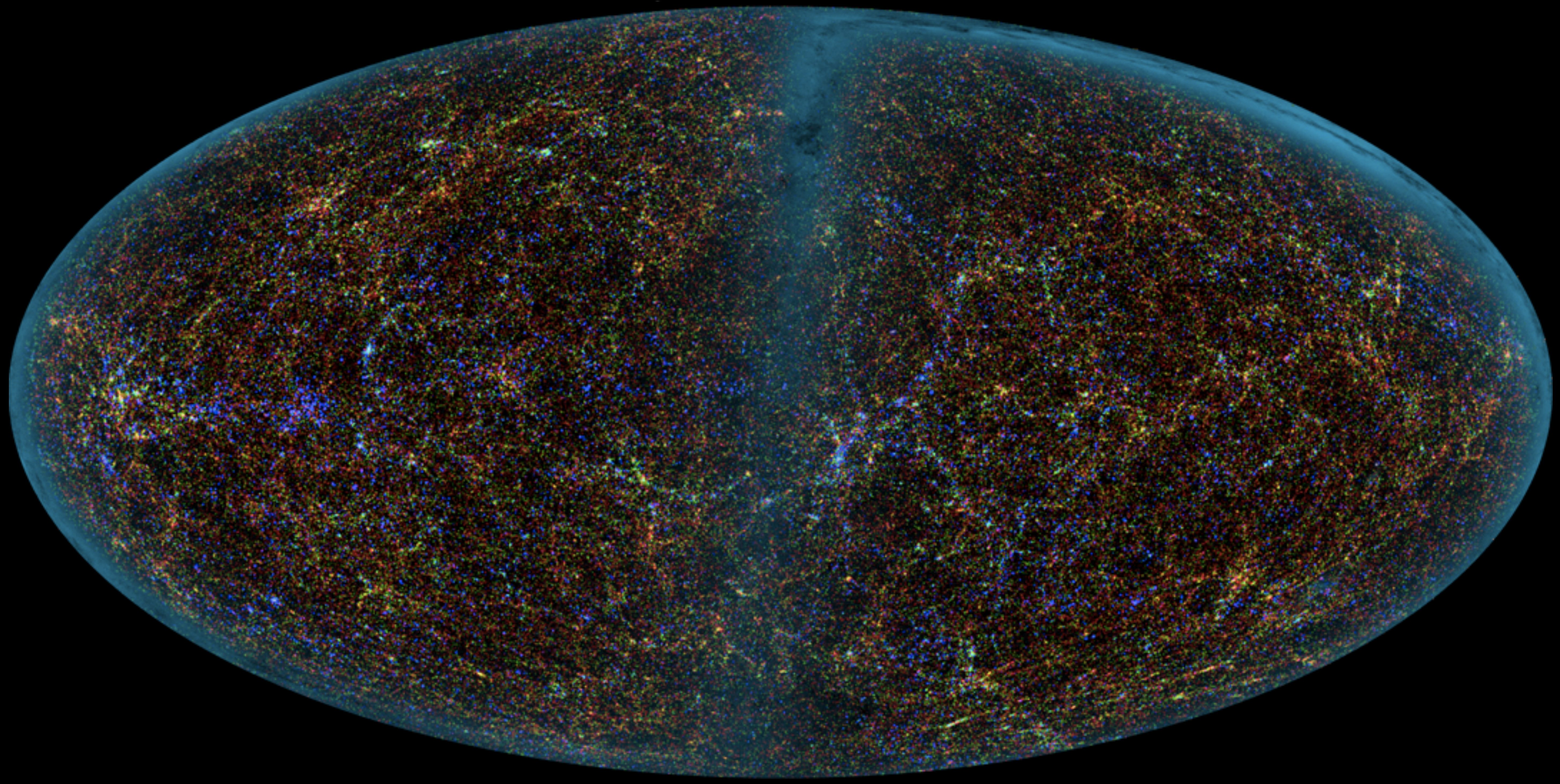
Cosmology
and Large Scale Structure



Today

Structure Formation

Cold Dark Matter

Homework 4 due next time

7 November 2024

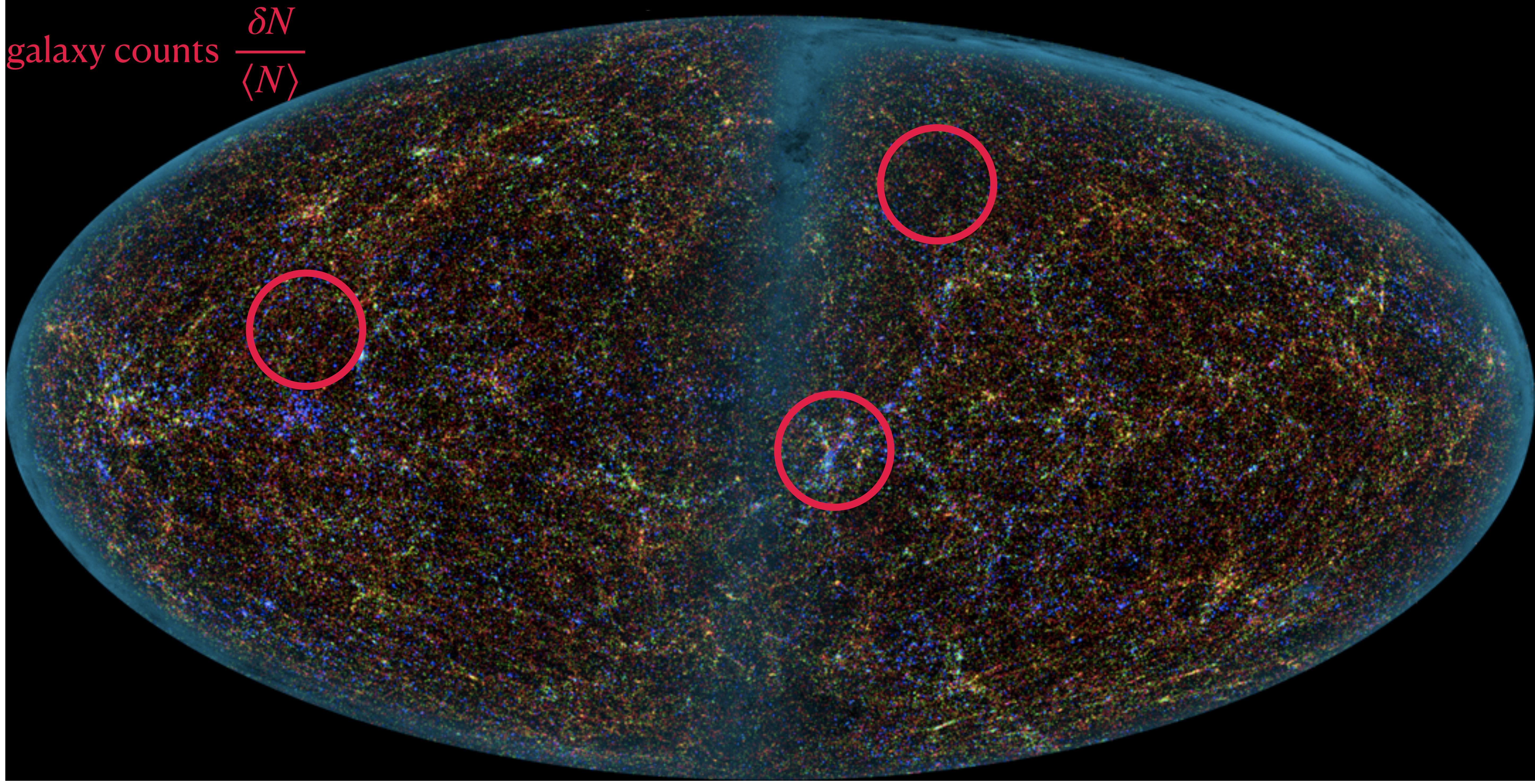
http://astroweb.case.edu/ssm/ASTR328/

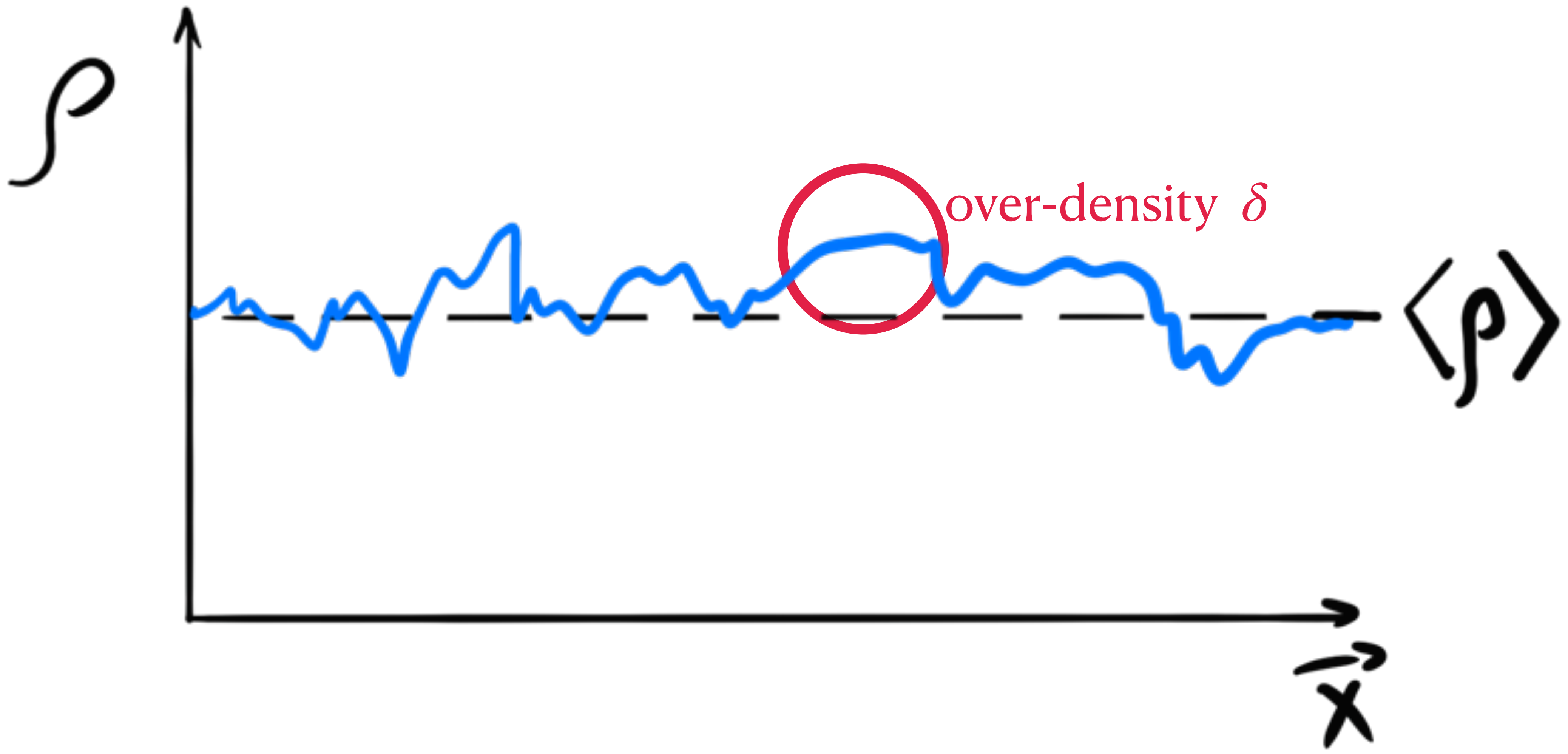
Structure formation basics:

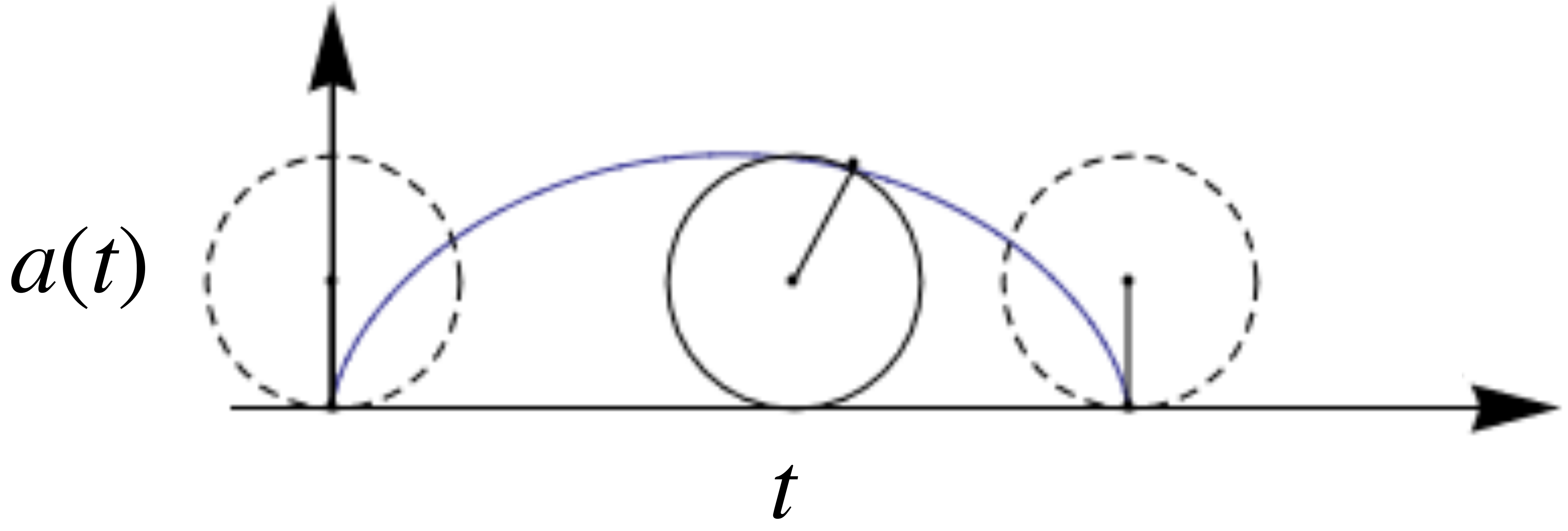
The mean density of the early matter-dominated universe is very close to critical:
$\langle \rho \rangle = \rho_c$ so $\Omega_m = 1$ to a good approximation.
However, there are some small

Density perturbations $\delta = \dfrac{\rho - \langle \rho \rangle}{\langle \rho \rangle}$

so these can act as locally closed universes with
$\rho = (1 + \delta)\rho_c$ (i.e., $\Omega_m > 1$) that will
re-collapse to form bound structures like galaxies.







