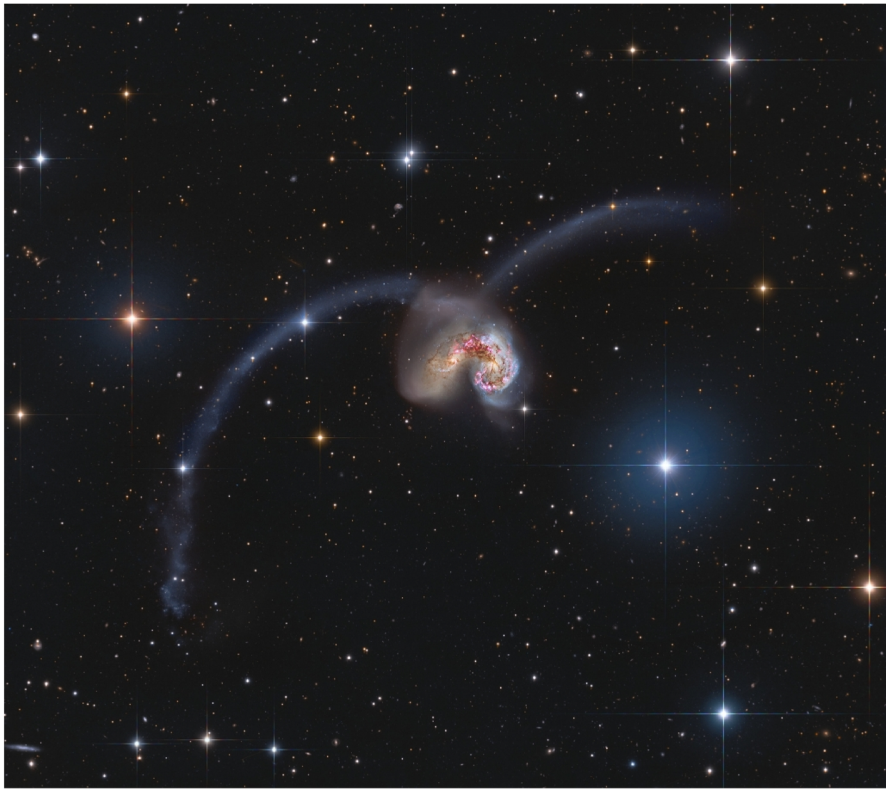
[26] Structure Formation (5/8/18)

Upcoming Items

1. Homework #6 due now.
2. Read Ch. 23.4 for next class and do the self-study quizzes.
3. Exam cover sheet, formula sheet, practice problems are posted
4. Do you want to do your evaluations in-class, or ask astro Qs today?

APOD 4/28/17: NGC 4038/39

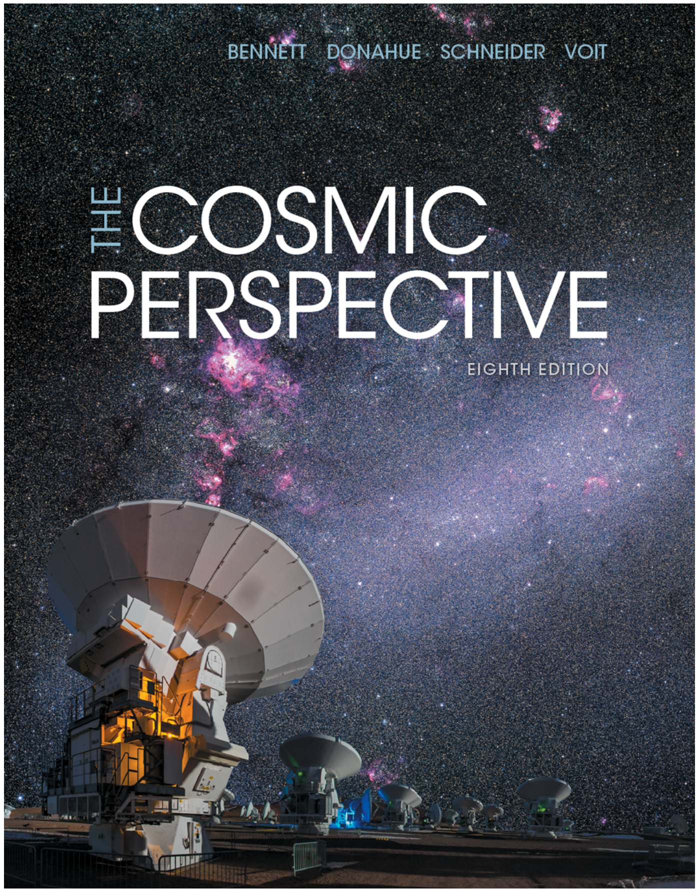


LEARNING GOALS

Ch. 23.3

For this class, you should be able to…

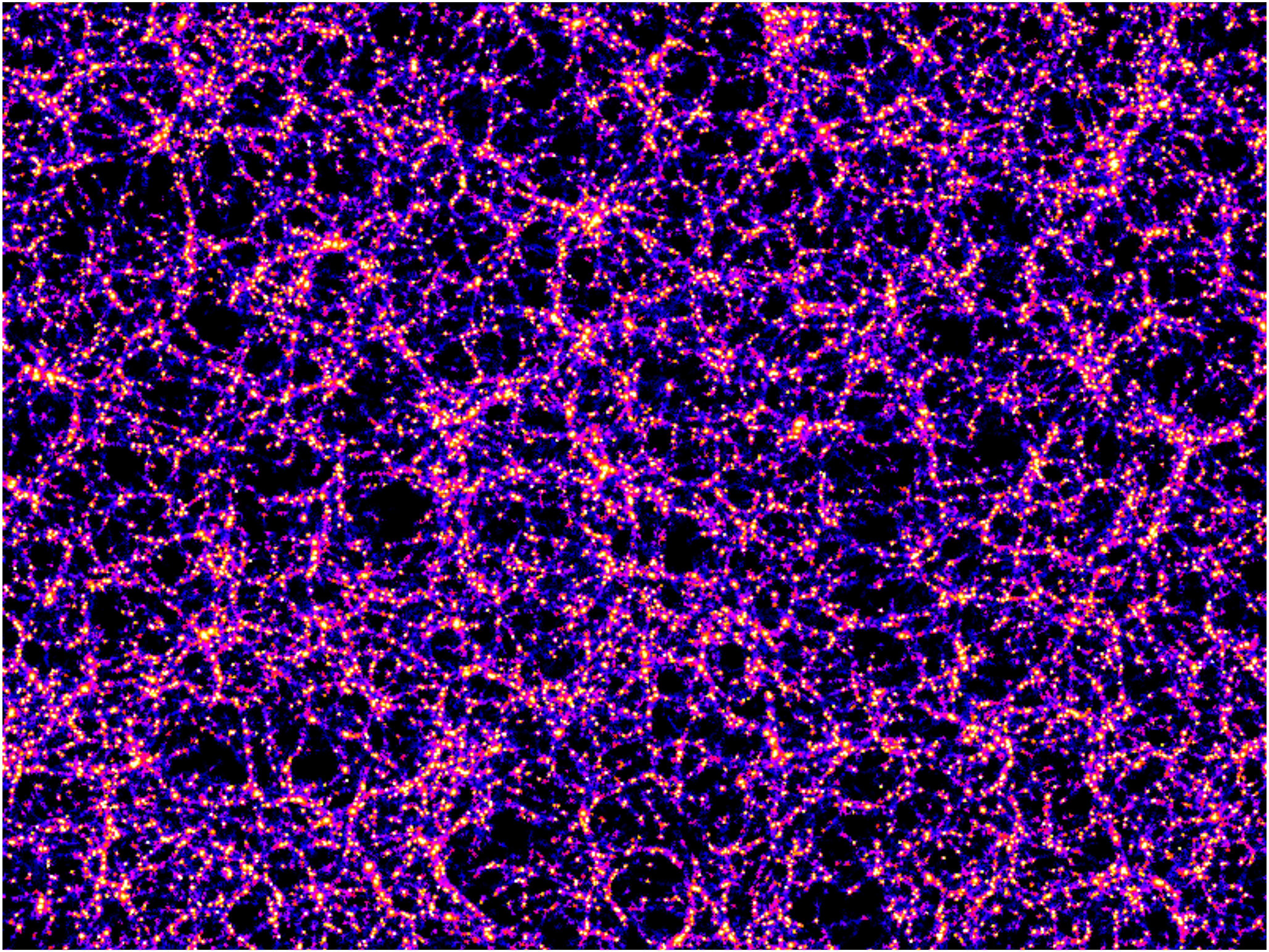
- … *describe the cosmological principles of homogeneity and isotropy and give evidence for the “bottom-up” theory of structure formation in the universe;*
- … *interpret the meaning of a galaxy’s mass-to-light ratio as it relates to the galaxy’s dark-matter content;*
- … *explain a current challenge related to cosmological simulations of structure formation.*



Any astro questions?

