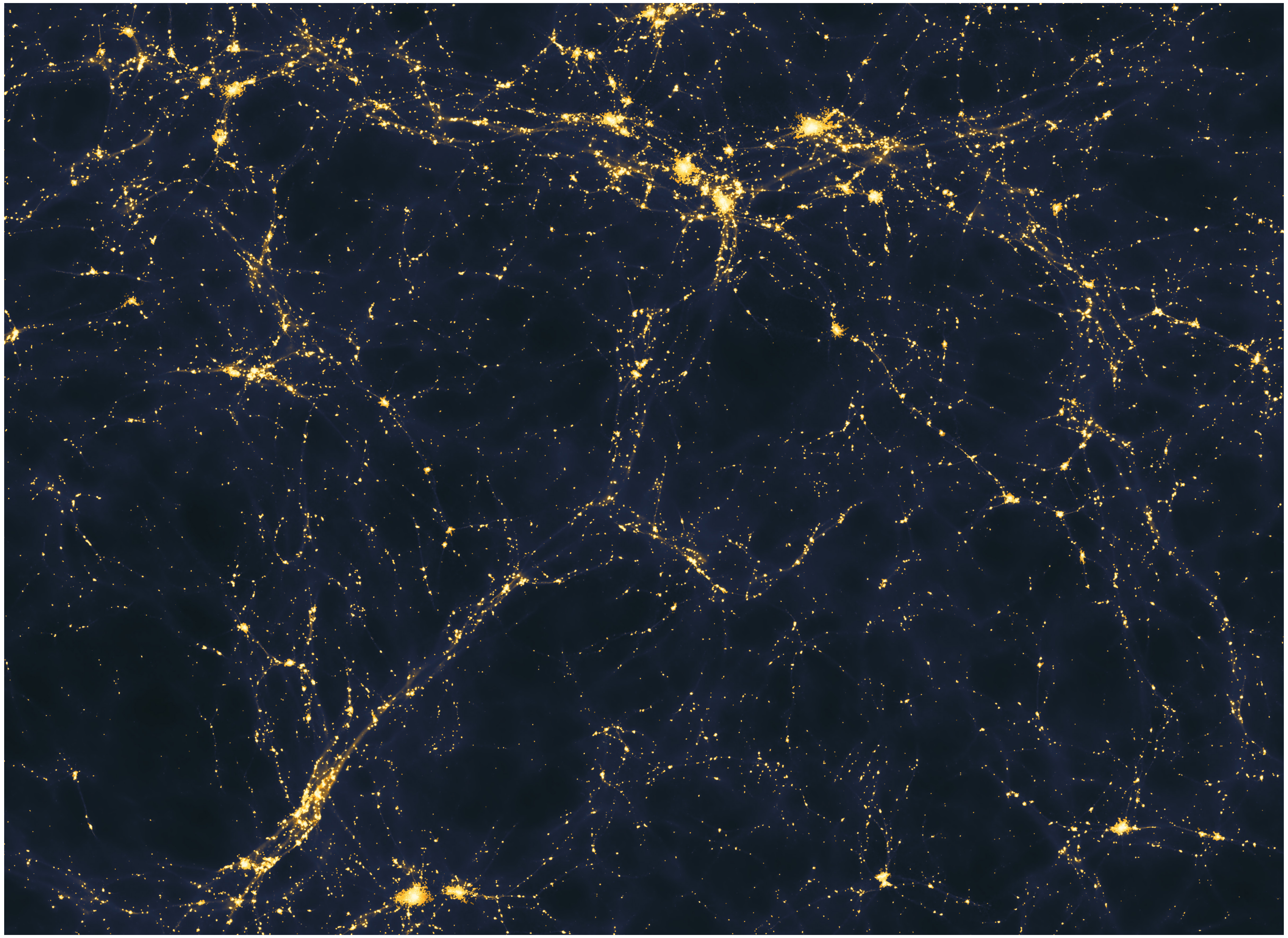
Cosmology
Lecture 15

Structure Formation II - Statistical Properties, Hot and Cold Dark Matter, and BAOs

Lectures

The Large Scale Structure of the Universe



As with the CMB, cosmologists aren't really that bothered about the positions of individual galaxies, they're much more interested in the *statistical* properties of the large scale structure.

By measuring the statistical properties of the large scale structure, cosmologists gain insights into the properties of the initial density fluctuations that it grew from.

Measuring the statistical properties of the LSS

To measure the statistical properties of the LSS, we will again consider that the “stuff” within the Universe (whether matter and/or radiation) forms a density field with small fluctuations within it: $\delta(\vec{r})$

To measure the statistical properties of these fluctuations, we’ll do the 3D analogy of measuring the statistical properties of the CMB: express it as a 3D Fourier Series…