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so these can act as locally closed universes with $\rho = (1+\delta)\rho_c$ (i.e., $\Omega_m > 1$) that will re-collapse to form bound structures like galaxies.

- Need to work out the growth rate:
  - grow as $\delta(t) \sim a(t)$ [linear growth].
- Need a statistical description of the distribution of fluctuations
  - the *power spectrum*
  - Gaussian random field
    - small fluctuations common
    - large fluctuations rare

Solutions from Felten & Isaacman (1986) Reviews of Modern Physics, **58**, 689

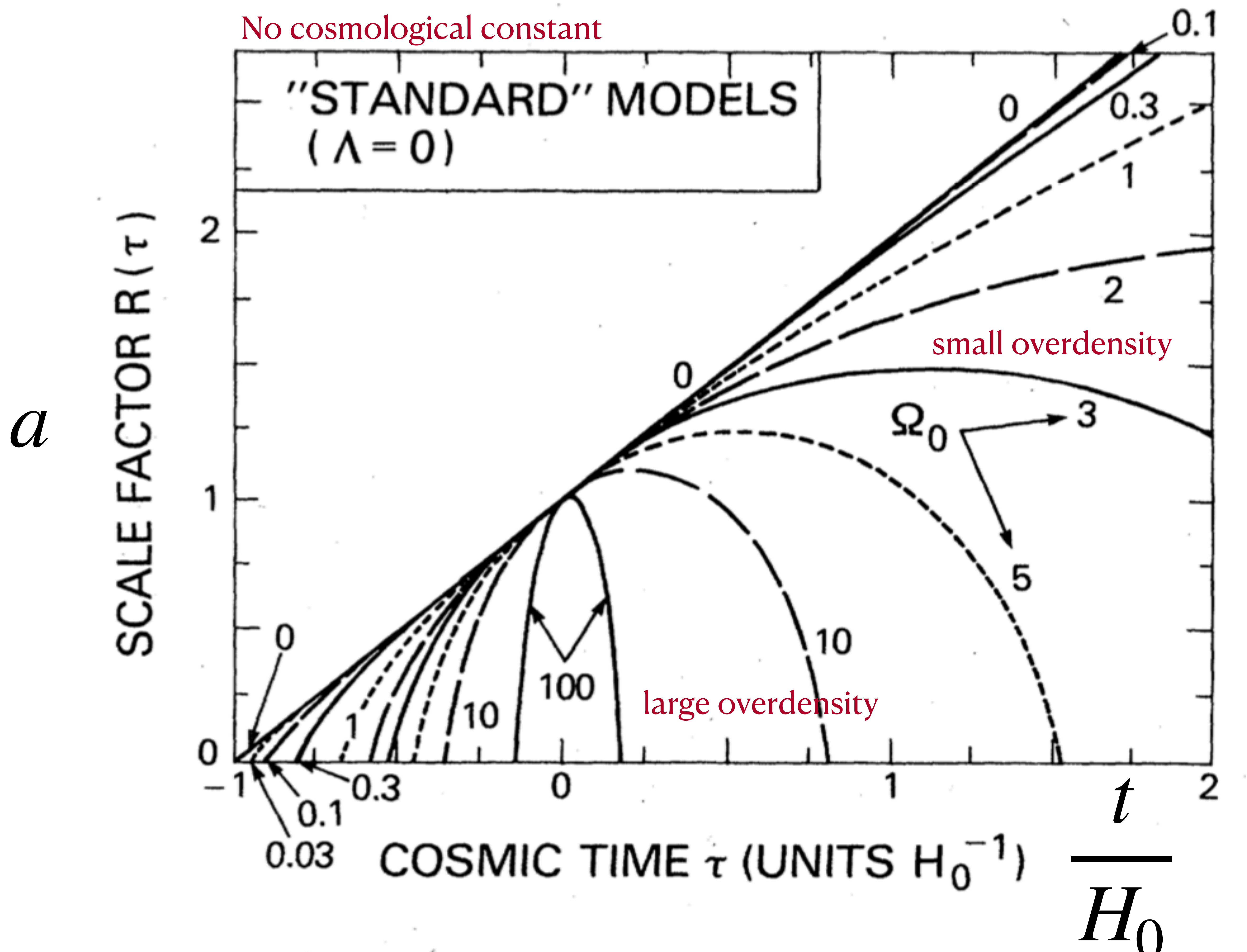


FIG. 3. "Standard" Friedmann models. The family of scale factors $R(\tau)$ for the "standard models" ($\Lambda = 0$). The free parameter, shown on the curves, is Ω_0. As shown by the τ intercepts, all models have ages ≤ 1 ($\leq H_0^{-1}$ yr).

Structure formation basics:

Density perturbations $\delta = \dfrac{\rho - \langle\rho\rangle}{\langle\rho\rangle}$

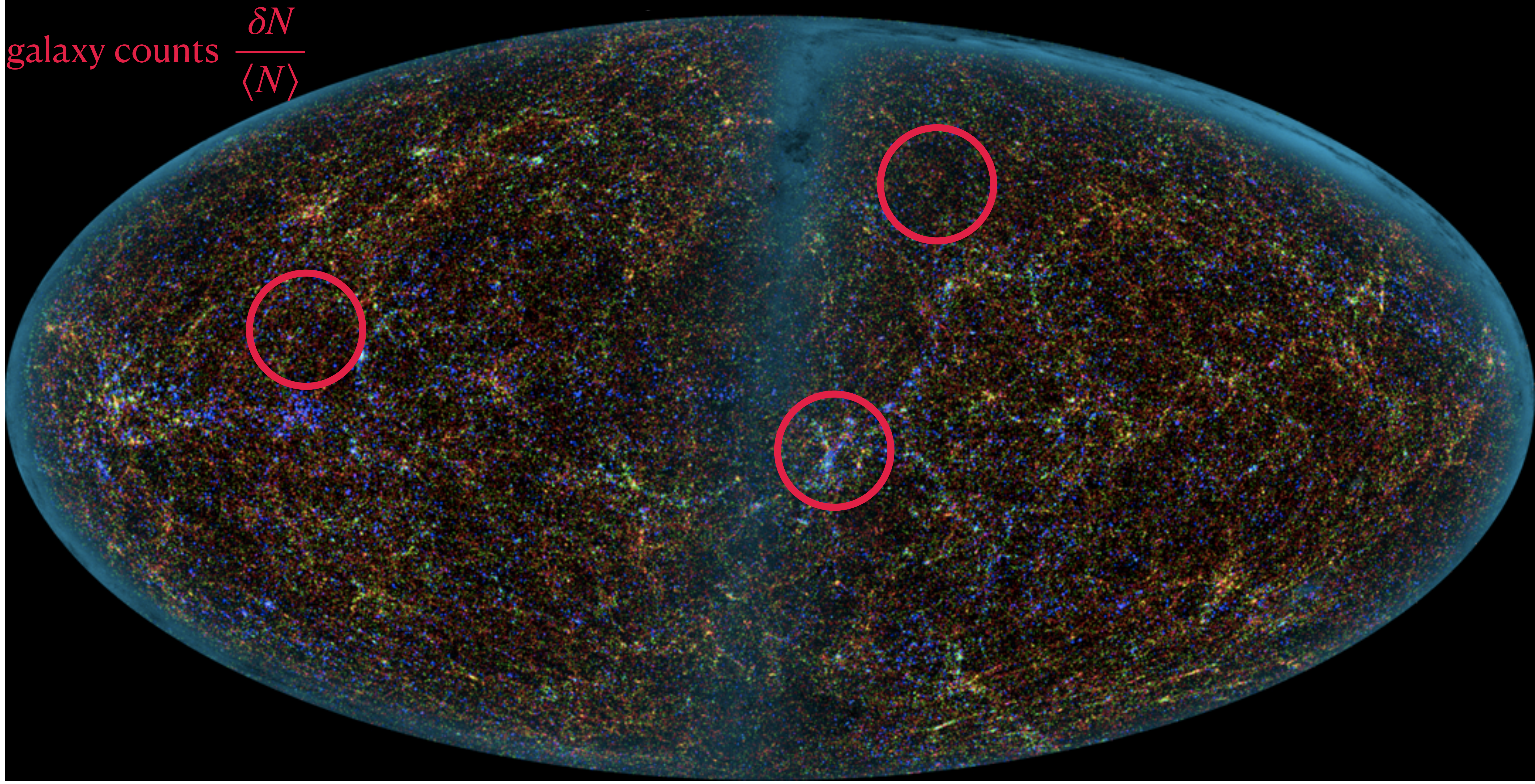
grow as $\delta(t) \sim a(t)$. `(Ryden 11.58)`

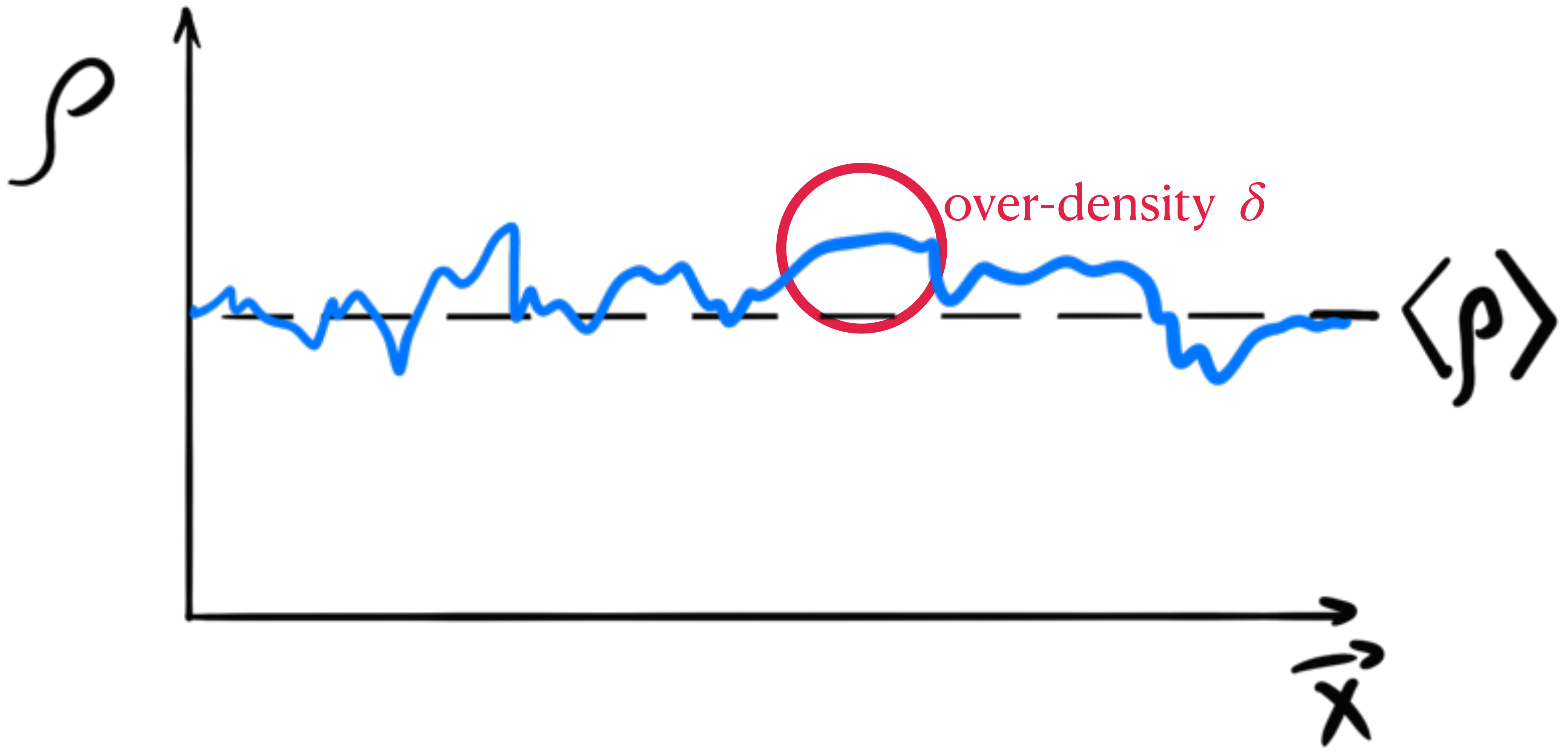
In the early universe, $\langle\rho\rangle = \rho_{\text{crit}}$.

At $z = 0$, we observe $\delta \approx \dfrac{\delta N}{\langle N\rangle} \approx 1$ on scales of 8 Mpc. So if $\delta(t) \sim a(t)$, then at $z = 1000$ we expect $\delta \approx 10^{-3}$.

Instead, we observe $\delta \sim \dfrac{\Delta T}{T} \approx 10^{-5}$

— off by a factor of 100!





