Sterrewacht Leiden

Origins & Evolution of the Universe

an introduction to cosmology – Fall 2014

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http://www.strw.leidenuniv.nl/~hoekstra/TEACHING/OEU/OEU.html

Our framework

In the previous two lectures we have developed a framework to explain the observations of the Universe.

Cosmological Principle

↓

FLRW metric

↓ + GR

Friedmann equation + acceleration equation

But the starting point is the cosmological principle… we need to check whether this is in agreement with the observations.

Distribution of galaxies

We can measure the number of galaxies in different directions and at different brightness in the sky. When a distribution is the same in all directions, it is **isotropic**.

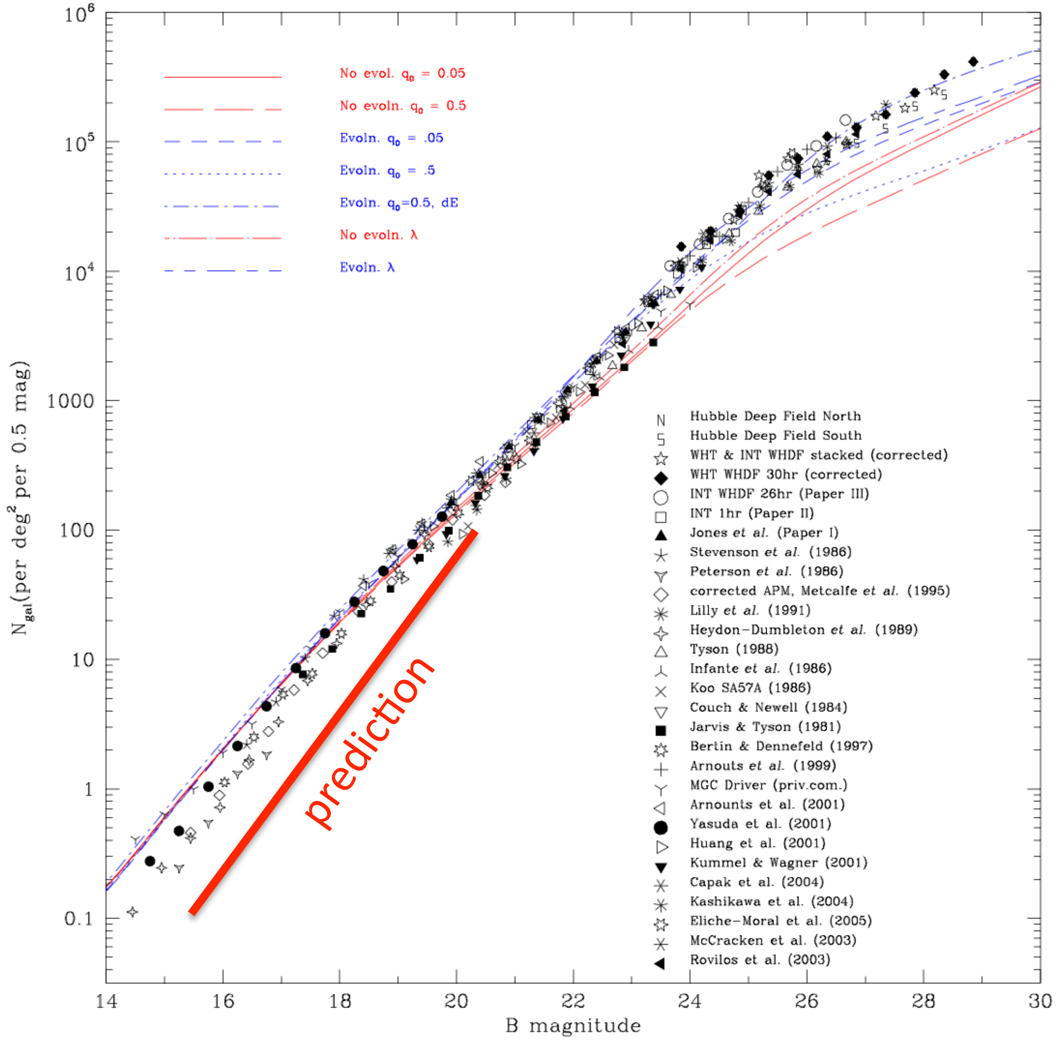
Consider a homogeneous distribution of identical sources:

- apparent flux at distance *r*: $S \propto r^{-2}$
- number of sources within distance *r*: $N \propto r^3$

⇒ the number of sources brighter than flux *S*: $N(>S) \propto S^{-3/2}$
(a source that is 100x fainter is 10x further away, an the volume is 1000x larger)

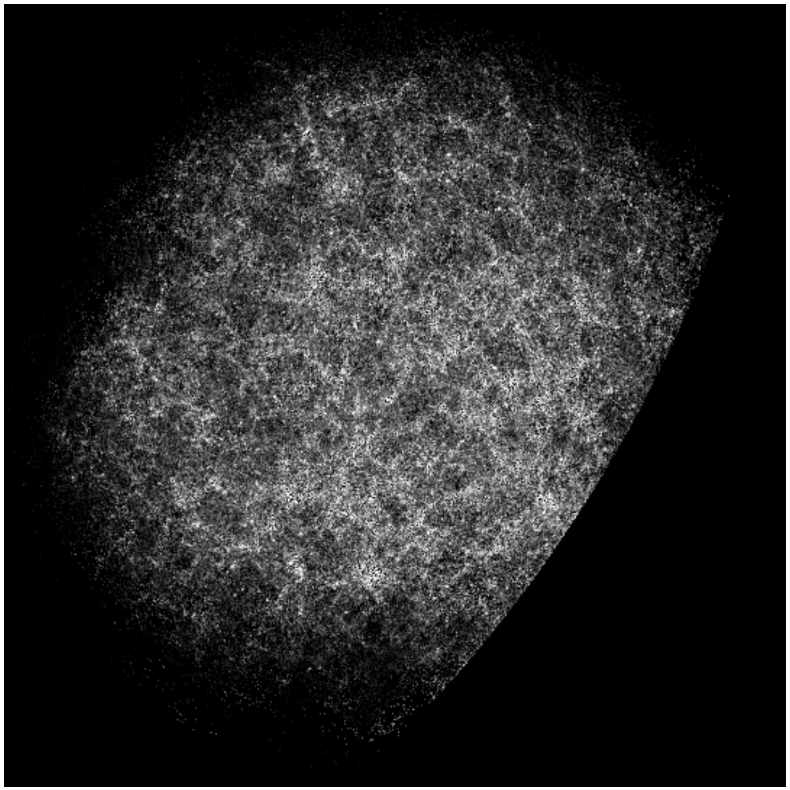
This can be generalized to a distribution of source luminosities

