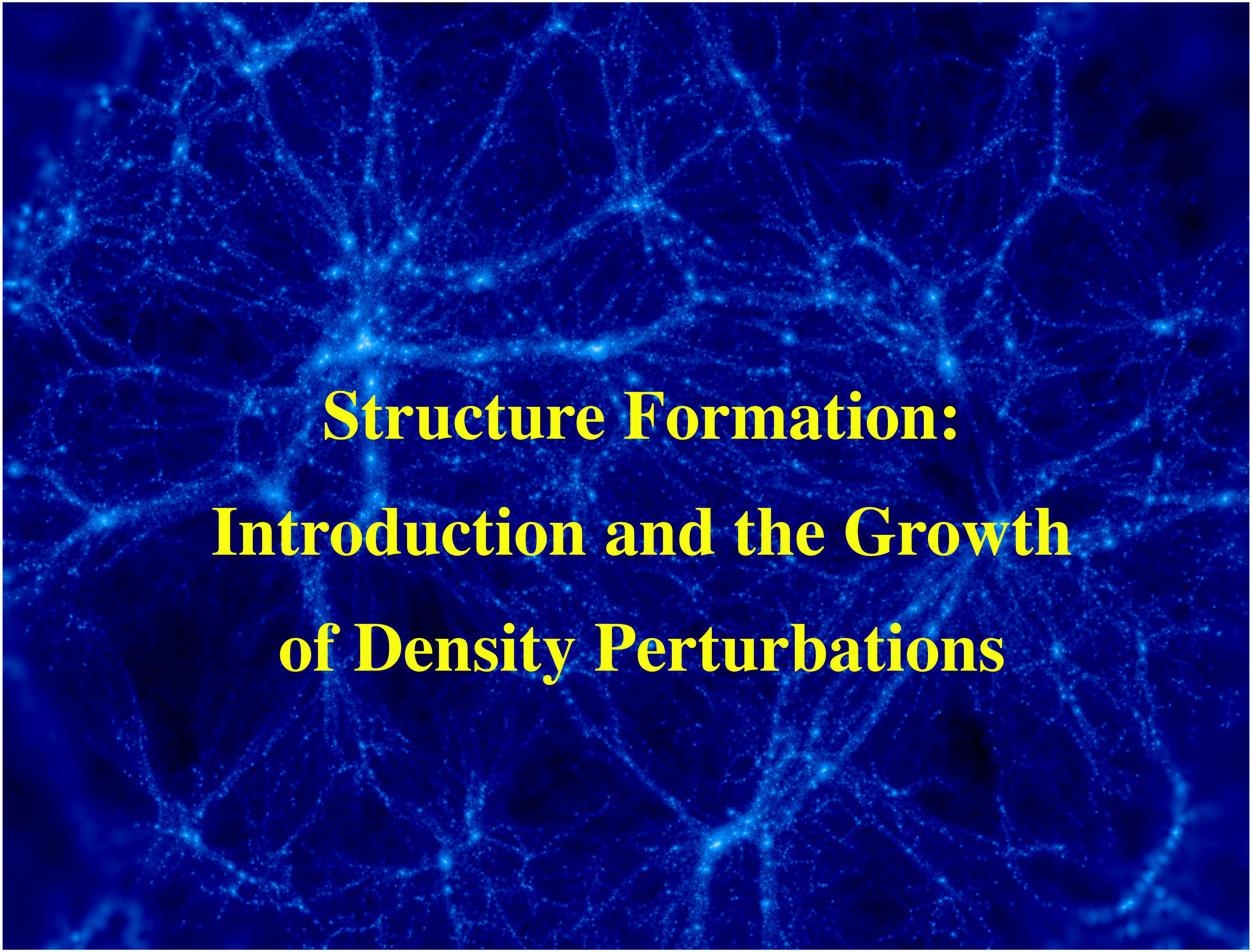
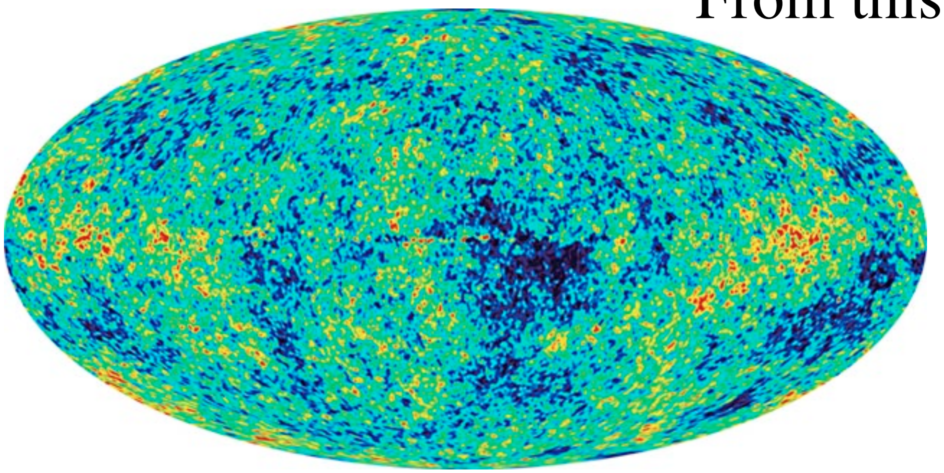
