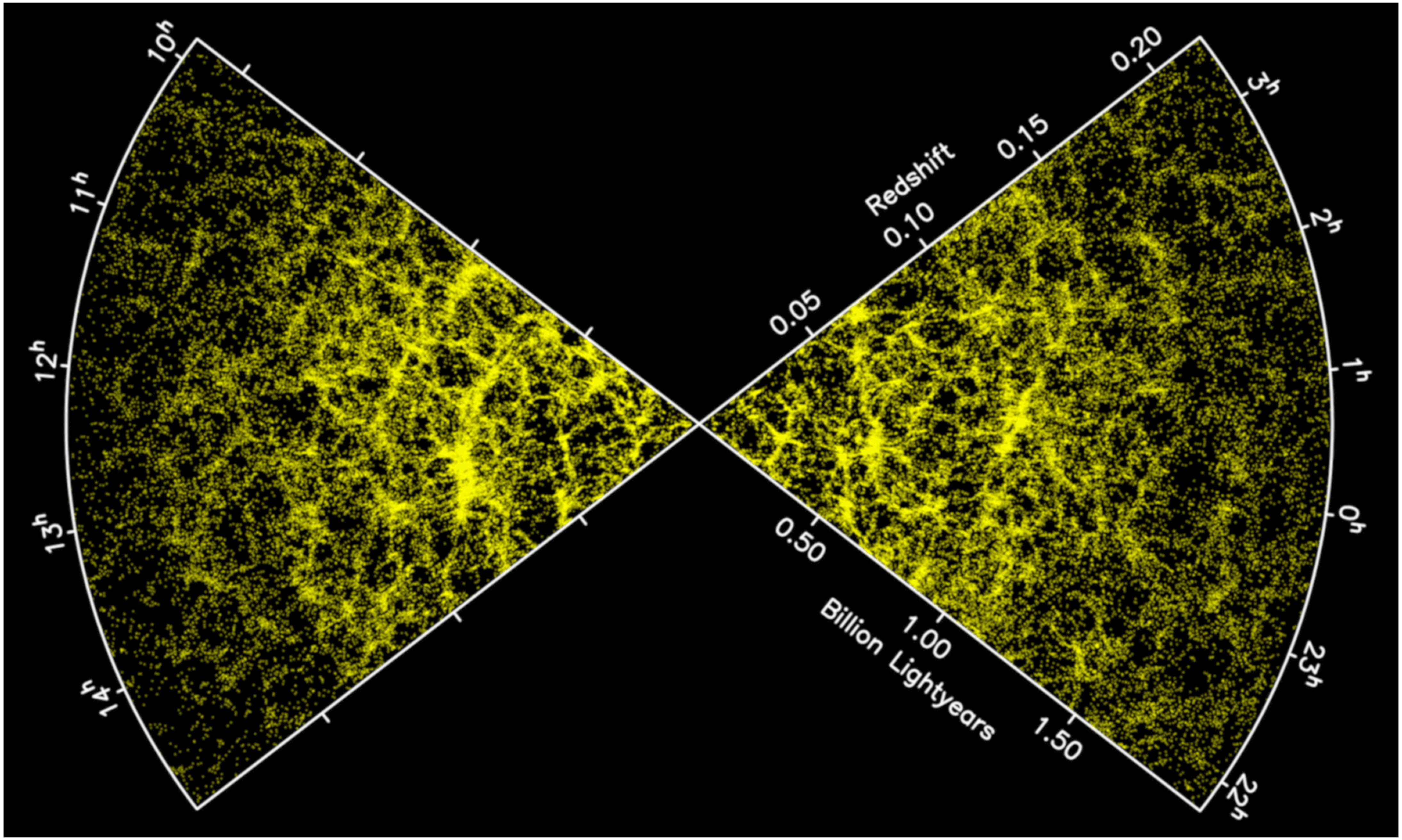
Cosmology
Lecture 14

Structure Formation I

Learning objectives

- Be familiar with the appearance of the large-scale structure;
- Understand how small fluctuations in matter density grow due to the effects of gravity;
- Understand the play-off between gravity and pressure in the process of structure-formation;
- What the Jeans Length is, and its importance for structure formation;
- How expansion affects structure formation.

The large scale structure of the Universe



The above image shows a map of around 200,000 galaxies, whose redshifts and positions have been mapped by the 2dF redshift survey. By measuring the positions and redshifts of the galaxies, a 3D map of the Universe (out to z=0.2ish) was produced.

The build-up of large scale structure

- While on very large scales (i.e., >100 Mpc), the Universe is homogeneous and isotropic, one smaller scales it is not.

