2012年 現代物理学

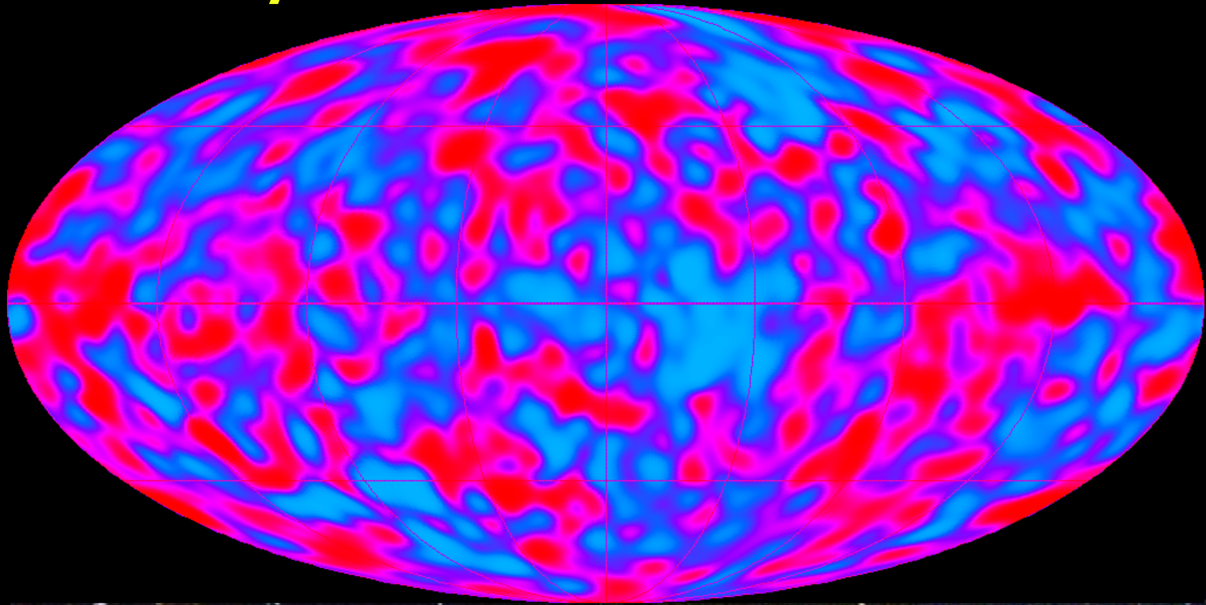
第二講
構造形成と宇宙の加速度的膨張

内容

1. 密度揺らぎの成長（続き）
2. コールドダークマターモデル
3. 遠方超新星とダークエネルギー

先週の復習

Very smooth initial state



Ending as a clumpy universe

Growth of linear perturbations in an expanding universe

The continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

The Euler equation

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + \frac{\nabla P}{\rho} + \nabla \phi = 0$$

The Poisson equation

$$\nabla^2 \phi = 4 \pi G \rho$$

板書

The growing mode solution

The combined equations (continuity, Euler, and Poisson) lead to the second-order ordinary differential equations:

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\,\bar{\rho}\,\delta = 0$$

which has two solutions.
The one we are interested in is the so-called "growing mode" which evolves as

$$\delta = D(t)\,\delta_{\text{initial}}$$

For a flat, matter-dominated universe, $D = a$
where a itself scales as $\sim t^{2/3}$
Density fluctuations grow with time in the early epoch.