You can't get here from there

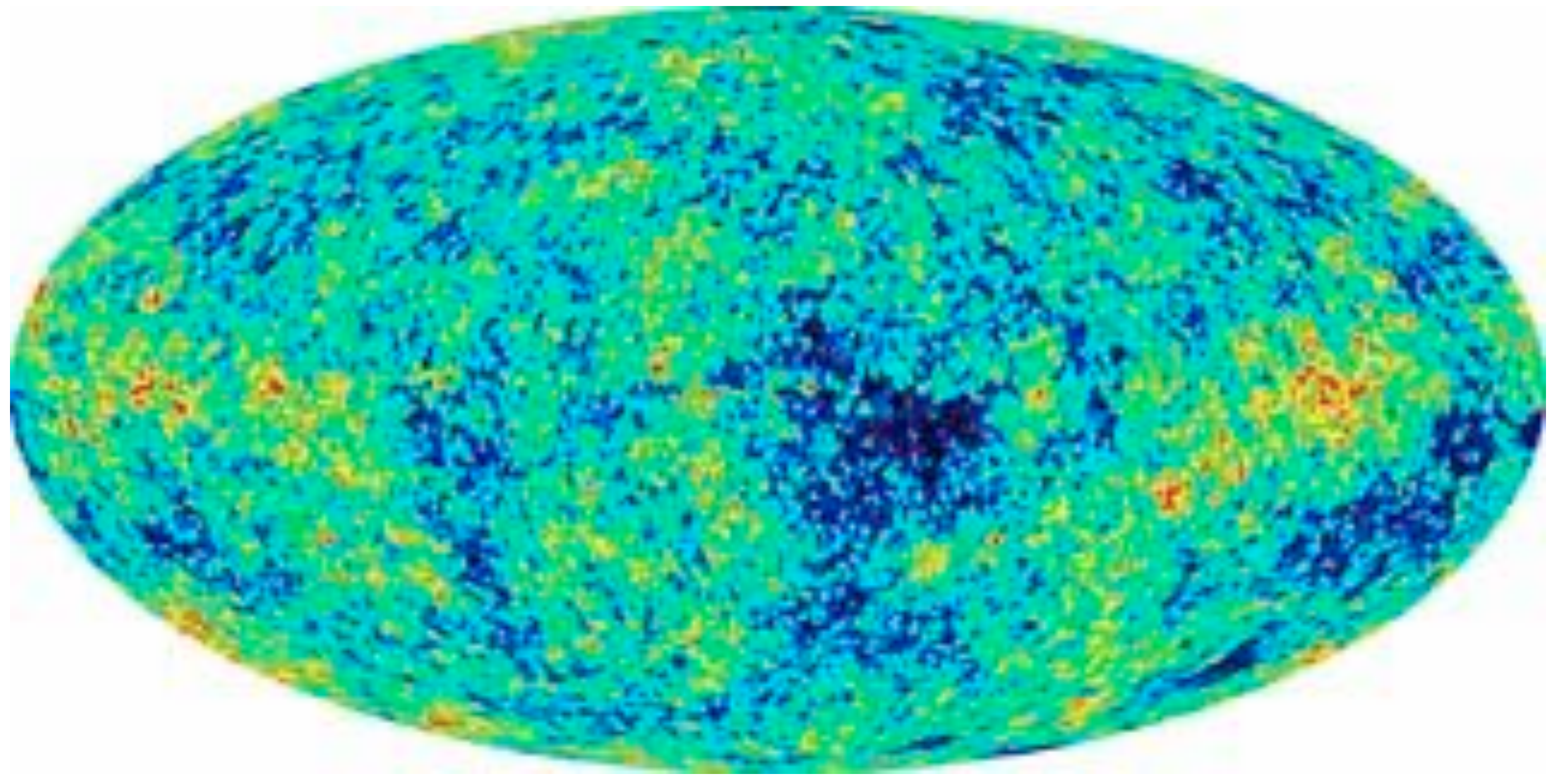
The factor of 100 offset in density and temperature fluctuations is a prime motivation for non-baryonic **cold dark matter** — a substance for which perturbations δ can grow sufficiently large while not leaving an imprint of corresponding magnitude on the CMB.

Radiation and baryon plasma tightly coupled at recombination, so a fluctuation in density is reflected by one in temperature: $\dfrac{\delta\rho}{\rho} \propto \dfrac{\Delta T}{T}$.

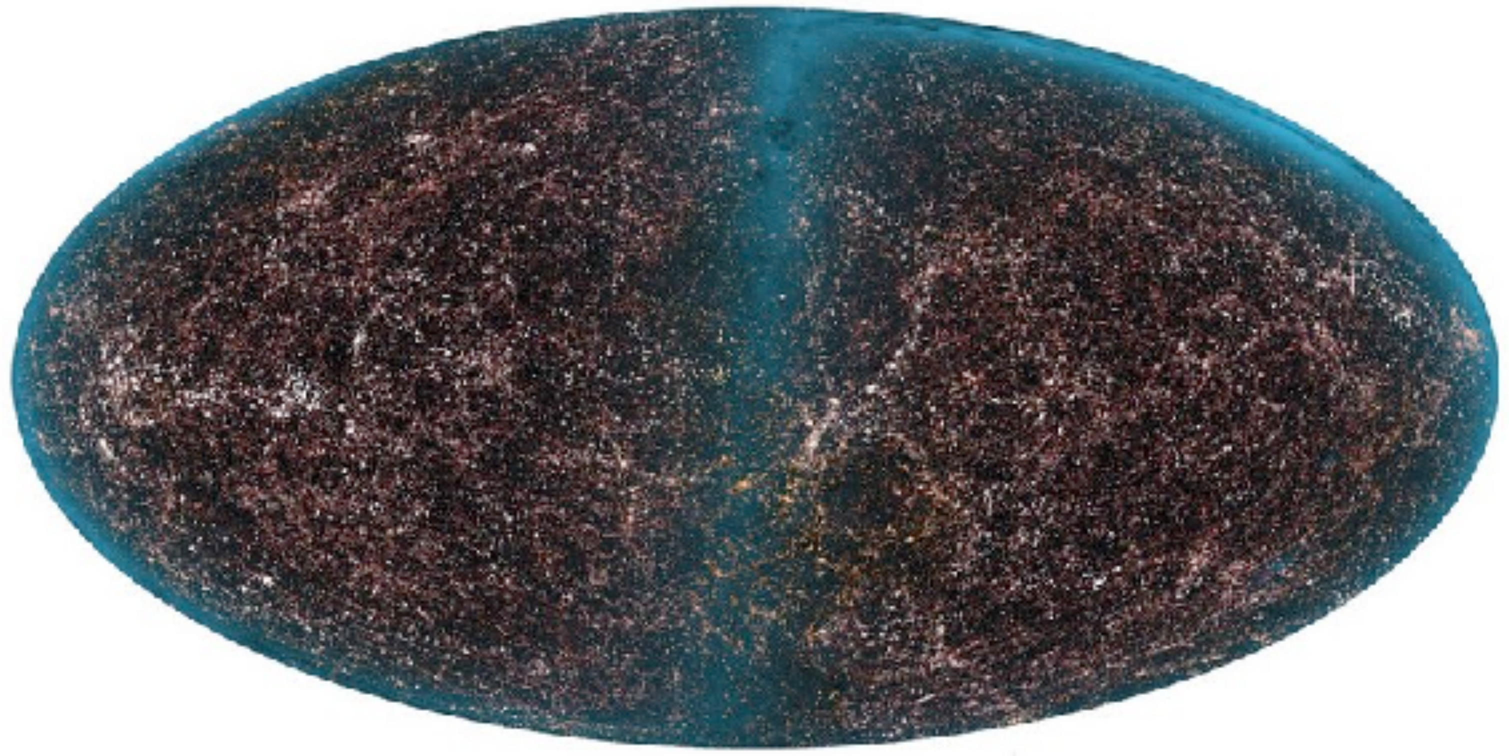
You can't get here from there

There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons (e.g., new particles with no E&M interactions).

CMB: t = 3.8 x 10^5 yr
$z = 1090$



Now: t = 1.35 x 10^{10} yr
$z = 0$



very smooth: $\delta \sim \frac{\Delta T}{T} \approx 10^{-5}$

very lumpy: $\delta \approx 1$

Structure only has time to grow by a factor of $\sim 10^3$ but is observed to have grown by a factor of $\sim 10^5$!

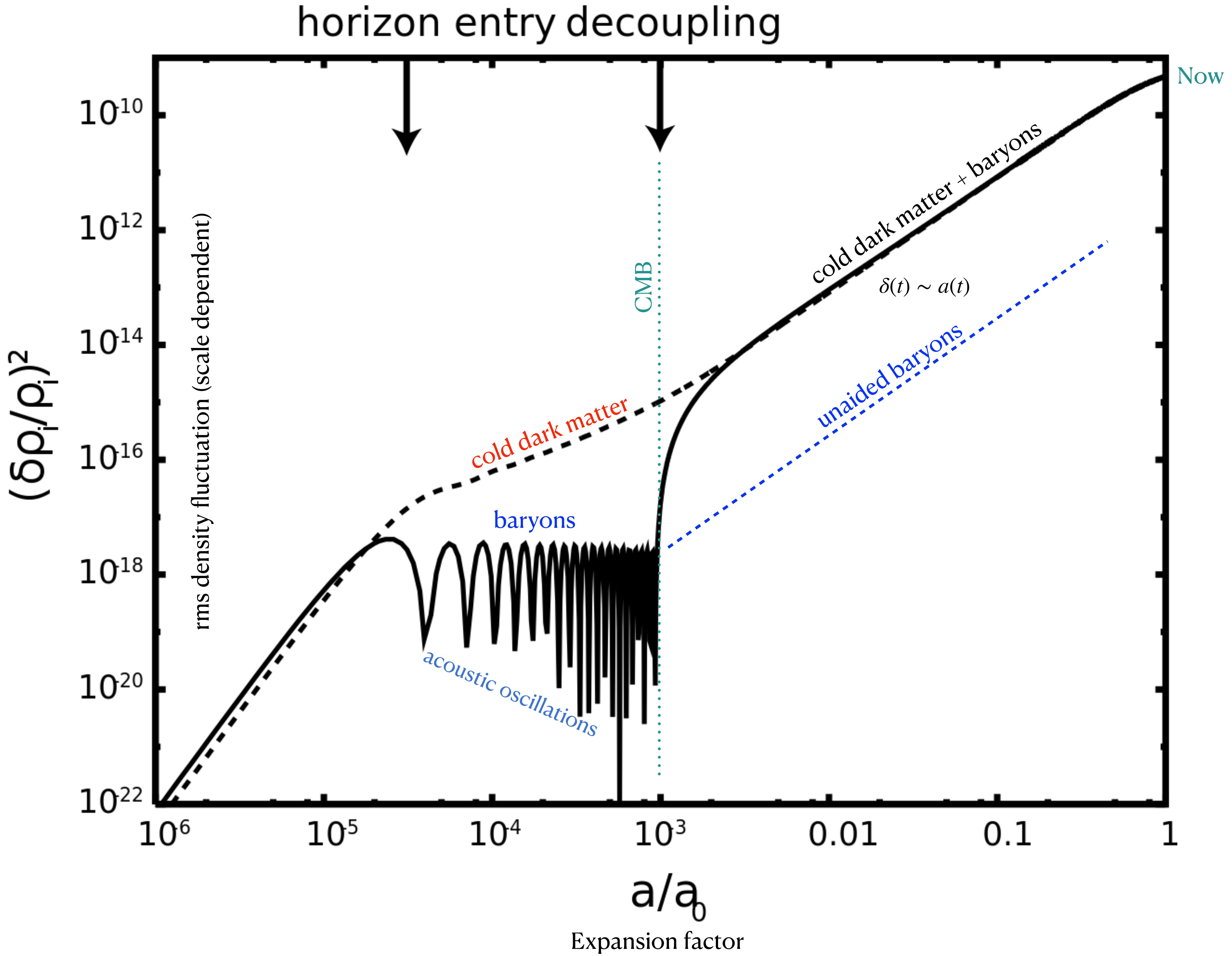
Along with BBN, the smoothness of the CMB was an important motivation for the **Cold Dark Matter** (**CDM**) paradigm.

You can't get here from there

Need something to kick-start the formation of structure. Gravity + baryons alone won't get the job done. Gravity will grow structure, but it is weak so acts slowly. The heavy baryons want to clump up via gravity, but the relativistic photons don't. This precludes structure formation before decoupling. The temperature fluctuations observed in the CMB set the starting point for the growth of large scale structure.

The conventional solution invokes non-baryonic cold dark matter - some new mass component that moves slowly ("cold" so it can clump) that doesn't interact with photons (so it can start to clump earlier).

The unconventional solution would be to modify gravity to speed the rate of growth of large scale structure.



Cosmologically, the only requirement to be CDM is

- dynamically cold (slow moving)
- non-baryonic (no E&M interactions)

could be

WIMPS

(or some other particle, but there are lots of extra particle-physics constraints on new particles)

or

Black Holes

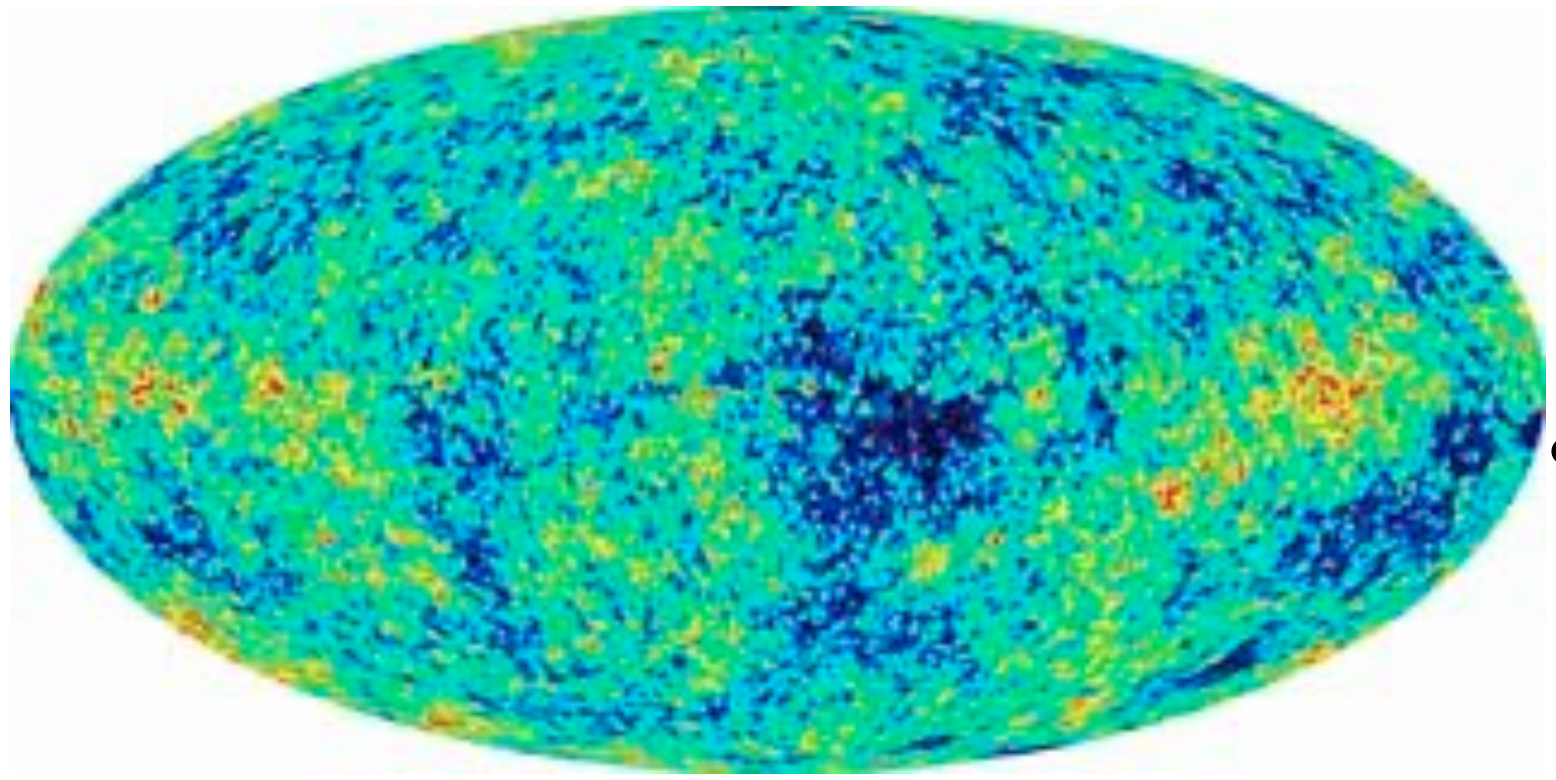
(masses of ~ 10^5 $M_{\odot}$ conceivable, but most mass ranges have been excluded by gravitational lensing observations)

WIMPs are considered the odds-on favorite CDM candidate because of the so-called `WIMP miracle': the relic density of a new weakly interacting particle is about right to explain the mass density.