Structure Formation

- Observations so far confirm the cosmological principles of homogeneity and isotropy on the largest scales.
- "Bottom-up" theory: galaxies formed first, then clusters.
- Computer simulations that use pressureless dark matter do a pretty good job matching observed large-scale structure.
  - Regions of higher density attract more dark matter.
  - Gas clouds collapse to form galaxies in these regions.
  - Groups of galaxies are still coming together in present day.
- Mass-to-light ratio (M/L): a way of expressing dark-matter content in galaxies (higher M/L ➔ more dark matter).
- Outstanding issue for simulations: predict more galaxy satellites than seen—feedback, or maybe too faint to see?



Cosmological Principles

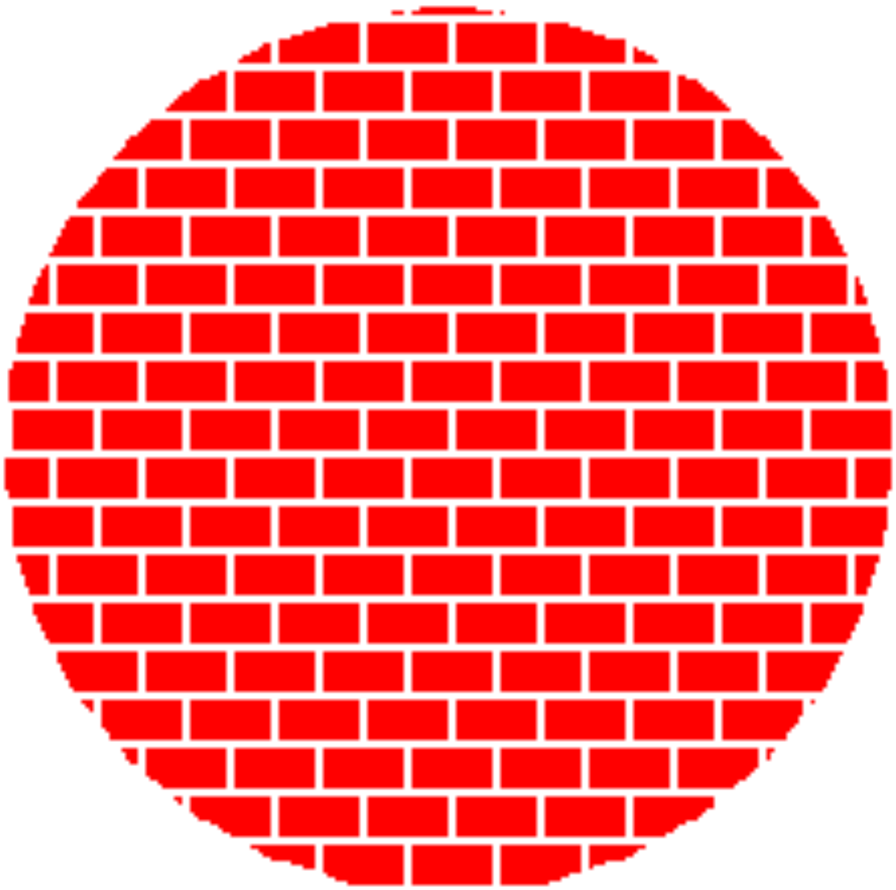
- We make two important *assumptions* about the distribution of matter in the universe. The assumptions are referred to as the **cosmological principles**.

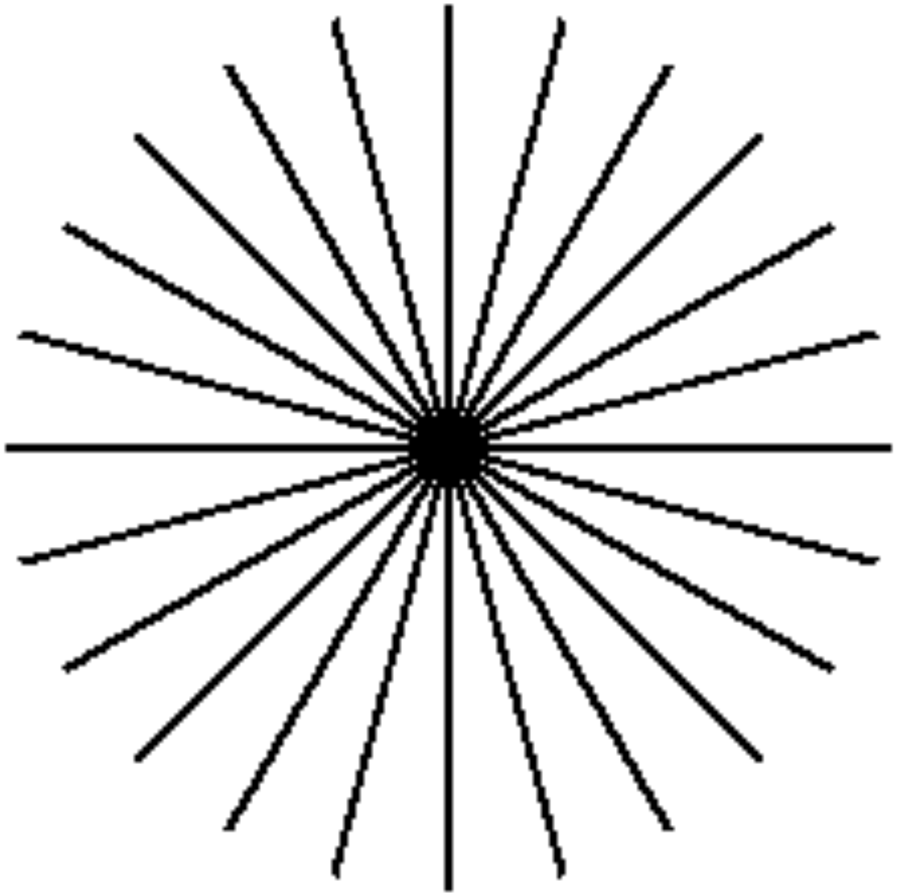
1. The universe is **homogeneous**—every place in the universe has the same average physical conditions as every other place.
   - This is clearly not true on "small scales" (since the universe has structure), but the assumption only applies to large scales.
   - According to this, there can be no center or edge to the universe… gives the **Generalized Copernican Principle** that there are no special points in the universe.
2. The universe is **isotropic**—there is no preferred direction in the universe.

Group Q: Are the principles different?

- We talk about two principles: homogeneity on large scales, and isotropy on large scales.
- But are they different from each other?
- In your groups, please try to come up with:
  An example of homogeneity without isotropy
  An example of isotropy without homogeneity
- Both would be as we see it, i.e., we see homogeneity in the first case, we see isotropy in the second case