クイズ2

物質優勢期における揺らぎの発展方程式

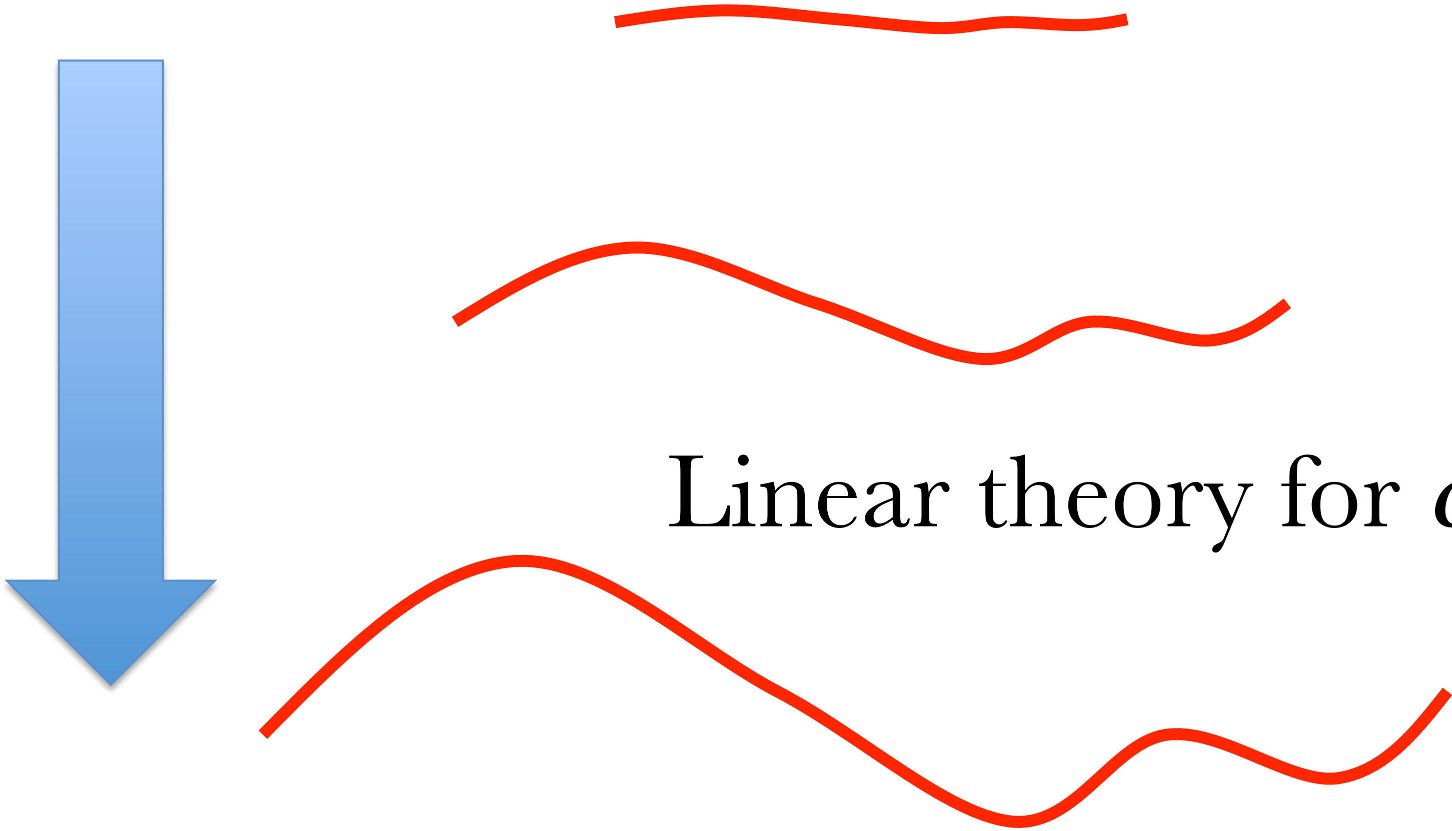
$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\,\bar{\rho}\,\delta = 0$$

を解いて δ の時間発展を議論しよう。

特に膨張が無かった場合との比較。

ヒント） 両辺に 2/3 をかけてみる

The growing mode solution



Amplitude ~ a in the matter dominated era.

