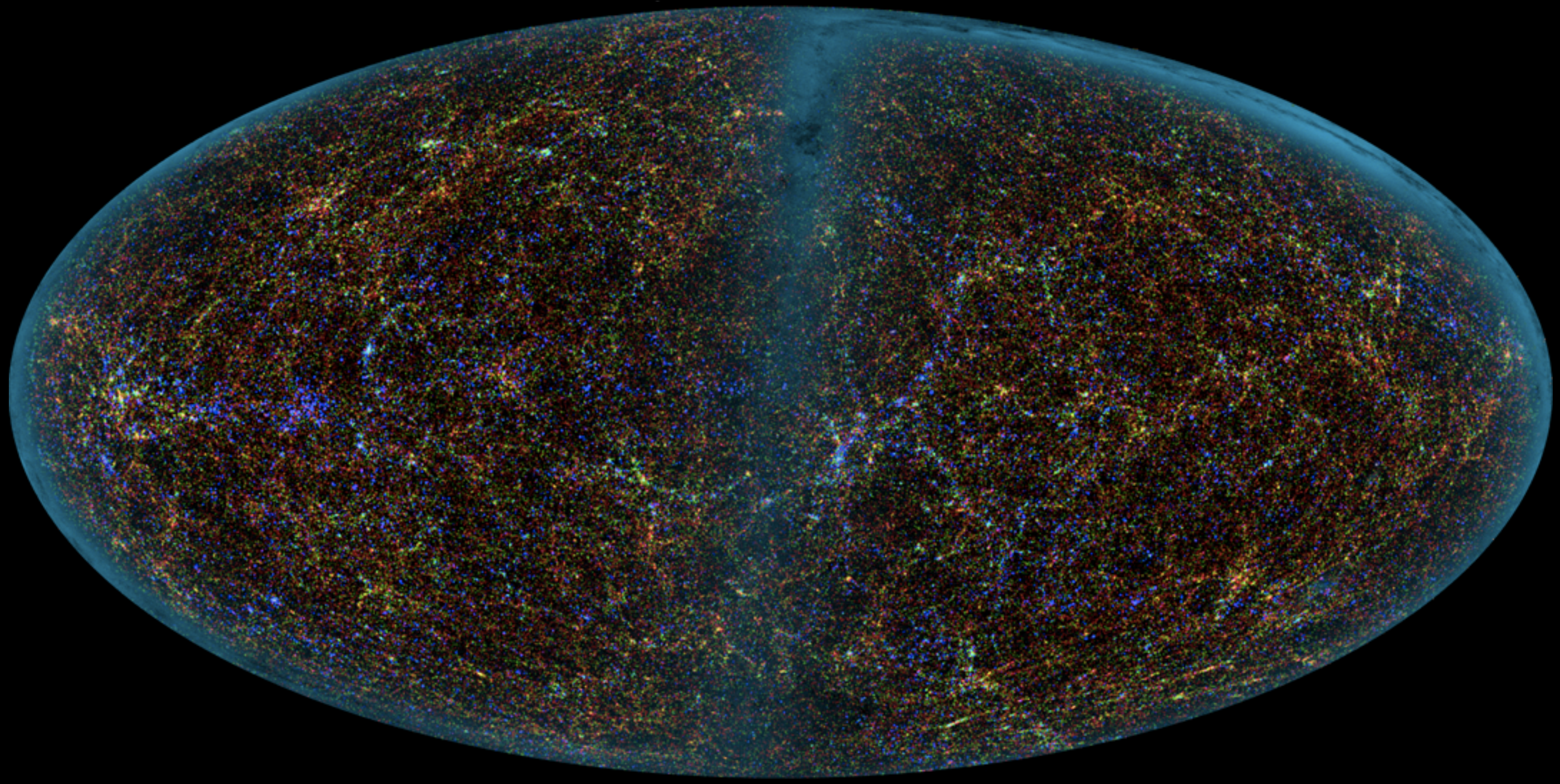
Cosmology
and Large Scale Structure



Today
Structure Formation
Cold Dark Matter

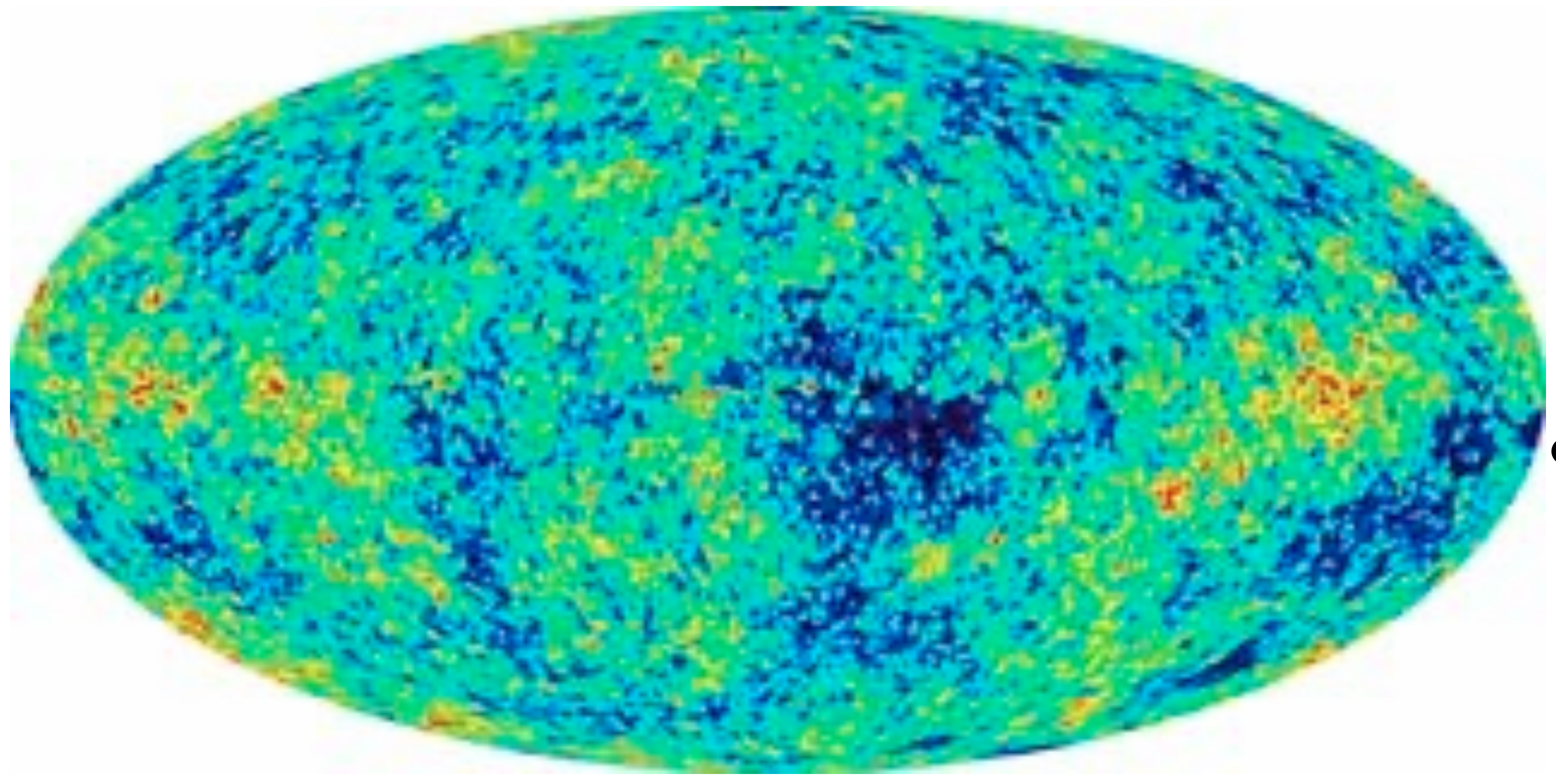
15 November 2022

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

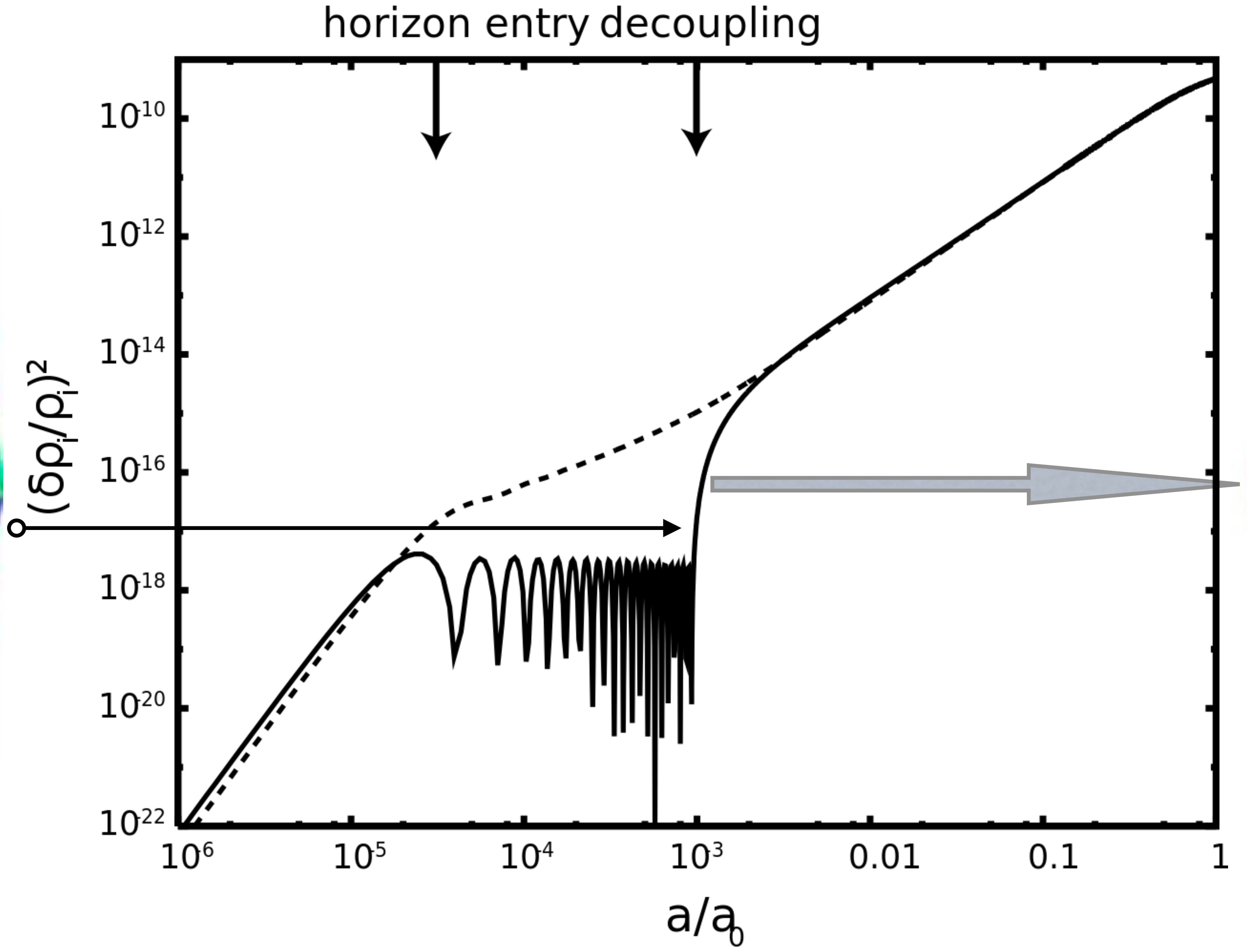
With CDM, you* can get here from there

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

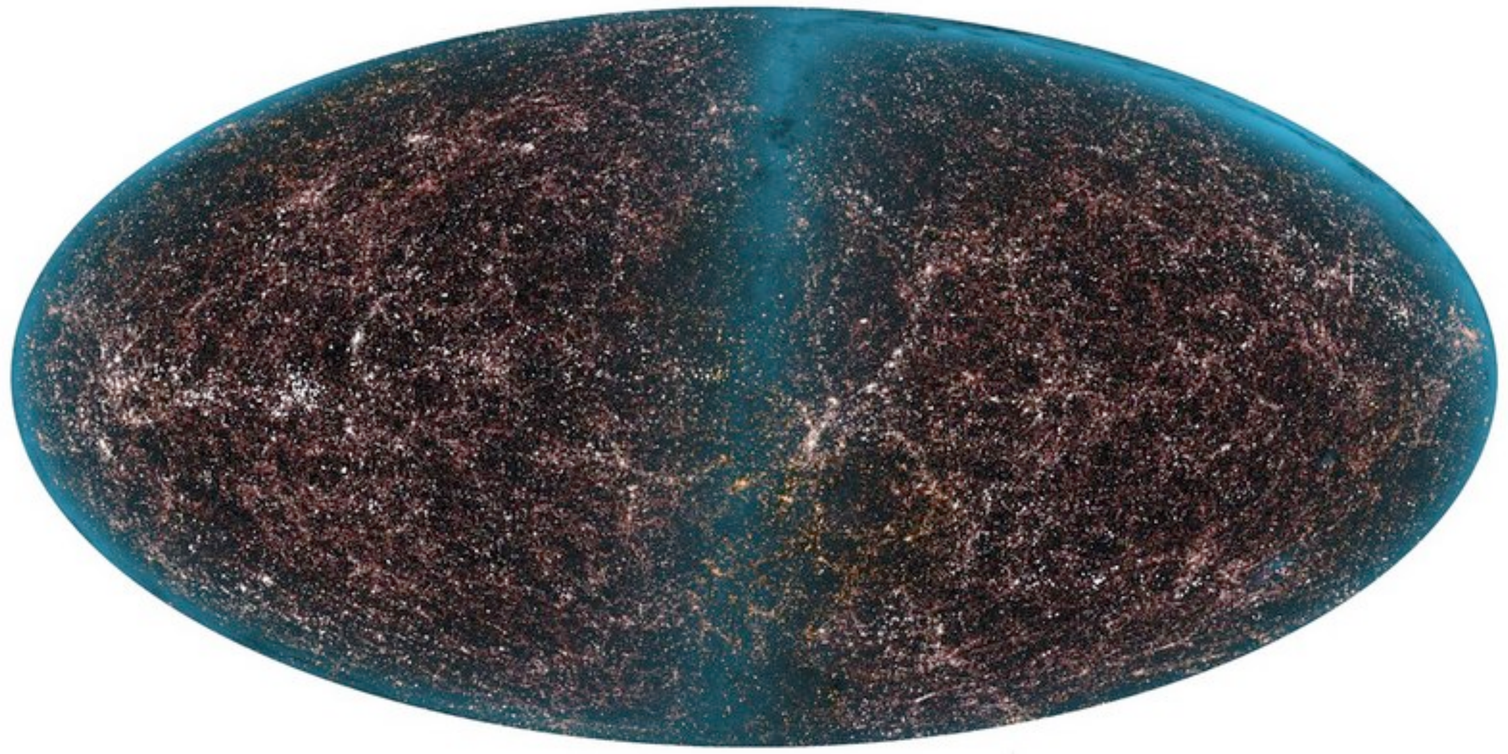
t = 3.8 x 10^5 yr



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

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)

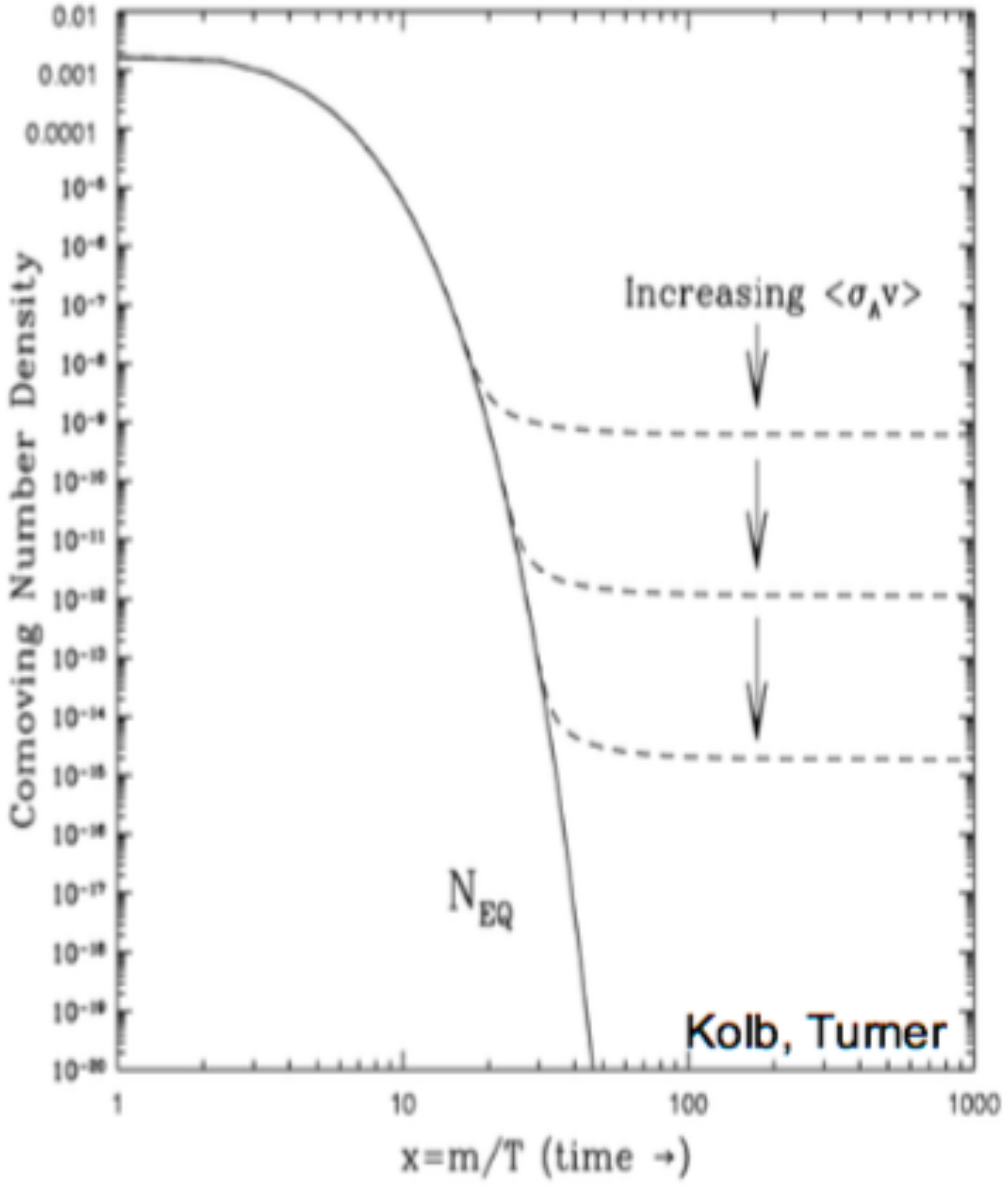
or

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.

THE WIMP MIRACLE

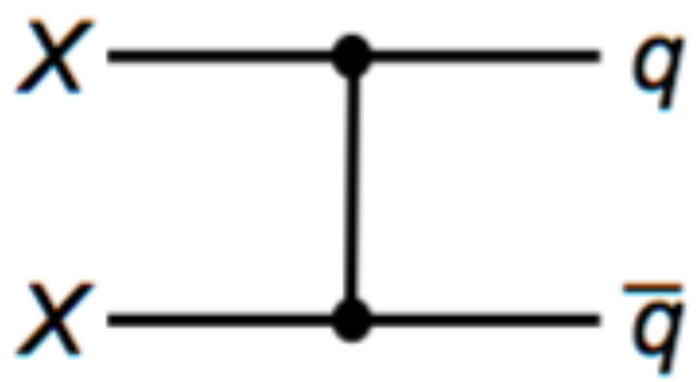


In the very early universe

- Assume a new (heavy) particle *X* is initially in thermal equilibrium