Homogeneity vs. Isotropy





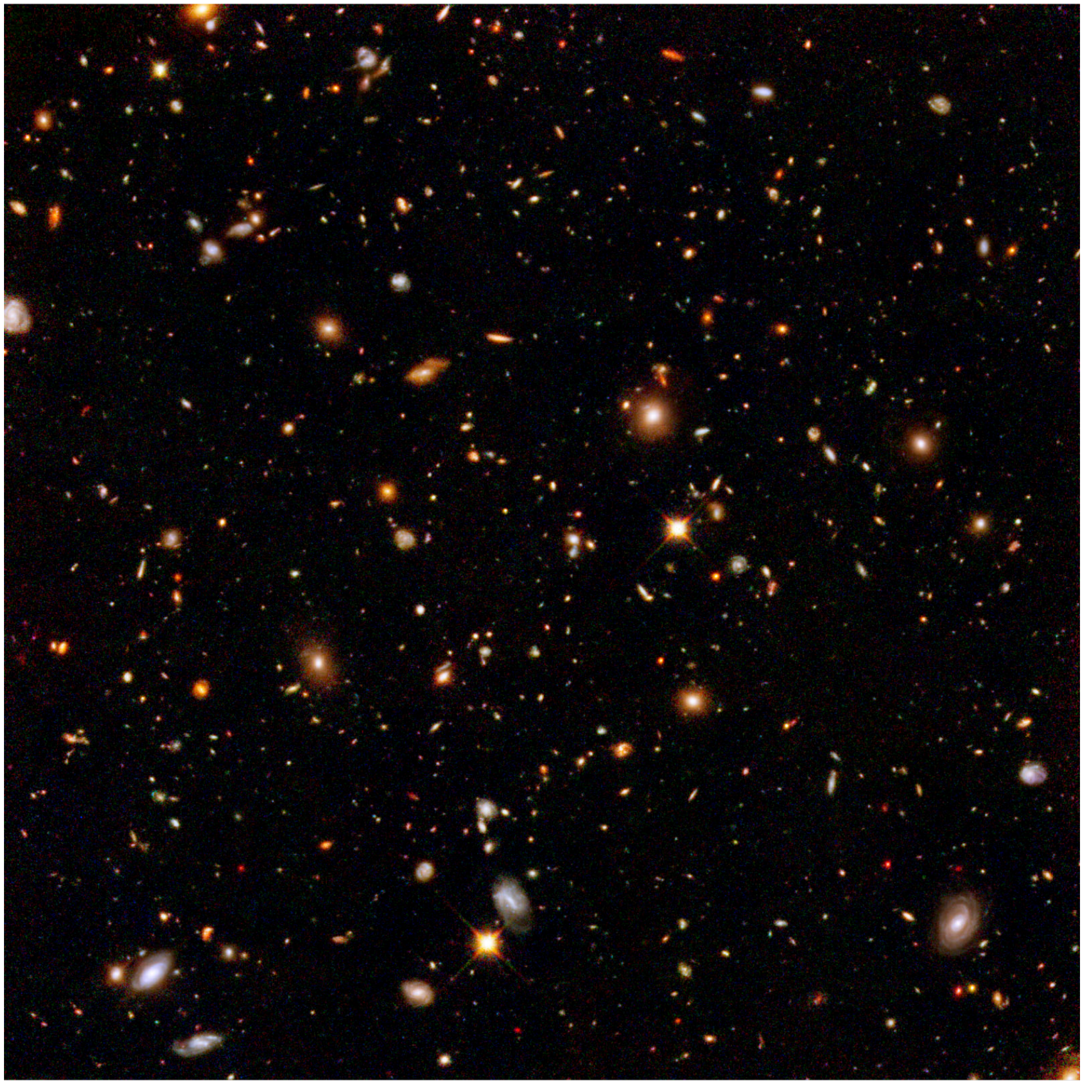
Left: homogeneous but not isotropic. Right: isotropic but not homogeneous.
From http://www.astro.ucla.edu/~wright/cosmo_01.htm

Cosmological Principles

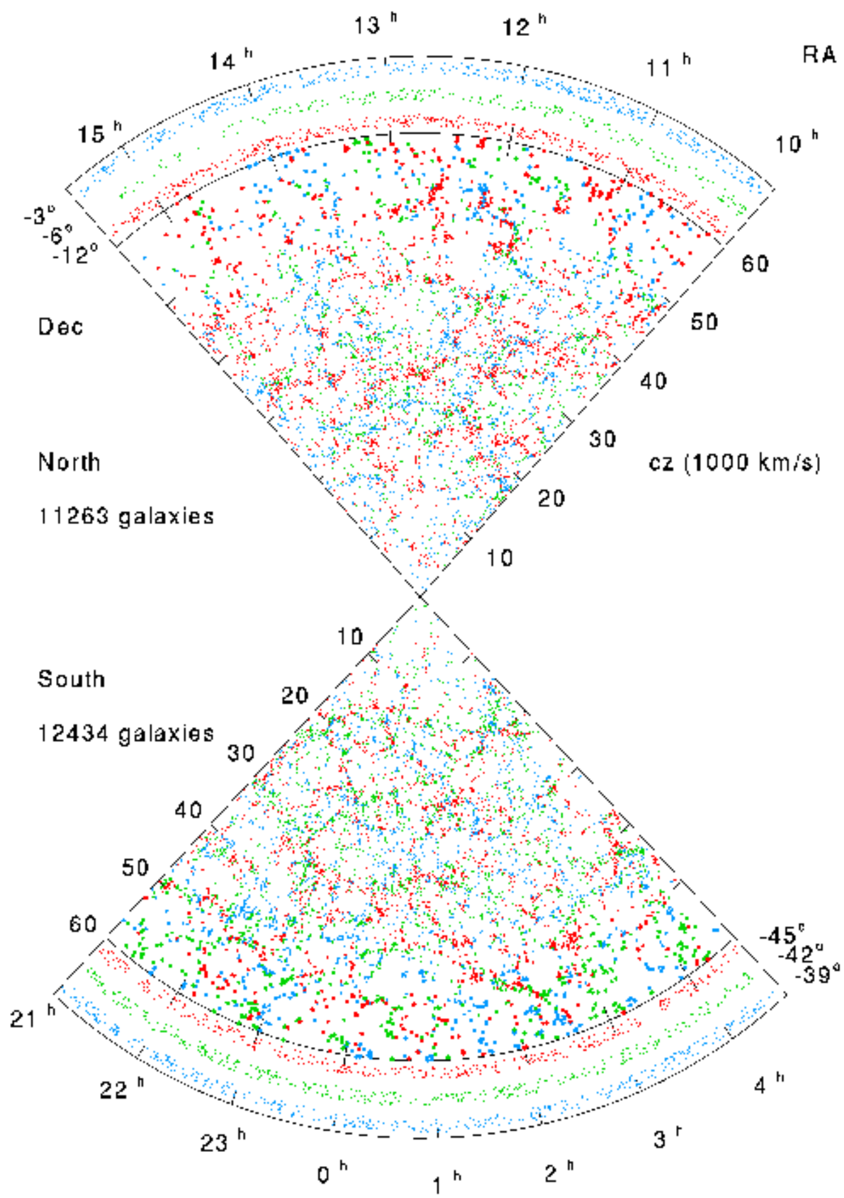
The universe looks about the same no matter where you are within it.

- Matter is evenly distributed on very large scales in the universe.
- The universe has no center or edges.

- The cosmological principle has not been proven beyond a doubt, but it is consistent with all observations to date.



Universe looks the same no matter which direction we look…



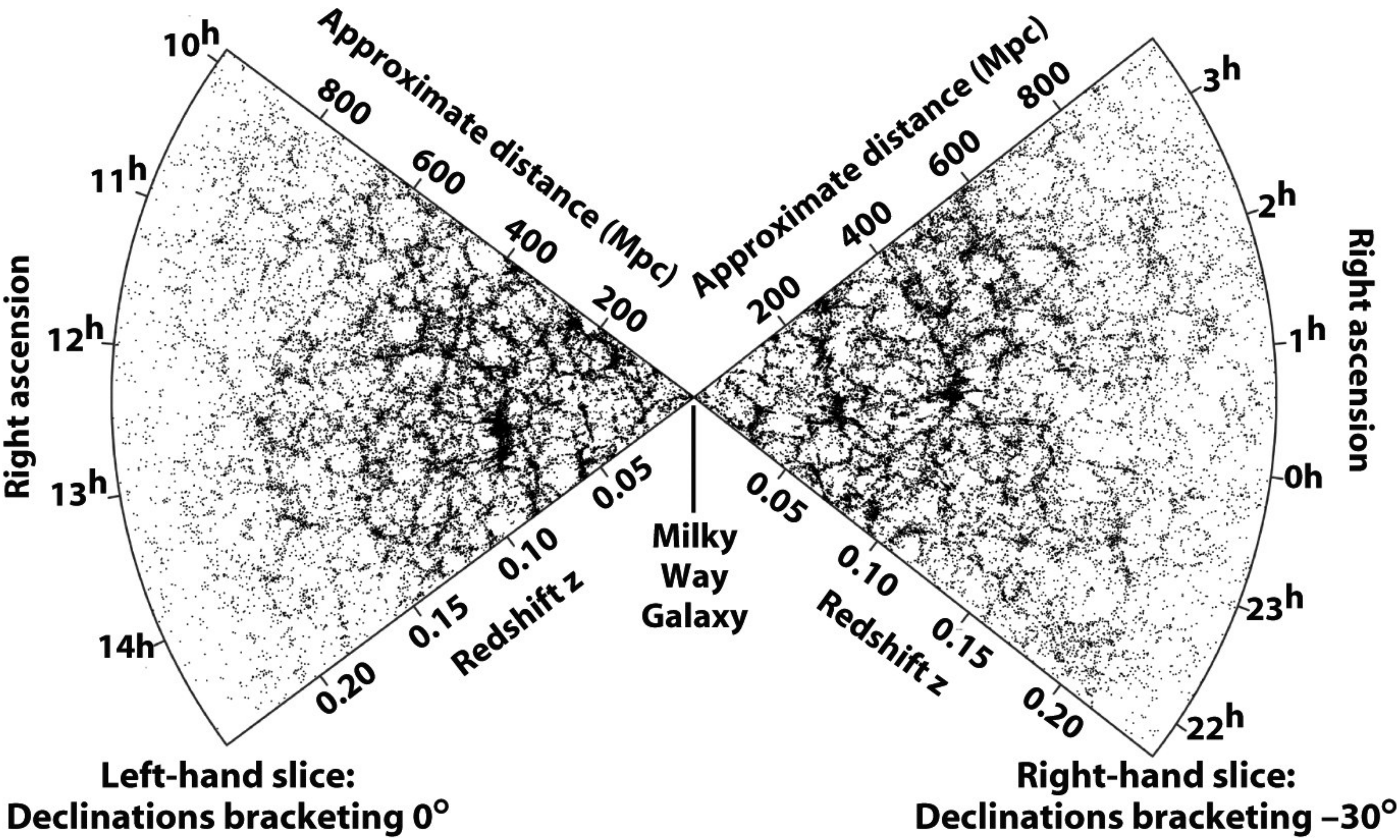
Las Campanas Redshift survey: this is (almost) a map of galaxies in our part of the universe.