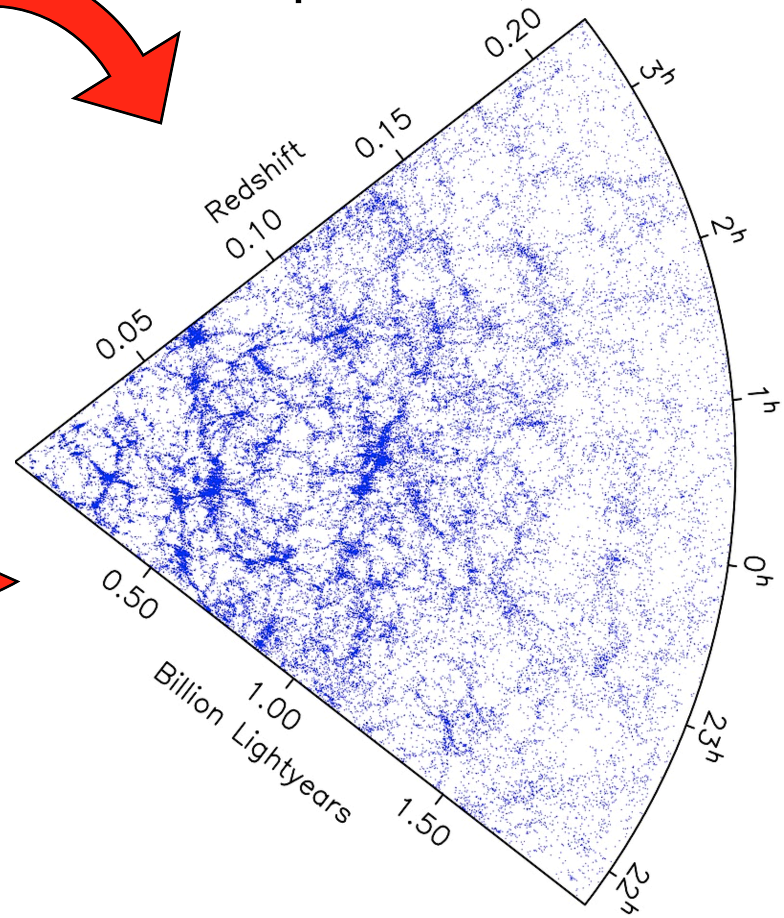

