Galaxy formation : cosmological context

(if you have done ASTR 328/428, review notes on the growth of structure)

At recombination (where we see Cosmic Background Radiation) $z \sim 1000$

the universe was hot and $\boxed{\text{very smooth}}$ → no longer smooth @ $z = 0$

But there were slight density variations

(amplified from quantum fluctuations by inflation)

They grow gravitationally over time

→ how they grow depends on cosmological model

Uniform Temperature

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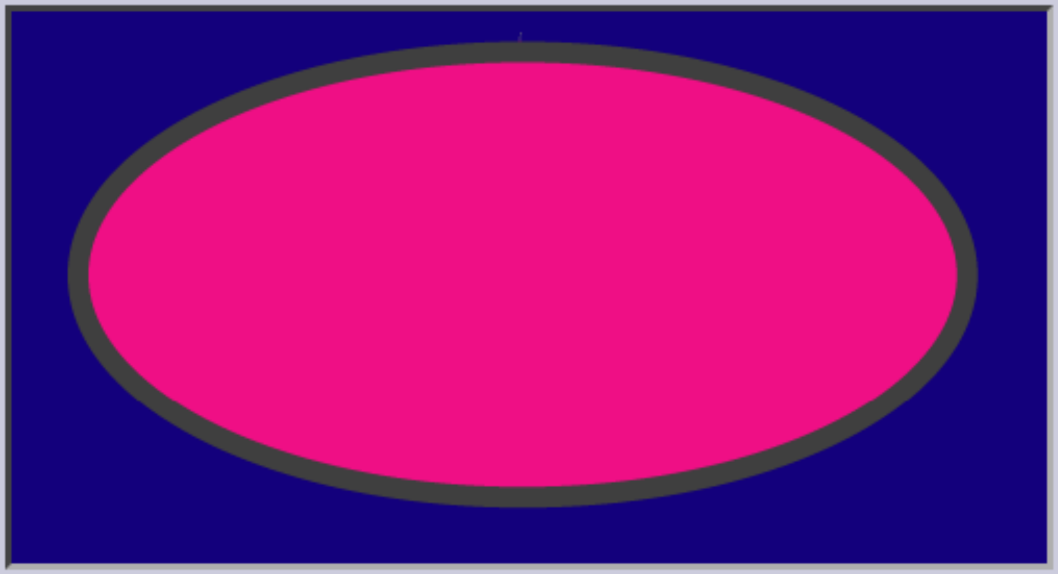
Key Concepts

- The CMB temperature on the sky is remarkably uniform

What COBE actually saw in the temperature of the CMB was at first glance remarkably boring:



i.e. the temperature of the CMB is the same in all directions with no variations whatsoever at the level of 1 part in 1000.

Slide from Wayne Hu, http://background.uchicago.edu/~whu/intermediate/map2.html

Our Motion

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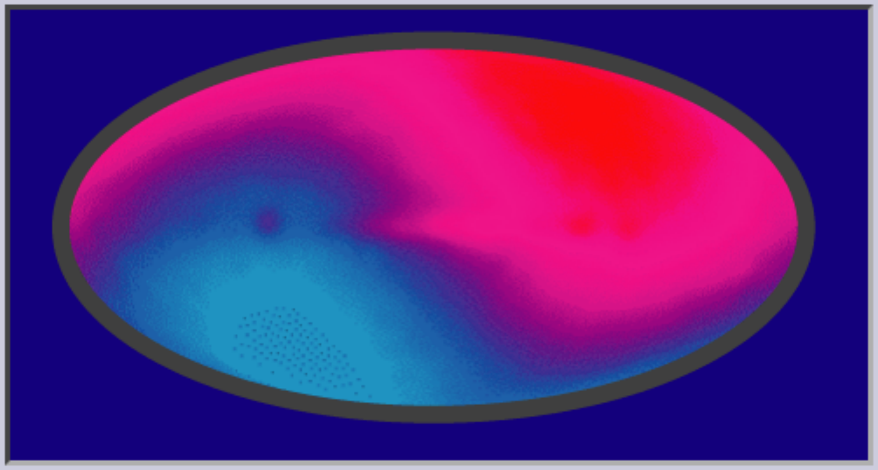
Key Concepts

- At the level of 1 part in 1000, the CMB temperature varies because of our motion with respect to it.