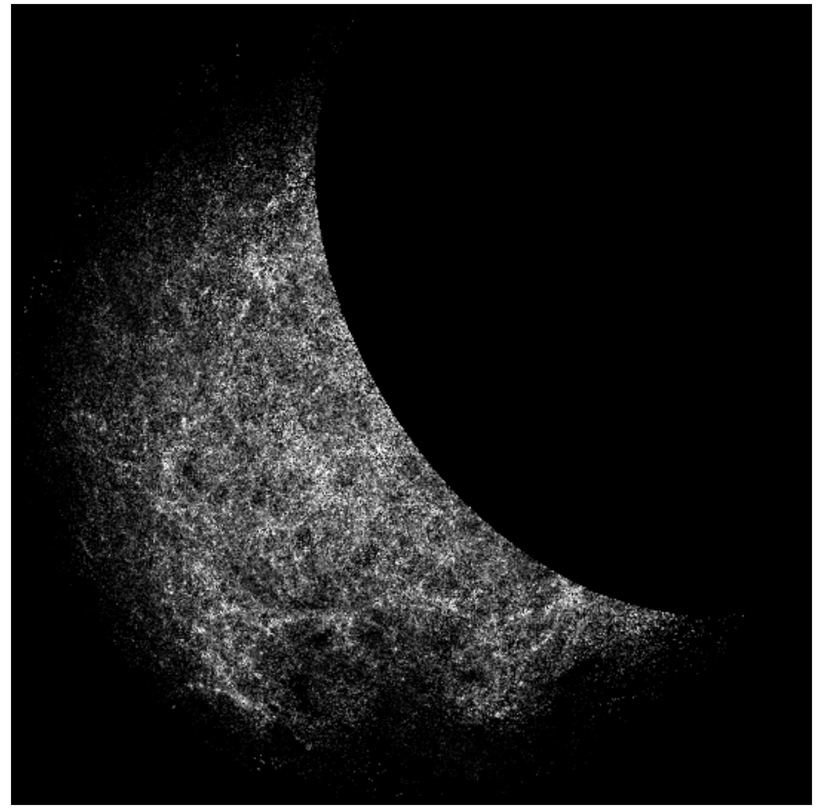
Test of homogeneity



Courtesy Nigel Metcalfe

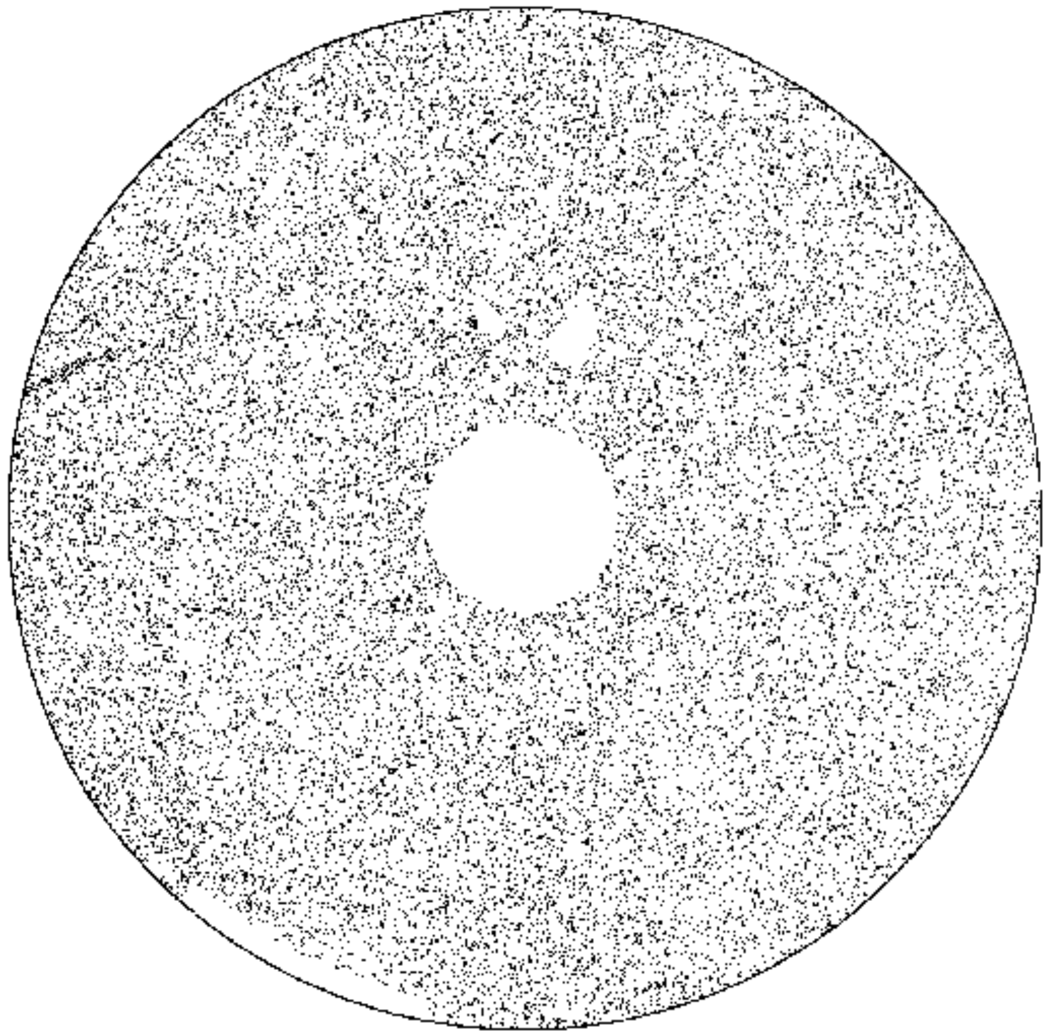
Distribution of nearby galaxies





The angular distribution of galaxies brighter than B~19 from the Lick galaxy catalog shows a lot of clustering.

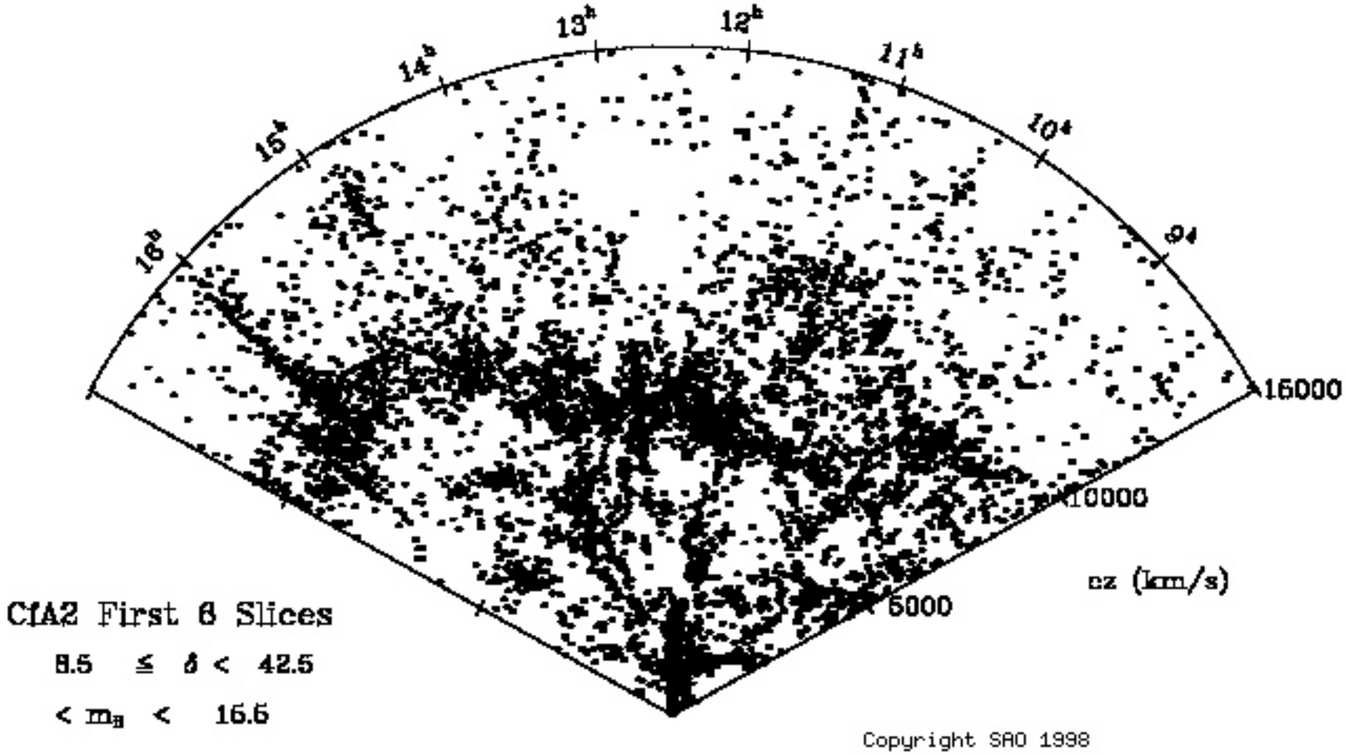
Distribution of radio sources



Gregory & Condon (1991): angular distribution of the 31,000 brightest 6cm radio sources