The Standard Cosmological Model

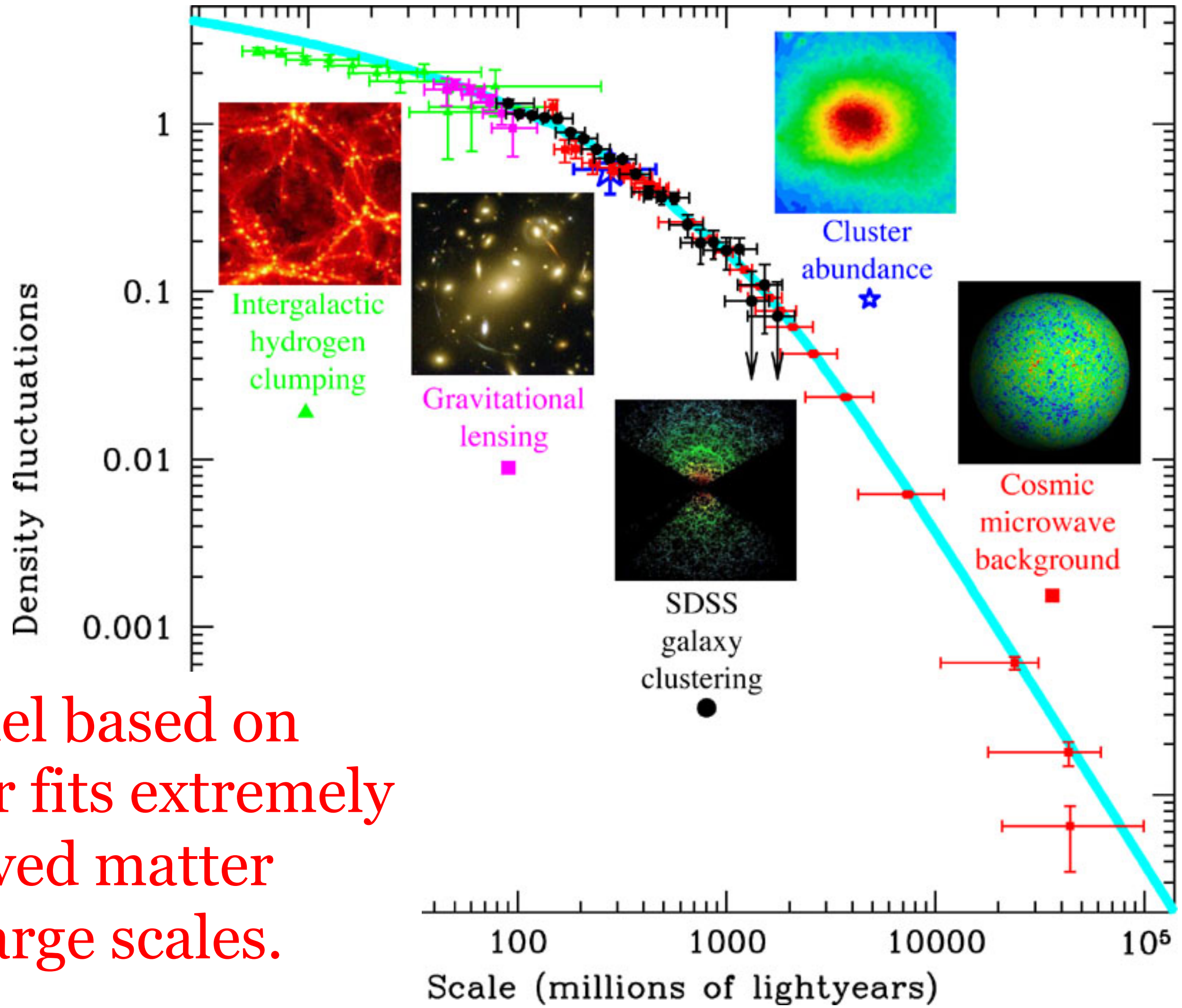
Inflation + Cold Dark Matter

In its very early phase, the universe went through a very rapid expansion phase called "inflation", where the density fluctuations were generated from quantum fluctuations of a scalar field.

The fluctuations are of a Gaussian random field (like a noise) and scale invariant. Just like the CMB anisotropies we observe today.

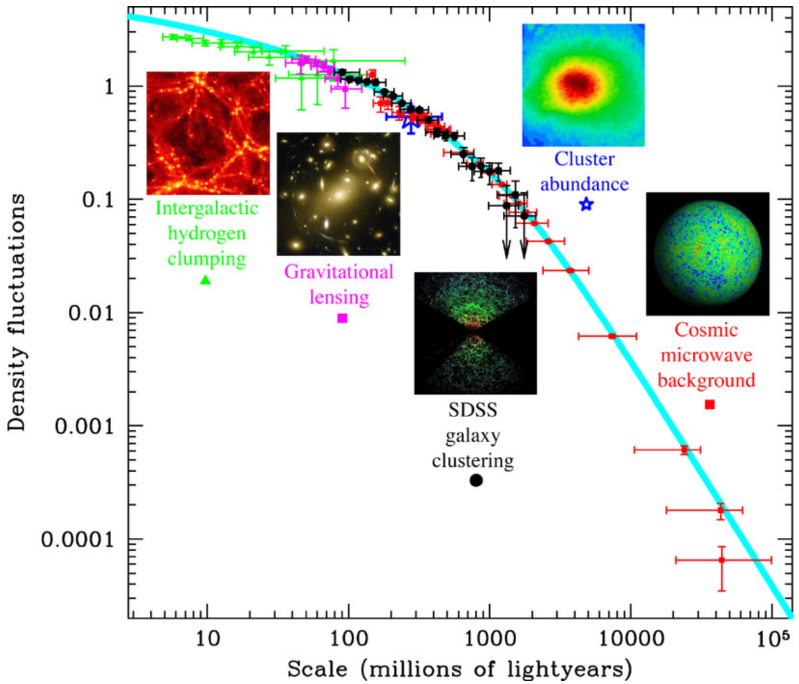
Eventually heavy Cold Dark Matter decoupled from the rest of matter and radiation. CDM dominates the matter content since then.