If we turn up the contrast on the previous map to see fluctuations at the level of one part in 1000, the COBE sky map looks like this:



Aside from some deviations about the equator, this pattern is a pure dipole. A dipole has its maxima and minima (red and blue here) pointed in opposite directions on the sky. This pattern is generated simply because we ourselves are moving with respect to the CMB and its temperature appears redshifted or blueshifted by the Doppler effect.

The map above has the equator placed according to where the galactic disk of the Milky way appears on the sky. Here we begin to see contamination from our own galaxy along the equator.

Slide from Wayne Hu, http://background.uchicago.edu/~whu/intermediate/map3.html

Large-Scale Anisotropy

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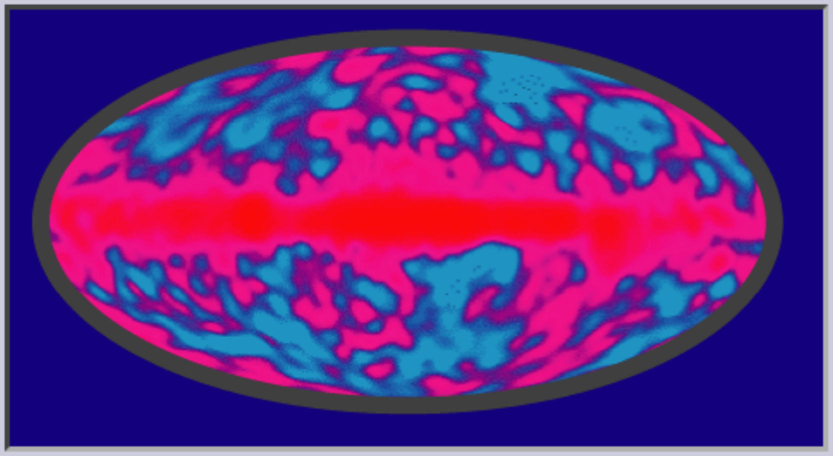
Key Concepts

- COBE showed that the CMB temperature varied at a level of 1 part in 100,000
- Variations are consistent with begin the quantum noise from inflation that formed structure through gravitational instability

If we remove the dipole and turn up the contrast on the previous map to the level of one part in 100,000, the COBE maps reveal:



Again, ignore the pattern around the equator as that is our own galaxy.

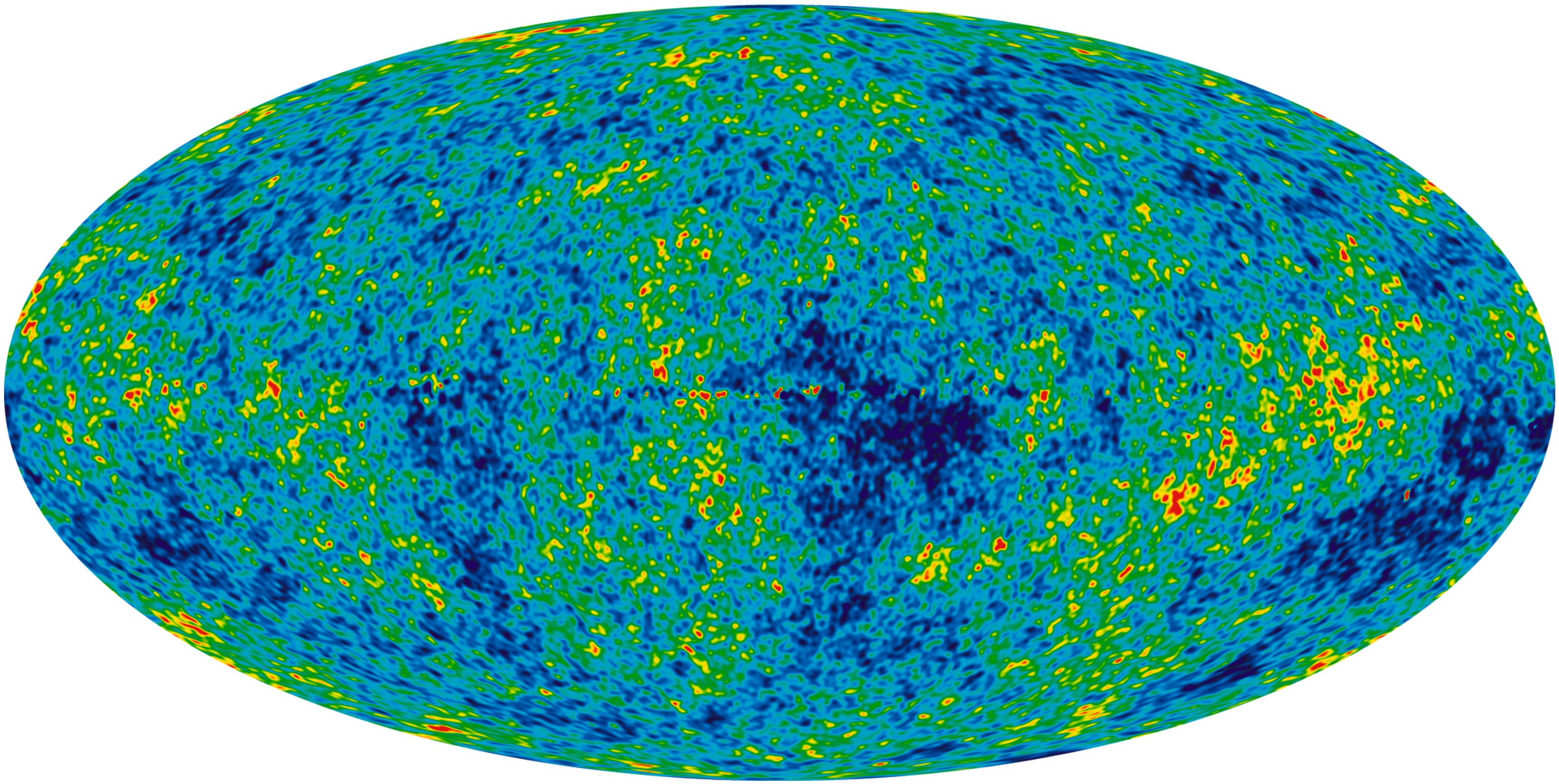
If you've never seen this map before, I'm sure your natural reaction is "Um, well it looks like noise to me".