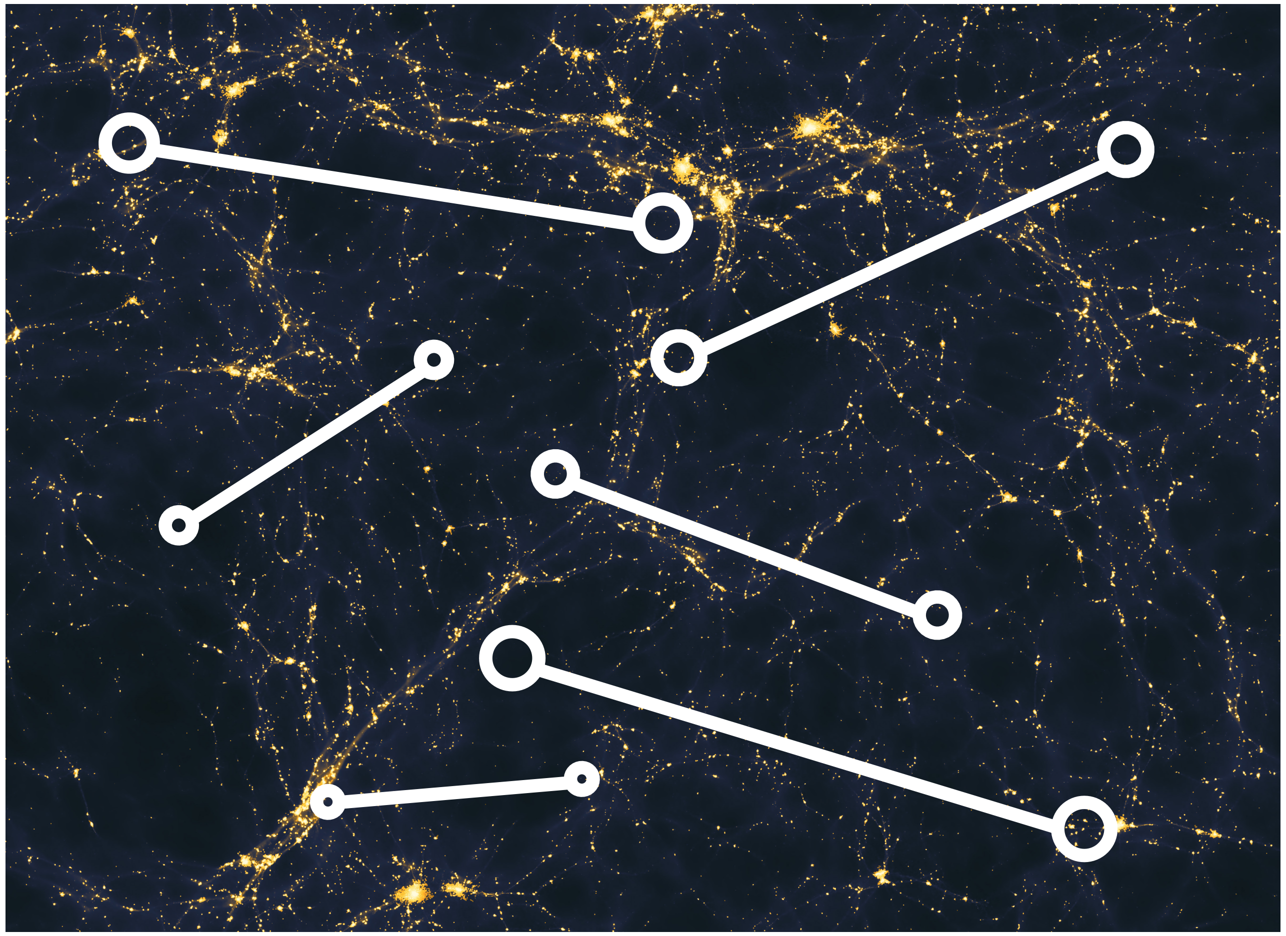
$$\delta(\vec{r}) = \frac{V}{(2\pi)^3} \int \delta_{\vec{k}} e^{-i\vec{k}\cdot\vec{r}} d^3k \qquad \text{where} \qquad \delta_{\vec{k}} = \frac{1}{V} \int \delta(\vec{r}) e^{i\vec{k}\cdot\vec{r}} d^3r$$

$\delta_{\vec{k}}$ then tells us the how matter is distributed on different scales. If the large scale structure broadly “repeats” itself on scales of 1/k, then that particular $\delta_{\vec{k}}$ will be large.

Note that big values of k correspond to small scales, and vice versa.

The Large Scale Structure Power Spectrum

And, just as with the CMB, we can calculate the power spectrum…



…which tells us on what scales the large scale structure is most strongly correlated with itself.

