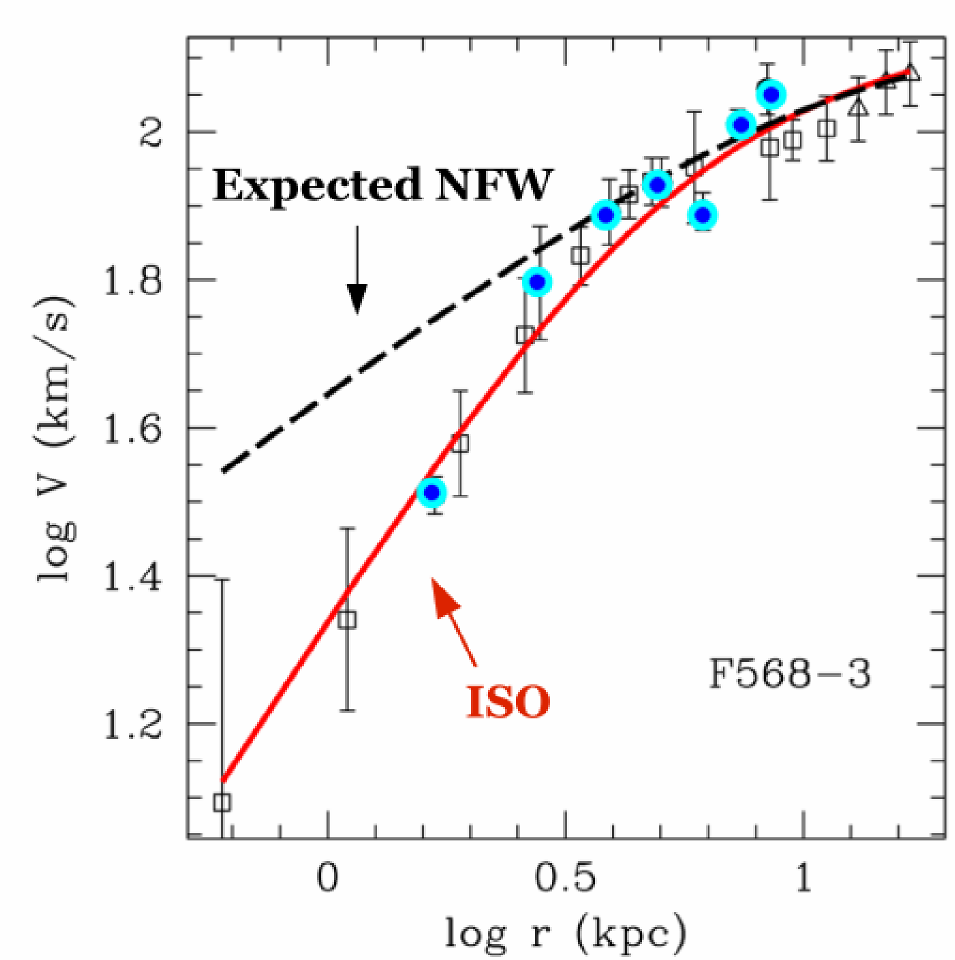
the amount of substructure depends on how cold the dark matter is and this could in principle be part of the solution