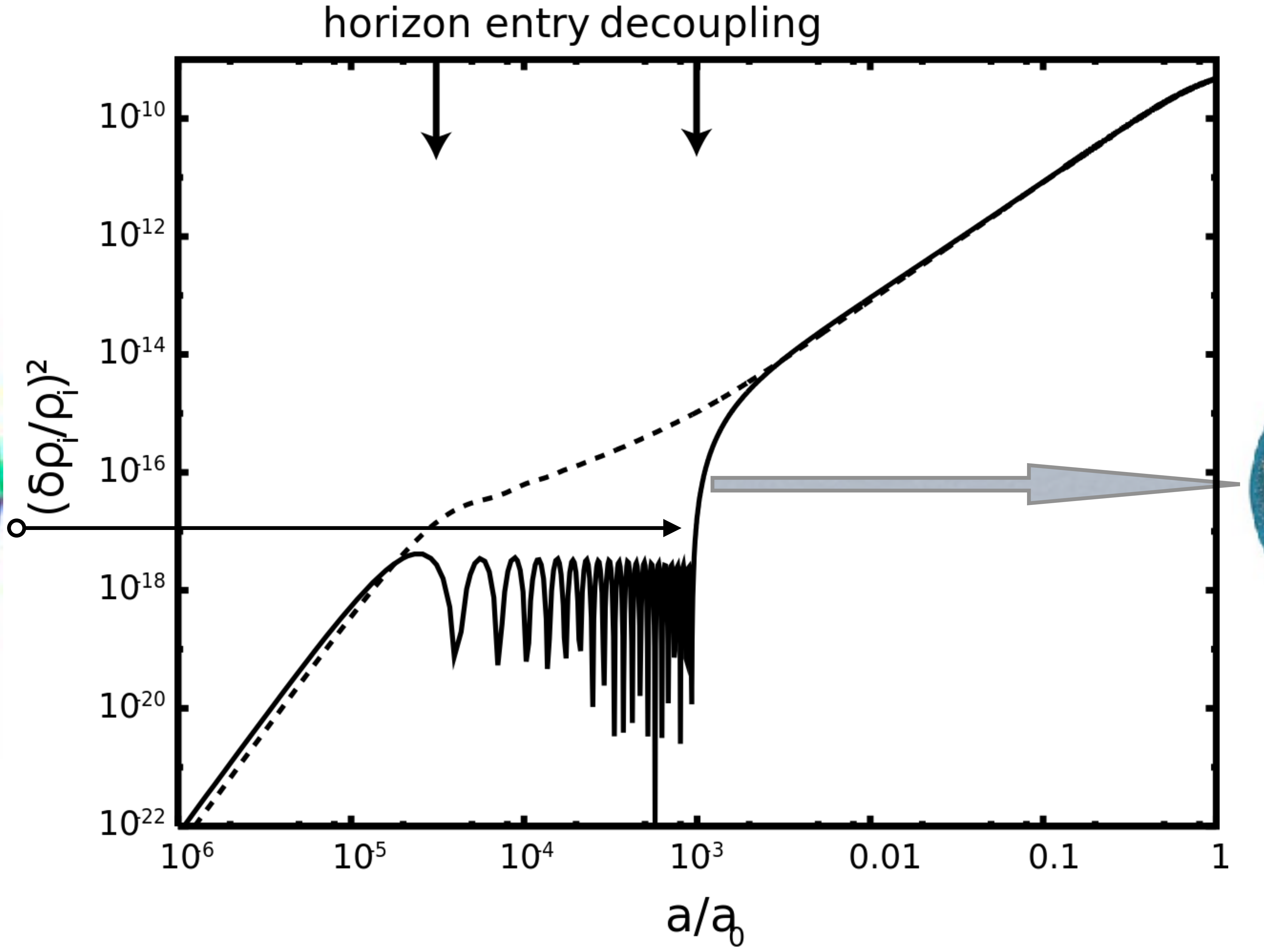
With CDM, you* can get here from there

*(side effects may include overconfidence and universal weight gain)

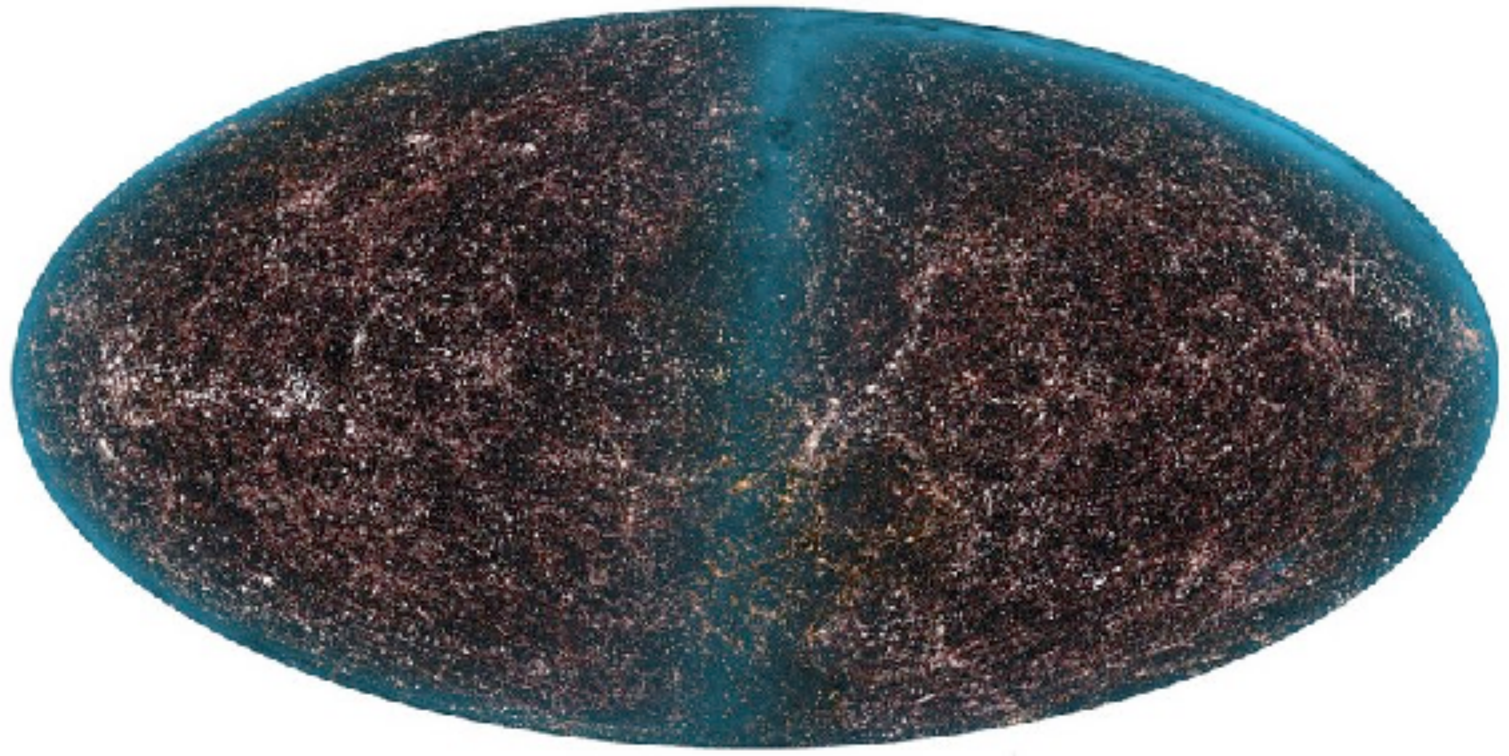
t = 3.8 x 10^5 yr



very smooth: $\delta\rho/\rho \sim 10^{-5}$



t = 1.4 x 10^{10} yr



very lumpy: $\delta\rho/\rho \sim 1$

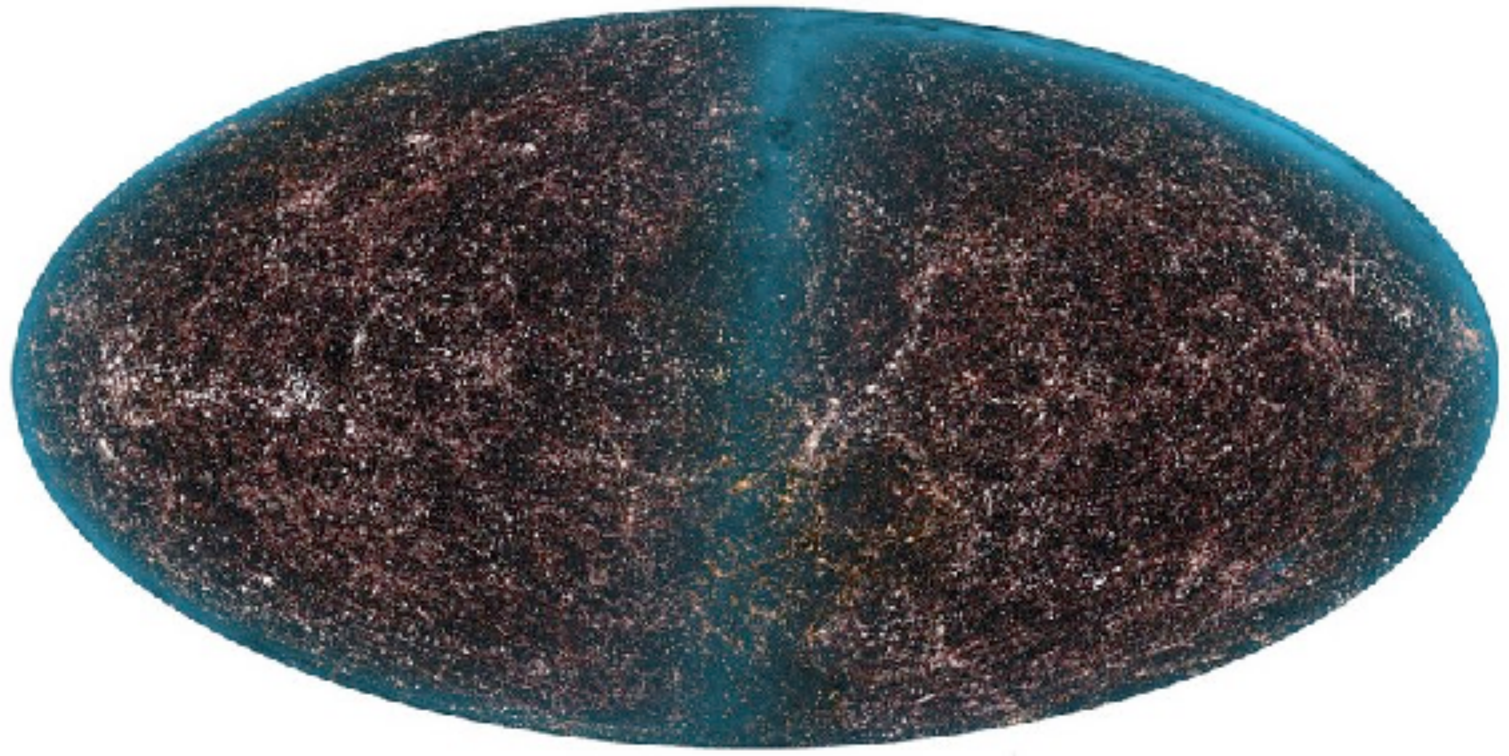
$$\delta \propto a$$

Spotting ourselves the existence of cold dark matter, large scale structure works out well