- Its relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

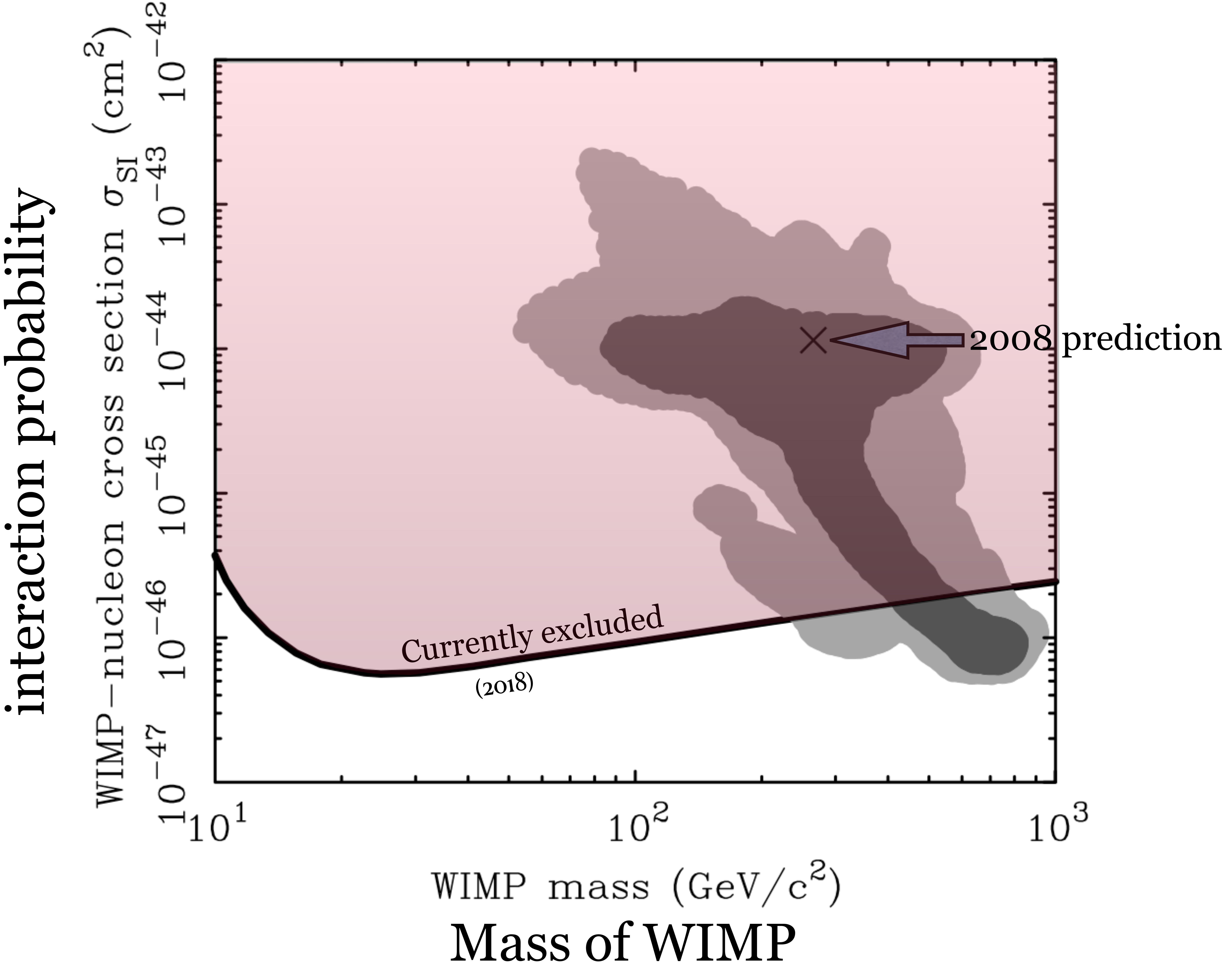
Originally expected $\sigma \sim 10^{-39}$ cm^{-2}, but only the thermal cross-section $\langle \sigma v \rangle$ matters here.

- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

Direct detection experiments have repeatedly excluded predicted WIMP properties

The original prediction of $\sigma \sim 10^{-39}$ is off scale, having been excluded long ago, BUT we can still get away with the "right" thermal cross-section $\langle \sigma v \rangle$ for the WIMP miracle if the mass is high enough for the velocity to be low.

Current data are exceedingly grim for the WIMP, but we stick with it out of habit and for lack of a better idea.