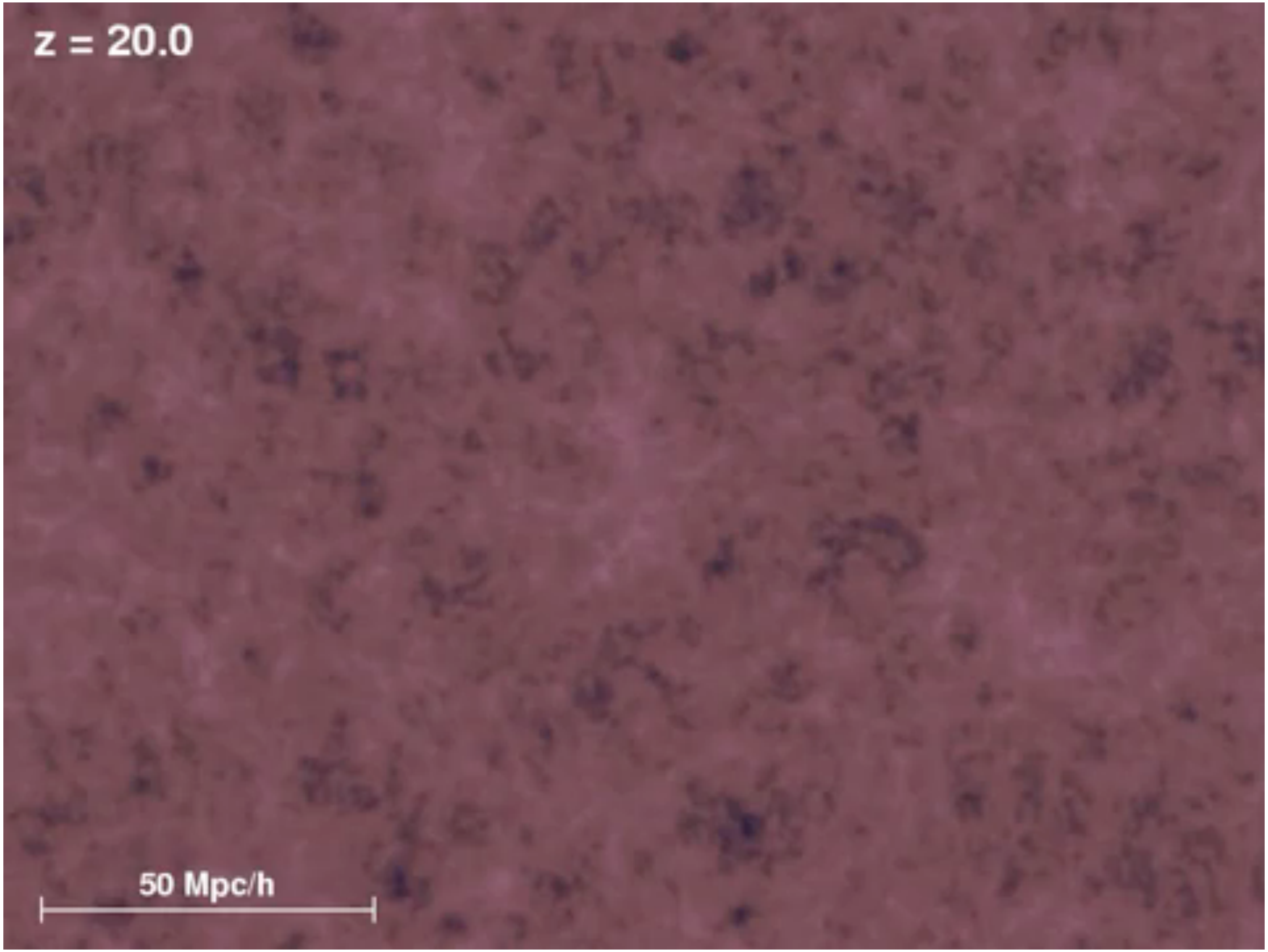
- Where did these inhomogeneities come from?

  - Imagine there were very slight inhomogeneities in the very early Universe (perhaps due to quantum fluctuations).

  - Gravity has the effect of amplifying these inhomogeneities: it is a positive feedback loop.