Large Scale Structure

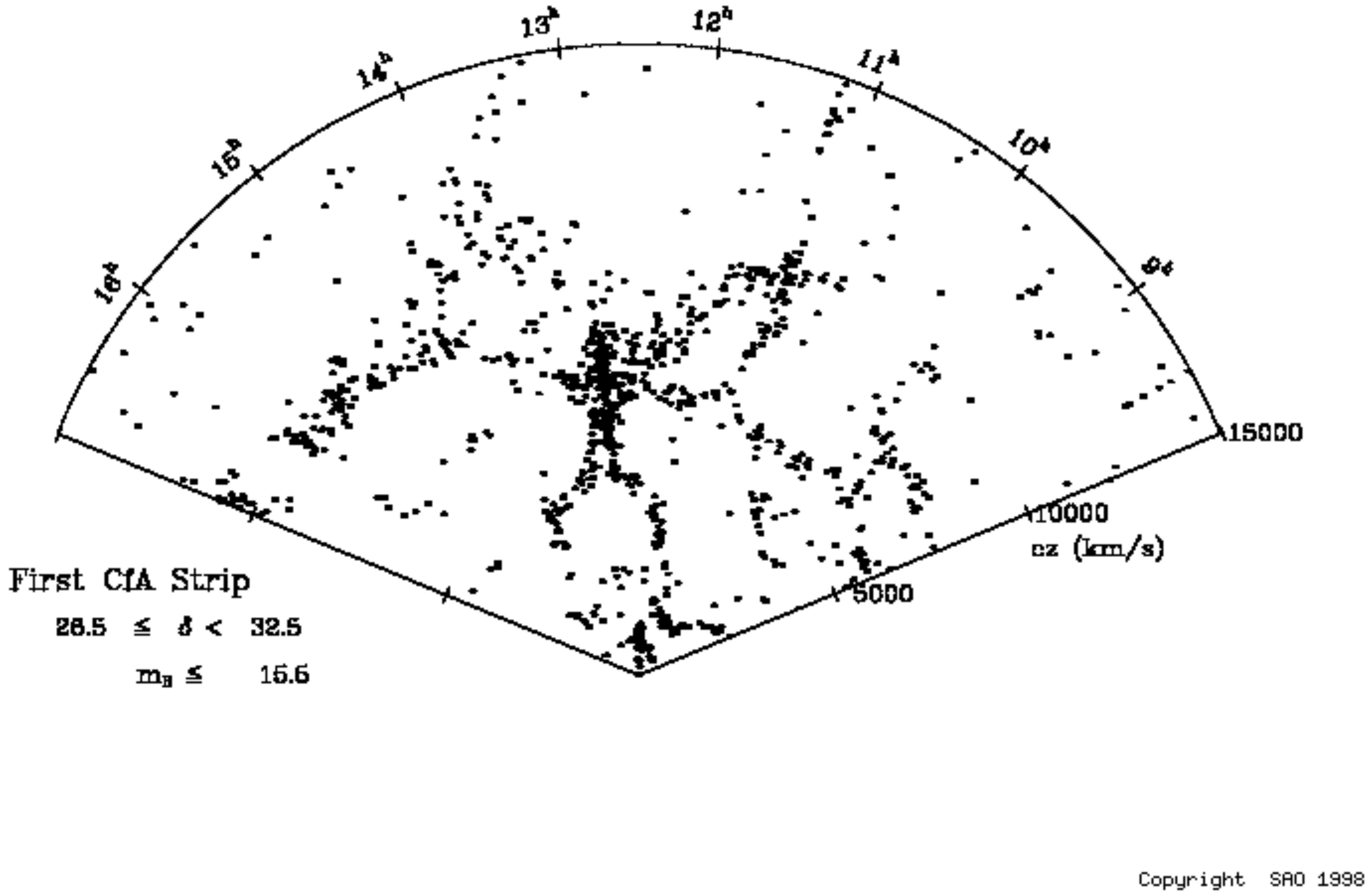
Redshift surveys locate galaxies in 3D space (α, δ, z)

Distribution of 2MASS galaxies as seen on the sky



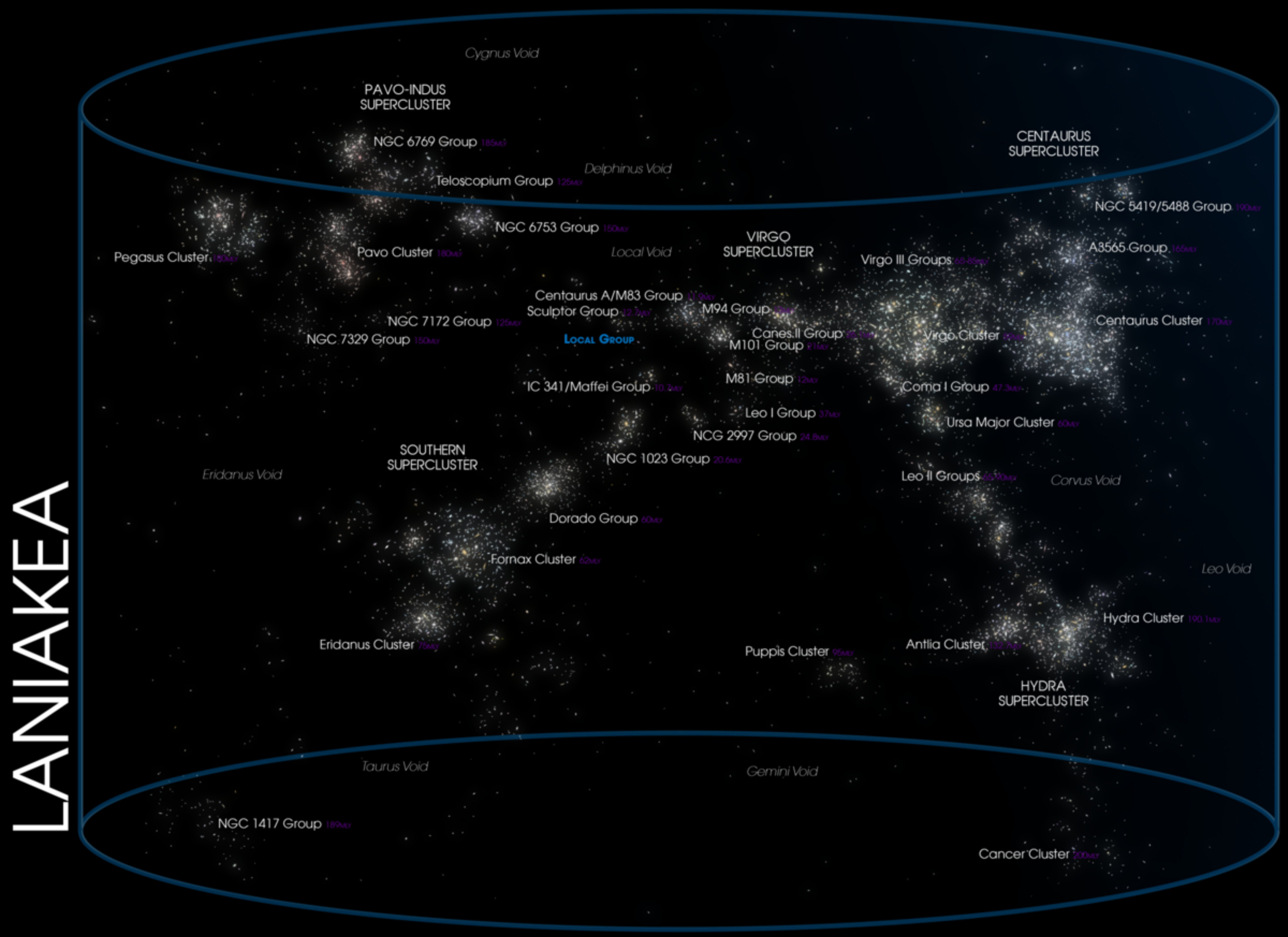
maps to right ascension α and declination δ

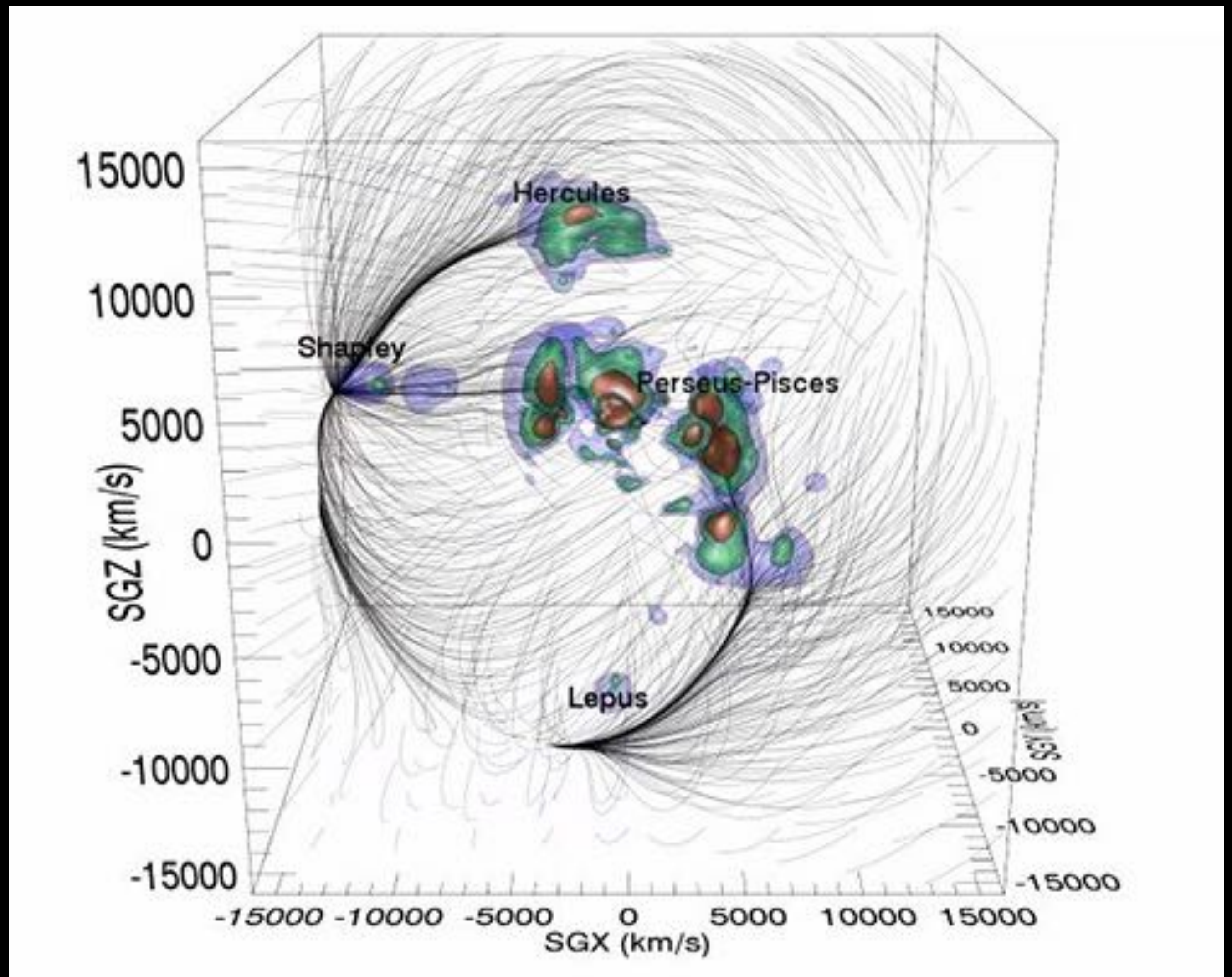
Distribution of CfA galaxies as seen in redshift z and right ascension α



This “stick-man” distribution came as a huge surprise at the time (1987) - cosmologists has expected something closer to homogeneity on this scale.