On large scales, you can see that it is approximately homogeneous.

Measuring Matter Distributions

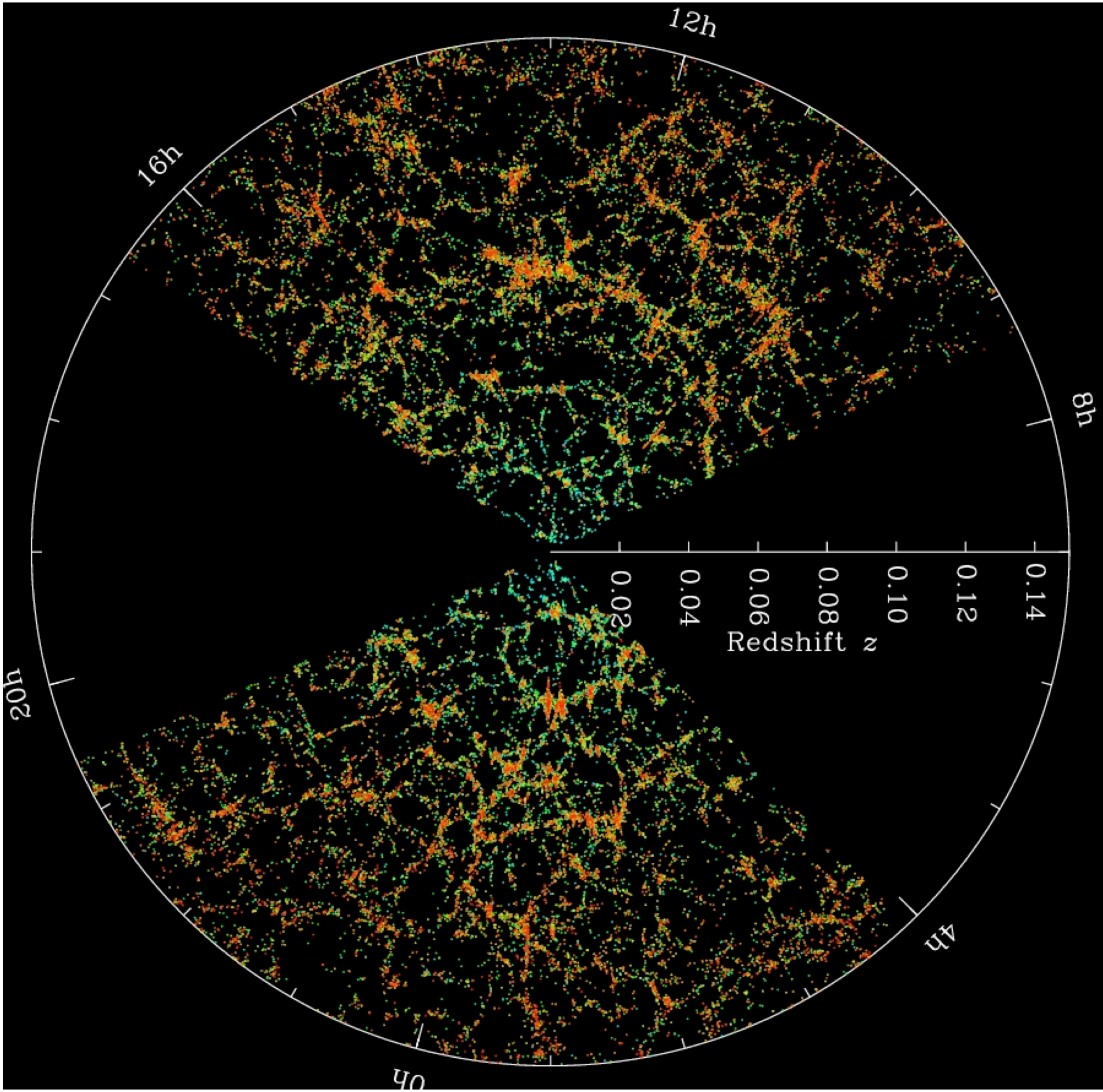
1. Galaxy counts.
   - Gives distribution of galaxies (stars) in space.
2. Weak gravitational lensing (and other techniques).
   - Gives distribution of total matter, which is mostly dark matter.
3. Quasar absorption lines (Lyman-α forest).
   - Gives distribution of atomic hydrogen gas (H I).

Each technique gives consistent results for how matter is distributed in the universe: filaments, sheets, and voids.



The 2dF galaxy survey

(62,559 galaxies)



Sloan Digital Sky survey, out to 2 billion light-years.

Other Key Observations

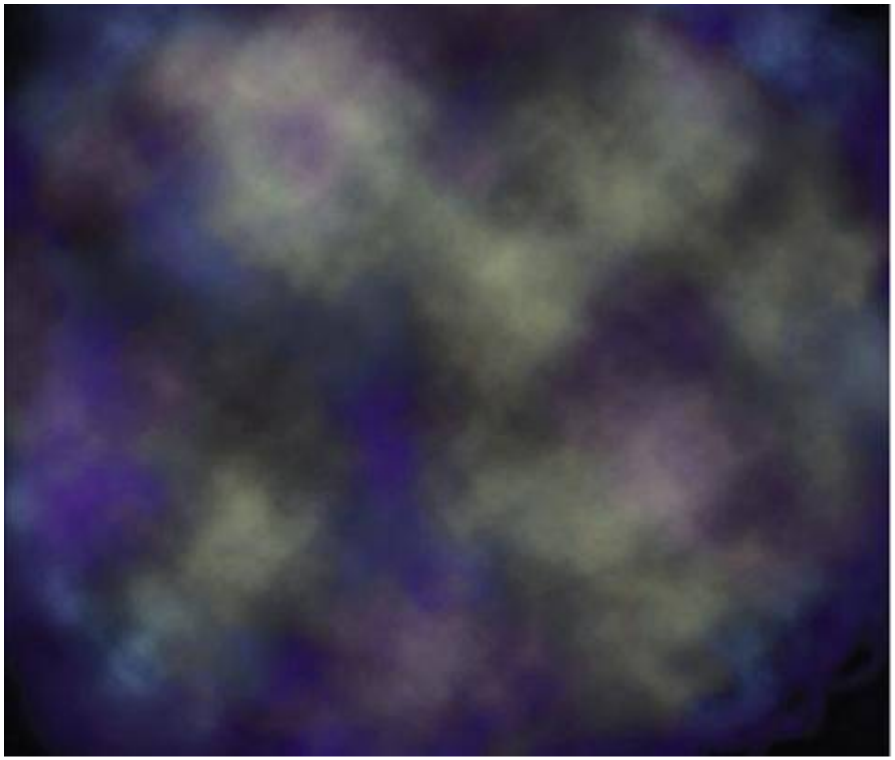
1. Very distant ellipticals ($z = 1$) still have old, red stars. Ellipticals must have formed very early.
2. Even globular clusters in the Milky Way have stars that are >10 Gyr old. Some formed within the first Gyr.
3. There are lots of bright blue galaxies at high redshift, implying enhanced star formation. In fact, the star formation rate has dropped over the last ~5 Gyr.
4. There are lots of interacting galaxies at high z, and many quasar host galaxies look perturbed, feeding a central supermassive black hole.