$$P(k) = \langle \left| \delta_{\vec{k}} \right|^2 \rangle$$

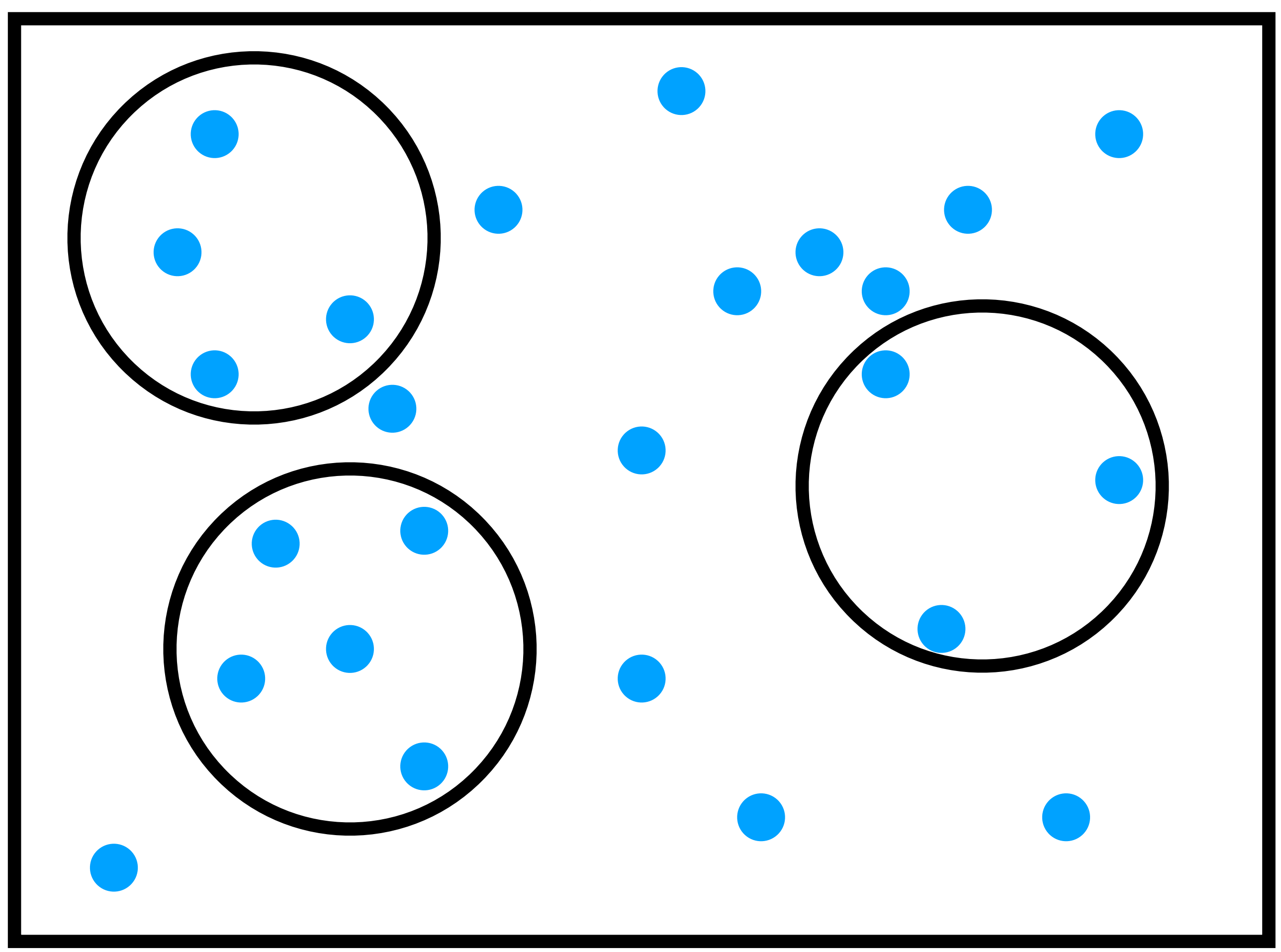
The power spectrum

The power spectrum produced by an inflationary model is expected to take the form:

$$P(k) = k^n$$

But, what would such a universe look like?

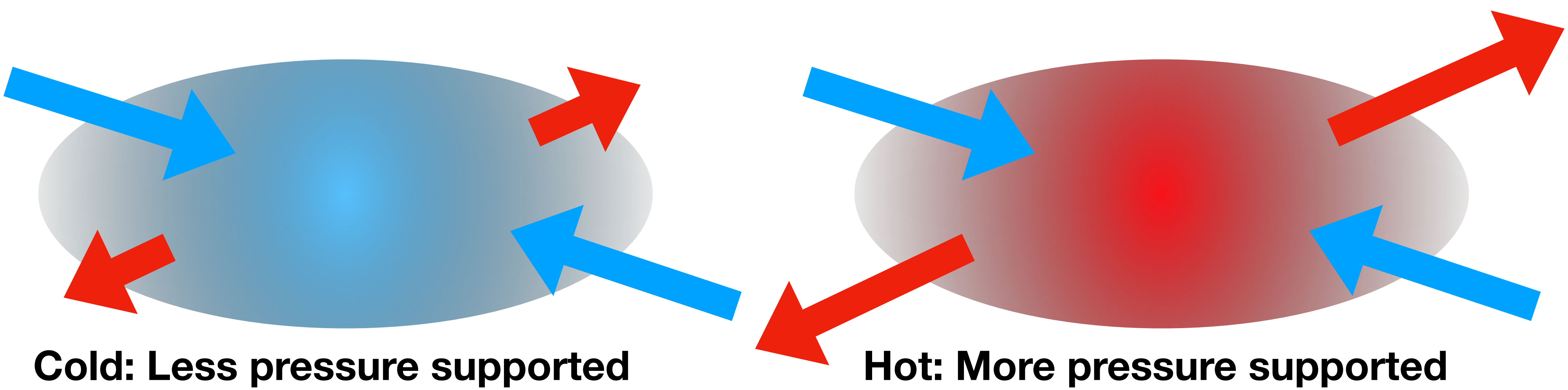
A Poisson universe, where n=0:



When n>0, we get a universe with more “power” at small scales

Hot vs. Cold Dark Matter

- As matter is attracted into clusters, groups and galaxies due to gravity, the shape of the power spectrum evolves over time.
- How it evolves, however, depends on the properties of Dark Matter, since that is the dominant source of gravity in the Universe.
- Specifically, it depends on how “hot” or “cold” dark matter is.
- If Dark Matter is made up of particles, then these particles must move with a random velocity dictated by their temperature.
- Hot Dark Matter is therefore more resistant to gravitational collapse than Cold Dark Matter.