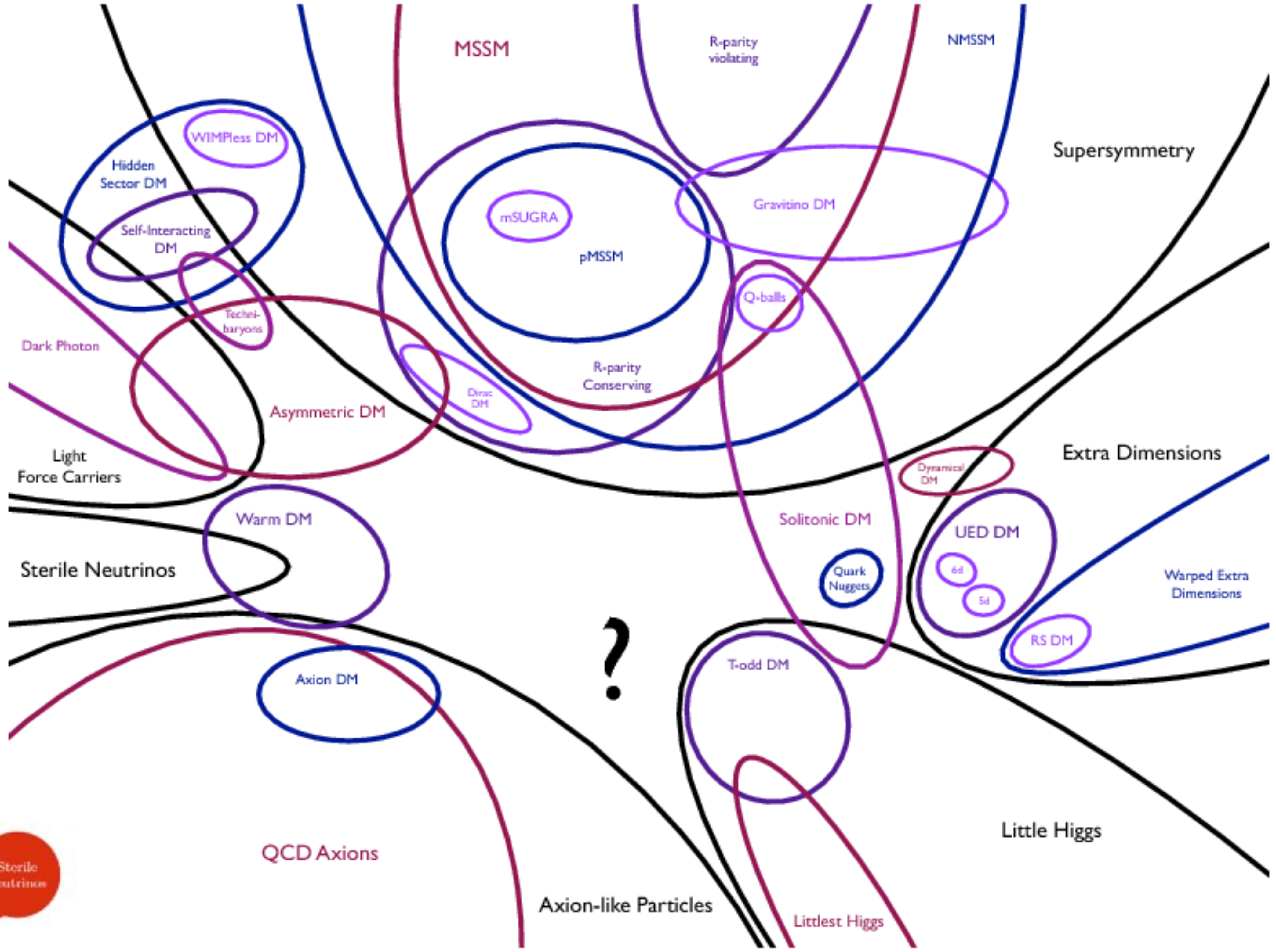


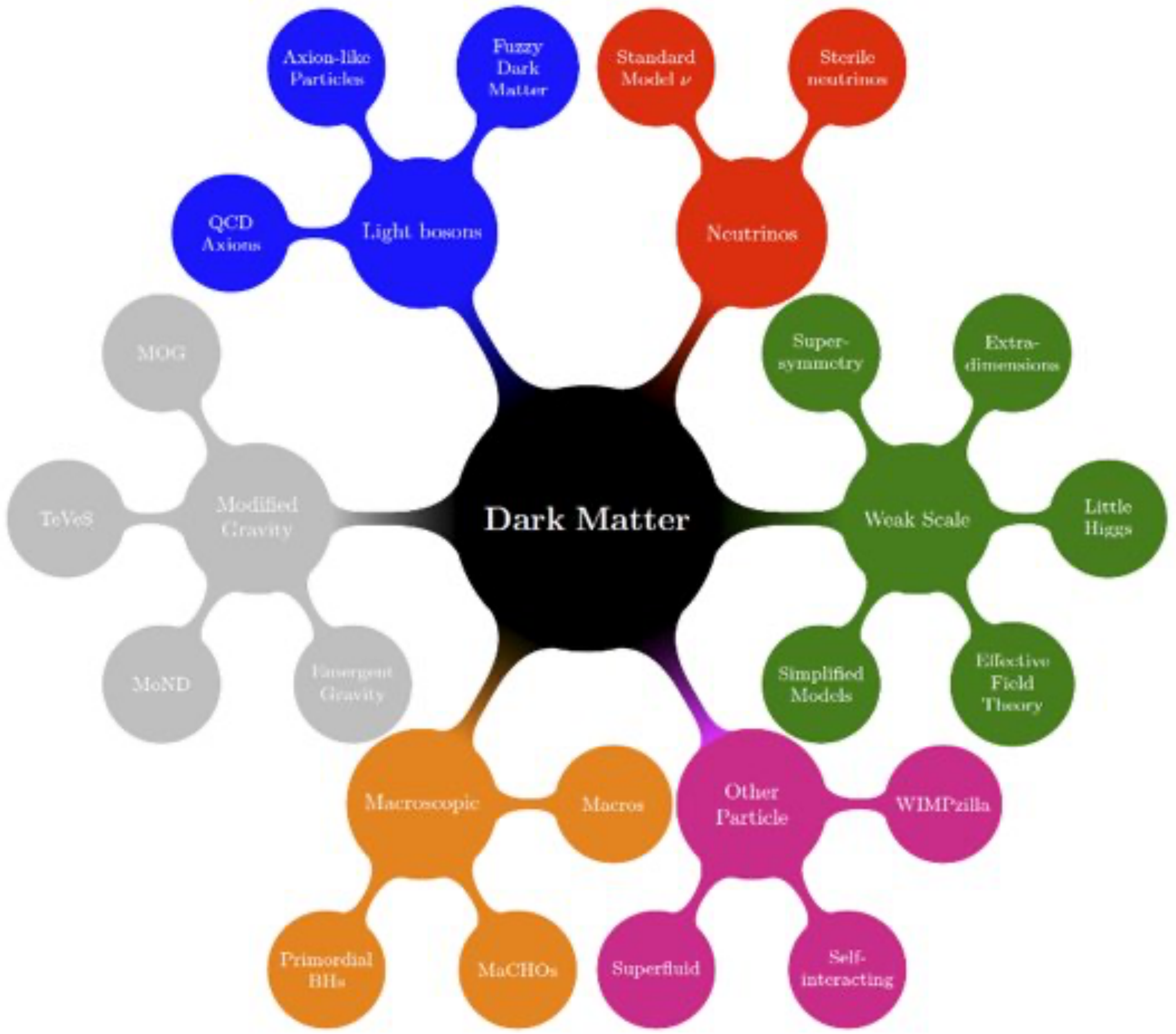
Lots of particle candidates for CDM:
WIMPs
Axions
Light dark matter
wimpzillas
etc.

Can imagine other candidates as well:

Warm DM
Self-interacting DM
etc.

and yet others... (Tim Tait)





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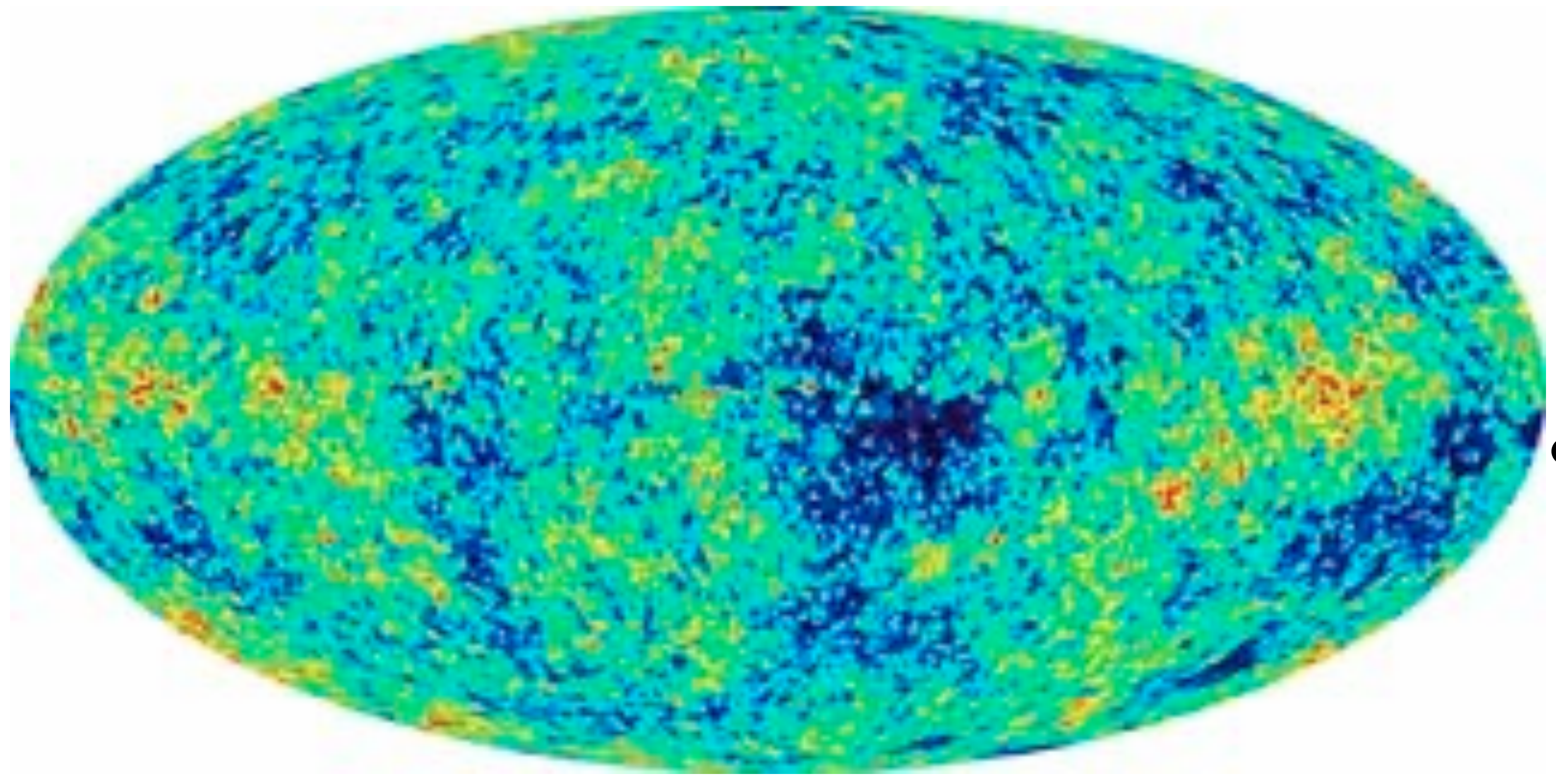

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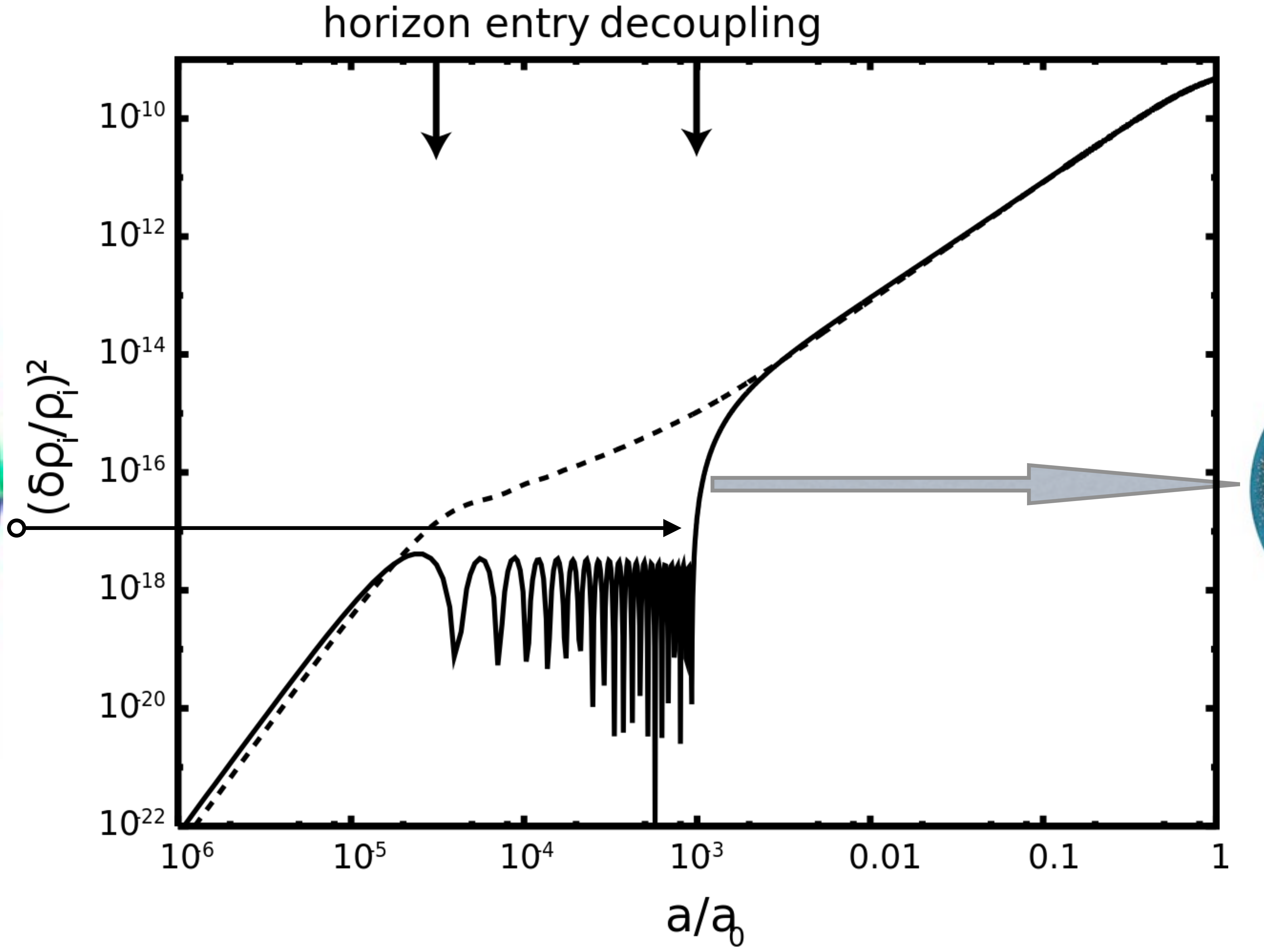