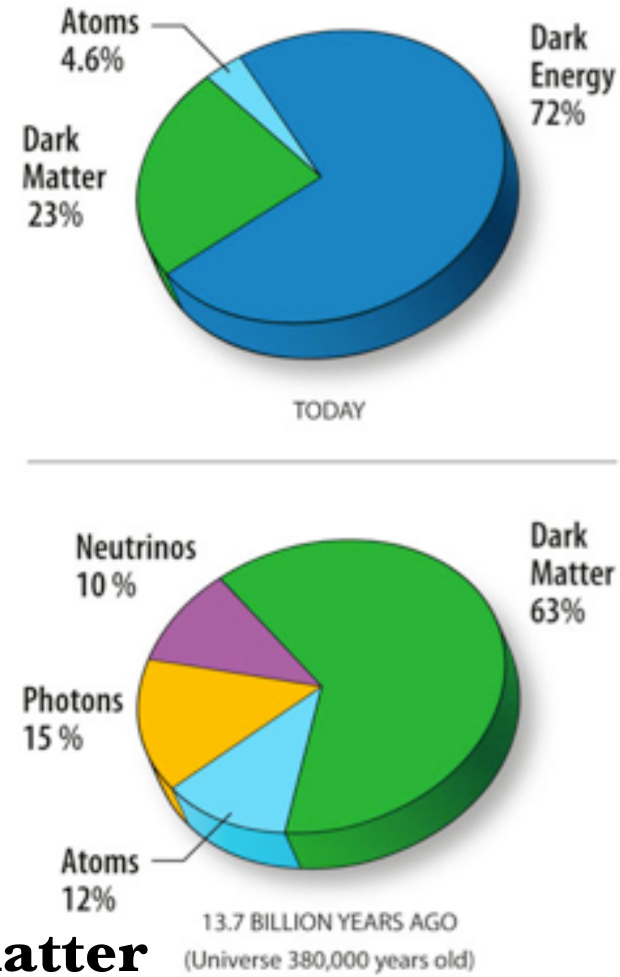
The standard ΛCDM model



A particular model based on Cold Dark Matter fits extremely well to the observed matter distribution on large scales.