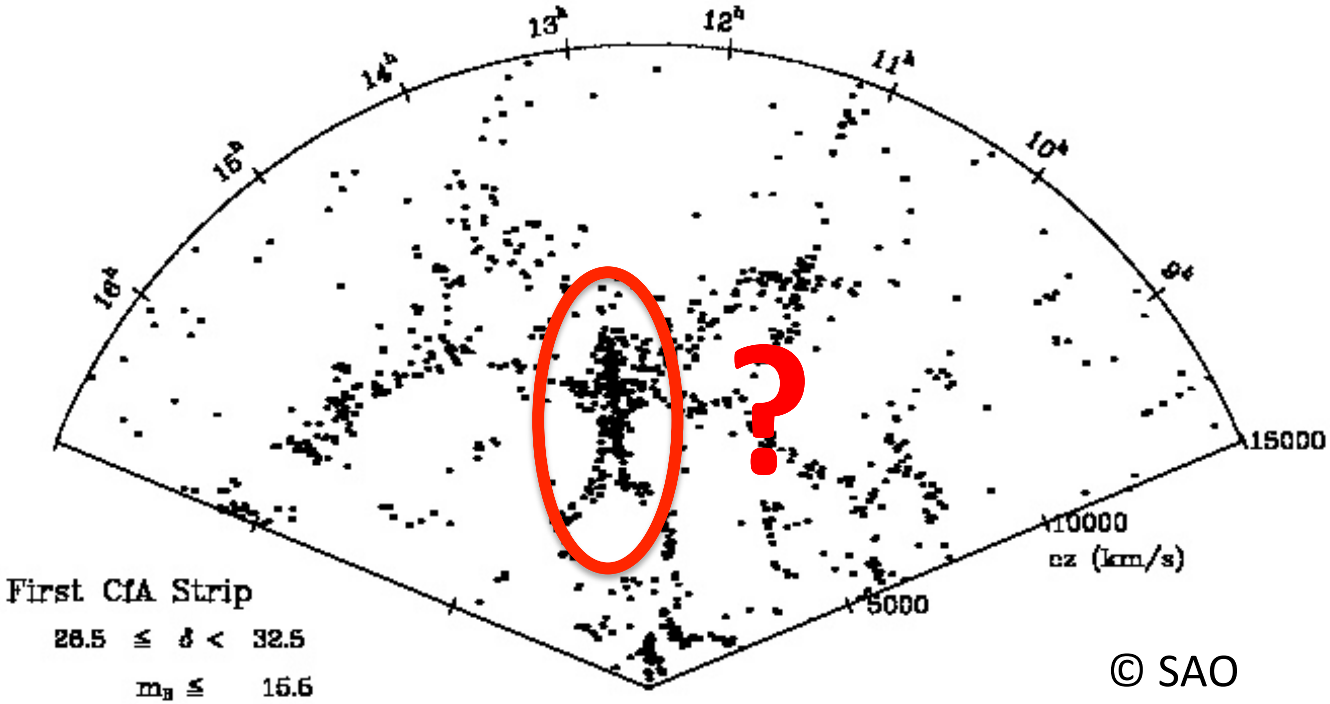
Redshift surveys

If the distances are large enough we can use the Hubble law to estimate distances: $r=v/H_0$.



The CfA redshift survey targeted 18,000 redshifts and took almost 10 years to complete.

Redshift surveys

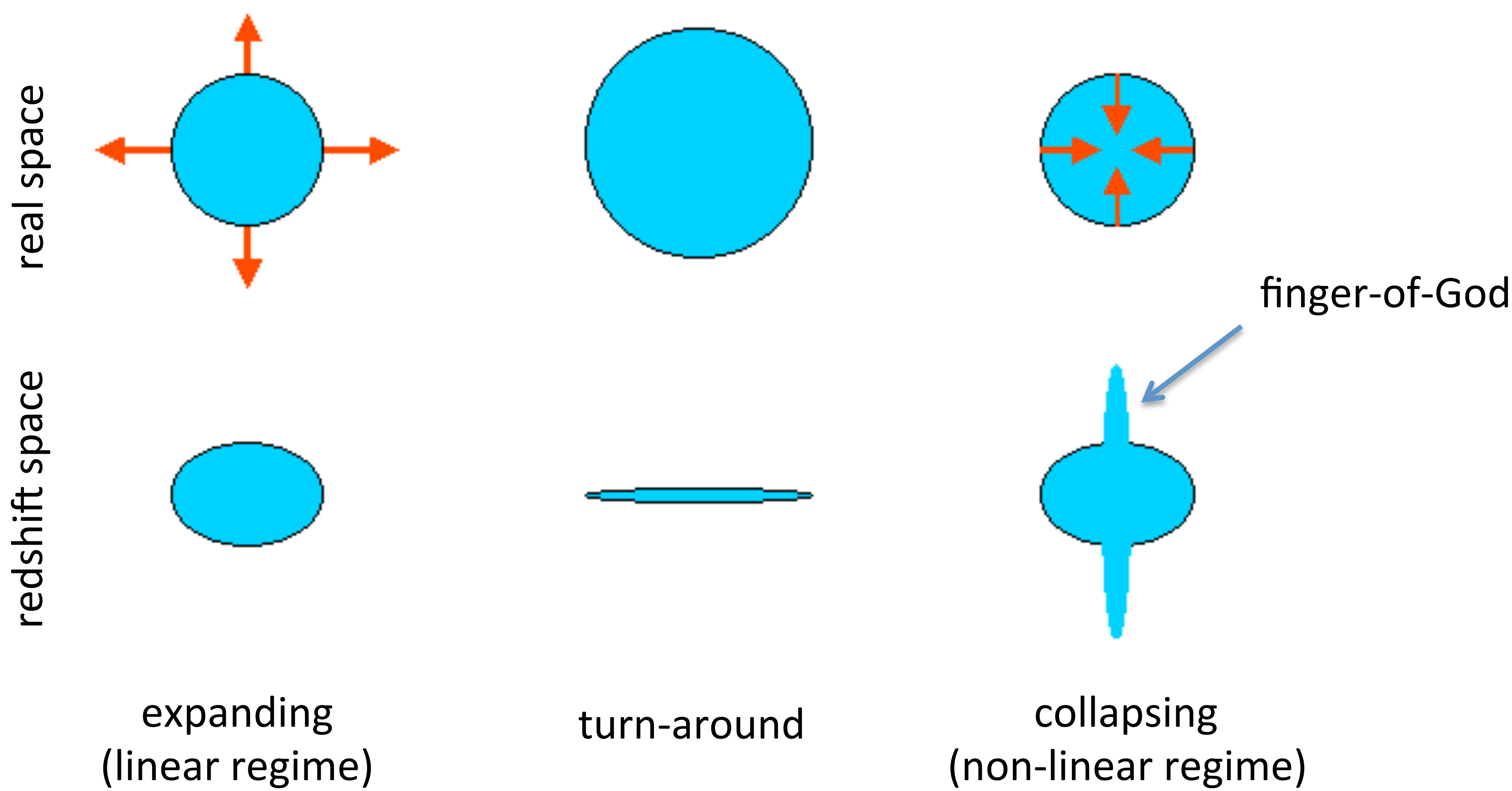


© SAO

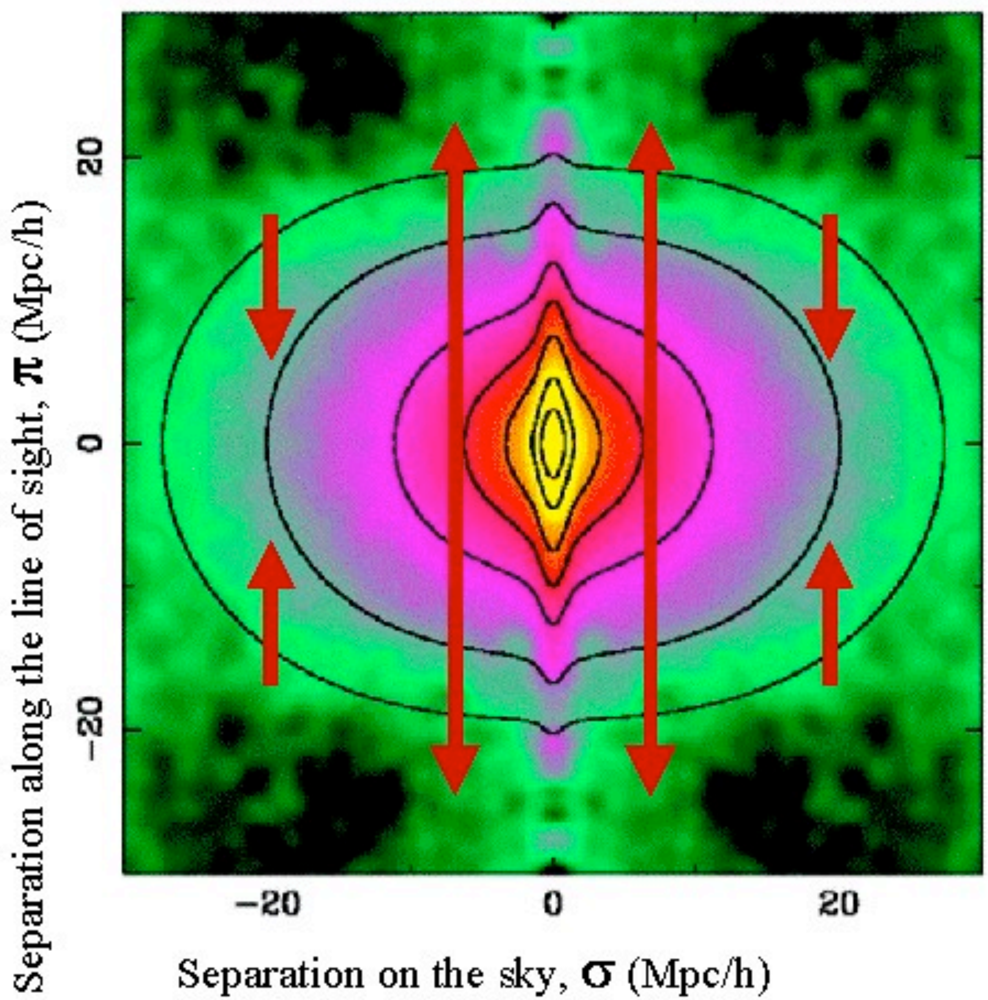
The nearby Universe shows a lot of structure!