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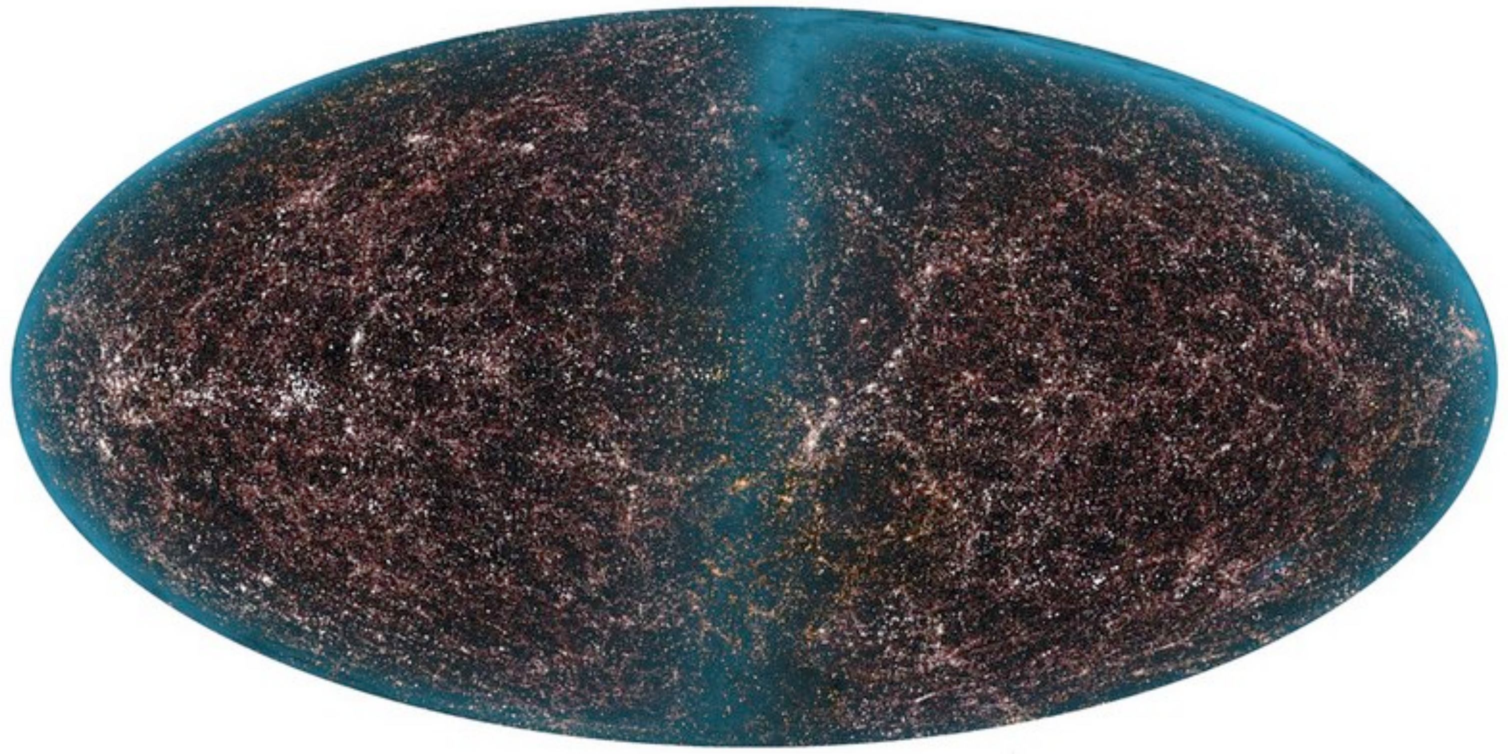

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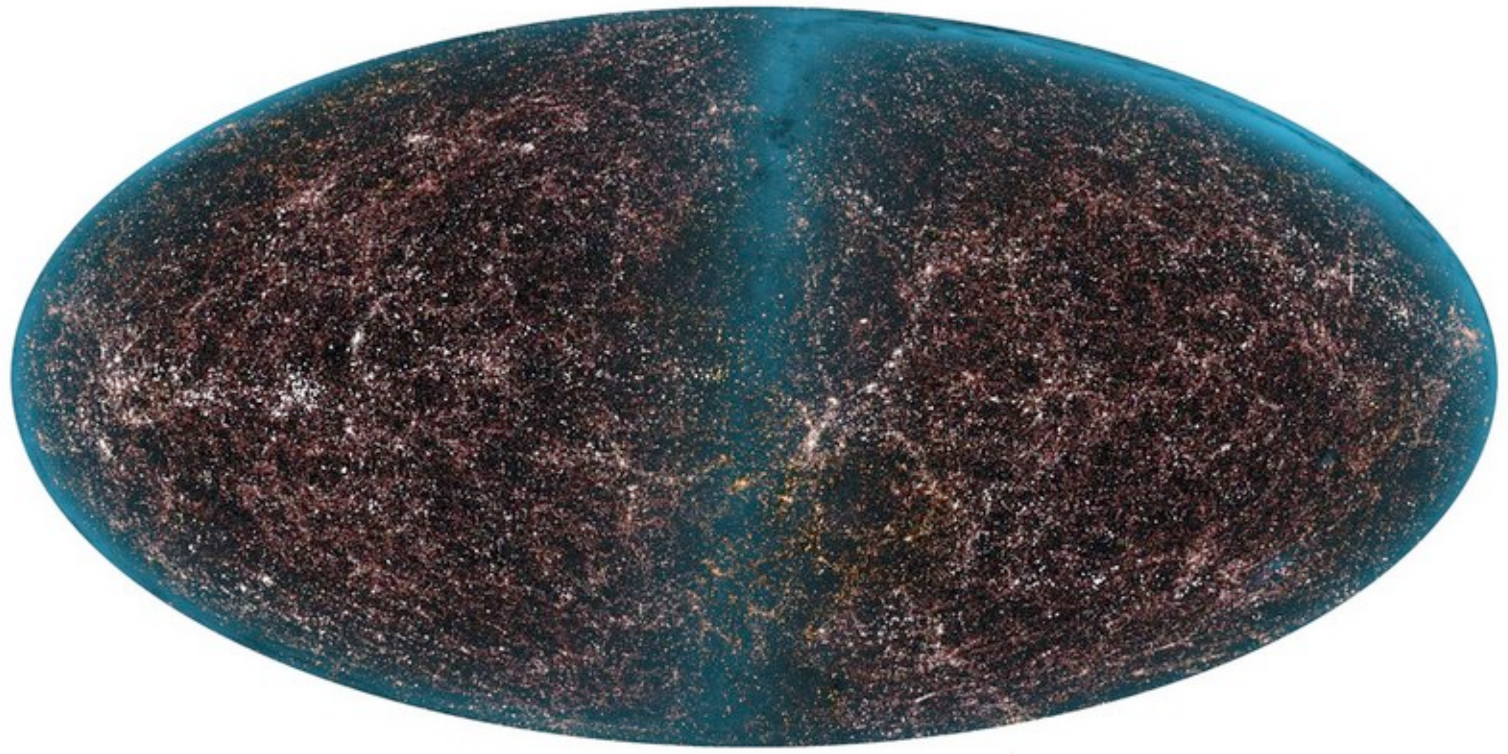
Large Scale Structure

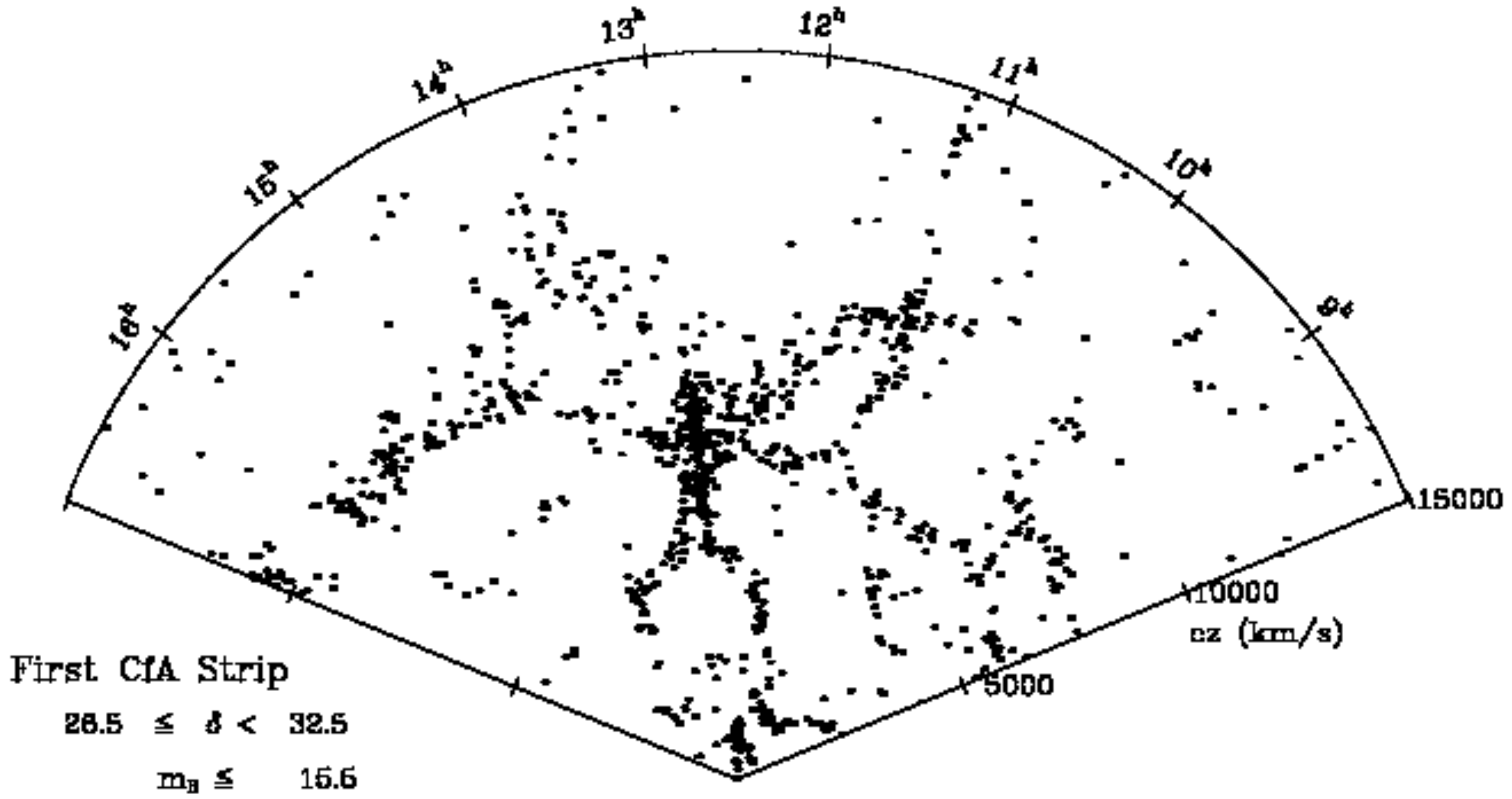
Redshift surveys locate galaxies in 3D space (α, δ, z)