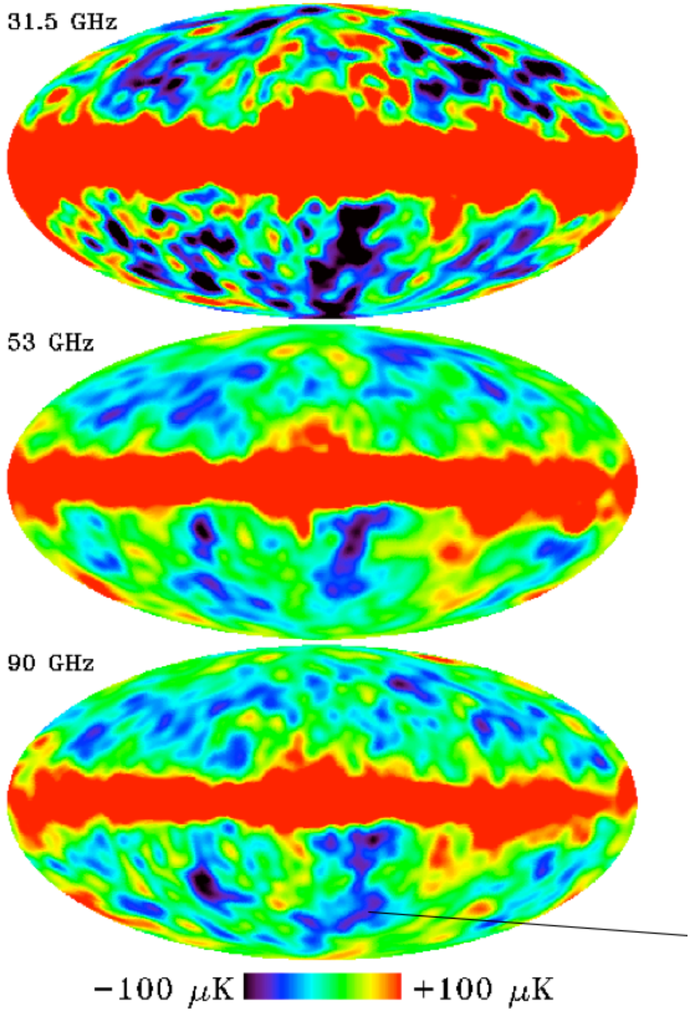
The standard ΛCDM model





4.6 % ordinary matter
23 % exotic (unknown) dark matter
72 % yet unknown dark energy

The "initial" amplitude



$$\frac{\Delta T}{T}\Big|_{\mathrm{COBE}} \sim 10^{-5}$$

In an over-dense region, there are slightly more photons, but the photons need to climb out of the gravitational potential well.
So, *does an over-dense region appear as hotter or colder ?*

Cold spot

Fluctuation growth since z=1089

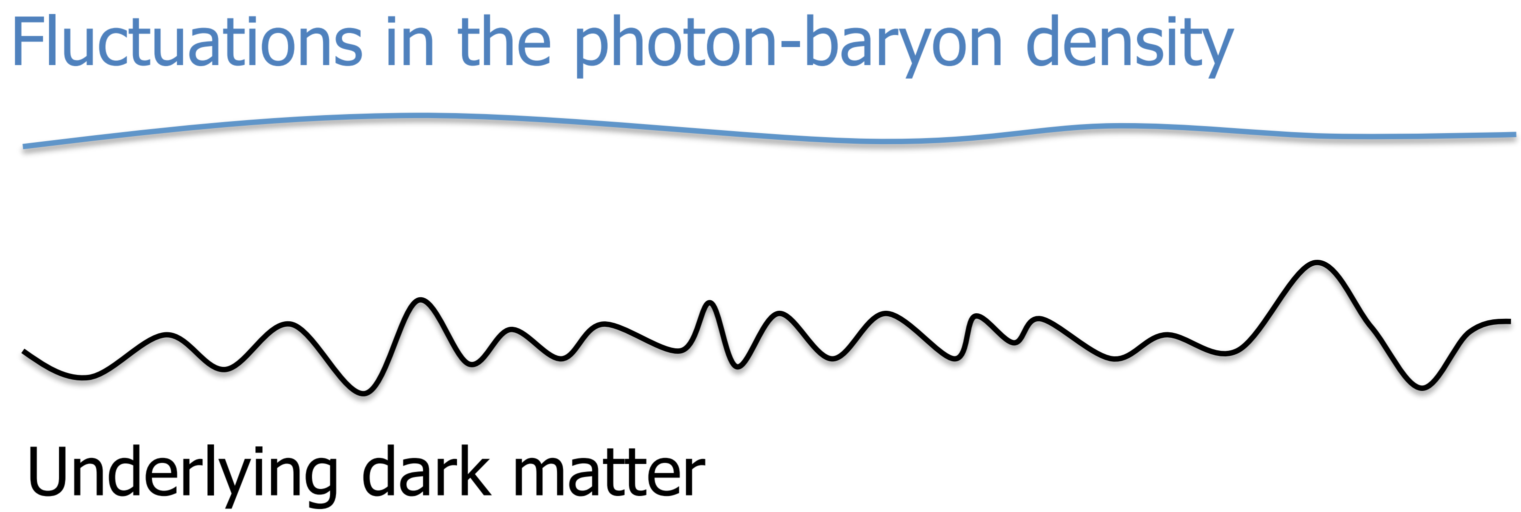
We have learned that the density fluctuations grow as $\sim a$ in a matter-dominated universe. The expansion parameter increases by a factor of $\sim$ 1090 since the recombination epoch when the fluctuation amplitudes were ~ $10^{-5.}$

Then the amplitude today would be ~ 10^{-2}

Adding Λ will only suppresses the growth at late time…

Dark matter helps

- Fluctuations on small-scales



Small-scale fluctuations with large amplitude can develop to clumps. These fluctuations cannot be seen in CMB because of tight photon-baryon coupling, i.e., distribution different from dark matter.