Well actually that is exactly what it is.

But not in the bad sense. We believe that we are seeing the direct result of random quantum noise in the early universe. We think that a rapid period of expansion took these seed fluctuations in the density of matter in the universe and brought them to cosmic scales. The fluctuations that COBE sees are of exactly the right order of magnitude to have all of large-scale structure in the universe to have grown from them by gravitational attraction. We call the process of gravitational attraction accreting matter around small seed fluctuations to form ever larger structures the gravitational instability model of structure formation in the universe.

Anyway the bottom line is: sure its noise but it's interesting noise.

Slide from Wayne Hu, http://background.uchicago.edu/~whu/intermediate/map4.html



Final cleaned CMB picture from WMAP 7-year data (much better spatial resolution than COBE) Linear scale from -200 to 200 microKelvin

To treat this mathematically, assume homogeneity / isotropy
gravity (no Λ)

(see Mihos 328/428 notes for more detail)
(Longair 'Galaxy formation' ch 11)

matter & radiation treated as fluid with density ρ, velocity $\vec{v}$
pressure p
grav. pot'l ϕ

$$\frac{d\rho}{dt} = -\rho \nabla \cdot \vec{v}$$ continuity equation

$$\frac{d\vec{v}}{dt} = -\frac{1}{\rho} \nabla p - \nabla \phi$$ equation of motion

$$\nabla^2 \phi = 4\pi G \rho$$ Poisson's equation

$\delta = \frac{\delta\rho}{\rho}$

We can then perturb the equations ($\rho \to \rho(1+\delta)$)
and watch how the perturbation δ grows as universe expands

Growth equation $\ddot{\delta} + 2\frac{\dot{R}}{R}\dot{\delta} = 4\pi G\rho\delta$ (R is scale factor of universe)

Two special cases :

(i) flat universe $\Omega_0 = 1$

$$\frac{\delta\rho}{\rho} = \delta \propto t^{2/3} \propto \frac{1}{1+z}$$

So, in flat universe, perturbations keep growing

(ii) empty universe $\Omega_0 = 0$ (if there ~~was~~ were only baryons, $\Omega_b \sim 0.05$
no dark matter
no dark energy)

$$\delta(t) = A + Bt^{-1}$$

A: stays constant

Bt^{-1}: decays

✳ If we only had baryons in our universe, the initial small perturbations would not grow into galaxies ✳