Redshift space distortions

$z_{obs}=z_{true}+\delta v/c$, dv depends on the density of the Universe and mass of the collapsing structure (density fluctuation)



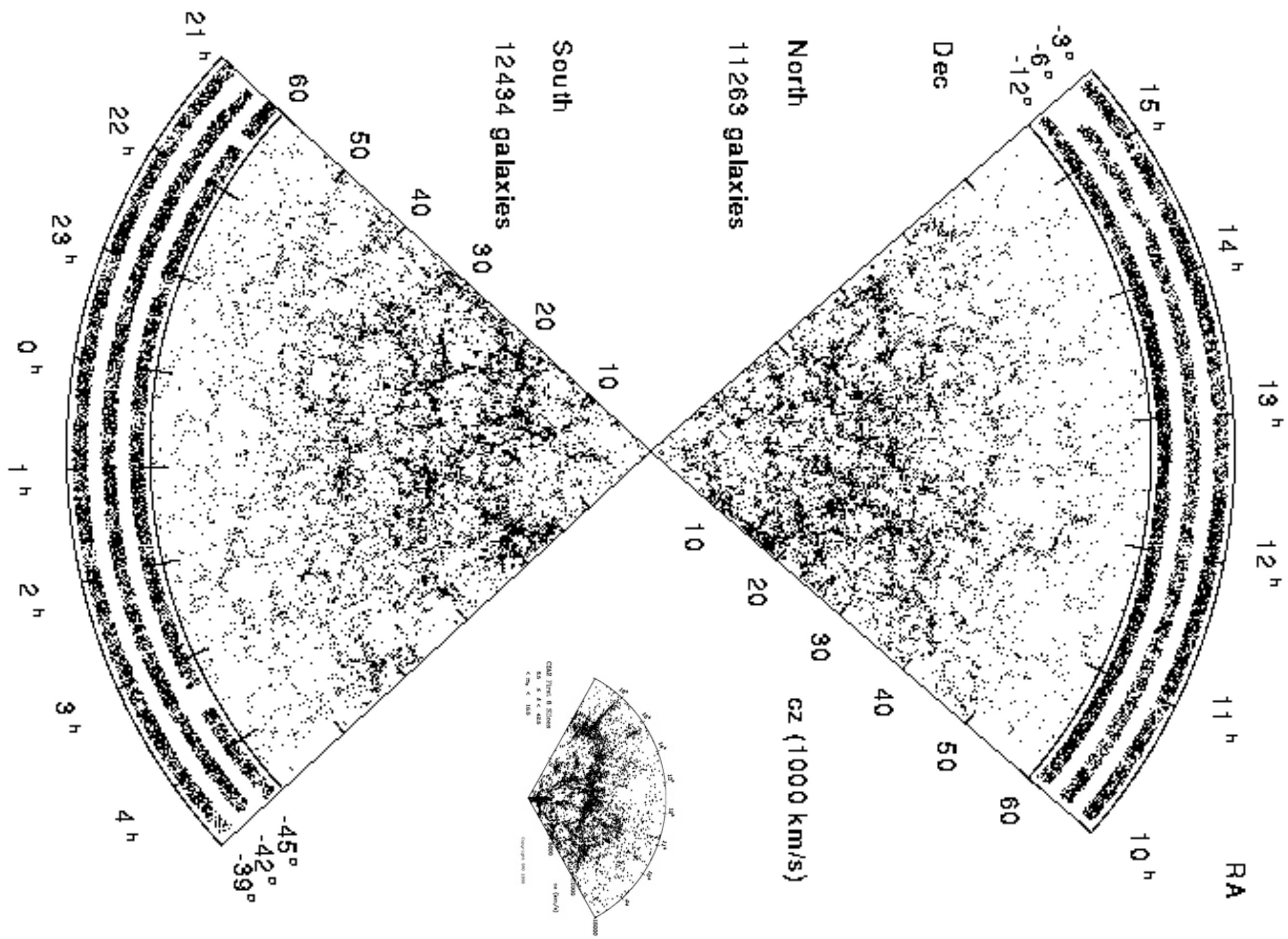
Redshift space distortions



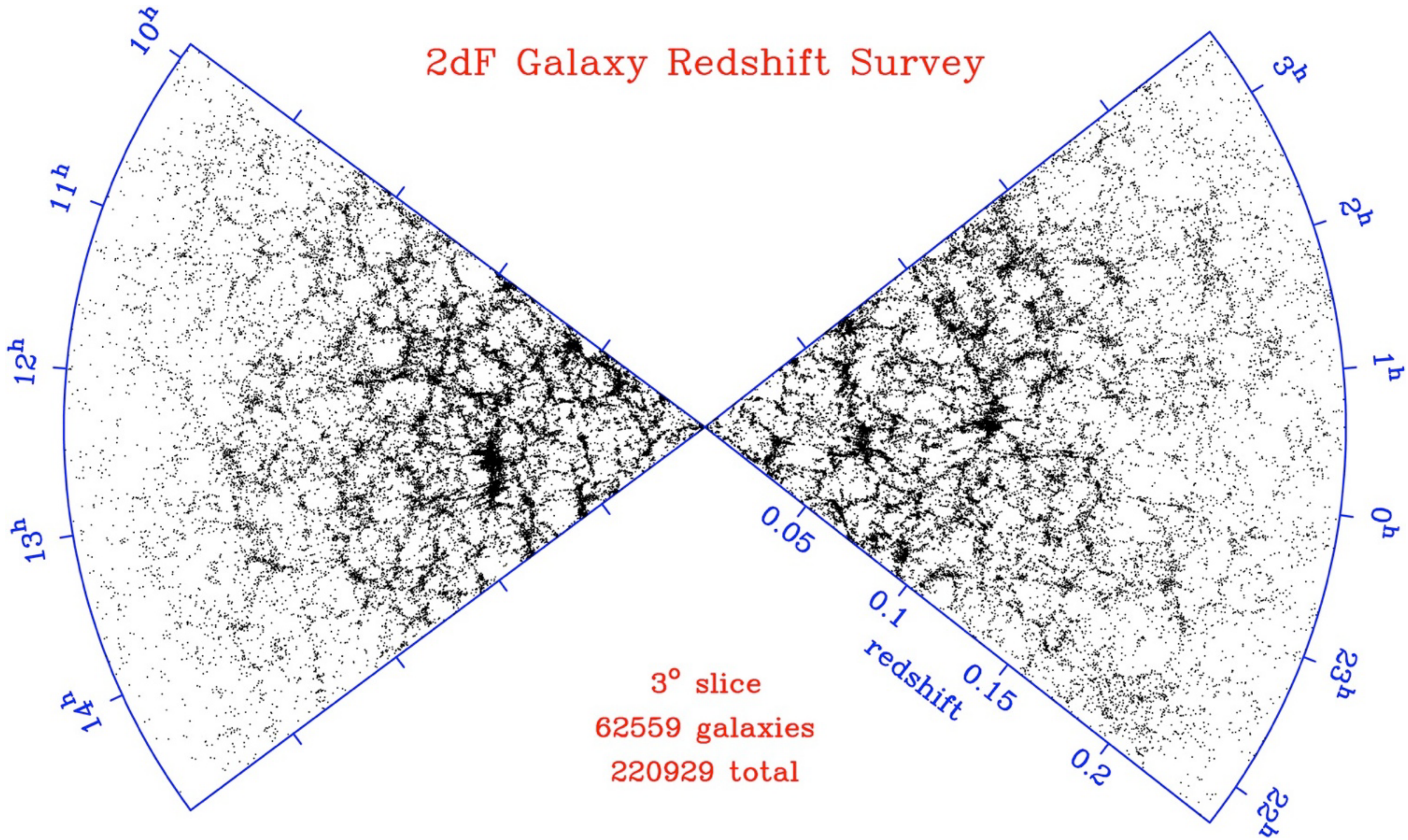
The 2dF Galaxy Redshift Survey Team (2001)