Distribution of 2MASS galaxies as seen on the sky



maps to right ascension α and declination δ

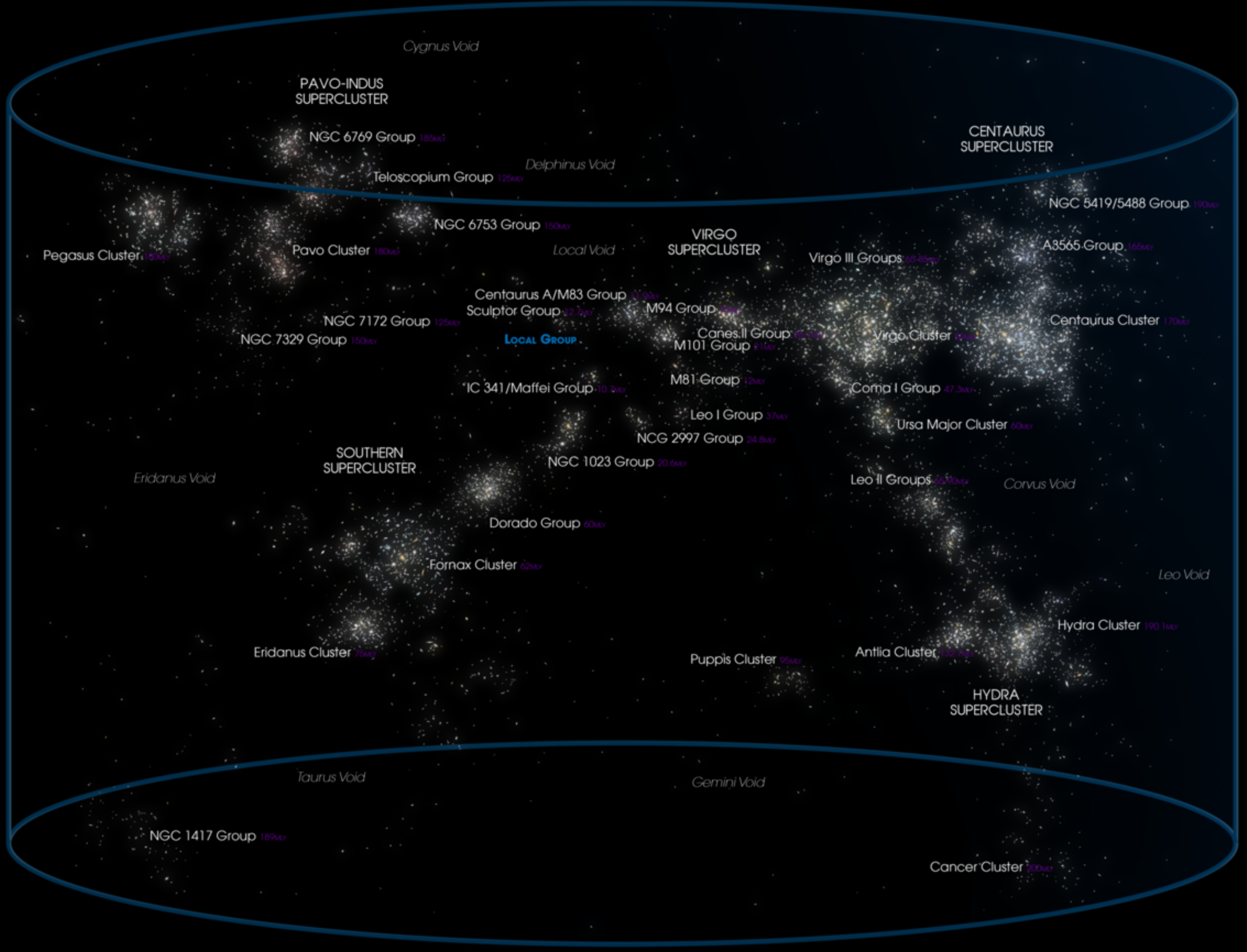
Distribution of CfA galaxies as seen in redshift z and right ascension α

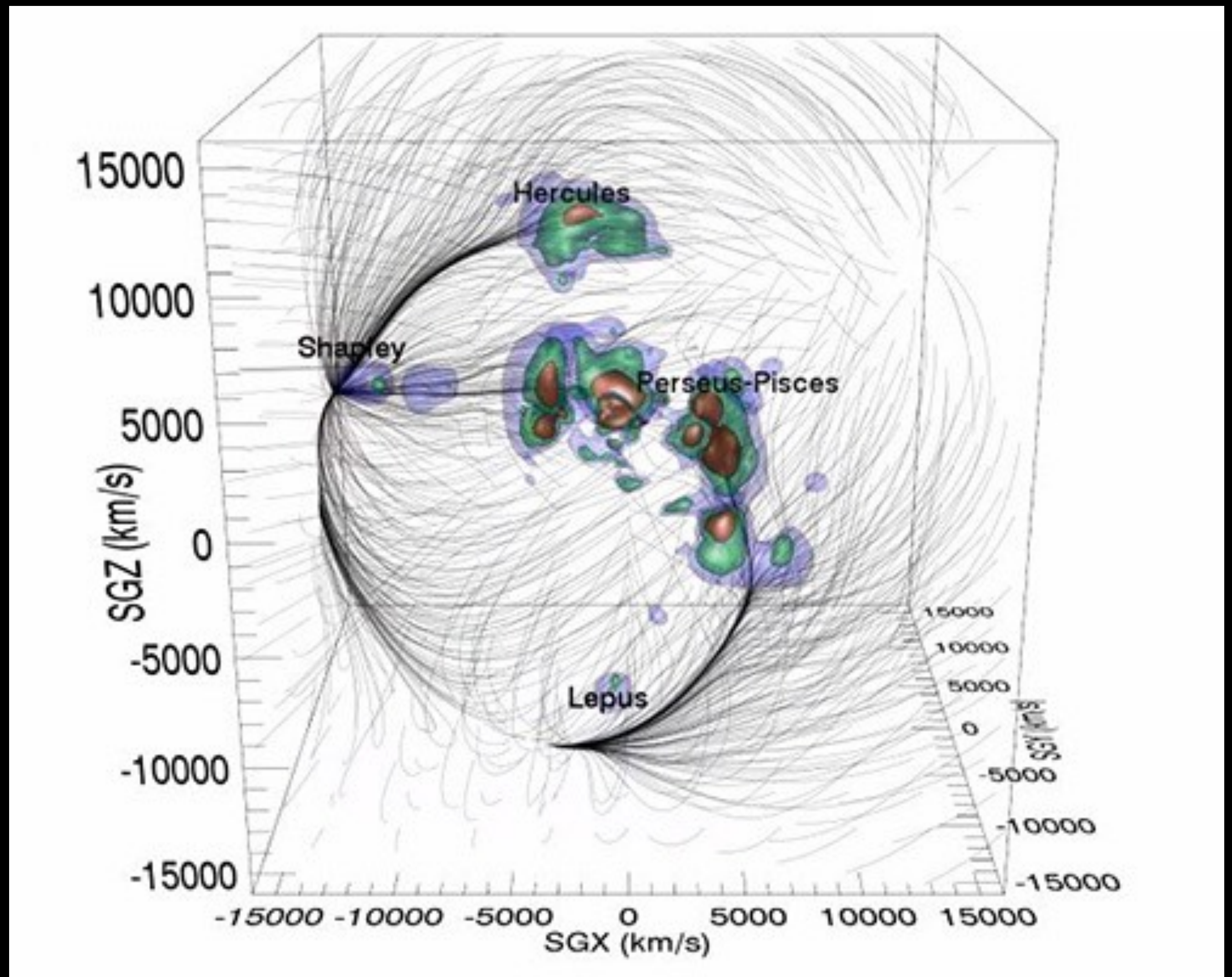


This "stick-man" distribution came as a huge surprise at the time (1987) - cosmologists has expected something closer to homogeneity on this scale.