→ Another reason we need dark matter ←

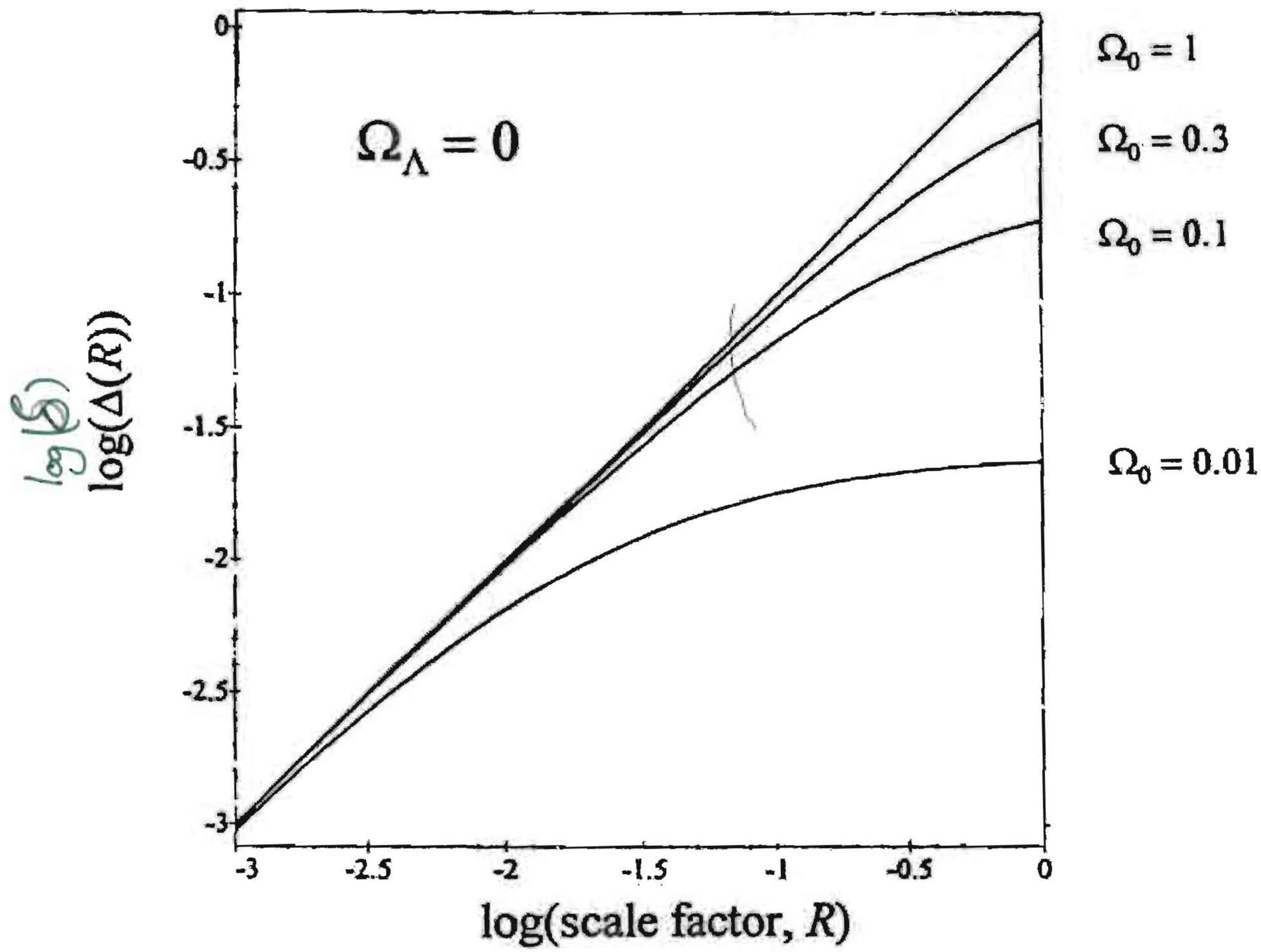


Fig. 11.4. The growth of density perturbations over the range of scale-factors $R = 10^{-3}$ to 1 for world models with $\Omega_\Lambda = 0$ and density parameters $\Omega_0 = 0.01, 0.1, 0.3$ and 1.