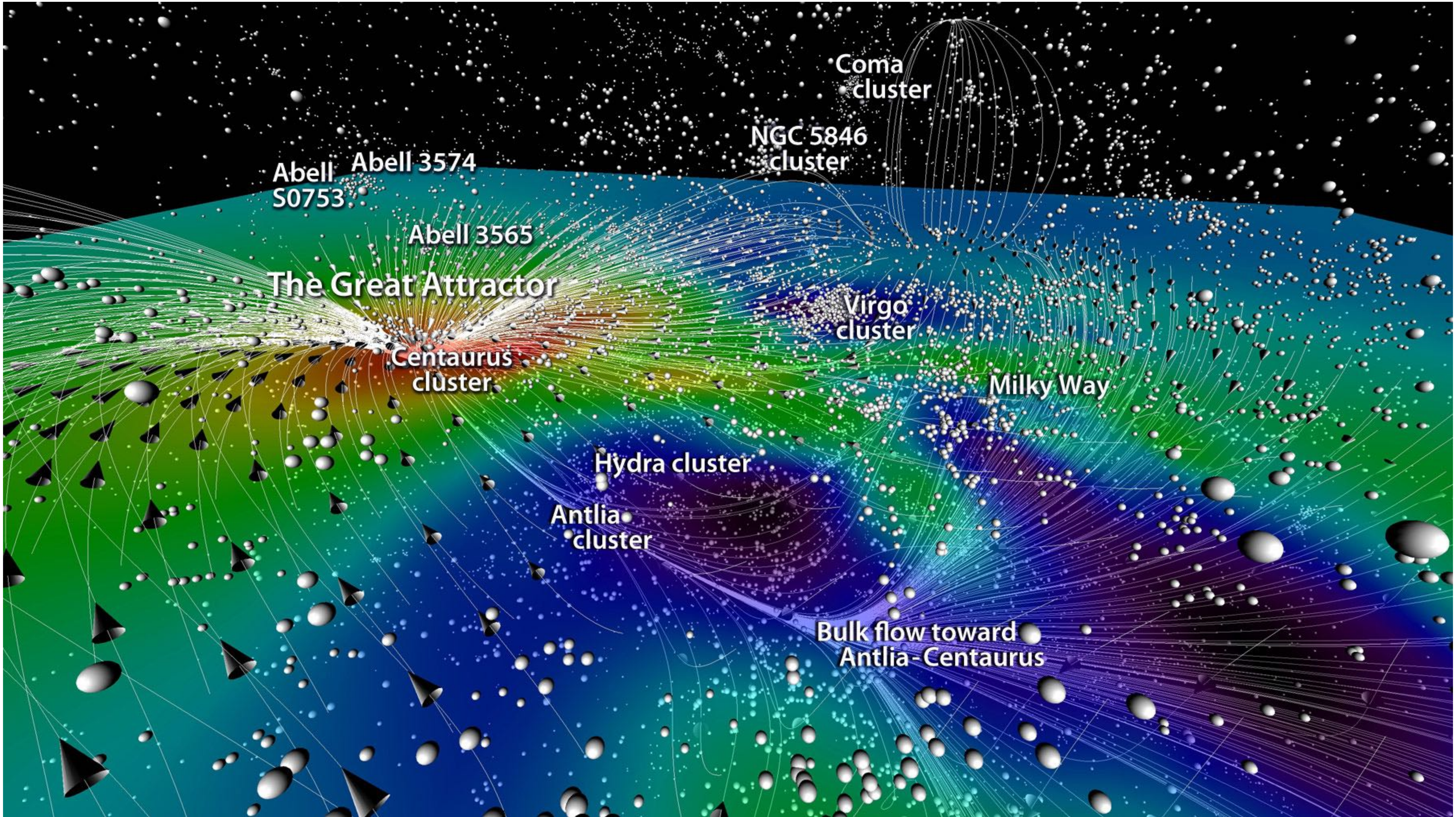
Laniakea - our local supercluster



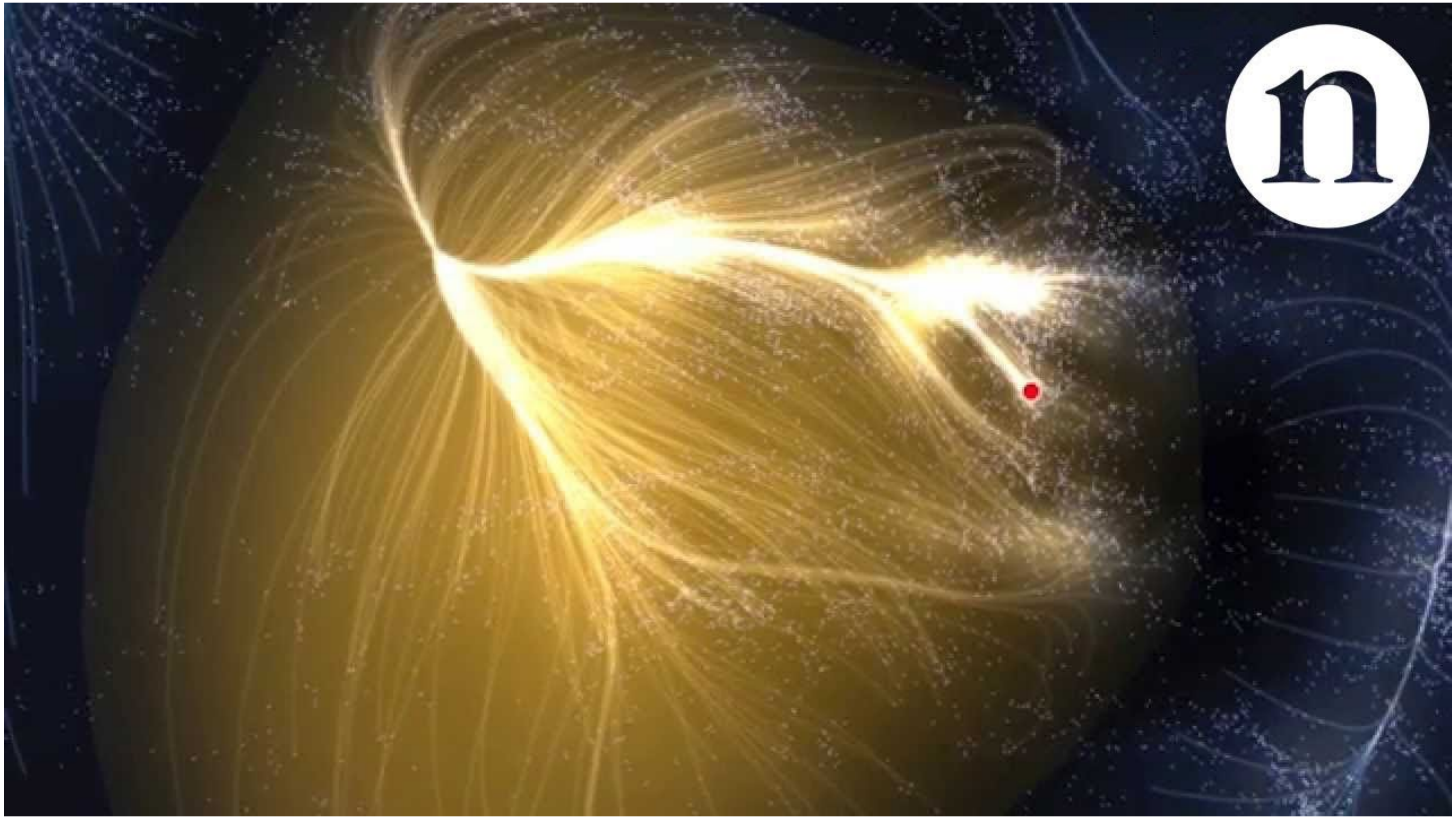


It's challenging to depict 3D information

There are large scale bulk flows as well as structure

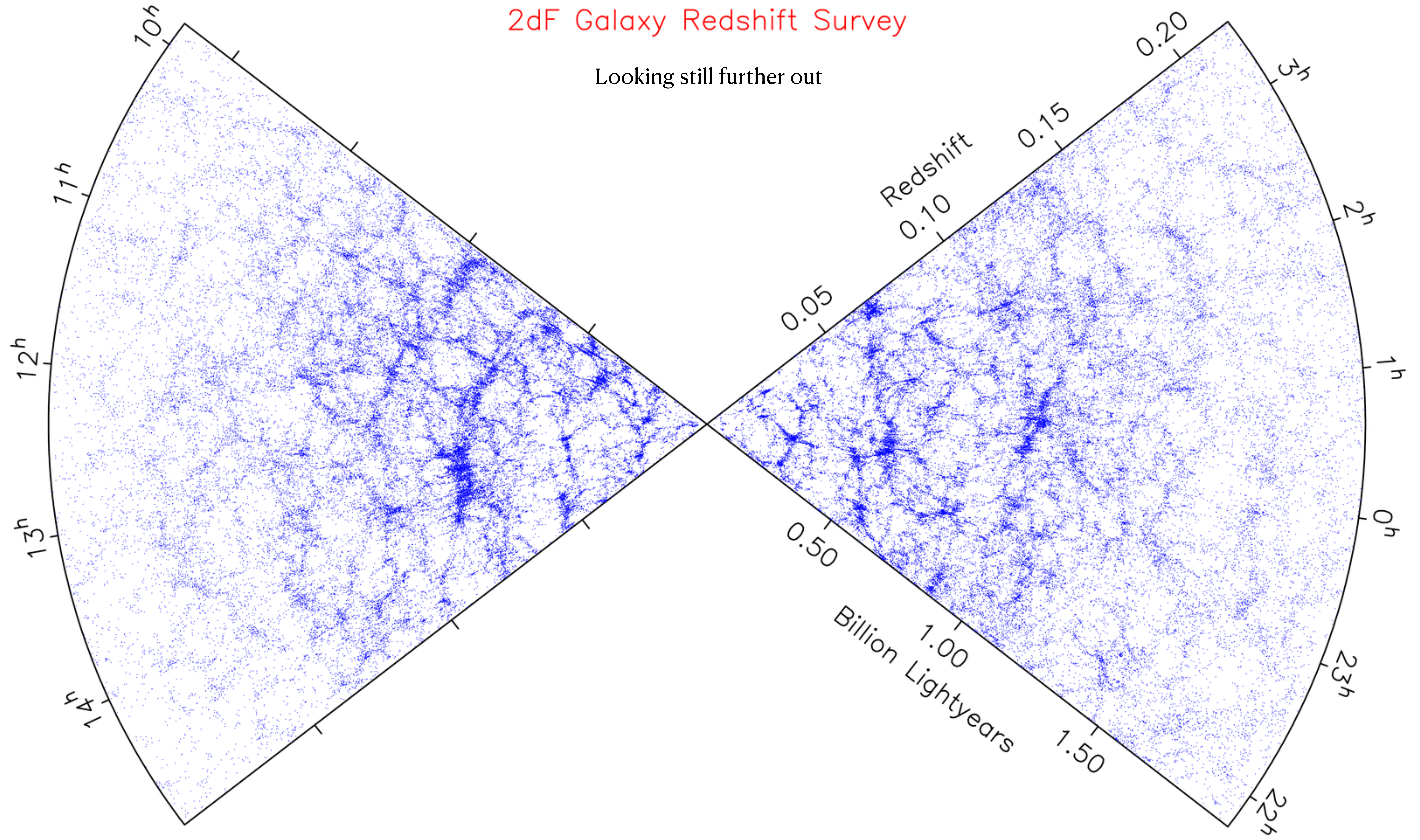


Laniakea - defined by peculiar velocities

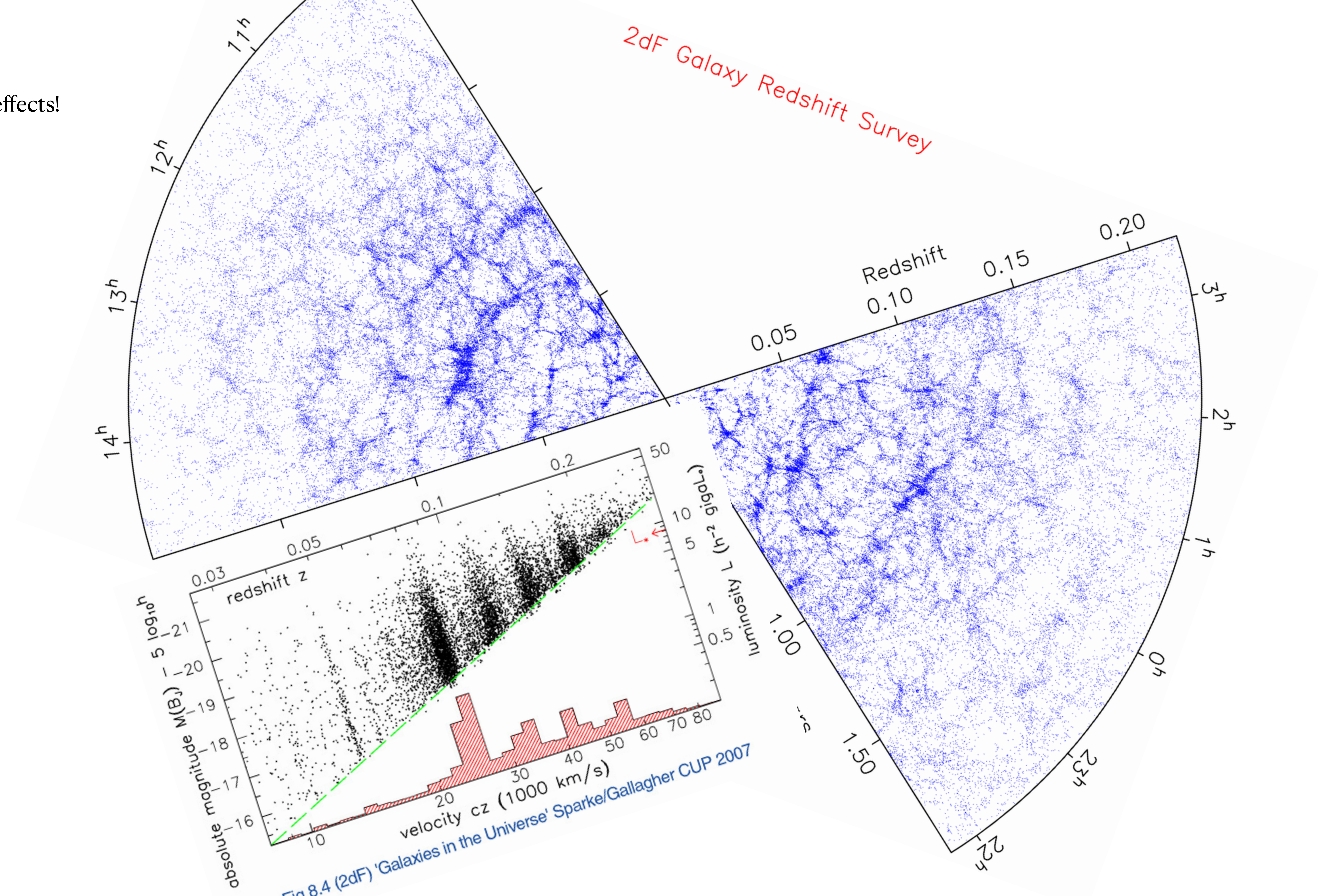


2dF Galaxy Redshift Survey

Looking still further out



Beware selection effects!



luminosity bias - only the brightest objects are traced to the edge of the survey

Large Scale Structure

Quantified with the **correlation function** $\xi(r)$ which is the Fourier transform of the **power spectrum** $P(k)$.

The correlation function is the excess probability of finding a galaxy near another galaxy over that in a random distribution.