Laniakea - our local supercluster

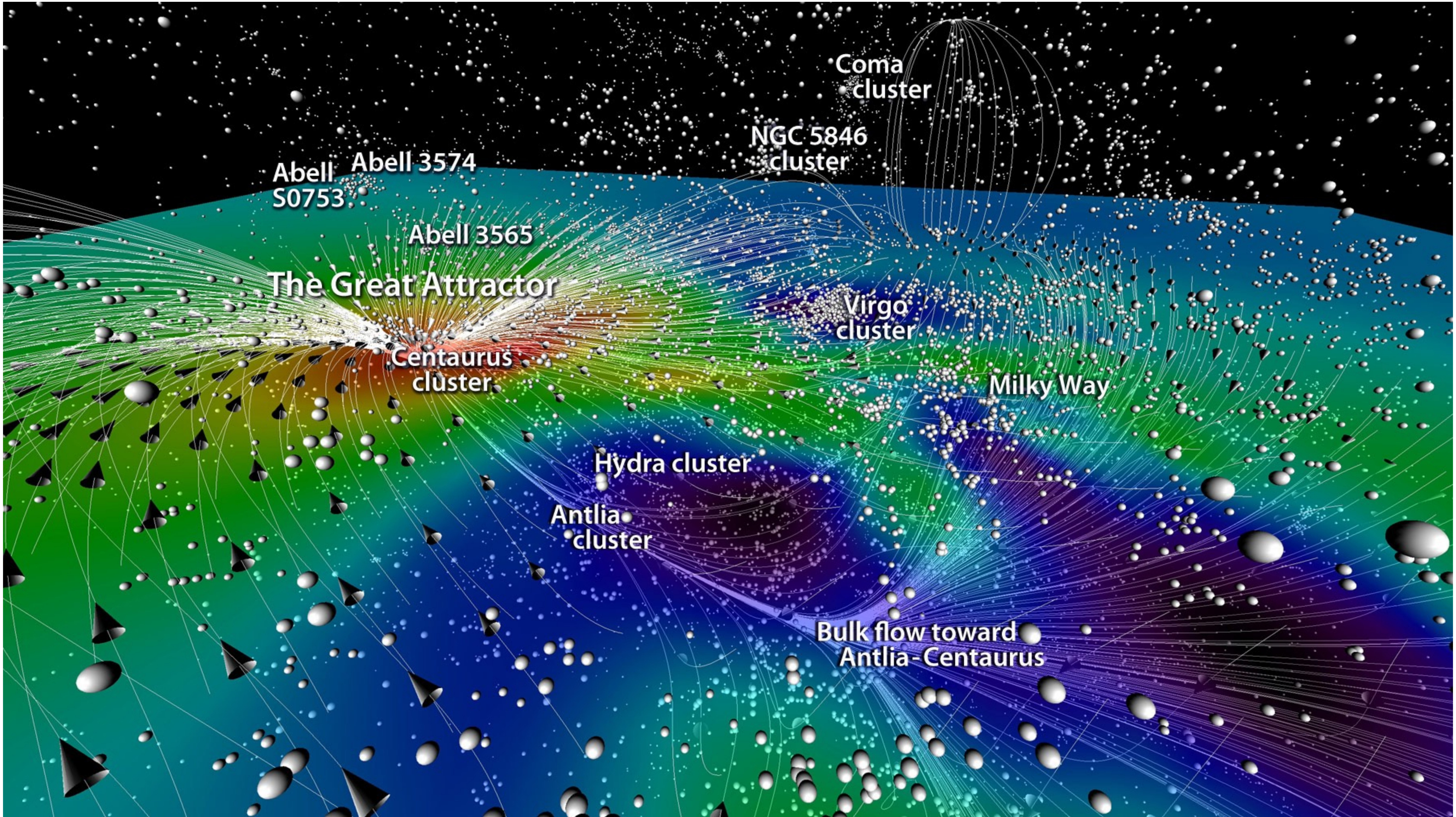
LANIAKEA



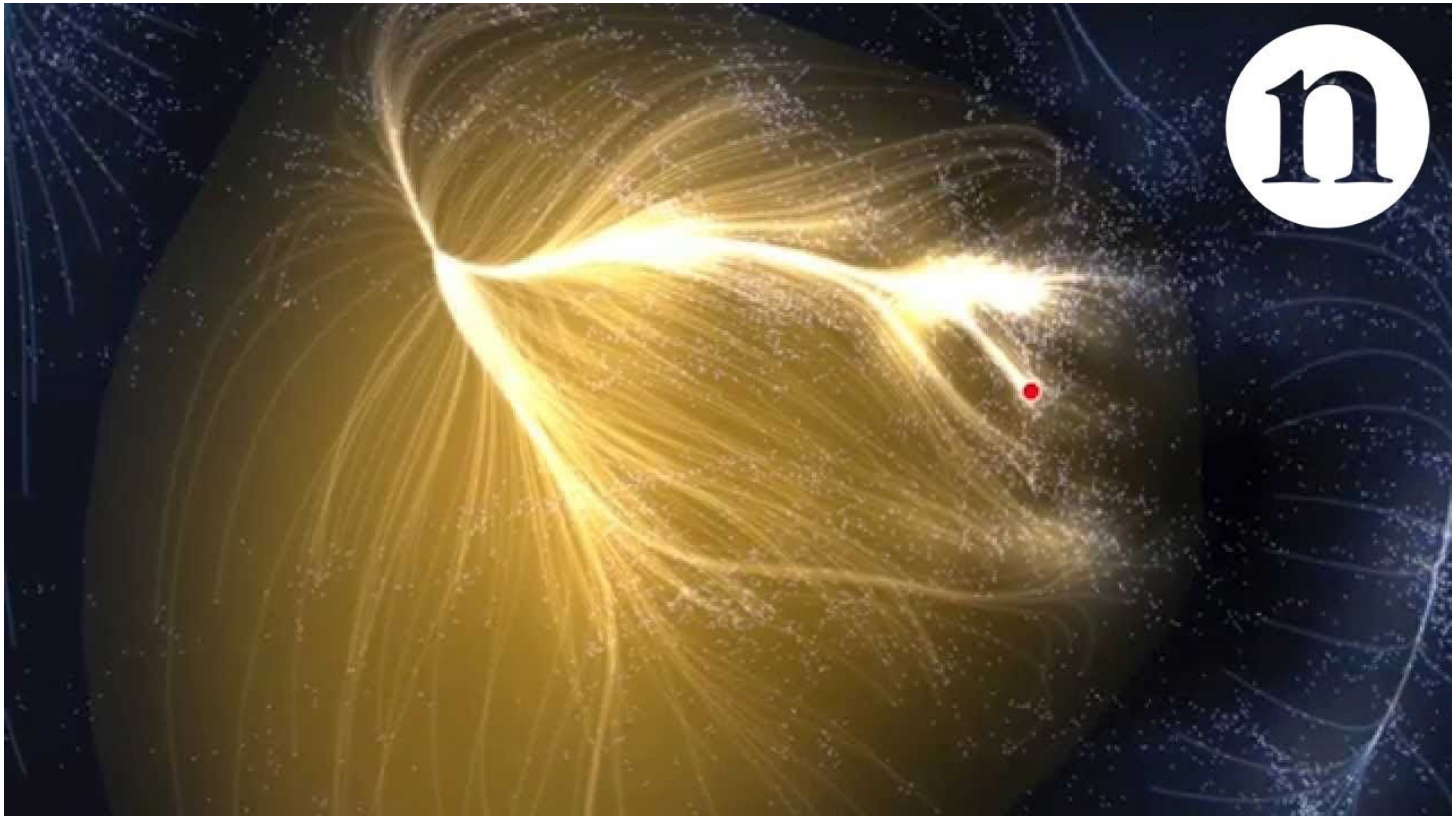


It's challenging to depict 3D information

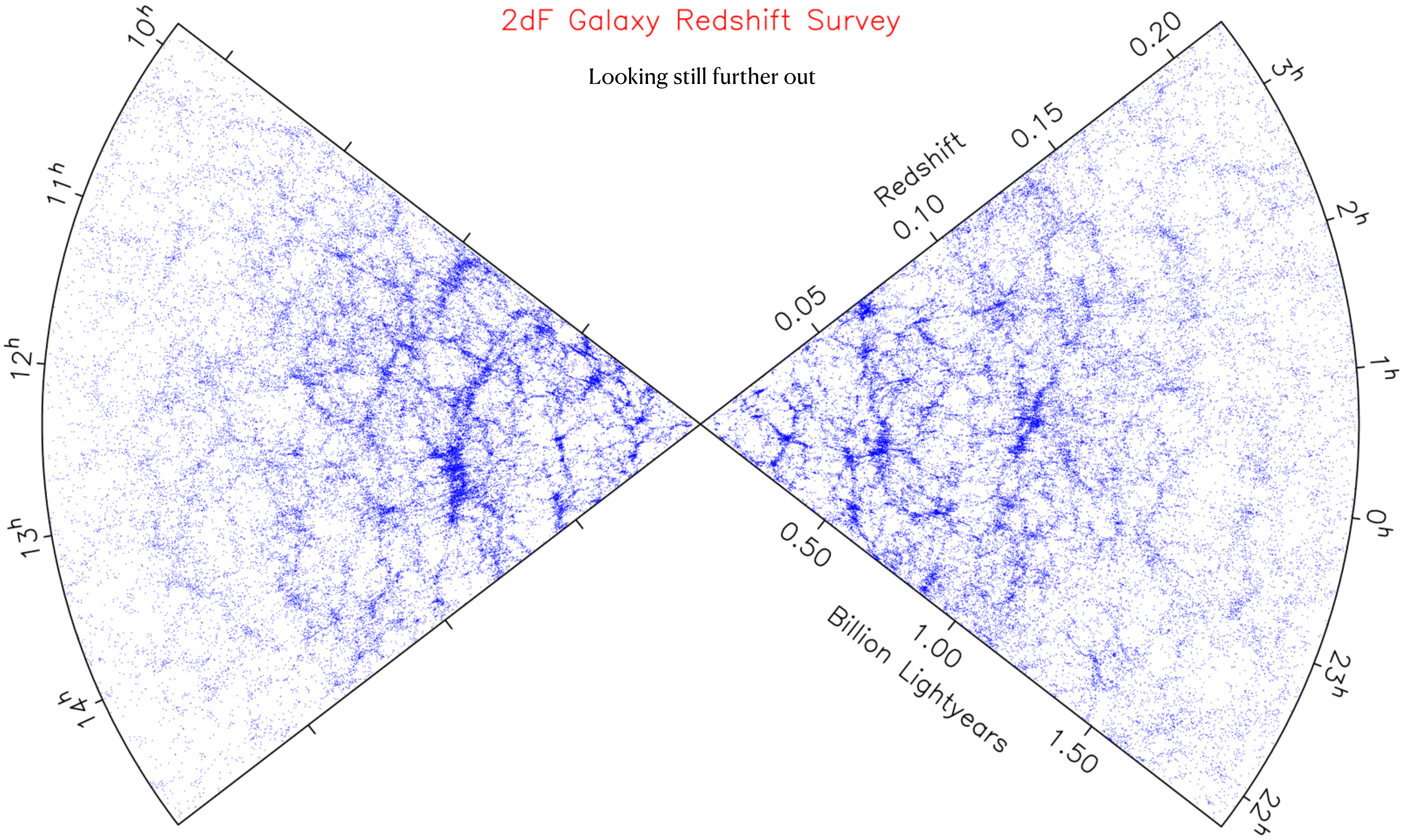
There are large scale bulk flows as well as structure



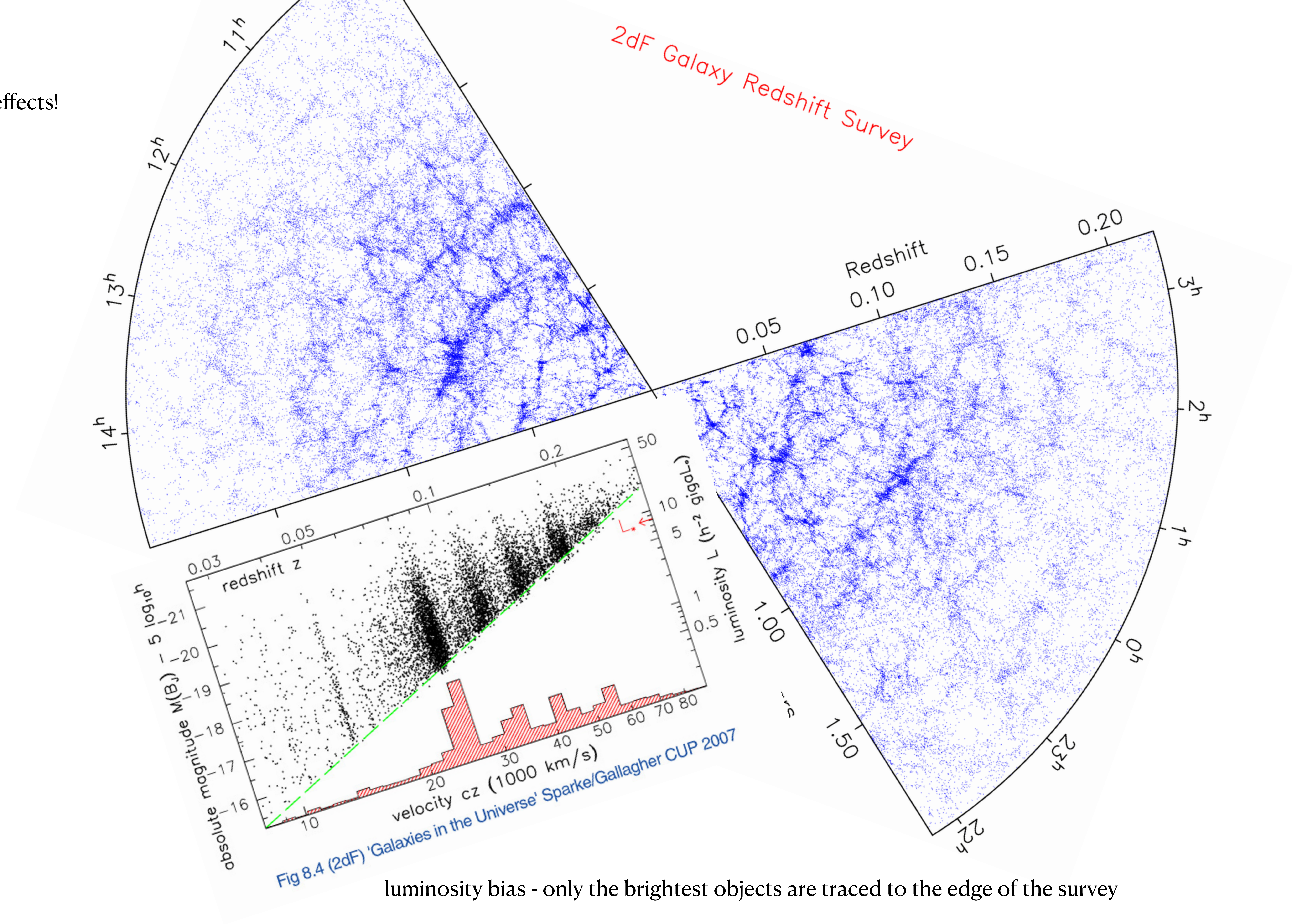
Laniakea - defined by peculiar velocities



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.