What about cosmology with Λ (preferred today)?

$$\Omega_m + \Omega_\Lambda = 1 \quad \text{(flat)}$$

baryons + dark matter

dark energy

- Early on, universe behaves like $\Omega_m = 1$
  So perturbations grow like $t^{2/3}$

- Things change around $z = \frac{1}{\Omega_0}$ ($= 3$ for $\Omega_0 = .3$)

- Perturbations grow faster than if $\Omega = 0$ (good!)
  But in this case, more slowly than $\Omega_m = 1$

- Things slow down when acceleration becomes important ($z \sim 0.5$, $\Omega_m = .3$)

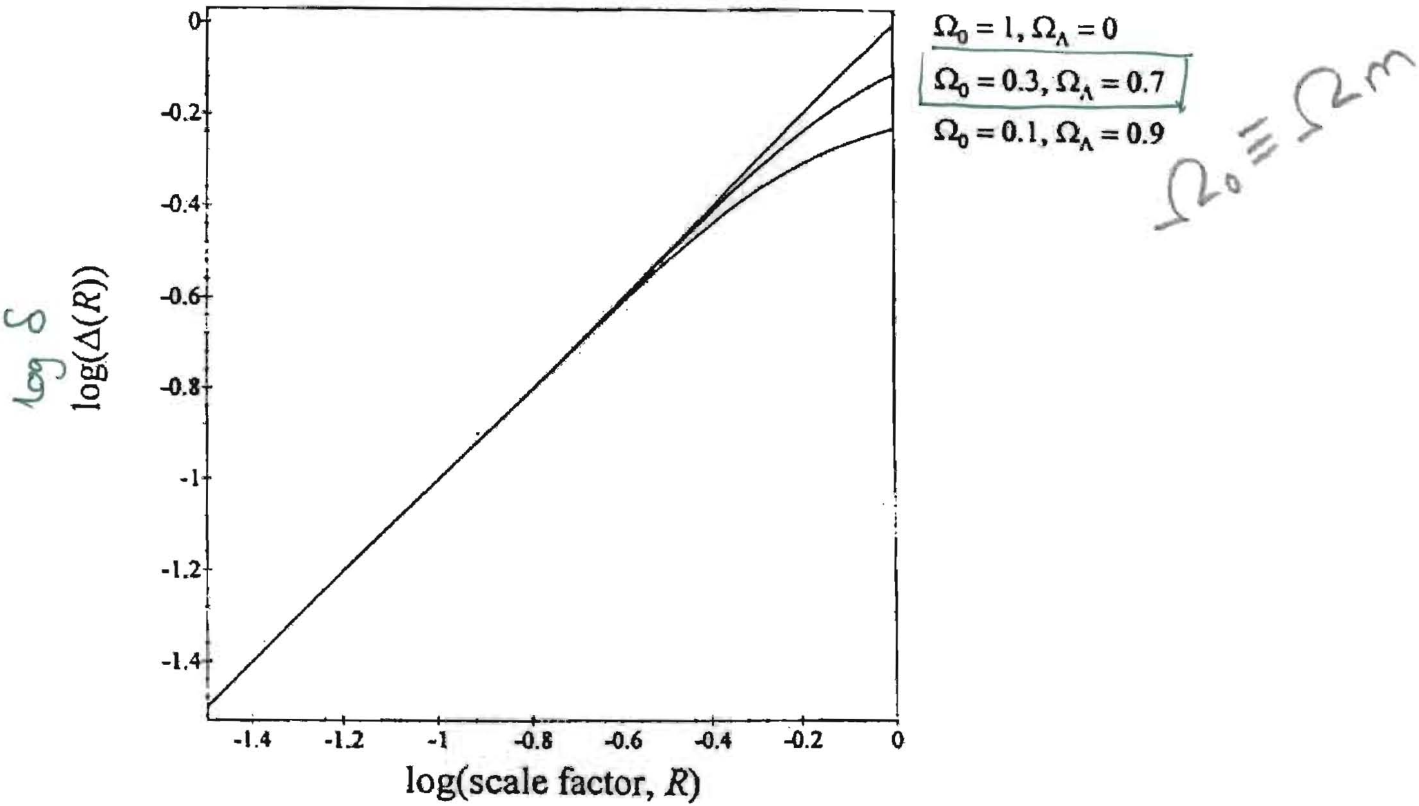


Fig. 11.5. The growth of density perturbations over the range of scale-factors $R = 1/30$ to 1 for world models with $\Omega_0 + \Omega_\Lambda = 0$ and density parameters $\Omega_0 = 0.1$, 0.3 and 1.

Biasing

We have seen that it is easier for initially dense regions of the universe to collapse early.

This is a result about dark matter, since this dominates the mass.

Galaxies (or even stars) may not form in all dark halos; they may only form @ the densest peaks.