Theoretical Interpretation

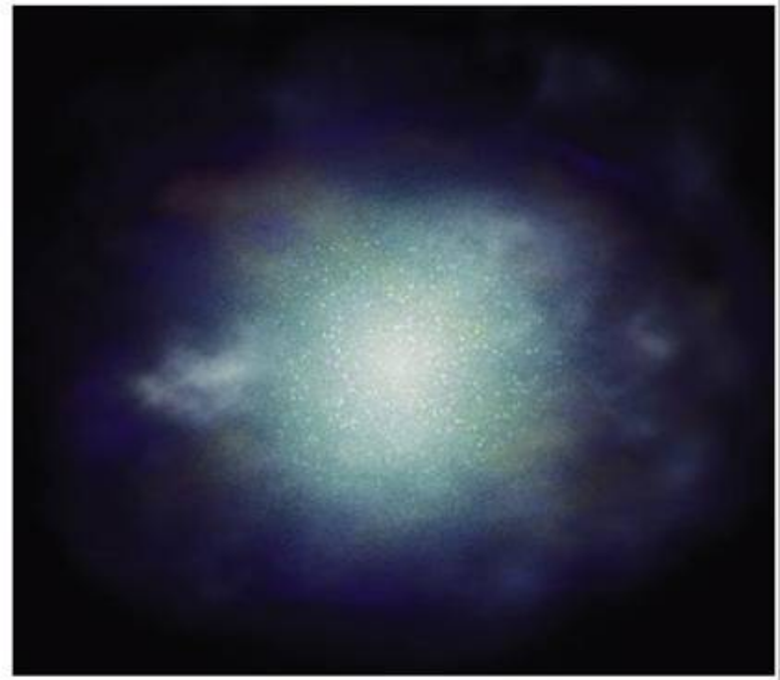
- Initially, density of universe was very uniform, but had very small perturbations. These perturbations grew to form structures we see today.
- Large scale: filaments, sheets, voids.
- Small scale: clusters of galaxies, individual galaxies.

Bottom-up Theory

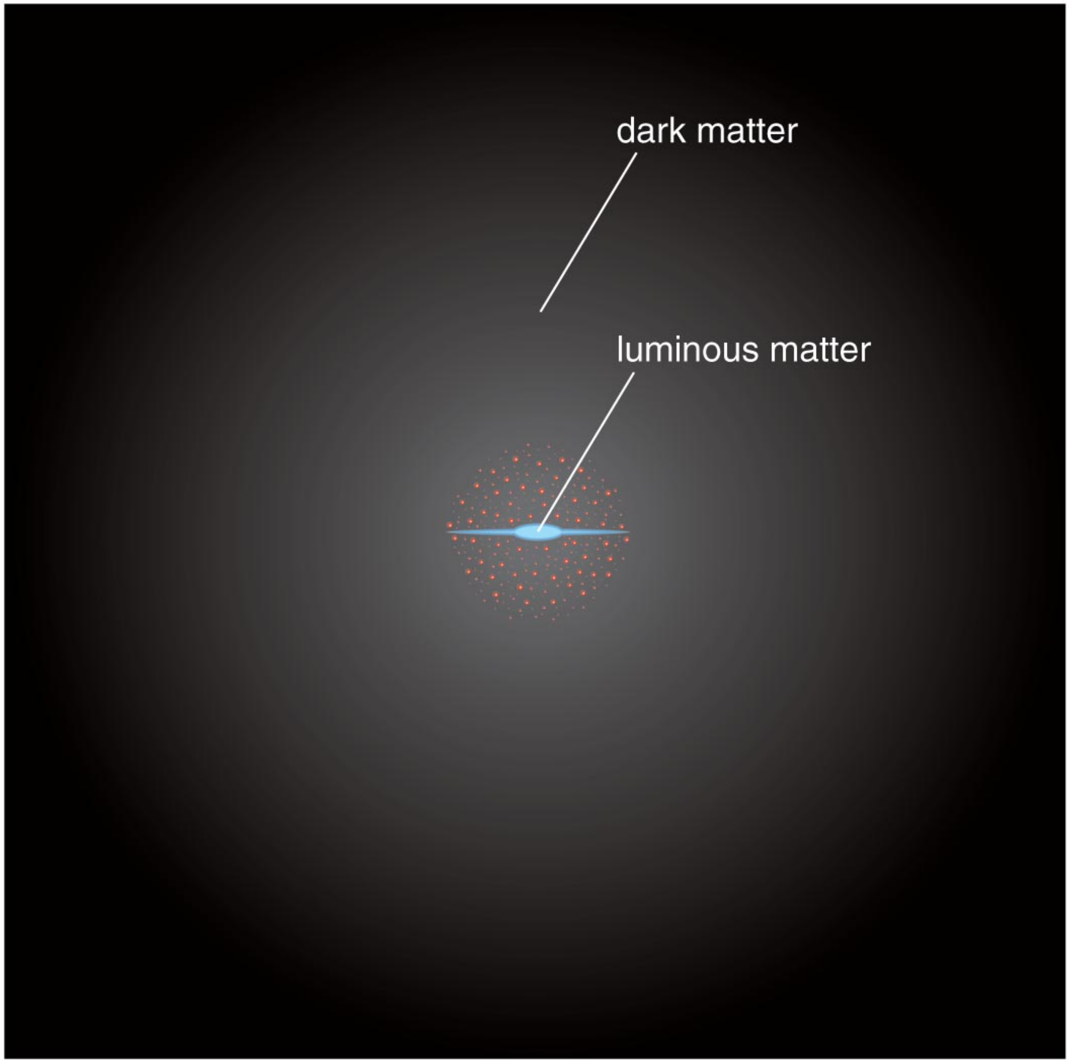
- Galaxies form first, collect into clusters; clusters collect into superclusters.
- Fits observations:
  1. Lots of star formation at high z.
  2. Lots of interacting galaxies at high z.
  3. Clusters of galaxies are recent: we see merging at $z = 0.5$.



$\Rightarrow$

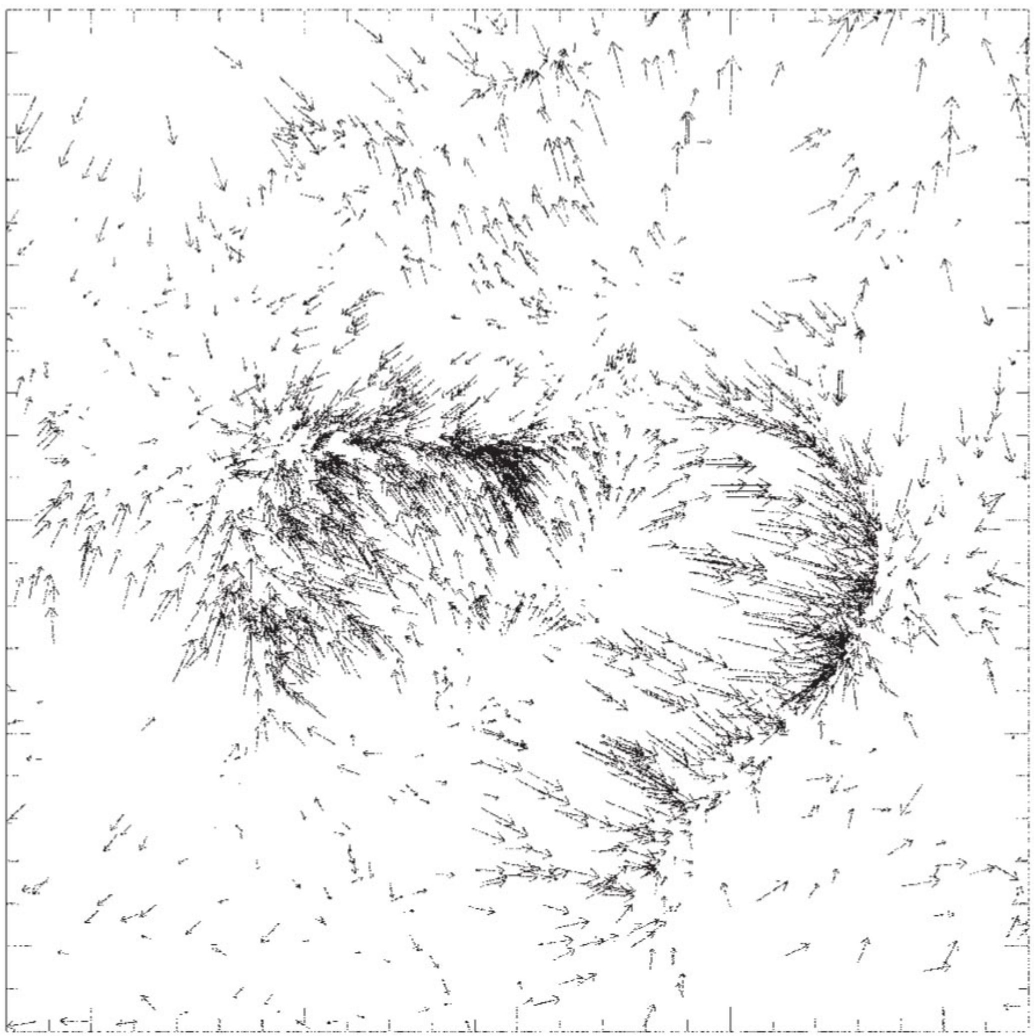


Gravity of dark matter is what caused protogalactic clouds (gas) to contract early in time.