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

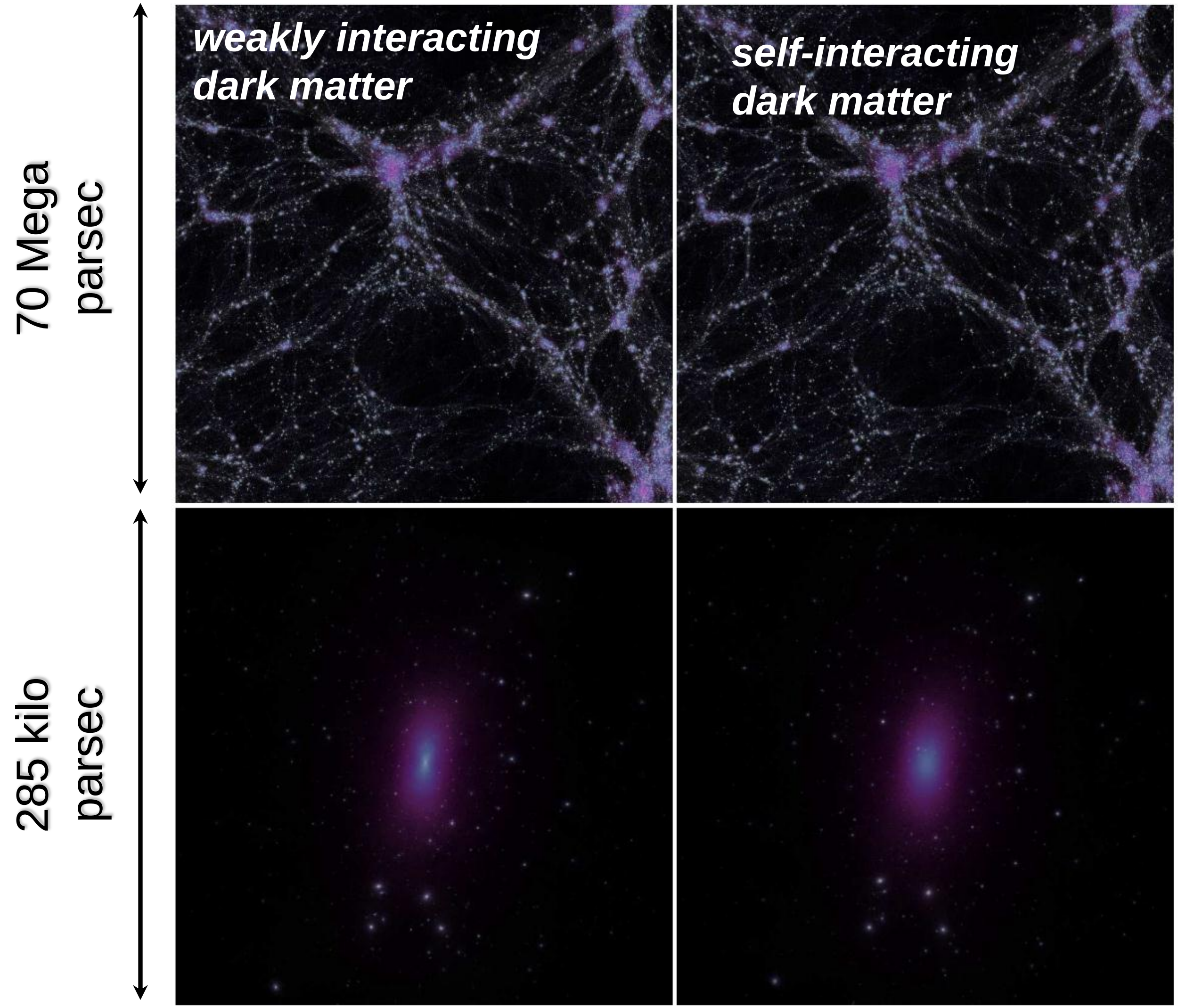
another widely discussed problem: density distribution in the centers of galaxies

slowly rising rotation curves are predicted, but observed rotation curves rise fast



predictions for the central density distribution can be different in models in which dark matter particles interact with each other sufficiently strongly…