Bigger redshift surveys

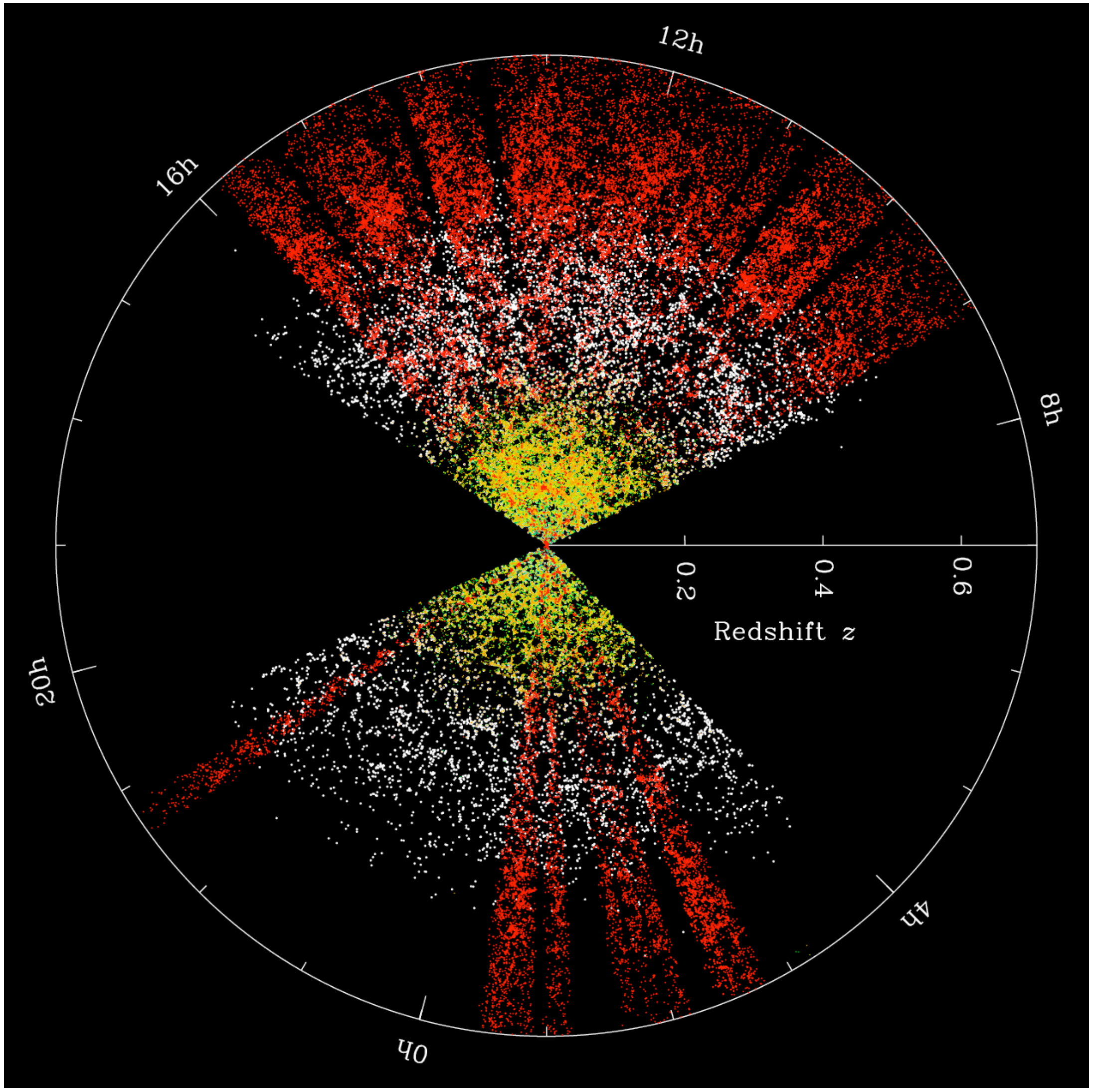
The Las Campanas redshift survey (26418 redshifts out to z~0.2) was the first to indicate homogeneity on large scales.



Even larger redshift surveys

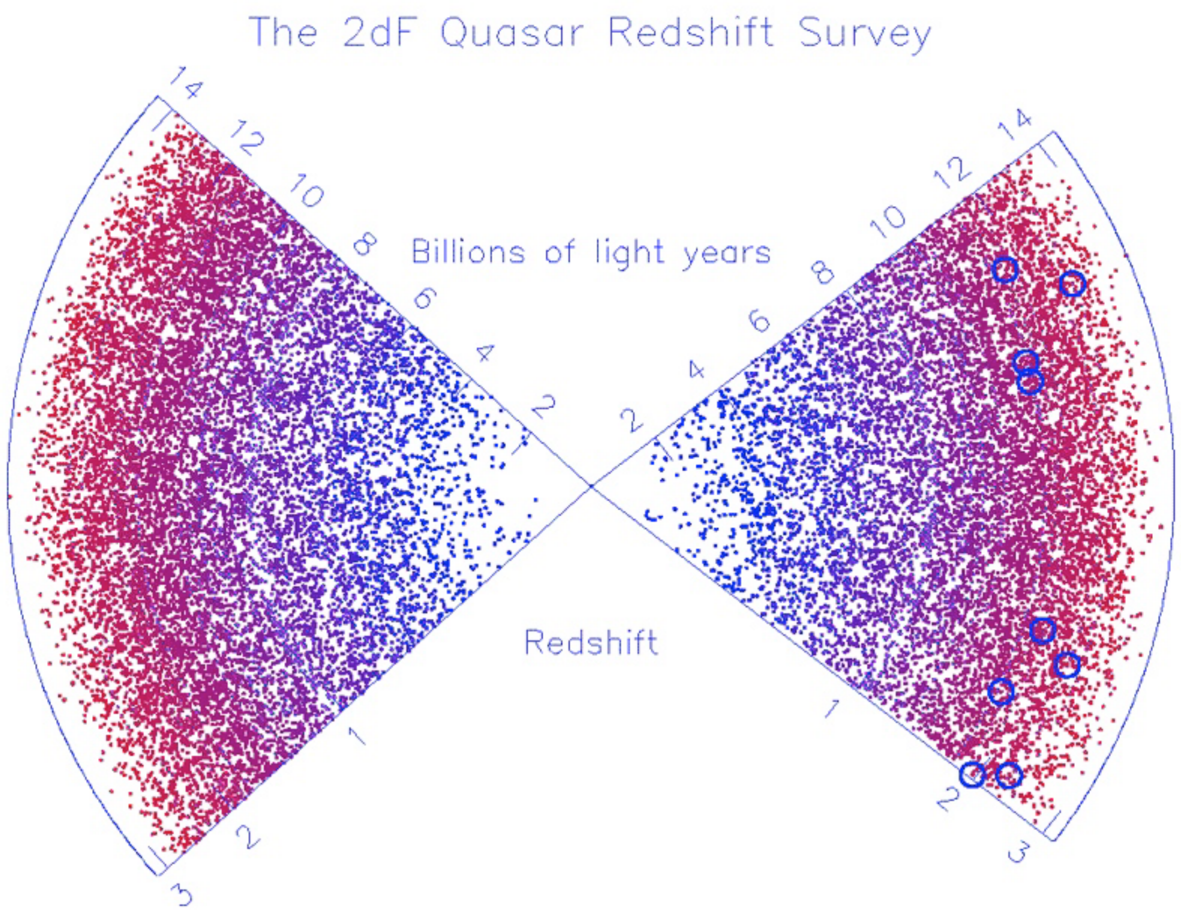


Even larger redshift surveys



SDSS-III (BOSS)

Look at distant objects



More distant objects are more homogeneous. These results also support **isotropy**.