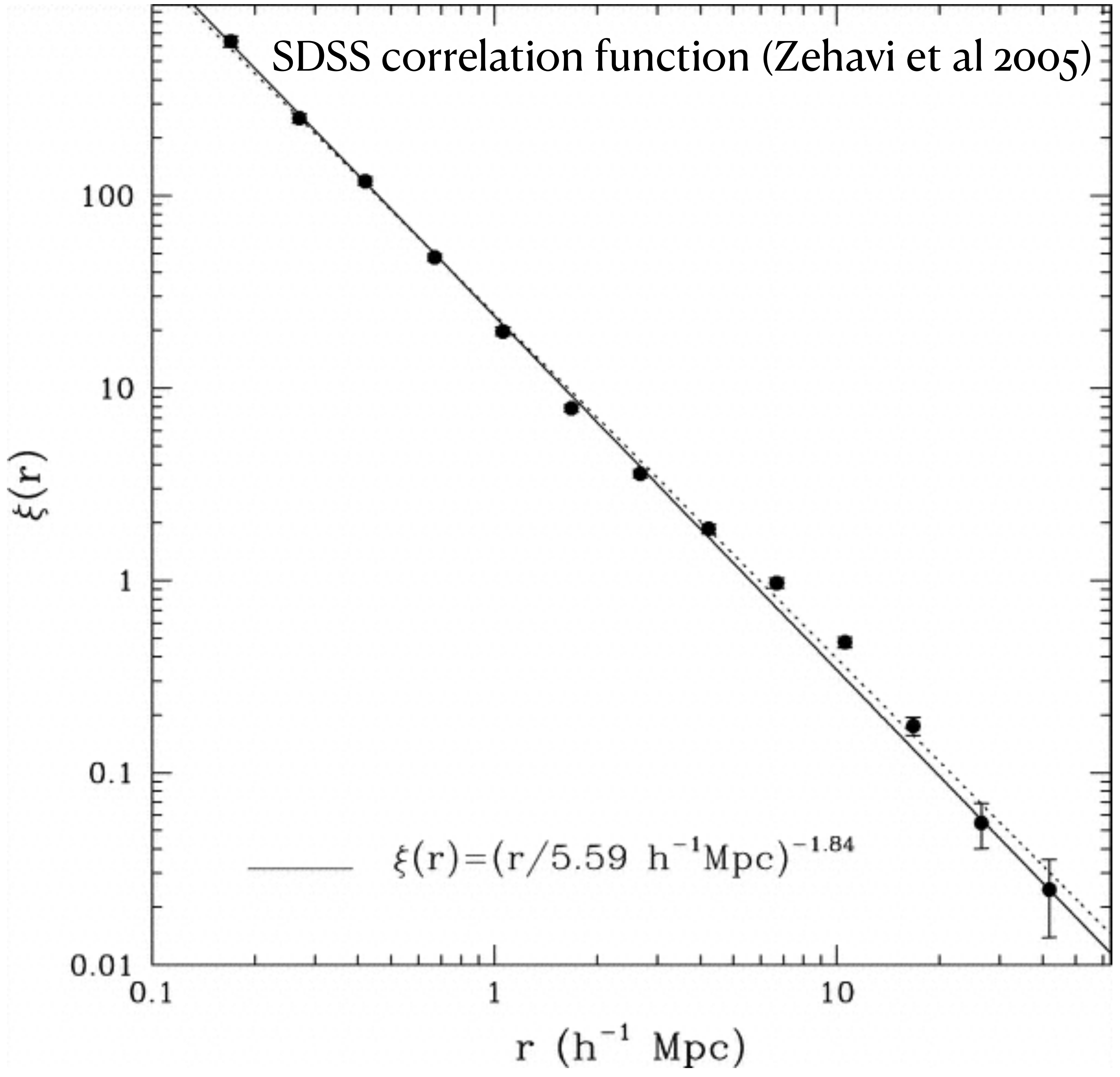
$$\frac{dN}{N} = [1 + \xi(r)]dV$$

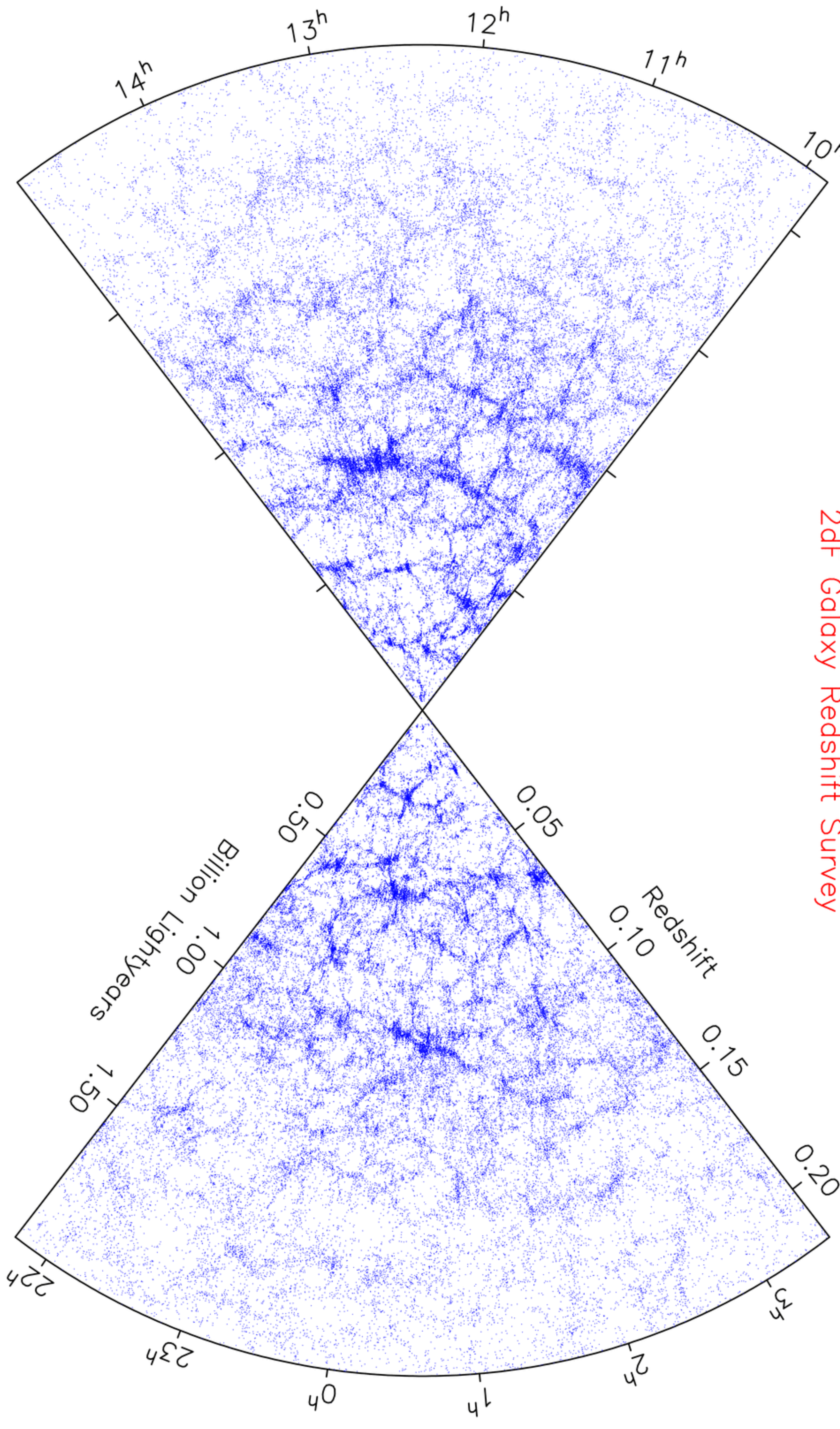
tolerably described as a power law

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

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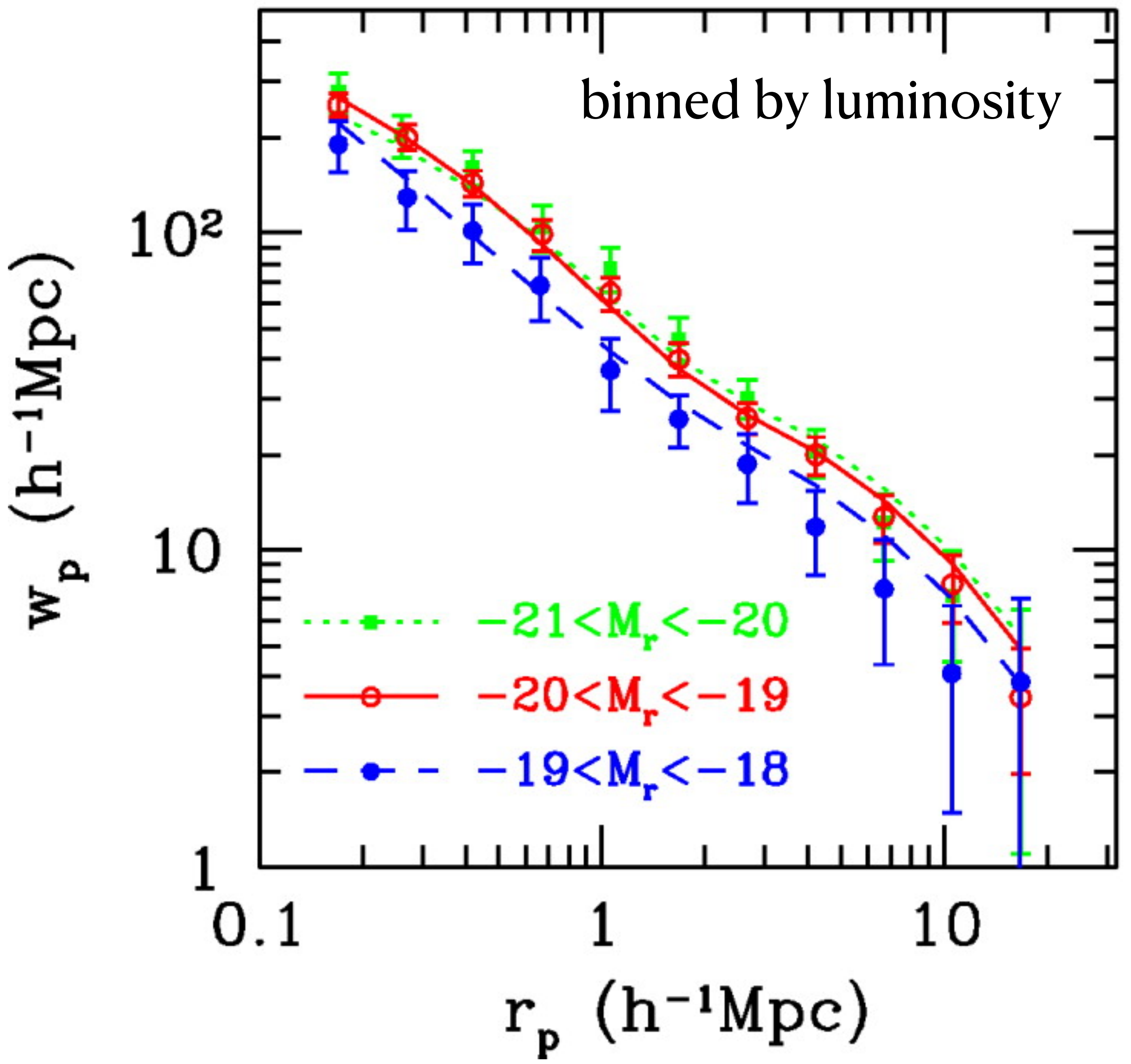
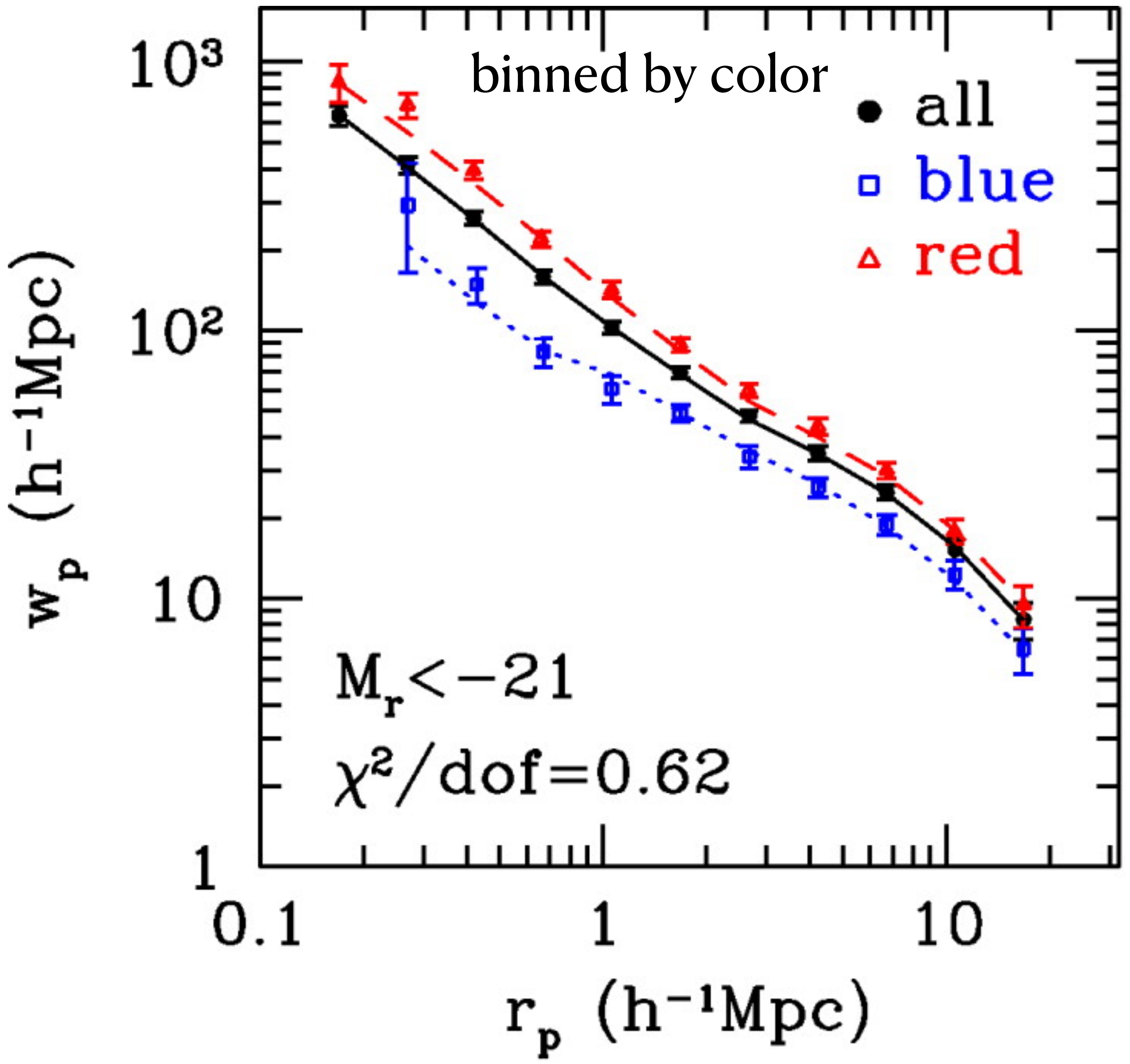
The correlation length depends on galaxy properties: *bright, red, early type* galaxies are more strongly clustered (large r_0) than *dim, blue, late type* galaxies.