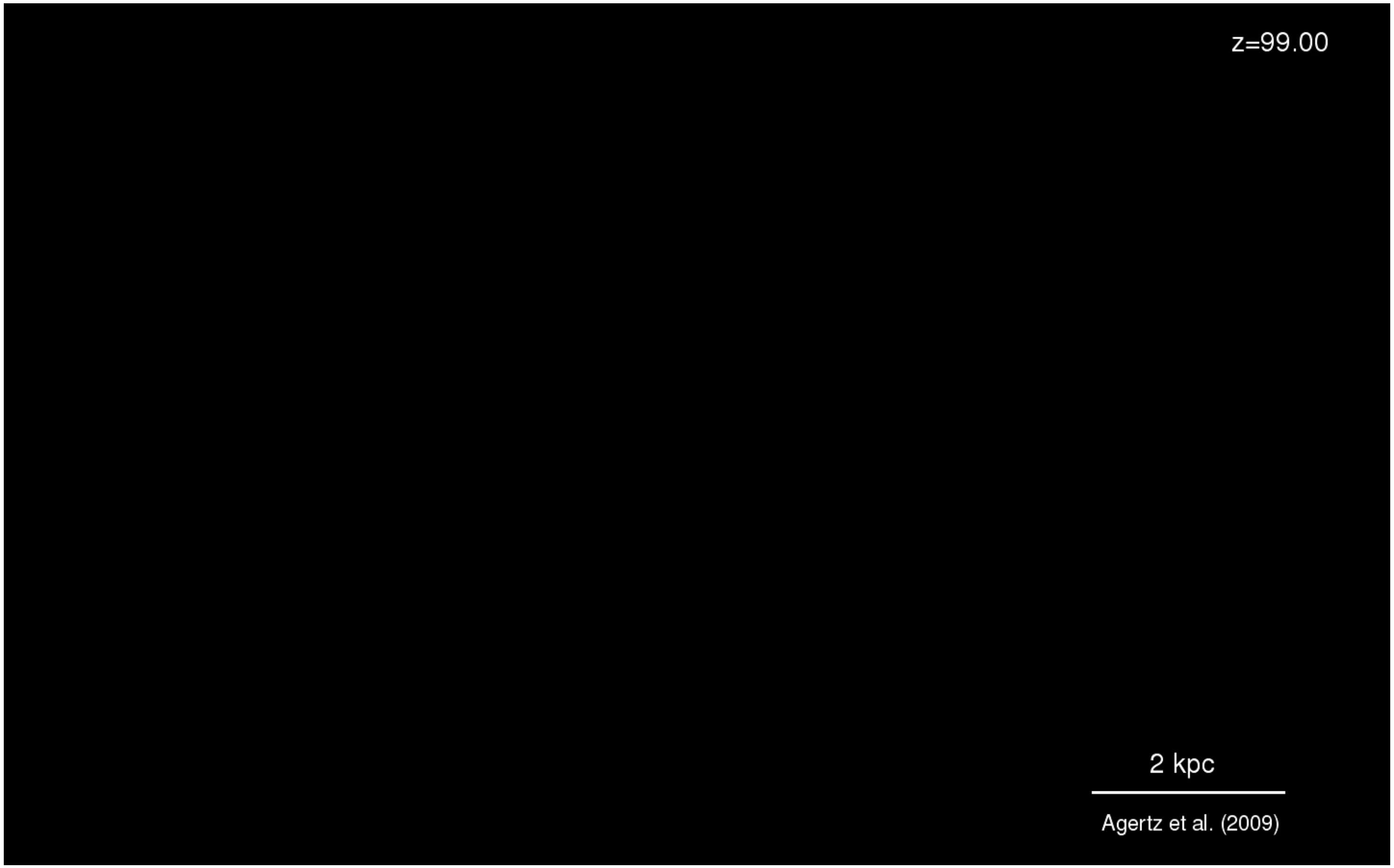
structure formation with WIMPs vs. structure formation with self-interacting dark matter



The figure is from a recent paper by Rocha et al.
http://arxiv.org/pdf/1208.3025.pdf

The current frontier: formation of galaxies in the CDM model

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



credit: Oscar Agertz (KICP fellow)