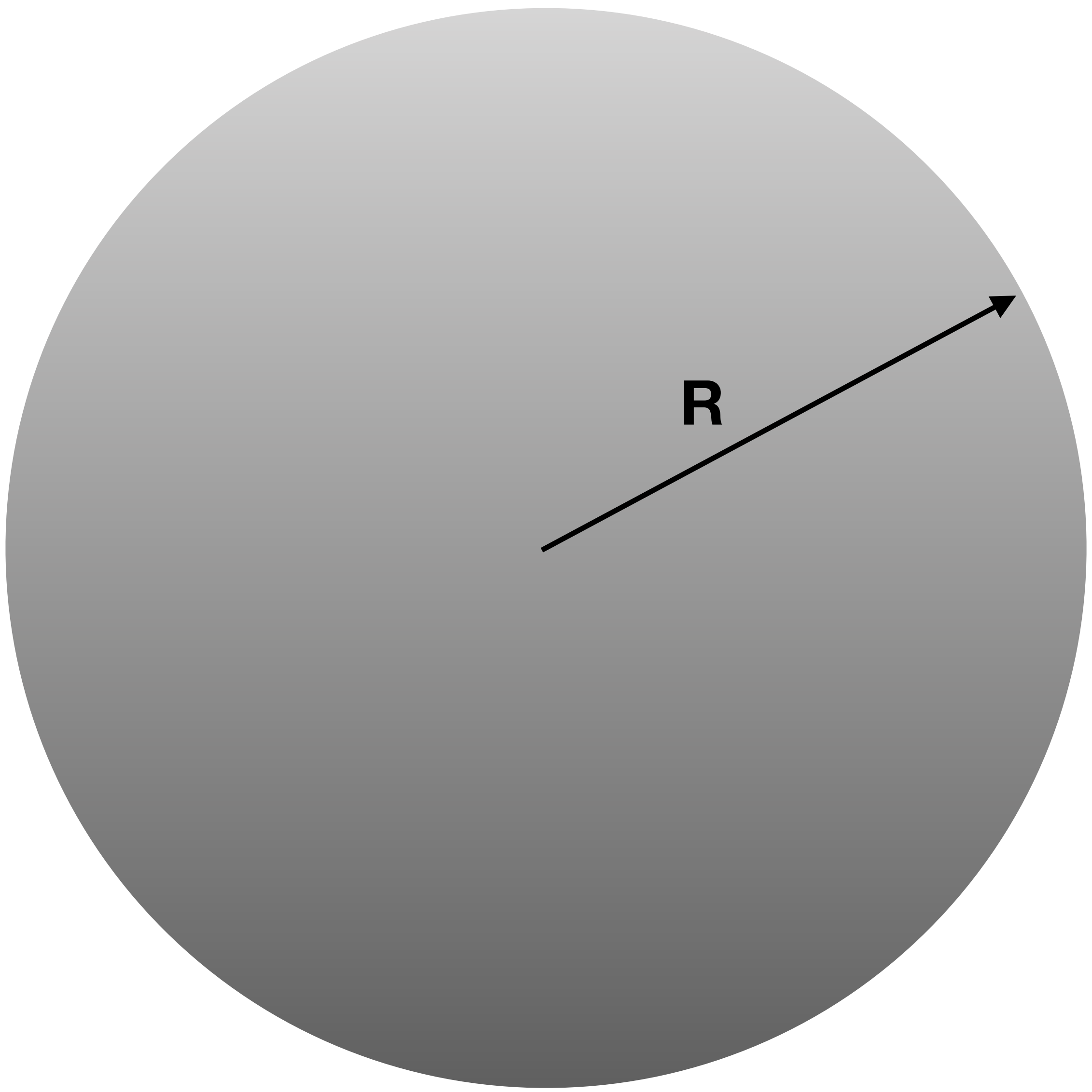
  - More dense regions have stronger gravity, which attracts more matter, which increases the density, which strengthens their gravity, and so on…

The build-up of large scale structure



The dense get denser

Consider a large sphere of radius R containing gas of overall density ρ, and a small density fluctuation δ:



As the sphere collapses due to the density fluctuation, the magnitude of the fluctuation increases as:

$$\ddot{\delta} = 4\pi G\bar{\rho}\delta$$

Which corresponds to:

$$\delta(t) = A_1 e^{t/t_{\rm dyn}} + A_2 e^{-t/t_{\rm dyn}}$$

where:

$$t_{\rm dyn} = \frac{1}{(4\pi G\bar{\rho})^{1/2}} \approx 9.6\ \text{hours}\ \left(\frac{\bar{\rho}}{1\ \text{kg m}^{-3}}\right)^{-1/2}$$

The Jeans Length

Pressure eventually prevents a gas cloud from collapsing completely.

So, can we figure out when a cloud of gas will collapse due to gravity, and when it will be supported by pressure?