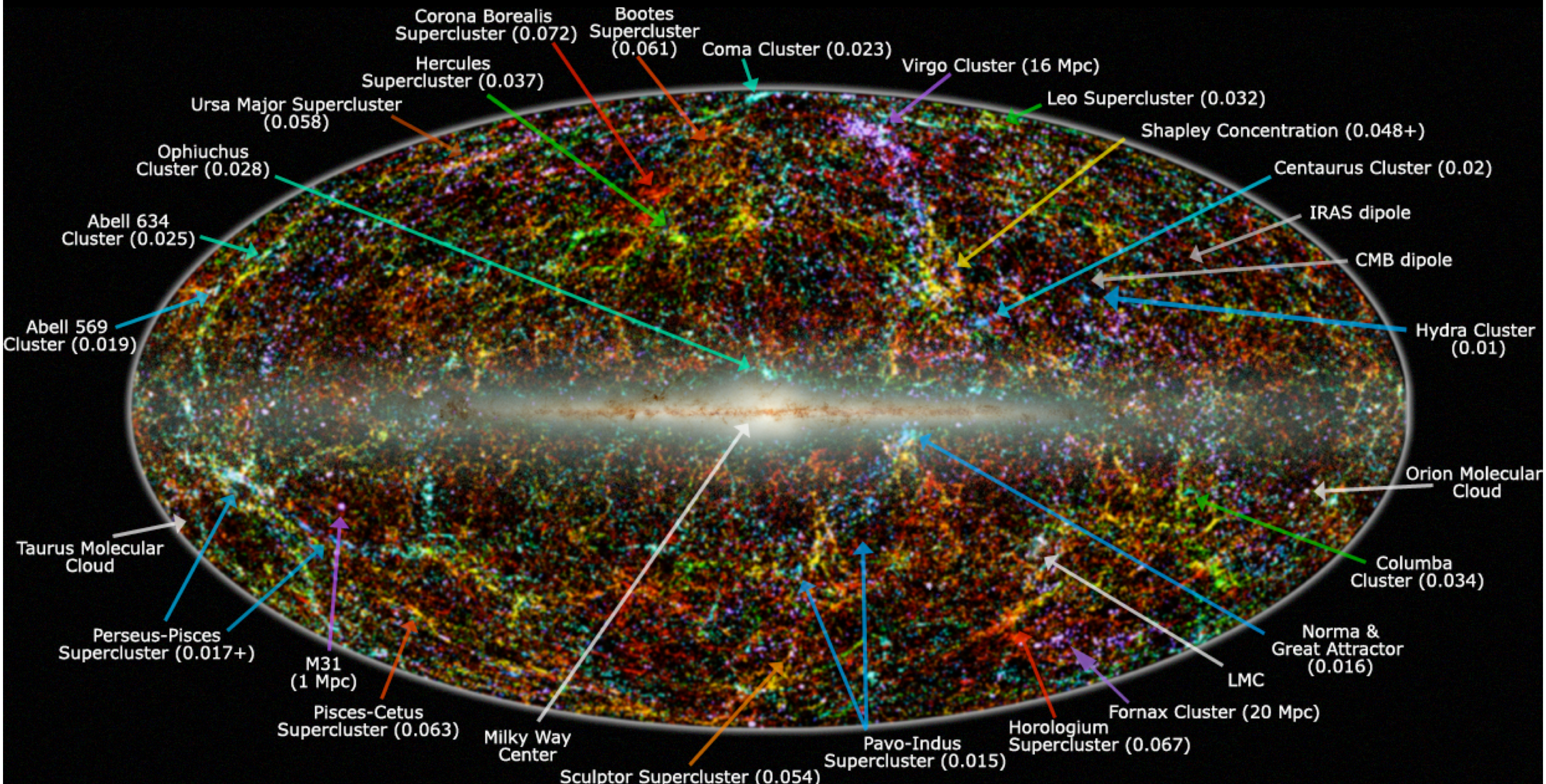
Dark matter can't collapse to the center because it doesn't radiate away its orbital energy.