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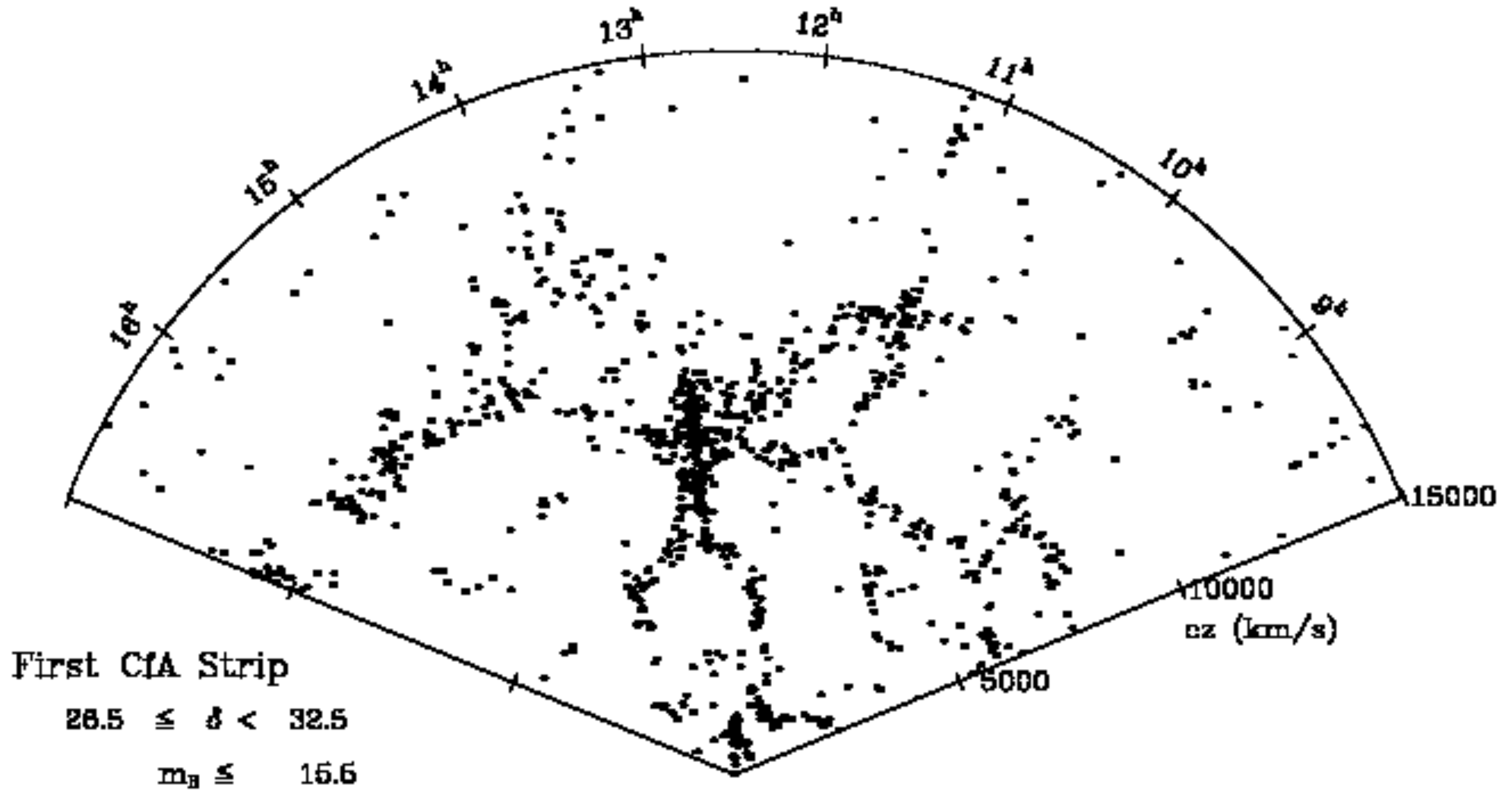
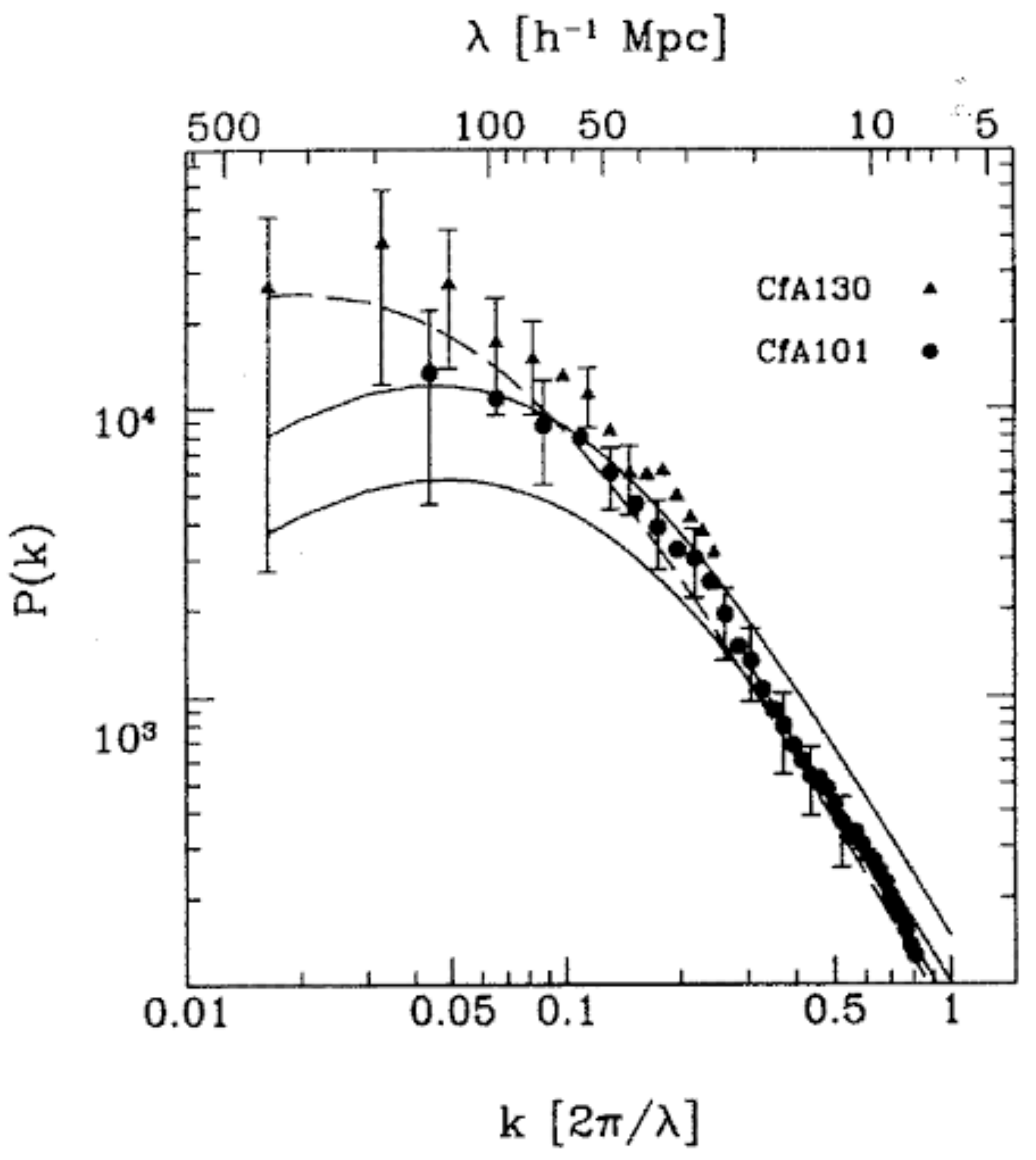
$$\xi(r) = \frac{V}{(2\pi)^3}\int P(k)e^{-\vec{k}\cdot\vec{r}}\, d^3k \qquad k = \frac{2\pi}{r}$$

The power is related to the rms of density fluctuations

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





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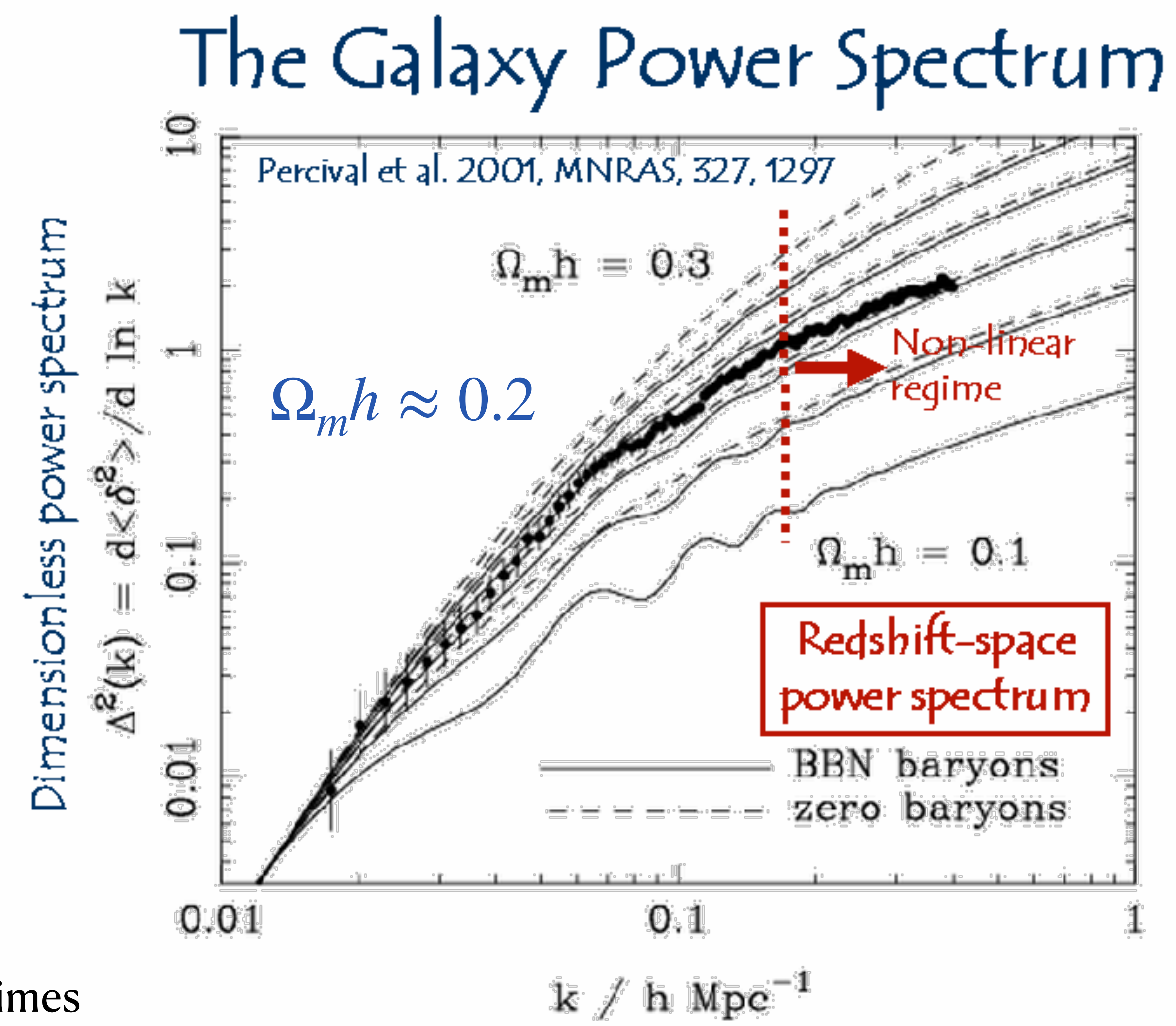
$$P(k) \propto |\delta(k)|^2 \propto k^n$$

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

The Galaxy Power Spectrum



The quantity $\Gamma = \Omega_m h$ is sometimes called the *shape parameter*