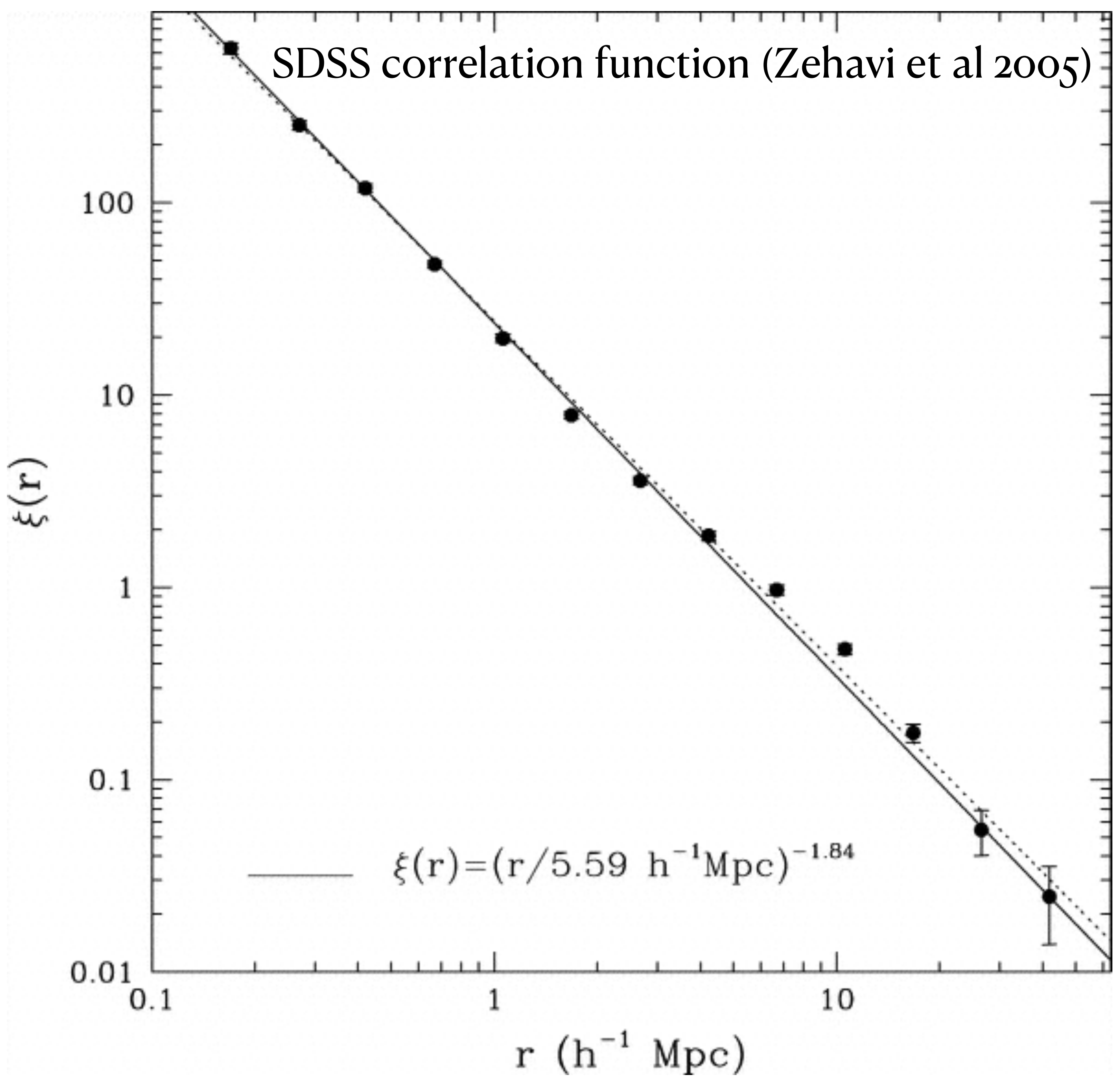
$$\frac{dN}{N} = [1 + \xi(r)]dV$$

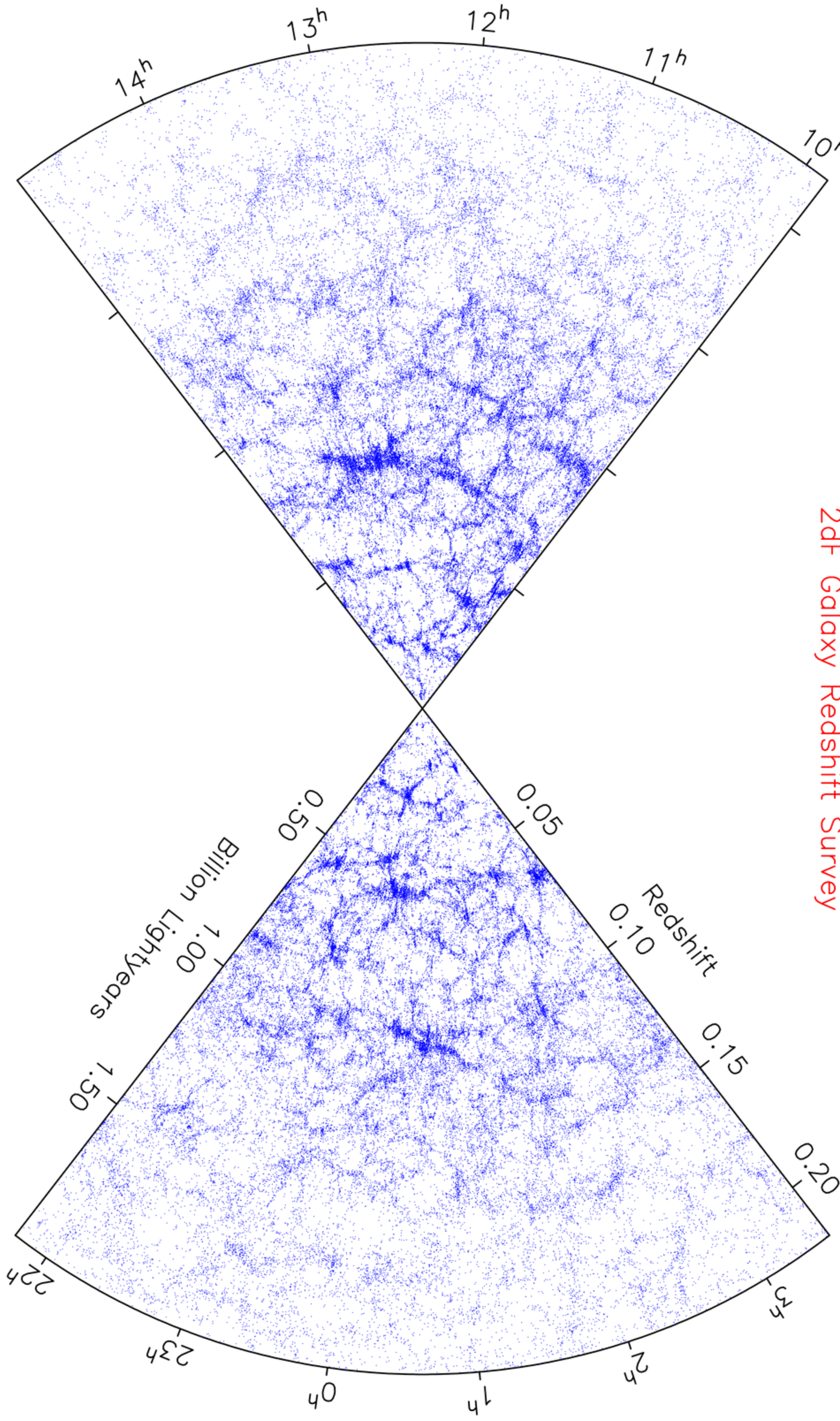
tolerably described as a power law

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

correlation length $\quad r_0 = 5.59h^{-1}$ Mpc

$$\gamma = -1.84$$





Quantified this way by Peebles, but goes all the way back to Vera Rubin's thesis in the '50s after Gamow asked her if there was a length scale on the sky.

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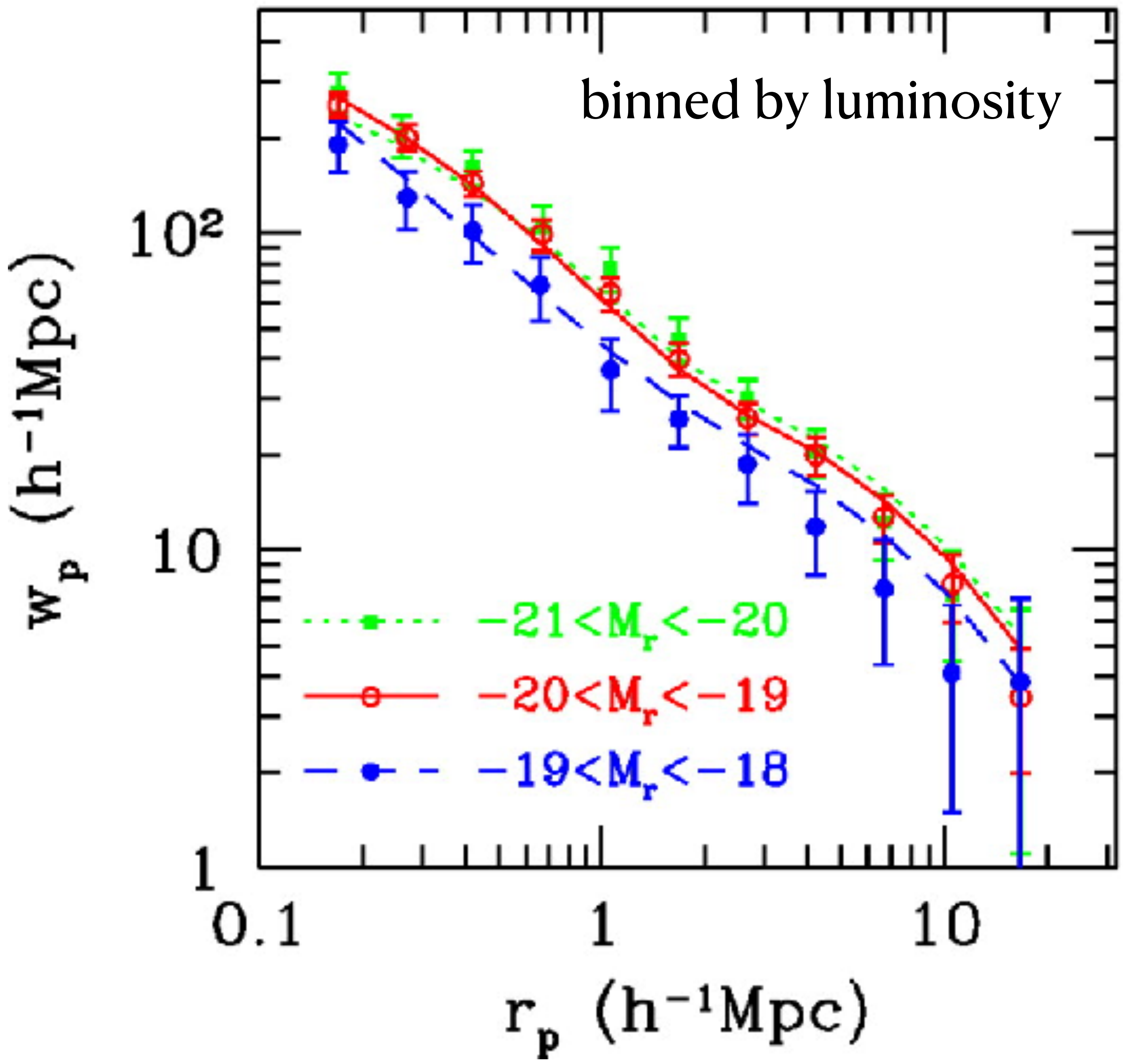
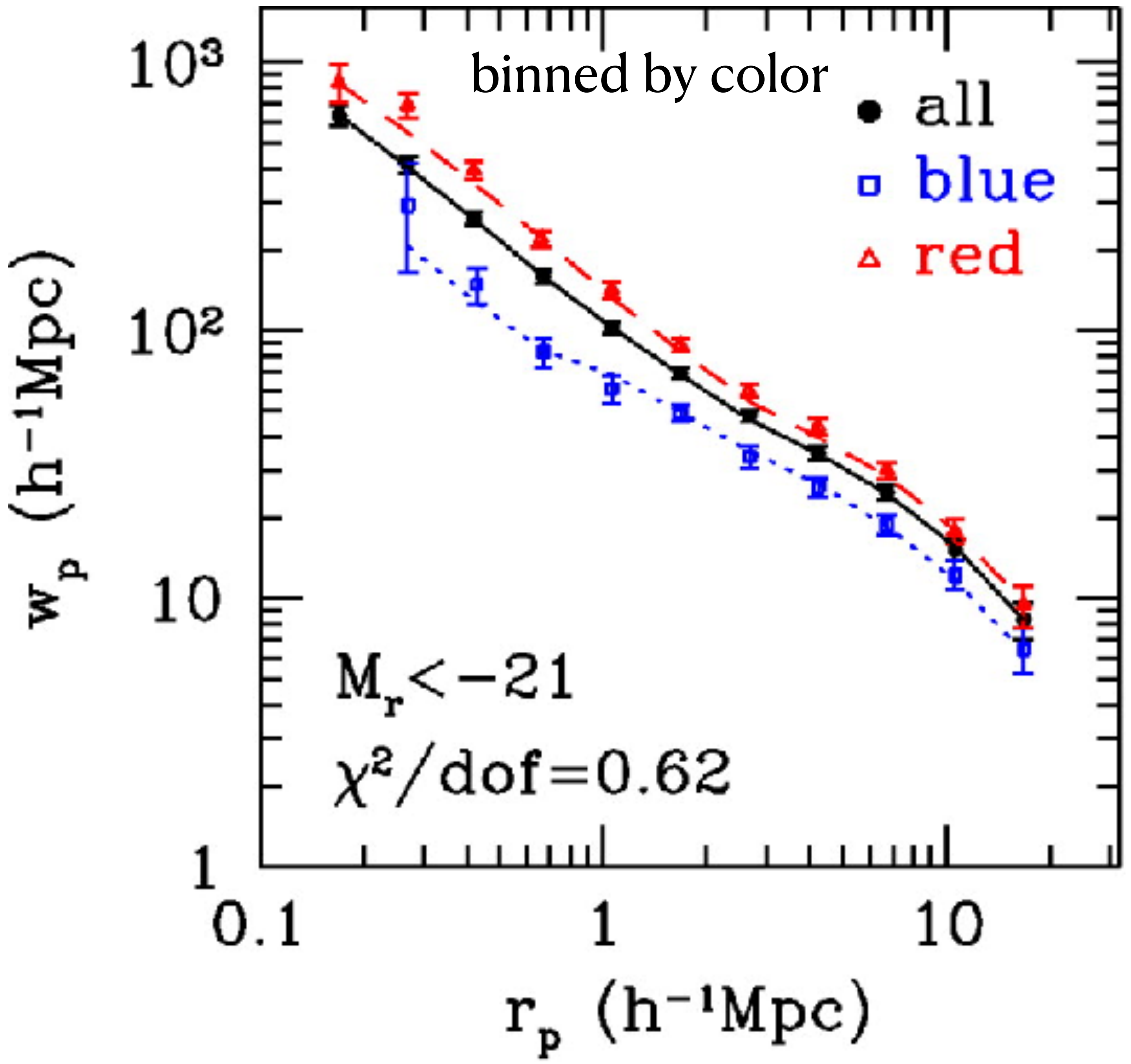
The correlation length depends on galaxy properties: *bright, red, early type* galaxies are more strongly clustered (large r_0) than *dim, blue, late type* galaxies.

Bright ellipticals mostly found in rich clusters of galaxies; spirals like the Milky Way are more frequently in small groups like the Local Group.

This is also known as the morphology-density relation (Dressler 1980).