For a cloud to be stable against collapse, its dynamical collapse time must be longer than the time it takes for a pressure-signal (which travels at the sound speed) to cross the cloud, i.e.,

$$t_{\rm pre} < t_{\rm dyn}$$

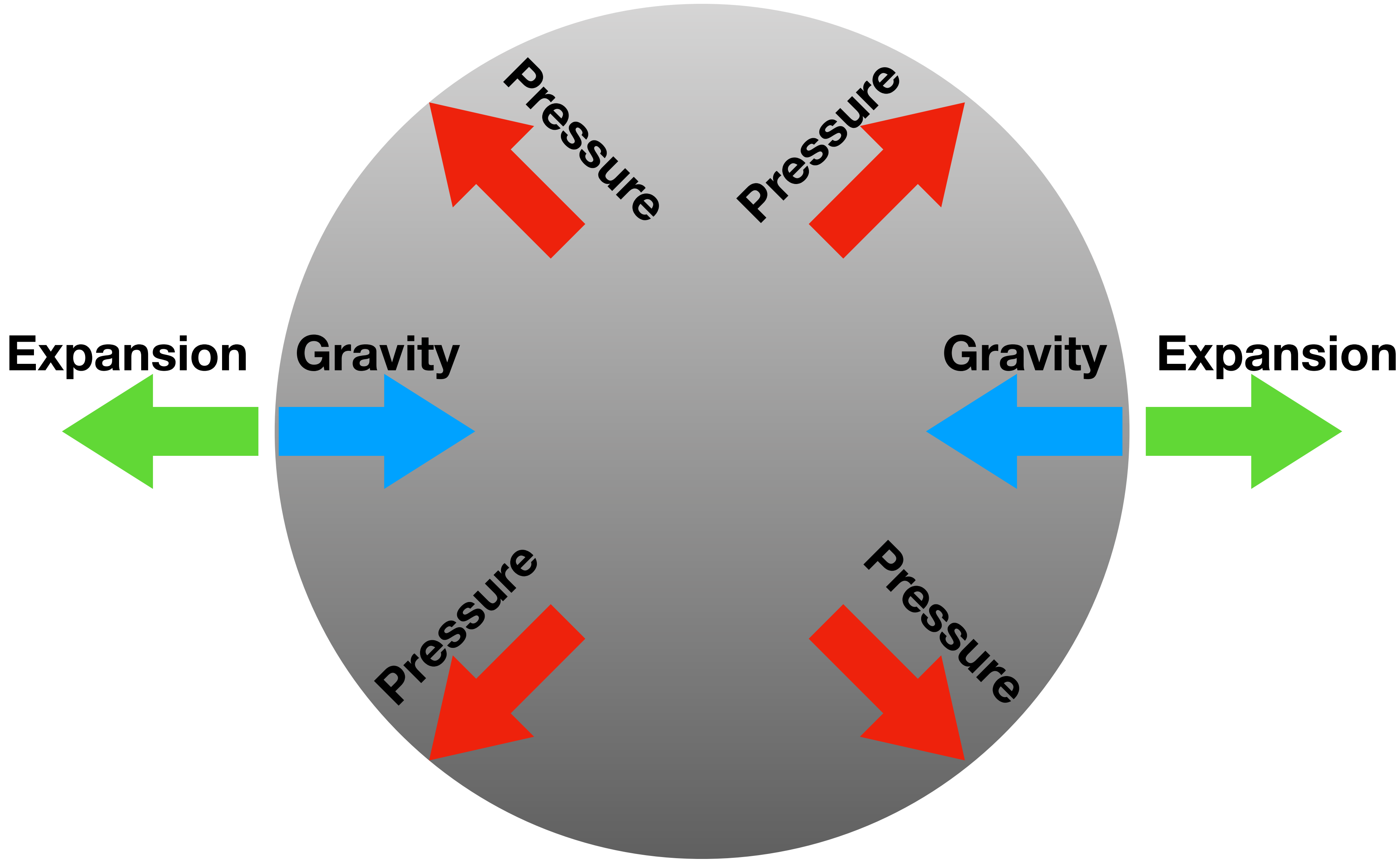
Meaning the radius of the cloud must satisfy:

$$R < c_s \left(\frac{c^2}{4\pi G \bar{\epsilon}} \right)^{1/2} = \lambda_J$$

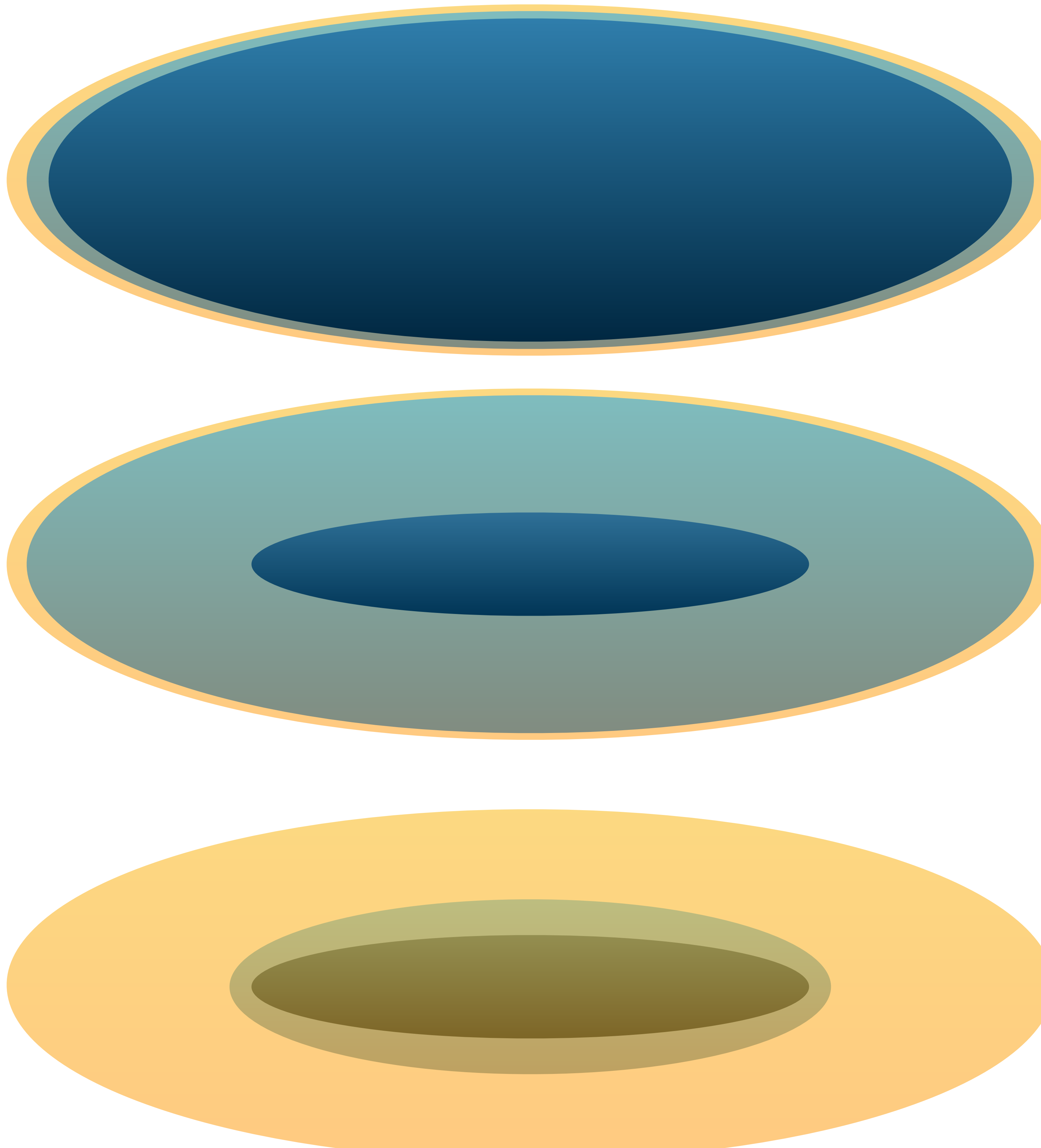
Gravitational collapse in an expanding universe

In an expanding universe, there is another factor to consider…

…the expansion of the universe will act against gravitational collapse.



Dark matter “pre-collapse”



z>3440

Radiation-
dominated:
Inefficient collapse

1090<z<3440

Matter-dominated:
Efficient collapse
of Dark Matter

z<1090

Matter-dominated:
Baryonic matter
falls into Dark
Matter structures

Getting the feel for it…

- Gravity acts to increase the amplitude of tiny fluctuations in energy density to produce the structure of today's Universe.

- Clouds of gas smaller than the Jeans length are immune to gravitational collapse due to pressure support;

- The Jeans length of a photon gas is huge, meaning structures could not form during the epoch of radiation-domination.

- Structure could only form once the Universe became matter-dominated and, to start with, only from Dark Matter.

- But, once baryonic matter decoupled from radiation, it was free to stream into the potential wells formed by the collapsing dark matter.