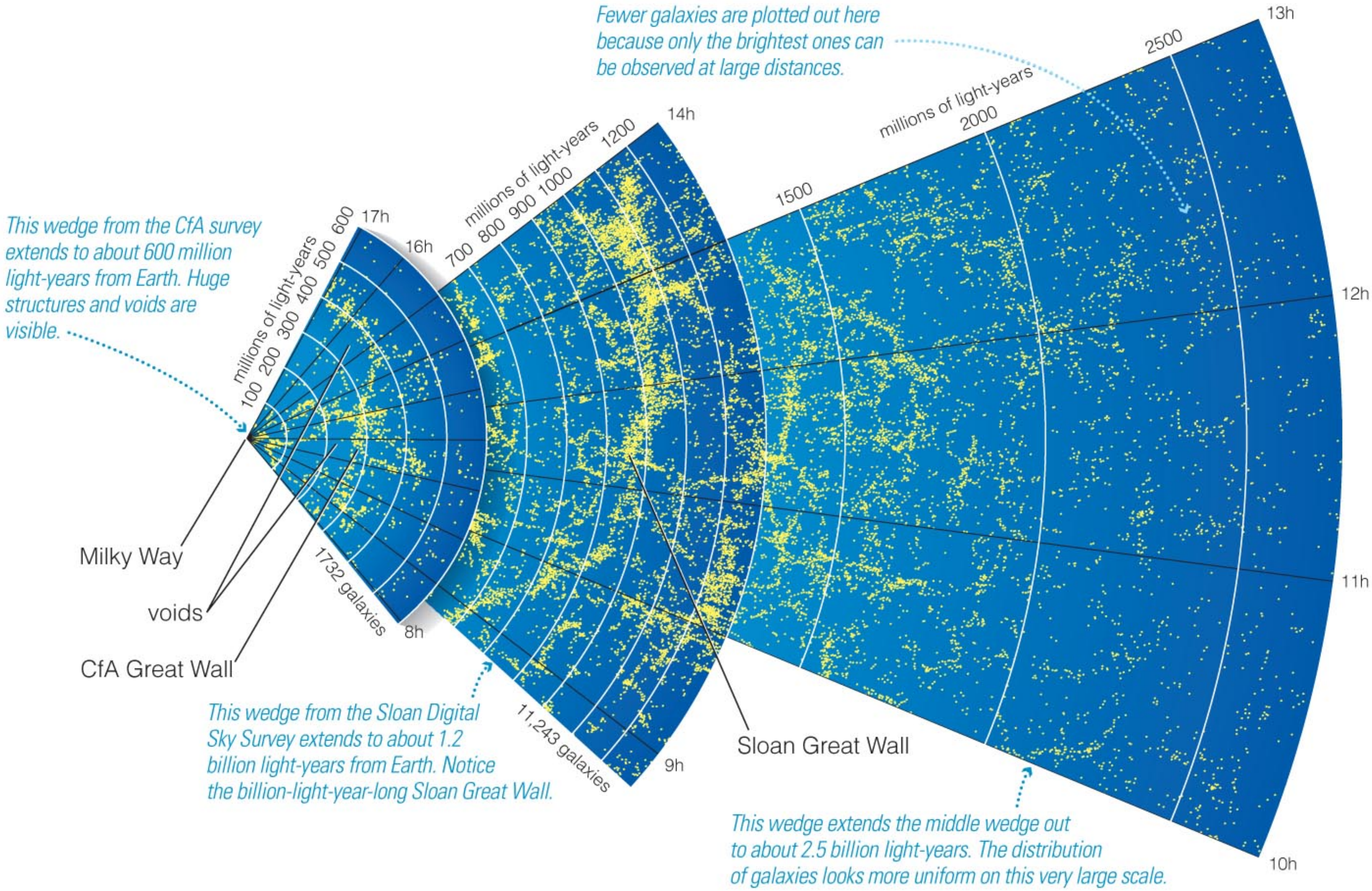
~ 600 Mly



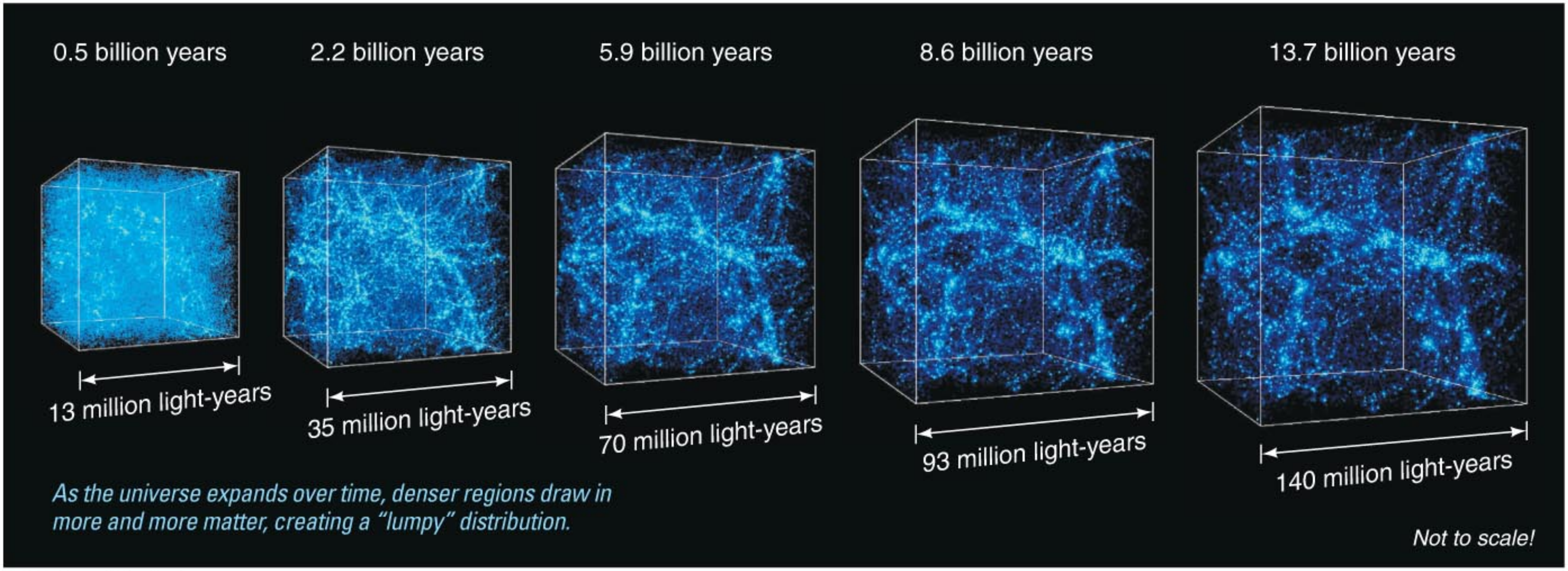
- Dark matter is still pulling things together.
- After correcting for Hubble's law, we can see that galaxies are flowing toward the densest regions of space.