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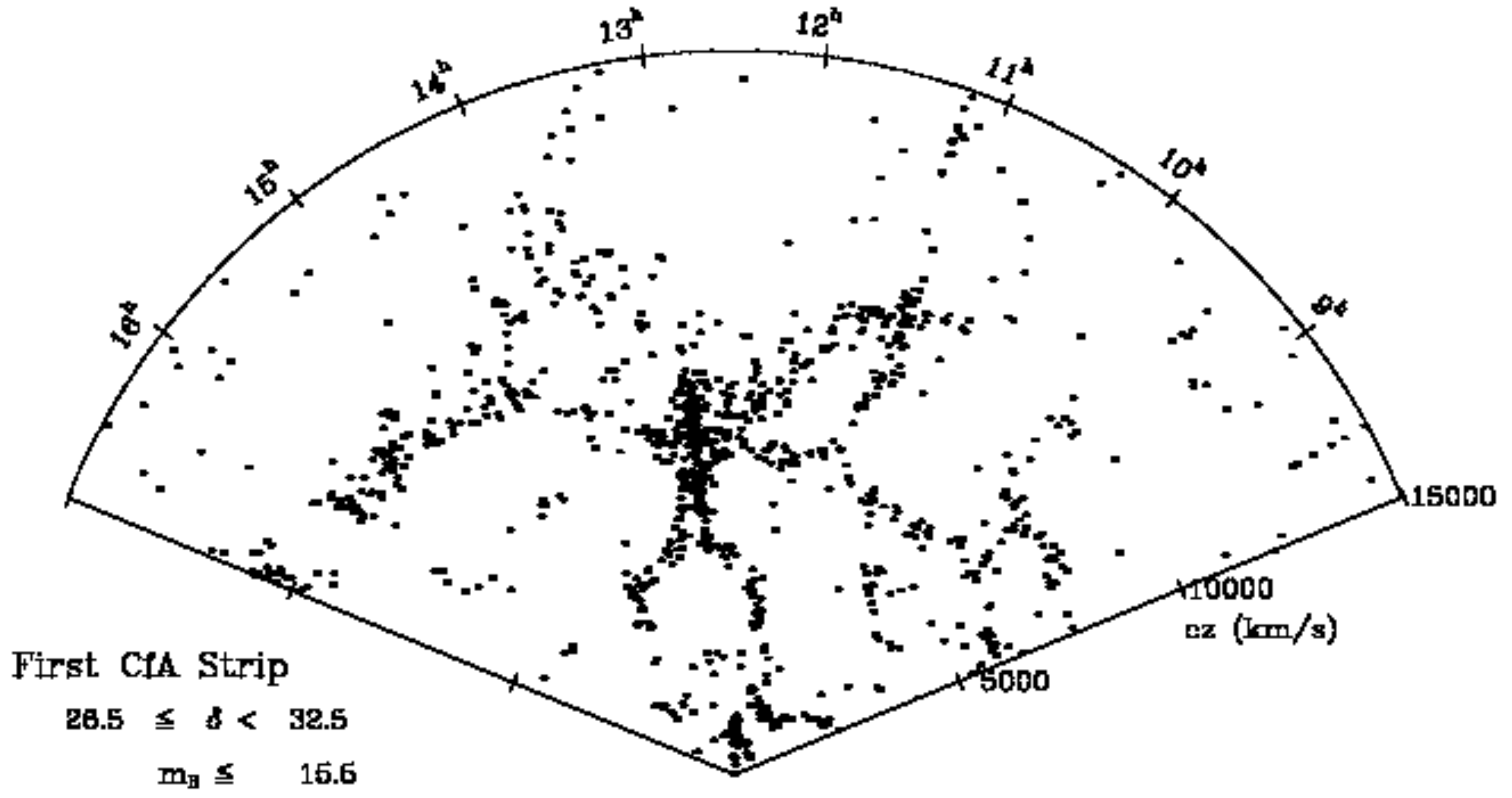
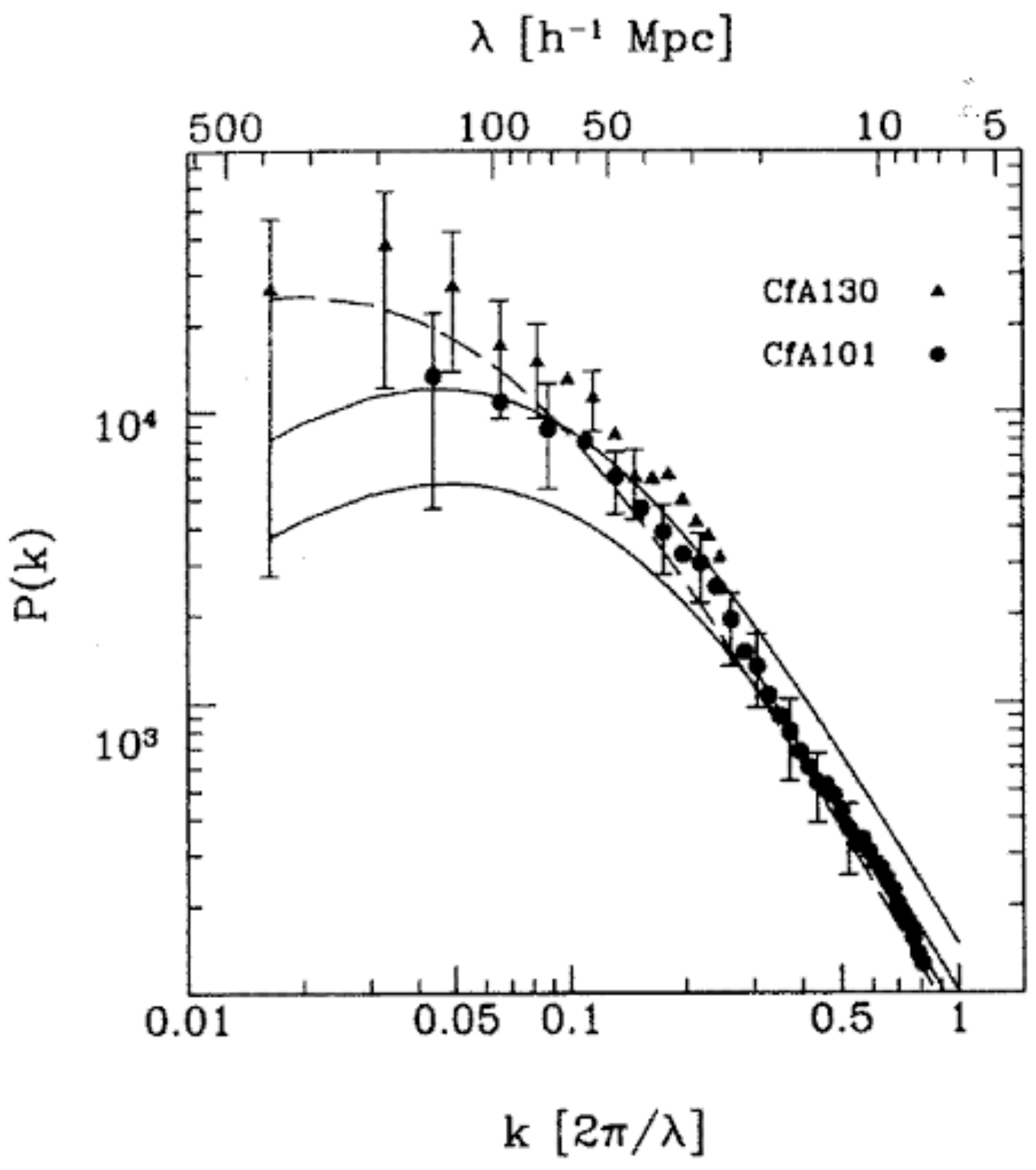
$$\xi(r) = \frac{V}{(2\pi)^3}\int P(k)e^{-\vec{k}\cdot\vec{r}}\, d^3k \qquad k = \frac{2\pi}{r}$$

The power is related to the rms of density fluctuations

$$P(k) \propto |\langle\delta(k)\rangle|^2$$





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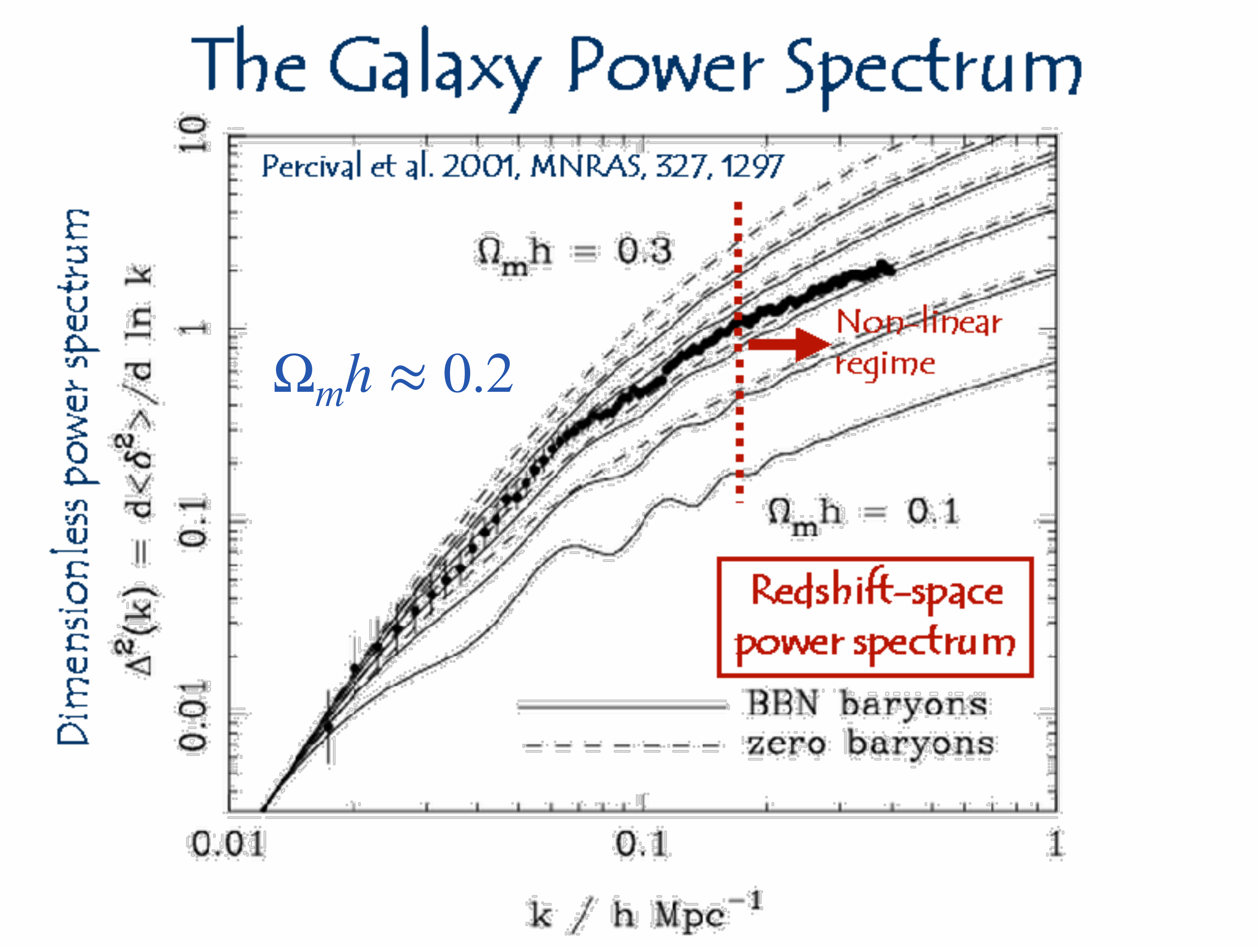
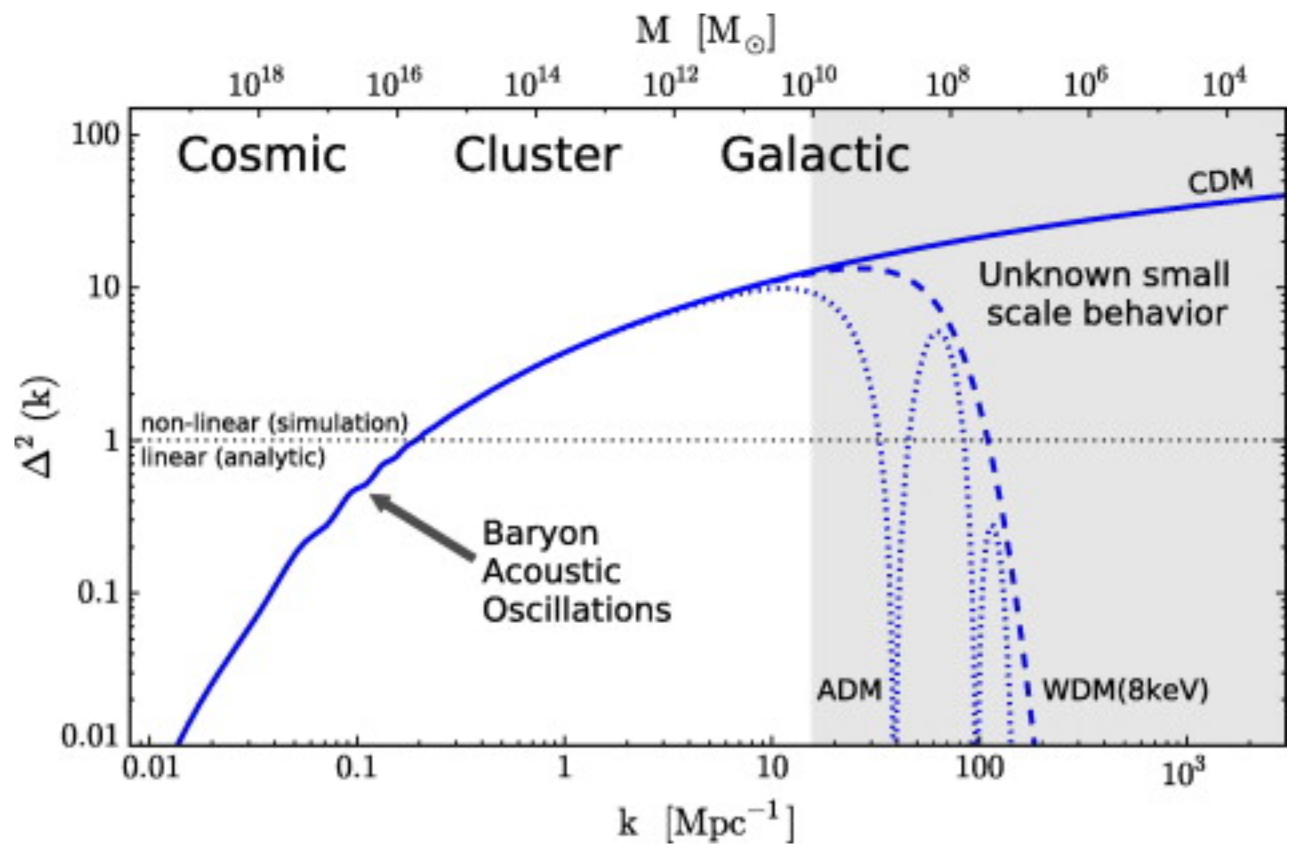
$$P(k) \propto |\delta(k)|^2 \propto k^n$$

with $n \approx 1$ (scale free) initially.





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