How does Dark Matter temperature affect collapse?

Consider a hot dark matter particle.

As the Universe expands, it will cool, but at early times, it will move relativistically.

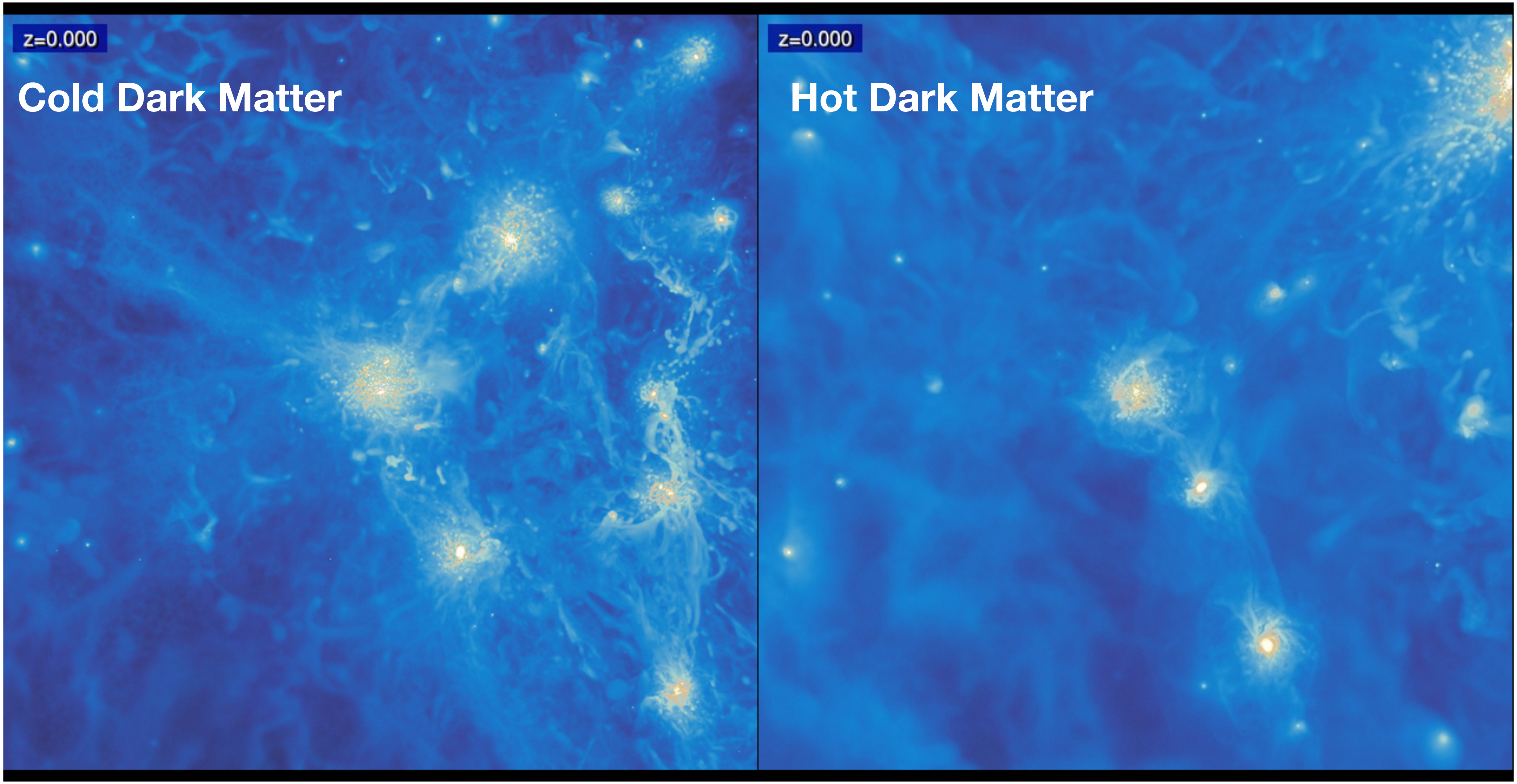
At some temperature, T_h, the DM particle will stop moving relativistically, with T_h given by:

$$T_h \approx \frac{m_h c^2}{3k} \approx 12000\ \mathrm{K} \left(\frac{m_h c^2}{3\ \mathrm{eV}}\right)$$

Which corresponded to a time:

$$t_h \approx 42000\ \mathrm{yr} \left(\frac{m_h c^2}{3\ \mathrm{eV}}\right)^{-2}$$