Biasing : $$\left(\frac{\delta\rho}{\rho}\right)_{galaxies} = b\left(\frac{\delta\rho}{\rho}\right)_{dark\ matter}$$

Early evolution : linear regime

We can treat the slightly overdense region as its own model universe :

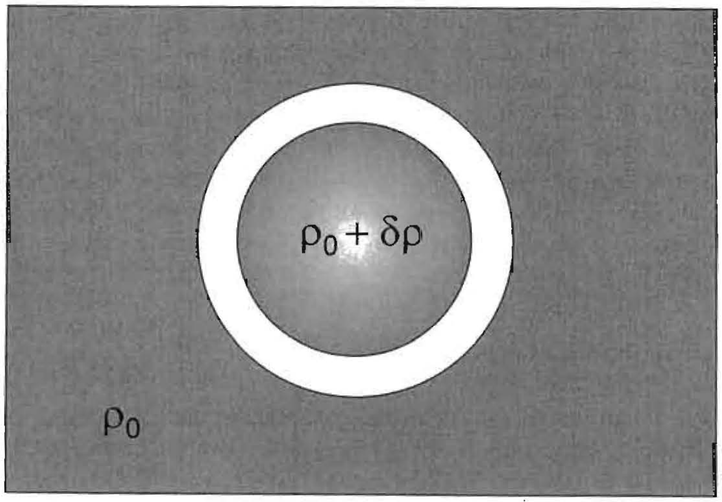


Fig. 11.1. Illustrating a spherical perturbation with slightly greater density than the average in a uniformly expanding Universe. The region with slightly greater density behaves dynamically exactly like a model Universe with density $\varrho_0 + \delta\varrho$.

Surrounding universe is flat, so will keep expanding. Overdense region is closed, so will expand and then recollapse. Density grows linearly with scale factor R

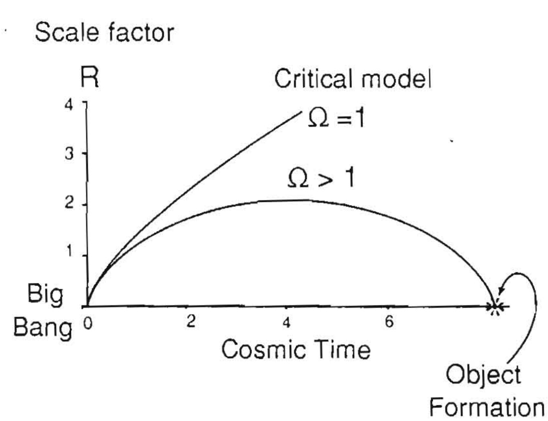


Fig. 11.2. Illustrating the growth of a spherical perturbation in the expanding Universe as the divergence between two Friedman models with slightly different densities.

Densest initial fluctuations will collapse first ; more modest over-densities will take longer to recollapse.

How far will the dark matter (& associated baryons) collapse?

As things fall into the growing gravitational potential wells, they gain kinetic energy. Eventually they settle into 'virial equilibrium' and obey the virial theorem

$$2K + U = 0$$

potential energy

kinetic energy

Let our idealized sphere collapse to half the size at turnaround (when it stops expanding & begins to contract) and conserve energy (dark matter doesnt radiate & cool)

Radius @ turnaround $= r_{max}$

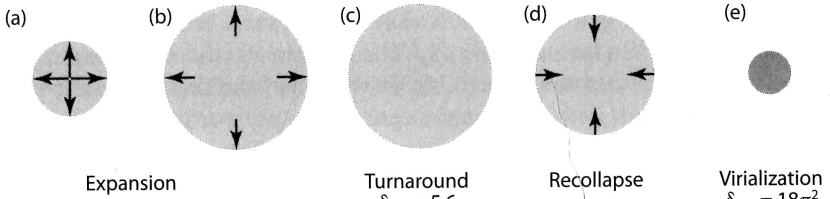
Uniform sphere has potential energy

$$U = \frac{-3GM^2}{5r}$$

at half maximum size, with energy conserved,

gain in k.e. = loss in p.e $= \dfrac{3GM^2}{5(r_{max}/2)}$

and $2K + U = 0 \Rightarrow$ virialized.


(a)
(b)
(c)
(d)
(e)
Expansion
Turnaround
Recollapse
Virialization

In summary: the dark matter will be in equilibrium when it has collapsed to half the radius at turnaround (when the halo separates from the Hubble flow)

$\boxed{Q}$ Galaxies are considerably smaller than half the radius of their associated halos @ turnaround.

How does the collapse go further?