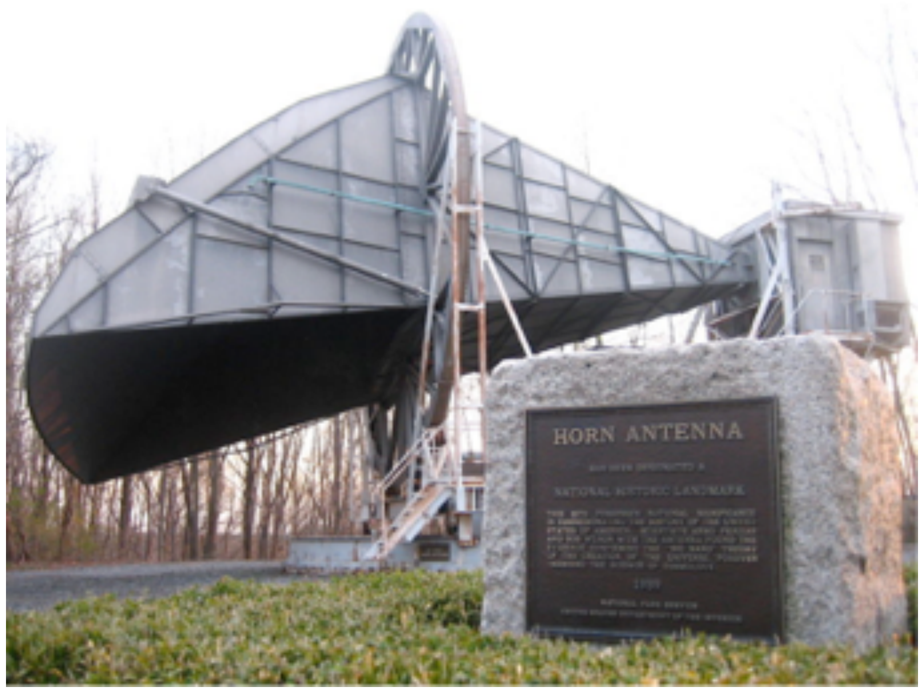
Homogeneity

On small scales the distribution of galaxies is "foam"-like, and we will explore the basic principle behind this later in this course.

The 2dF galaxy redshift survey and the even larger Sloan Digital Sky Survey clearly demonstrated **statistical** homogeneity.

However, the best evidence comes from…

Cosmic Microwave Background

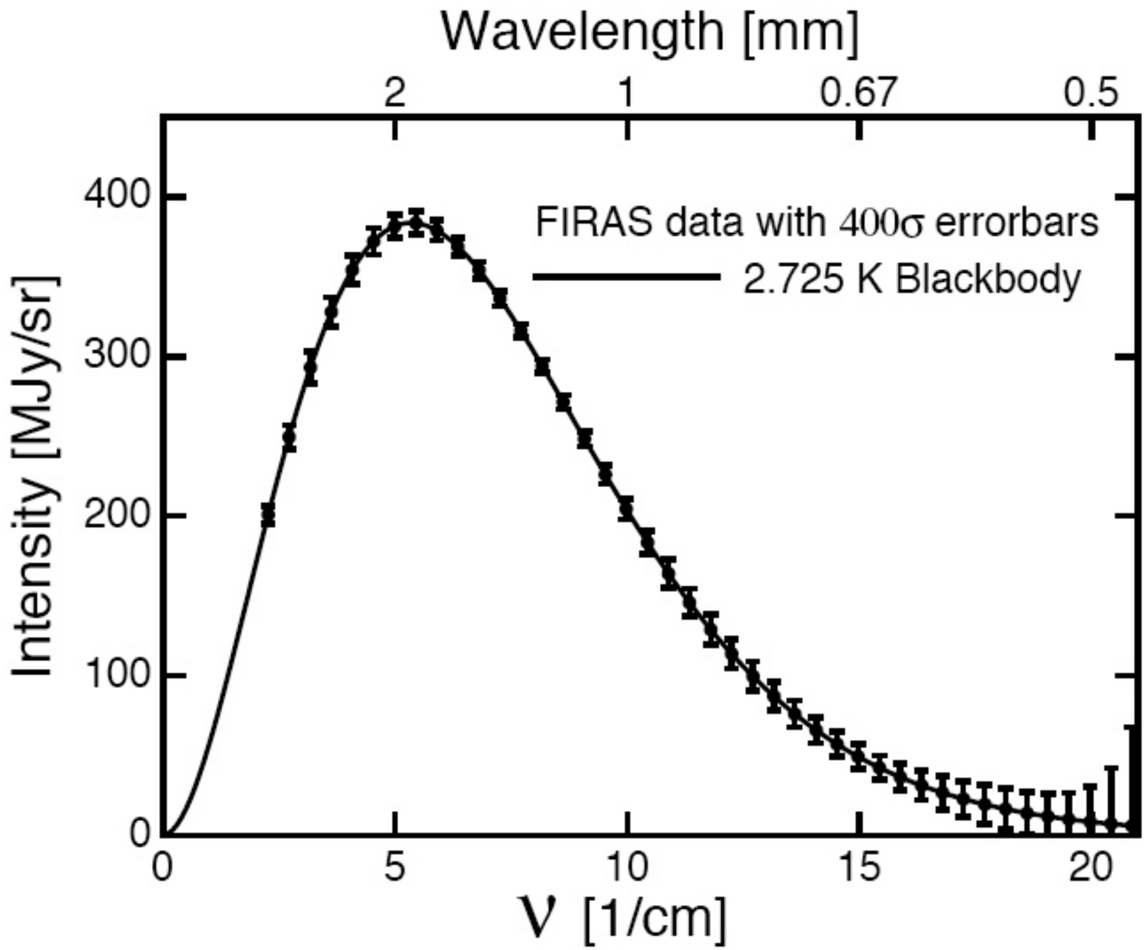


In 1964 Penzias & Wilson detected radio noise that came from all directions. This discovery made cosmology a genuine science topic! It has developed into the prime tool for precision cosmology and the measurements keep improving .

Extremely smooth

The COBE DMR data on a temperature scale from 0 - 4 K:
the CMB brightness is near-uniform.

Perfect Black Body?



The CMBR emission peaks in mm-wave part of spectrum and is (still) the most precisely measured perfect black body with T = 2.72548±0.00057 K.

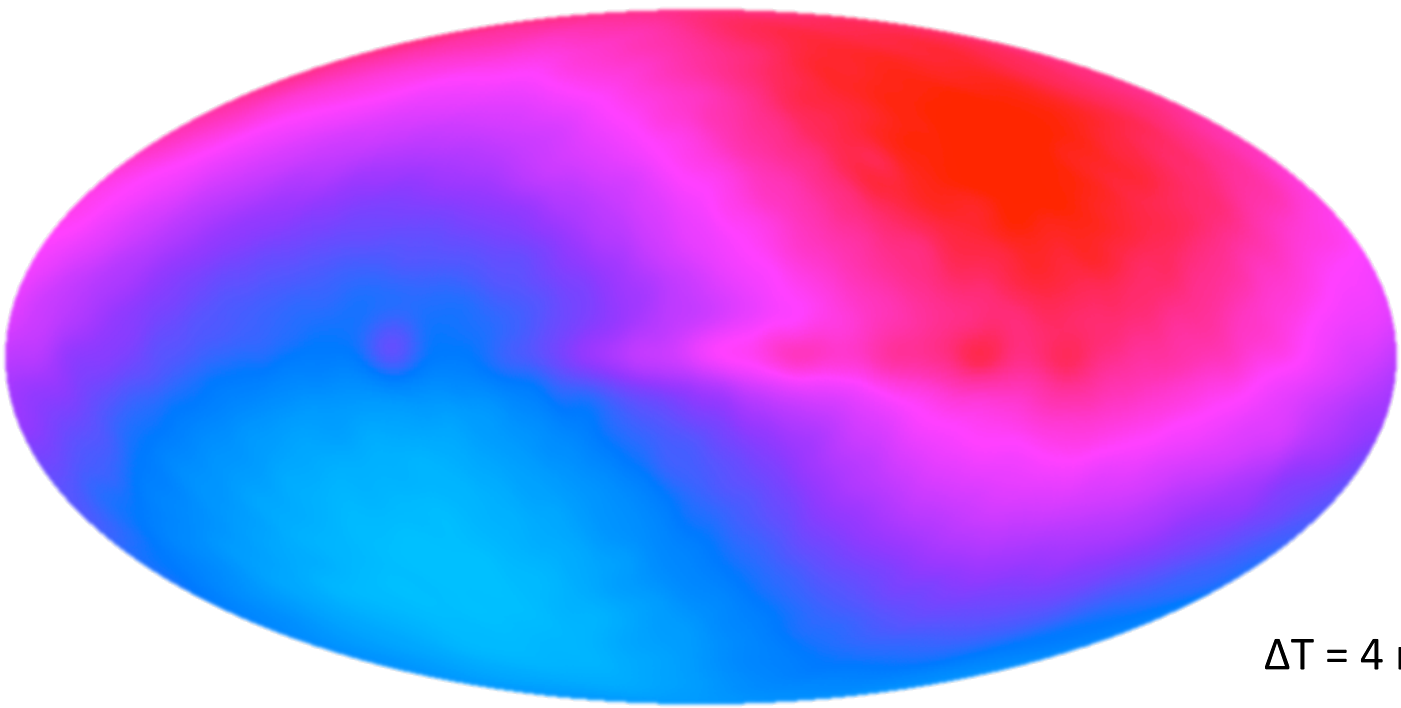
Energy-density of radiation

$$\varepsilon_{rad} = \alpha T^4$$

$$\alpha \equiv \frac{\pi^2 k_B^4}{15\hbar^3 c^3} = 7.565 \times 10^{-16}\, Jm^{-3}K^{-4}$$