Structure formation: Hot vs. Cold Dark Matter



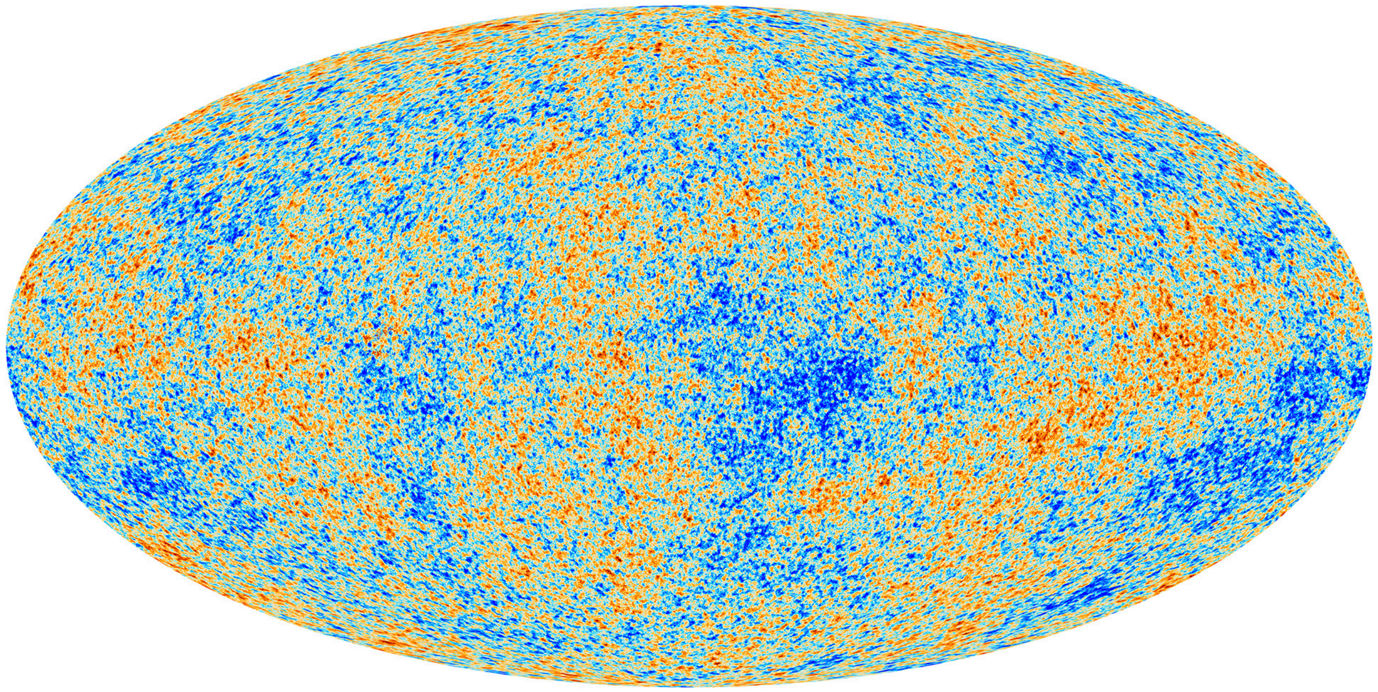
Dark Matter simulations predict that there would be far less small-scale structure in a hot Dark Matter universe than we see in the real Universe.

Baryon Acoustic Oscillations

In addition to Dark Matter, the Universe also contains Baryonic Matter.

The ability of Baryonic Matter to interact with photons has left its imprint on the large scale structure in the form of *Baryon Acoustic Oscillations (BAOs).*

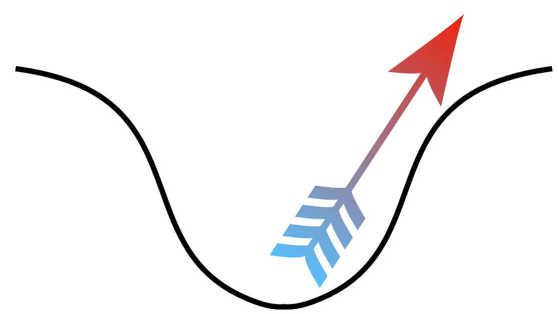
BAOs are are a legacy of decoupling, so lets remind ourselves of that time via the CMB:



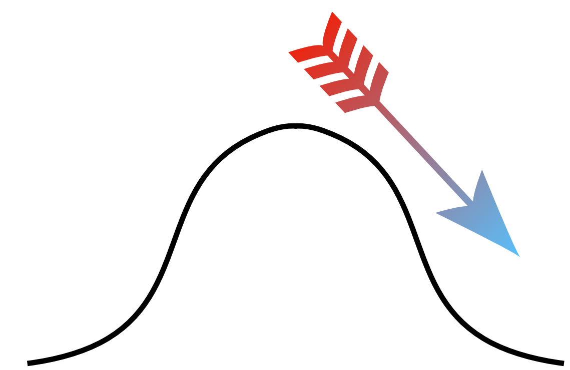
The “speckles” in the CMB

The “coolspots” in the CMB correspond to the densest parts of the Universe at the time of decoupling, and vice-versa.