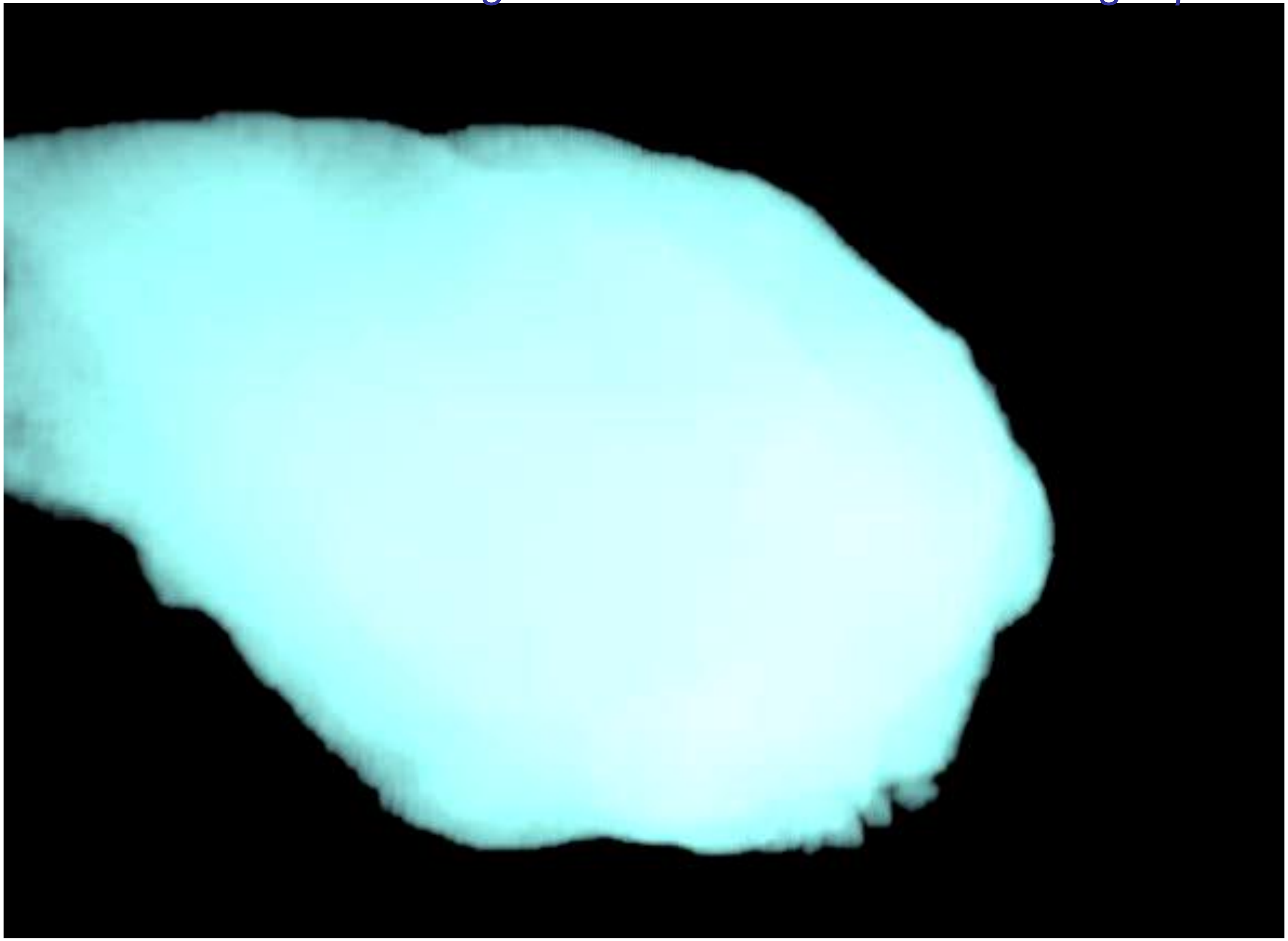
http://www-theorie.physik.unizh.ch/~agertz/CLUMPS/High_resolution_version_of.html

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.***

- ***Much 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 some modifications can be in store (warm dark matter, self-interacting dark matter). Attempts to discover dark matter and identify dark matter particles will be one of the most exciting science stories of the next decade!*