Legend (2MASS XSC): cyan $z < 0.01$ green $0.01 < z < 0.04$ red $0.04 < z < 0.1$

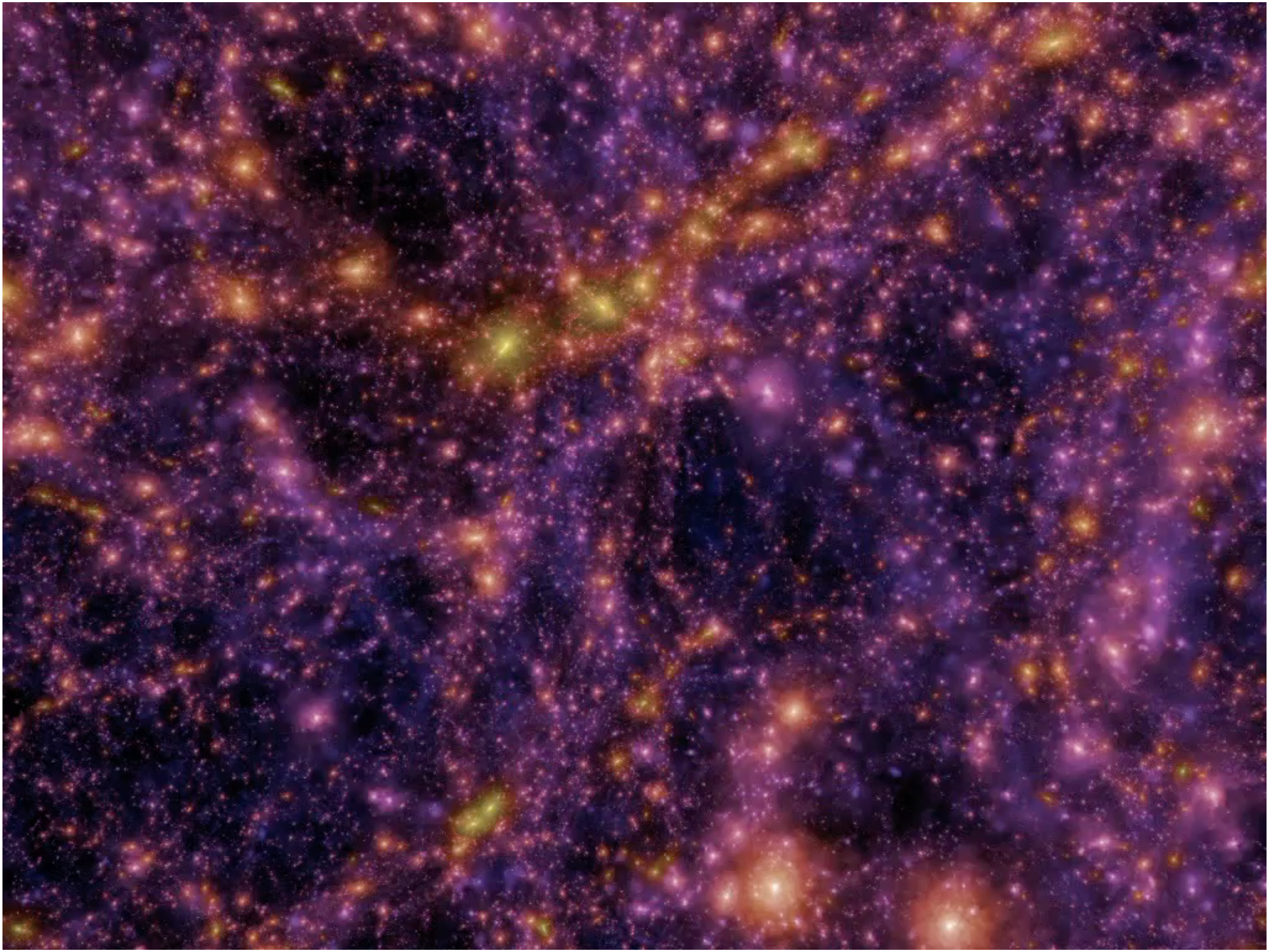


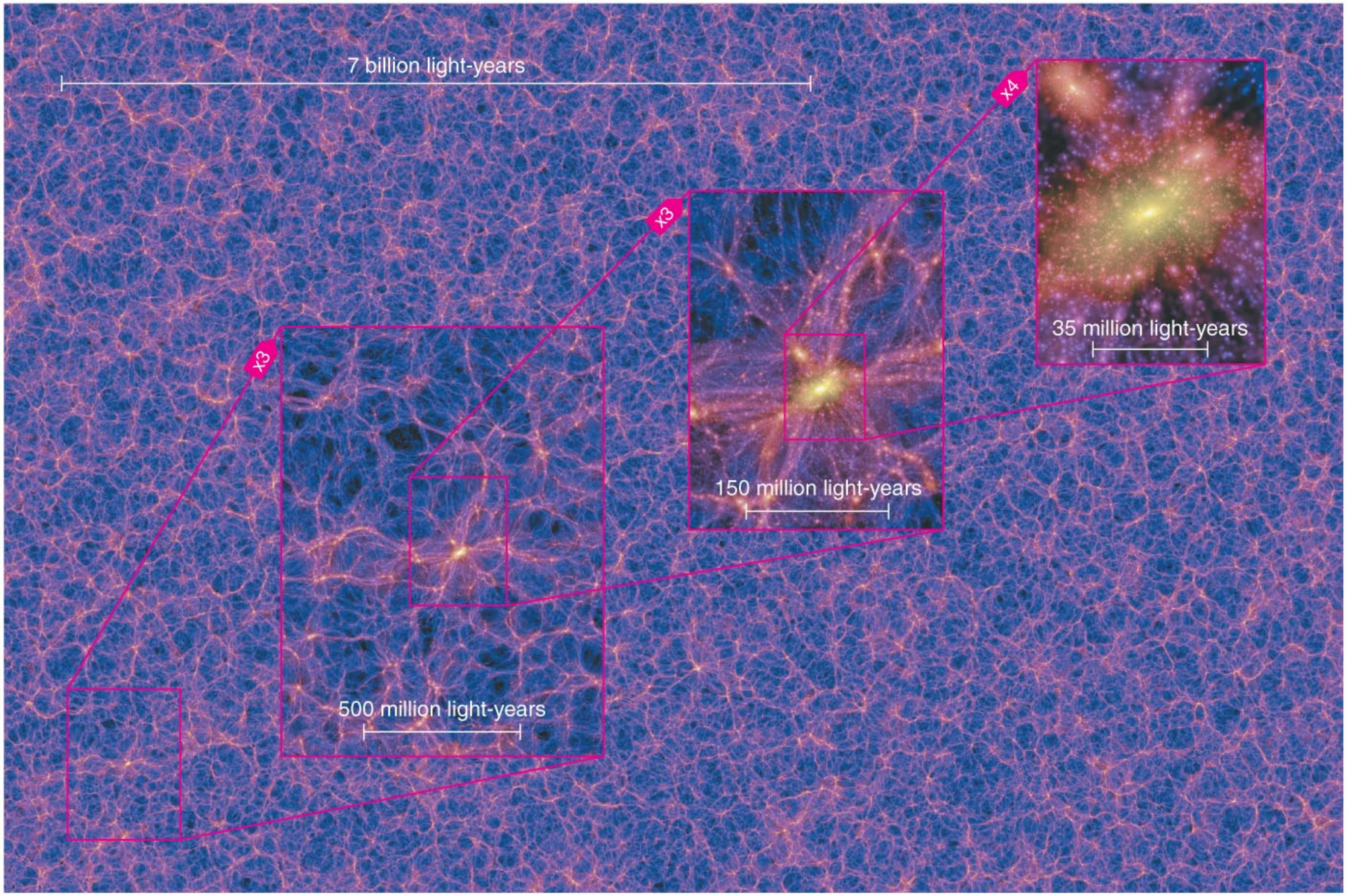


Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids***.



Models show that gravity of dark matter pulls mass into denser regions—the universe grows lumpier with time.

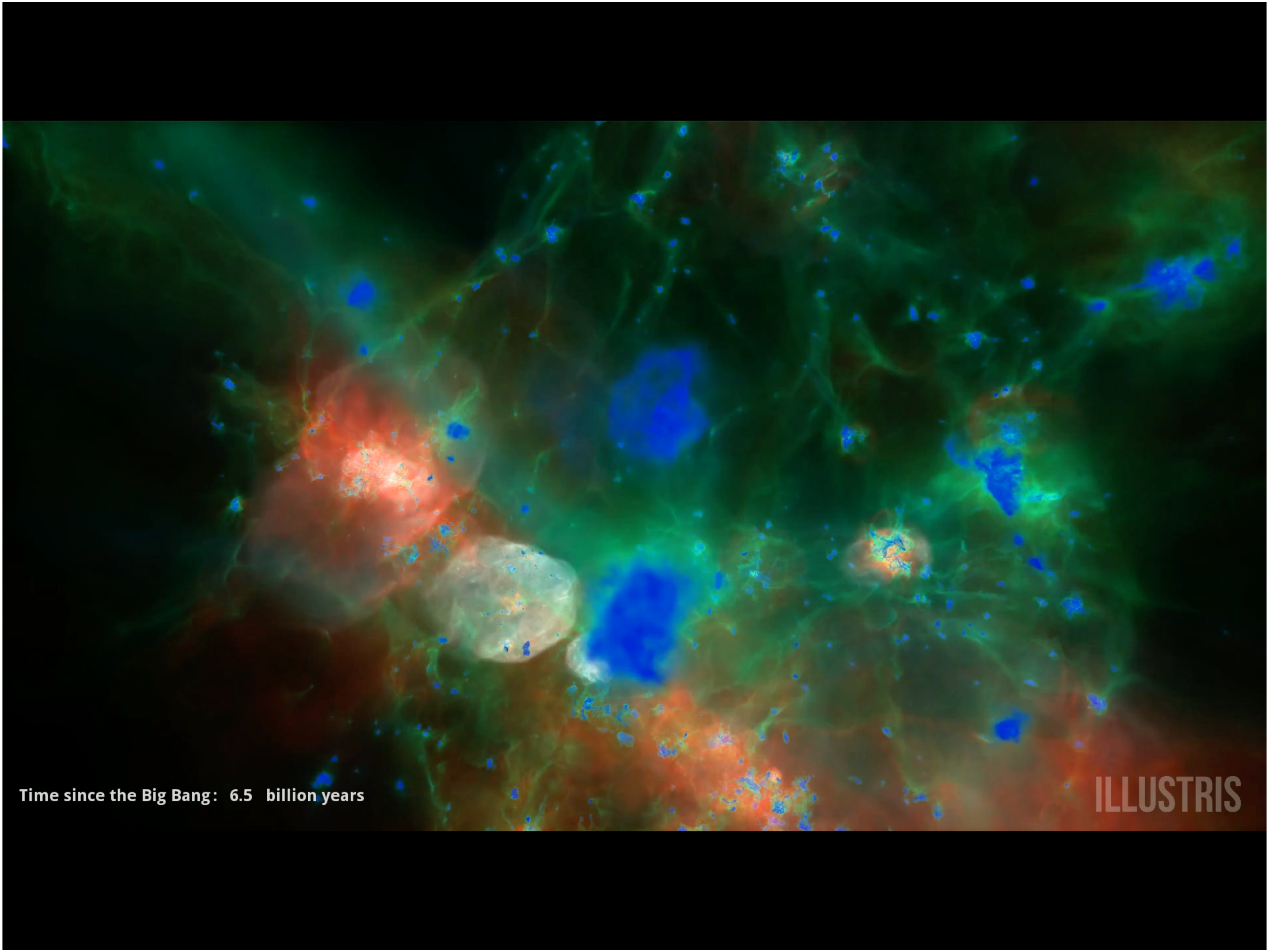




Structures in galaxy maps look very similar to the ones found in models in which dark matter is pressureless.

Numerical Simulations

- The Millennium simulation, carried out at the Max-Planck-Institut für Astrophysik in 2005, set the record for N-body simulations, with over 10 billion particles.
- However, the simulation used now-outdated cosmological parameters.
- At MIT a more ambitious project that includes full hydrodynamics and goes until $z = 0$ was run: the Illustris simulation.
- Simulations trade off between scale and physics.


Time since the Big Bang: 6.5 billion years
ILLUSTRIS

Mass-to-light Ratio

- Galaxies can be characterized by their *mass-to-light ratio:*

$$\frac{M}{L} = \frac{\text{mass of object (in } M_{\text{Sun}})}{\text{luminosity of object (in } L_{\text{Sun}})}.$$

- By definition, $M/L = 1$ for the Sun.
- Recall for stars, $L \propto M^{3.5}$, so $M/L \propto M^{-2.5}$.
  - Therefore, for hot/luminous massive stars, $M/L < 1$.
  - For cool/faint low-mass stars, $M/L > 1$.
- For galaxies, high M/L indicates more dim stars, more dark matter.
  - E.g., for Milky Way, $M/L \sim 10$.
  - For ellipticals, $M/L \sim 10\text{–}20$. (Some dwarfs can have $M/L >> 100$.)

The Missing Satellites Problem

- Also known as the dwarf galaxy problem: cosmology simulations predict there should be many more tiny dark-matter halos than are currently seen.
  - E.g., There are tens of dwarf galaxies in the Local Group, with around 10 orbiting the Milky Way, but typical simulations predict hundreds.
- Possible solutions:
  1. Smaller halos do exist but attract relatively little normal matter to make stars, so they are hard to find! E.g., in 2007, Keck observations found 6 of 8 newly discovered ultra-faint Milky Way dwarf satellites were around ~99.9% dark matter ($M/L \sim 1{,}000$).
  2. Dwarf galaxies may be tidally disrupted or consumed by larger galaxies, perhaps more than currently modeled in simulations.

Recall: Quantum Fluctuations

- **Question**: How does the universe go from being homogeneous to being full of structure?
- **Basic idea**: Something introduced very small disturbances into the universe at very early time. Those perturbations grew due to the action of gravity (close analogy with Jeans instability).
- Slightly more detail of the standard model:
  - Initial disturbances ("seed perturbations") were quantum fluctuations introduced during inflation ($t \sim 10^{-35}$ s).
  - The perturbations grow very slowly due to action of gravity until matter starts to dominate the energy density of the universe ($t \sim 70{,}000$ yr)… they then start to grow faster.
  - Perturbations are at level of 1 part in 10^5 at epoch of recombination… this produces observed anisotropies in cosmic microwave background.
  - They continue to grow after that, eventually forming a filamentary structure of dark matter. This is the "skeleton" for galaxy formation!