Gravitational potential



A photon in a region of high density at decoupling gets redshifted

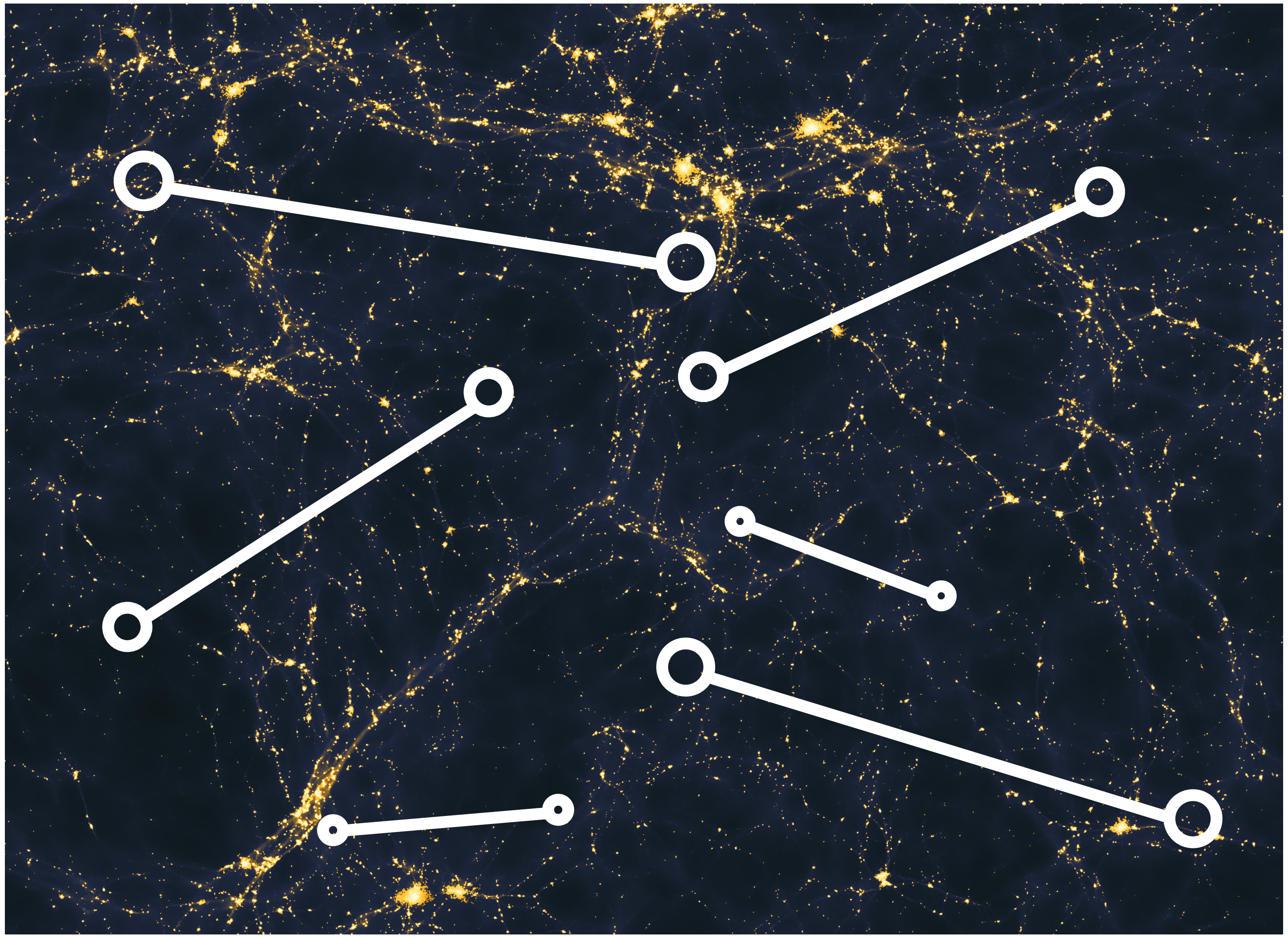


A photon in a region of low density at decoupling gets blueshifted

The high density regions eventually collapsed to form the high mass superclusters we see in today’s Universe.

What would be the size of these fluctuations today?