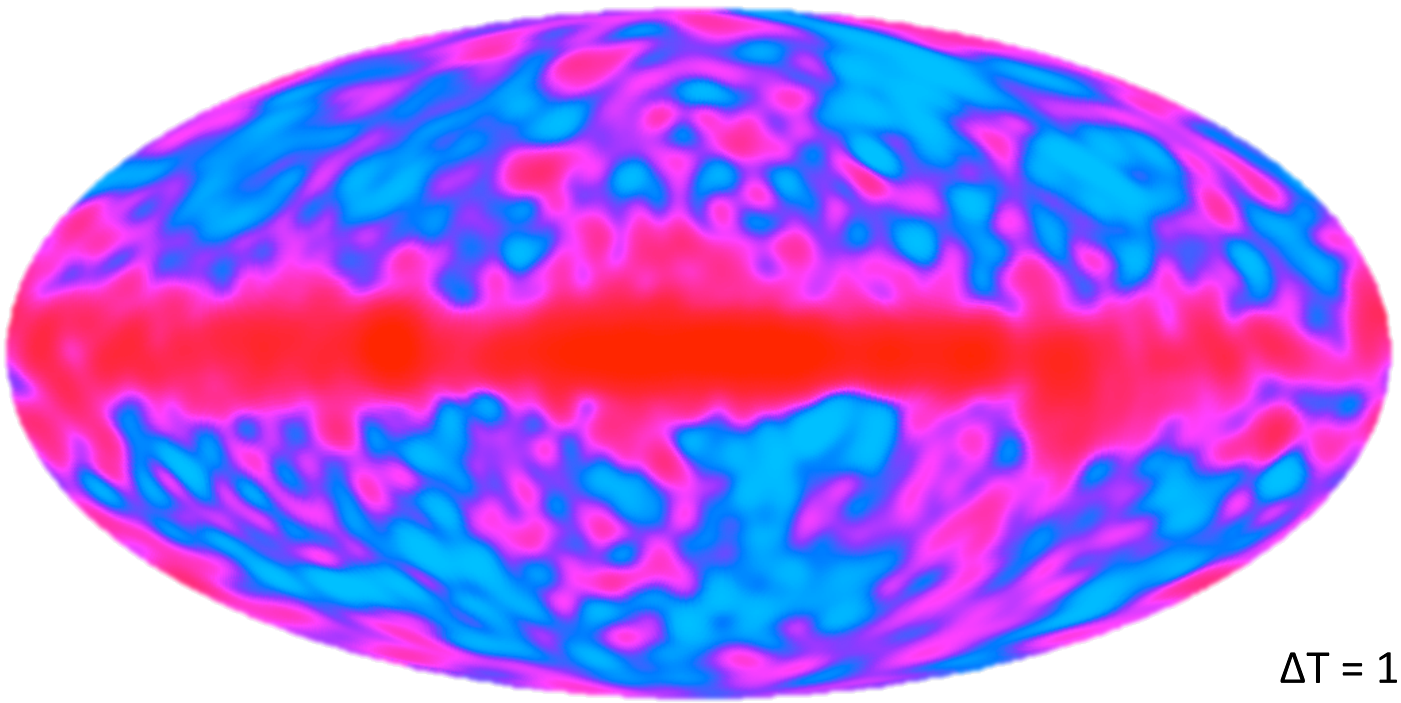
$$\Omega_{rad} = 2.47 \times 10^{-5}\, h^{-2}$$

Very smooth



Some structure is seen when the mean is subtracted: we see a some emission from the Galaxy and a dipole…

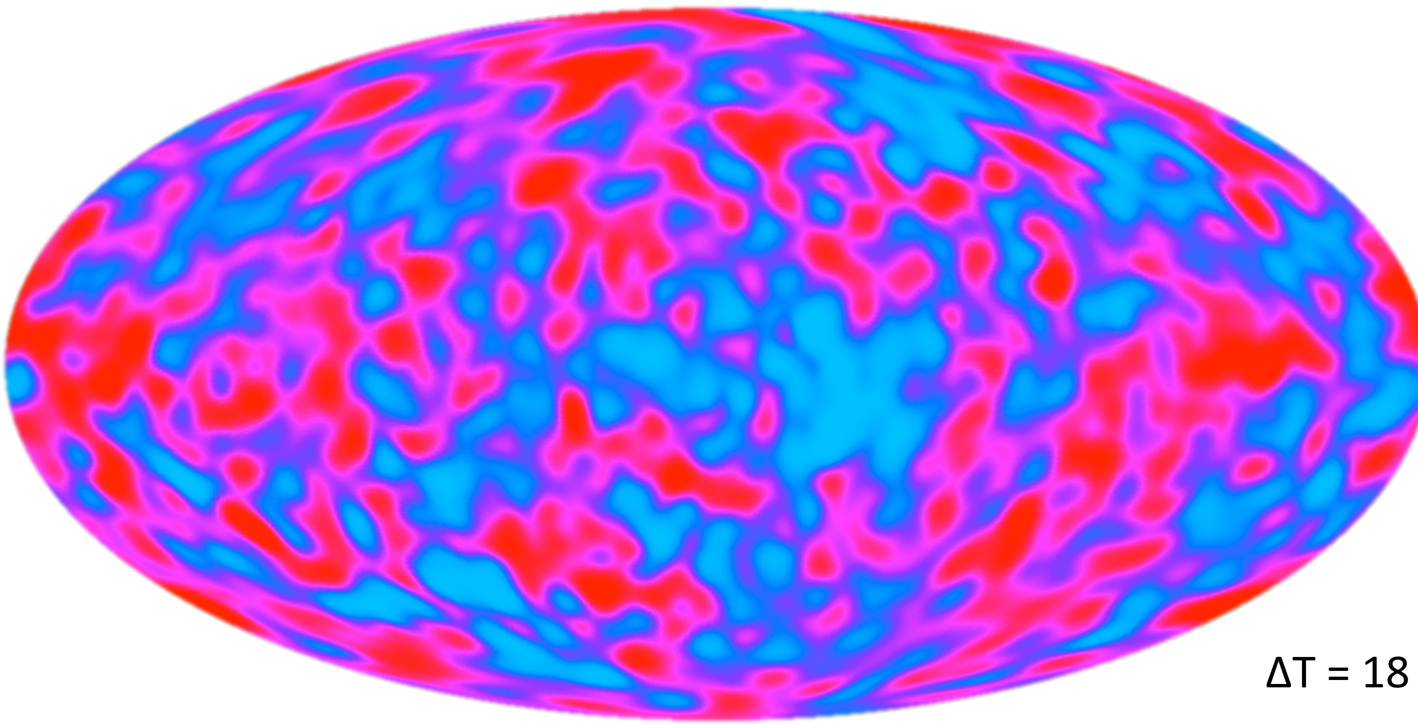
Very smooth



ΔT = 18 μK

The dipole is cause by our own peculiar motion and can be removed. Now we see clear emission from the Galaxy and …

Very smooth



ΔT = 18 μK

… temperature fluctuations that are of cosmological origin. These are the seeds of the large-scale structure.

Lots to learn from the CMB

In the next lecture we will start exploring what we can learn from the CMB.