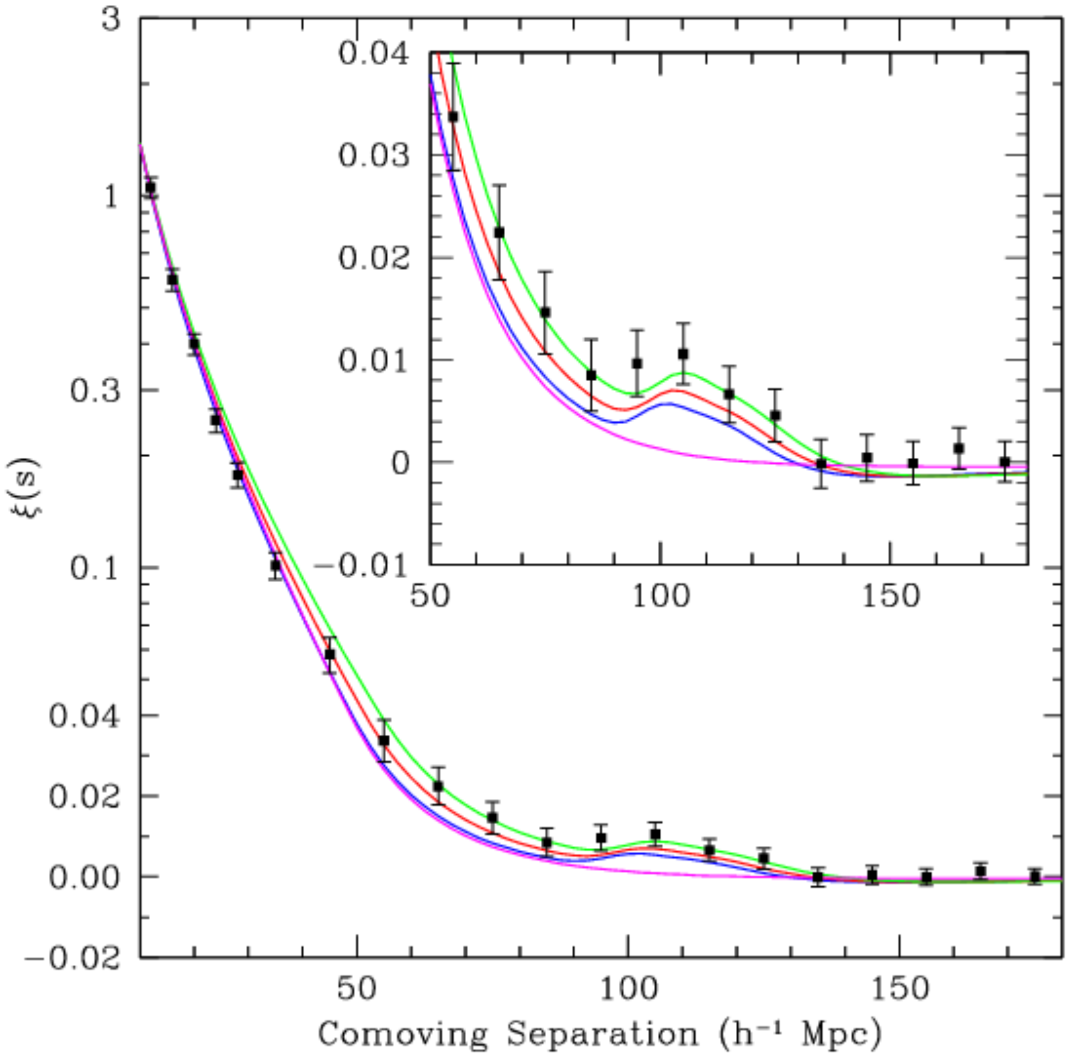
Detecting BAOs today



Cosmologists measure the correlation between density fluctuations in the same way they measure temperature fluctuations in the CMB.

In the case of density fluctuations, however, they must consider three dimensions, thereby requiring precise redshift measurements.

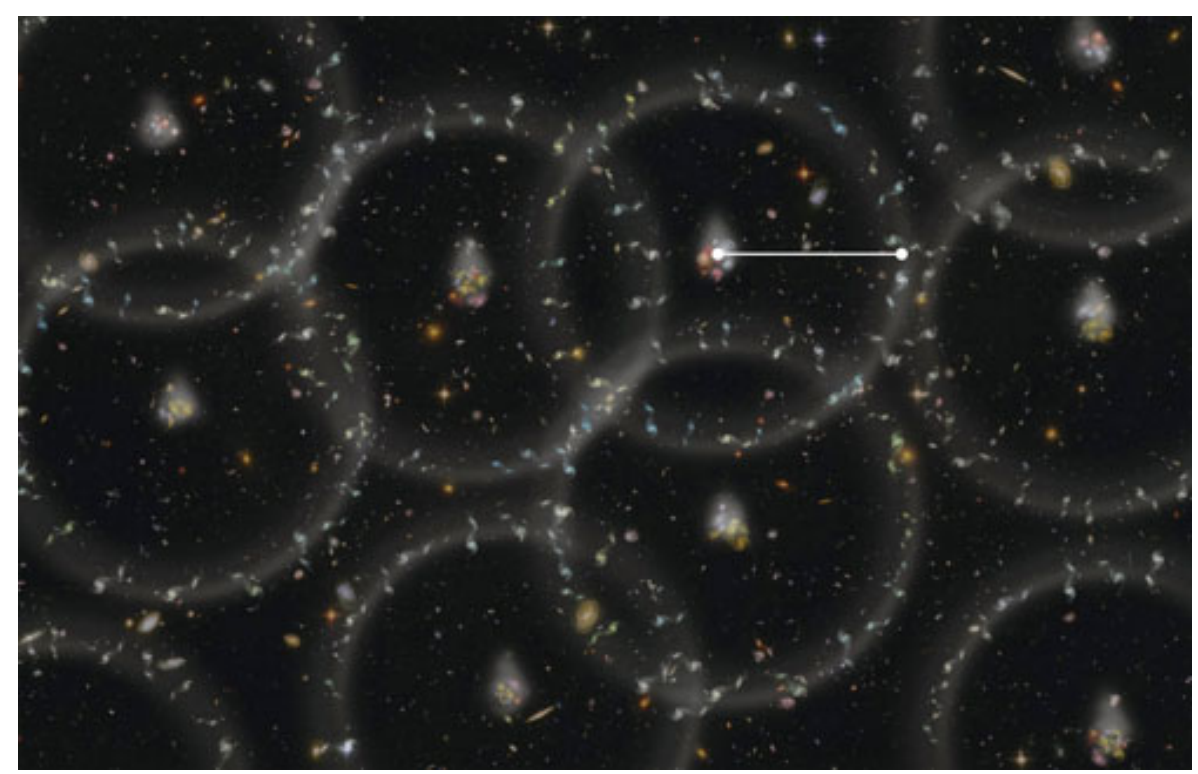
Detecting BAOs today



This plot shows the correlation in density fluctuations for galaxies at z<0.04. The strong correlation at small scales is due to gravitational collapse. The “bump” at $100h^{-1}$ Mpc ~ 150 Mpc is due to Baryon Acoustic Oscillations.

BAOs are the imprint of photon-matter interaction at the time of decoupling in today’s density distributions.

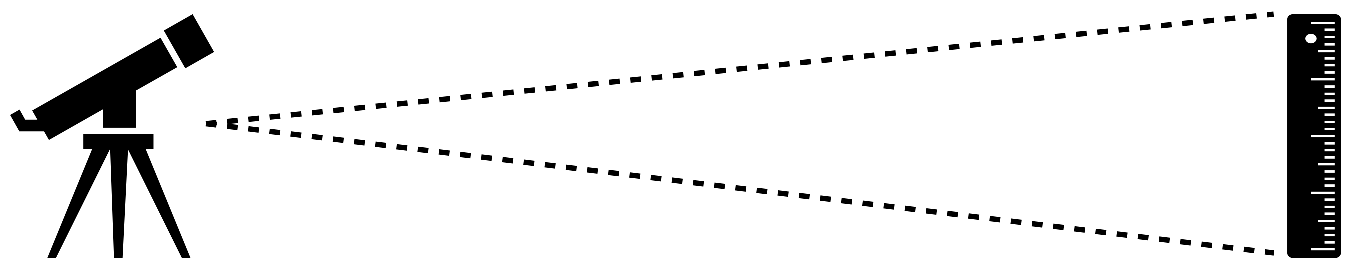
The image to the right shows a *highly* exaggerated representation of BAOs in the current Universe.



BAOs and Cosmological Parameters

Since the sound travel distance is set by Physics, we can use the BAO scale as a standard ruler.

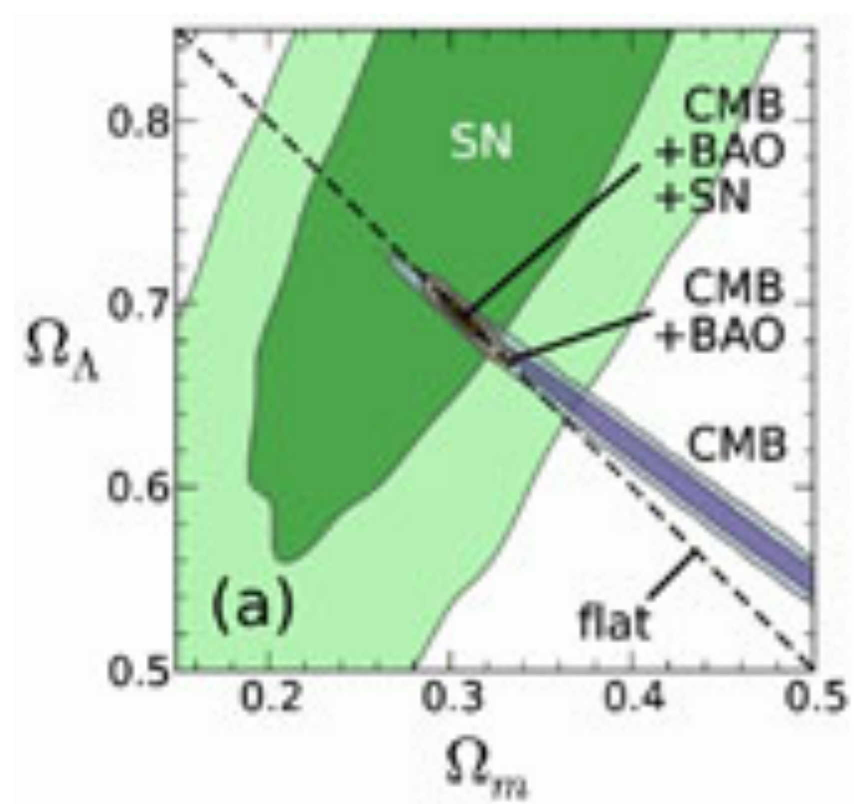
Angular size



d_A

$$l = \theta d_A$$

As such, it can be used as another independent means to help pin-down cosmological parameters:



Getting the feel for it…

- Just as with the CMB, cosmologists can study the statistical properties of the density fluctuations that we see as the Large Scale Structure.

- These properties can provide important insights into the make-up of the Universe.

- For example, the “temperature” of Dark Matter affects the collapse of different scaled structures (galaxies vs. superclusters).

- They can also be used to measure Baryon Acoustic Oscillations - a relic of the fluctuations in the CMB - which are used as a standard ruler to measure cosmological parameters.