Some topics that we will address

- Can these small fluctuations explain the large-scale structure we see in the local Universe?
- If so, do we understand why the fluctuations are so small?
- What causes these fluctuations?

For now, we conclude that the observations are in excellent agreement with a homogeneous and isotropic universe.

Distances & redshift

Redshift is related to the change in scale factor since emission, but does not depend on cosmology. What if we could measure distances?

How are distances defined in an expanding universe?

What does redshift tell us?

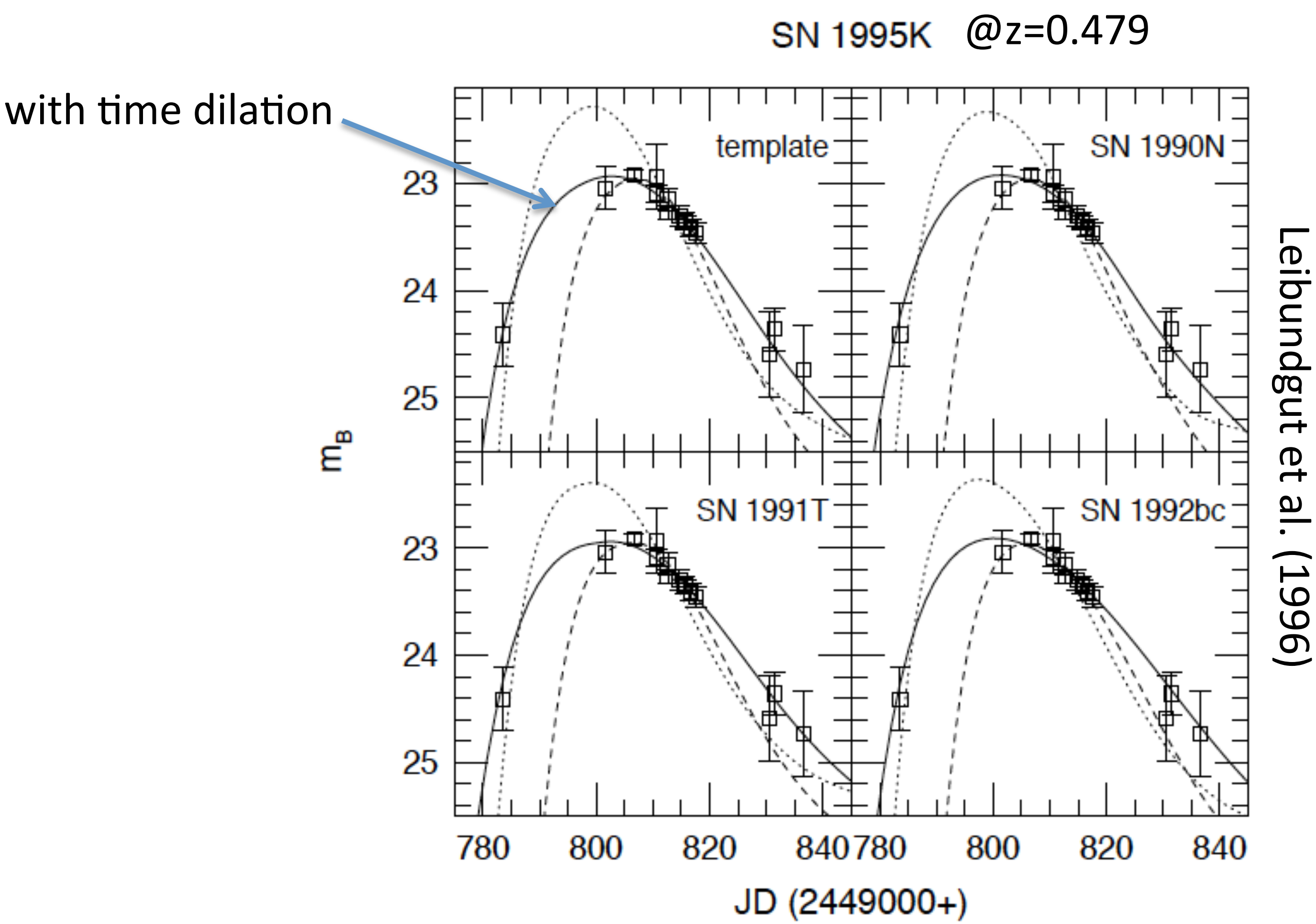
Interpretation of redshift

We interpret the redshift as a consequence of the expansion of the Universe, but is this interpretation correct?

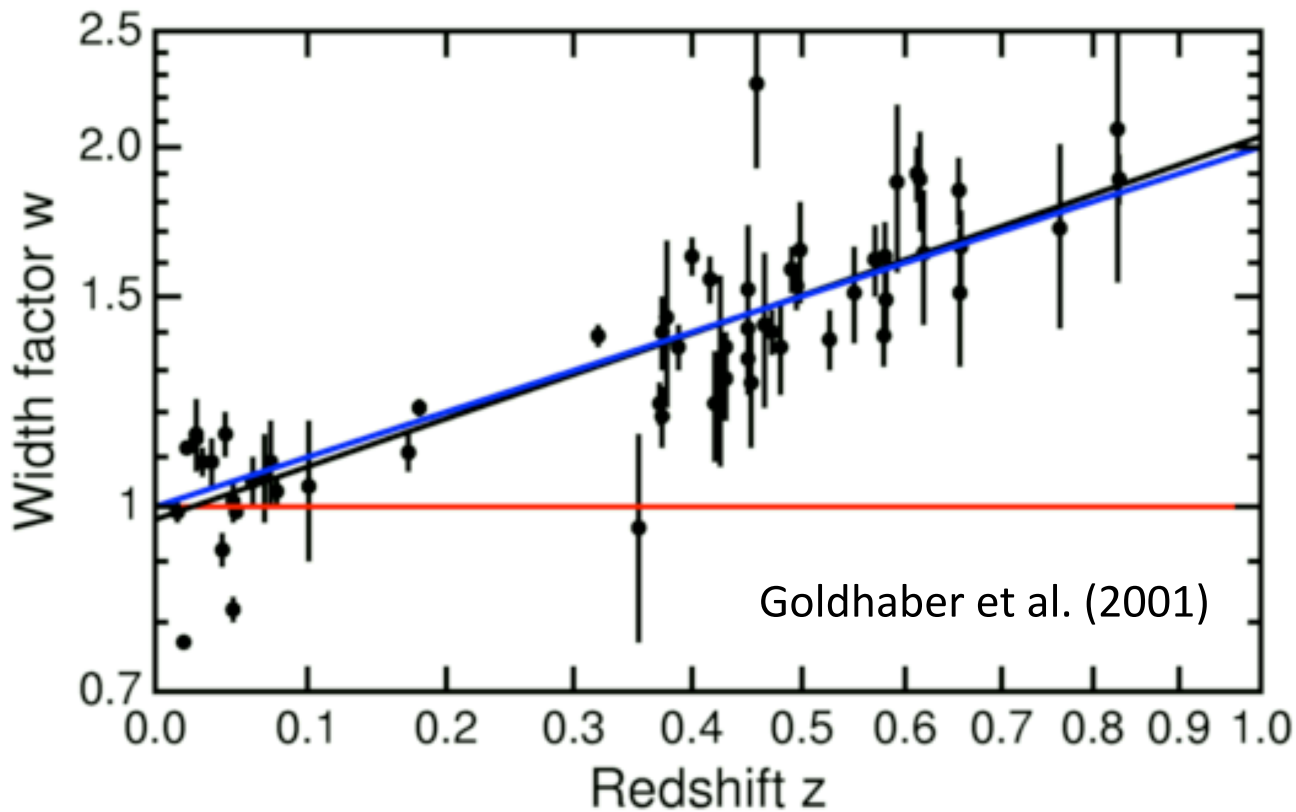
For instance “tired light” has been proposed as a mechanism to explain the distance-redshift relation (this suggestion has many problems of its own…).

We can study the light curves of very distant ($z>1$) supernovae: their light curves decay on timescales of ~100 days in the rest frame, driven by the radioactive decay of $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$.

Observation of time dilation



Interpretation of redshift



Supernovae at greater redshifts are seen to take longer to decay: it scales linearly with the redshift: the redshifts are true reflections of Doppler shift.

How far can we see?

Light travels at finite speed - no physical signals can be faster

As the universe has a finite age, there must be a limit…
However the universe also expands, which complicates things.

A key question is which parts of the universe can influence, or have influenced, each other: *which parts are in causal contact*?

Horizon in flat Ω_m=1 model