Structure Formation:
Introduction and the Growth
of Density Perturbations

Structure Formation and Evolution

From this ($\Delta\rho/\rho \sim 10^{-6}$)



to this
($\Delta\rho/\rho \sim 10^{+2}$)

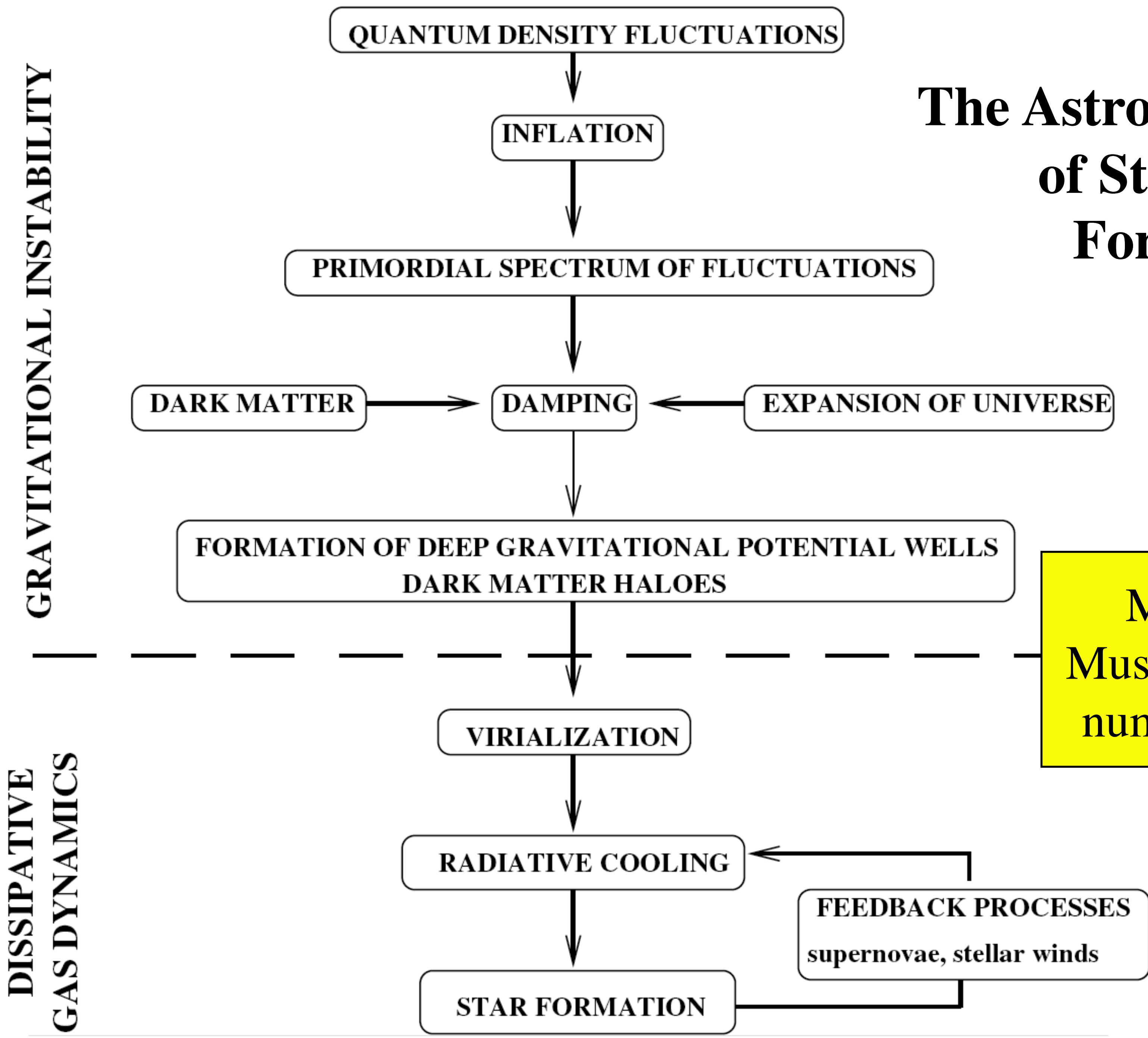


to this
($\Delta\rho/\rho \sim 10^{+6}$)

Origin of Structure in the Universe

- Origin and evolution of the structure in the universe (galaxies, large-scale structures) is a central problem in cosmology
- Structure is generally thought to arise through a growth of density perturbations which originate in the early universe
  - We think they came from quantum fluctuations in the scalar field that caused inflation, and were then amplified by the exponential inflation of the universe
- What do we know about the early structure formation?
  - We see CMB fluctuations with $\delta T/T \sim 10^{-6} \sim \Delta\rho/\rho$, since radiation and baryons are coupled before recombination
  - High-z objects: We observe galaxies and quasars at $z > 6$. A galaxy requires an overdensity of $\sim 10^6$ relative to the mean
- Can we get to the such large density enhancements required for galaxies, clusters, etc., by evolving the small fluctuations we see in the CMB?

The Astrophysics of Structure Formation



Messy!
Must be done numerically

Linear Growth of Density Fluctuations

How do fluctuations in density evolve with time? For simplicity, consider a flat, matter-dominated universe with $\Omega_m = 1$ (a good approx. for the early times).

The Friedmann equation is:

$$H^2 - \frac{8}{3}\pi G\rho = -\frac{k}{R^2} = 0$$

Now consider a small area with a slight overdensity of matter, it will evolve slightly differently:

$$H^2 - \frac{8}{3}\pi G\rho' = -\frac{k}{R^2}$$

Subtract the two equations:

$$-\frac{8}{3}\pi G(\rho' - \rho) = -\frac{k}{R^2}$$

Rewrite this as:

$$\rho' - \rho = -\frac{3k}{8\pi G R^2}$$

Linear Growth of Density Fluctuations

We can define δ as the ***fractional overdensity:***

$$\delta \equiv \left(\frac{\rho' - \rho}{\rho}\right) = -\frac{3k}{8\pi G R^2 \rho}$$

But note that:

$$\delta \sim \frac{1}{R^2 \rho} \sim \frac{1}{R^2 R^{-3}} \sim R$$

Since $R \sim (1+z)^{-1}$, $\boxed{\delta \sim (1+z)^{-1}}$

And this is the linear growth of density fluctuations.

Evolution of the density contrast between two redshifts is then

$$\frac{\delta_f}{\delta_i} = \frac{(1+z)_i}{(1+z)_f}$$

Linear Growth of Density Fluctuations

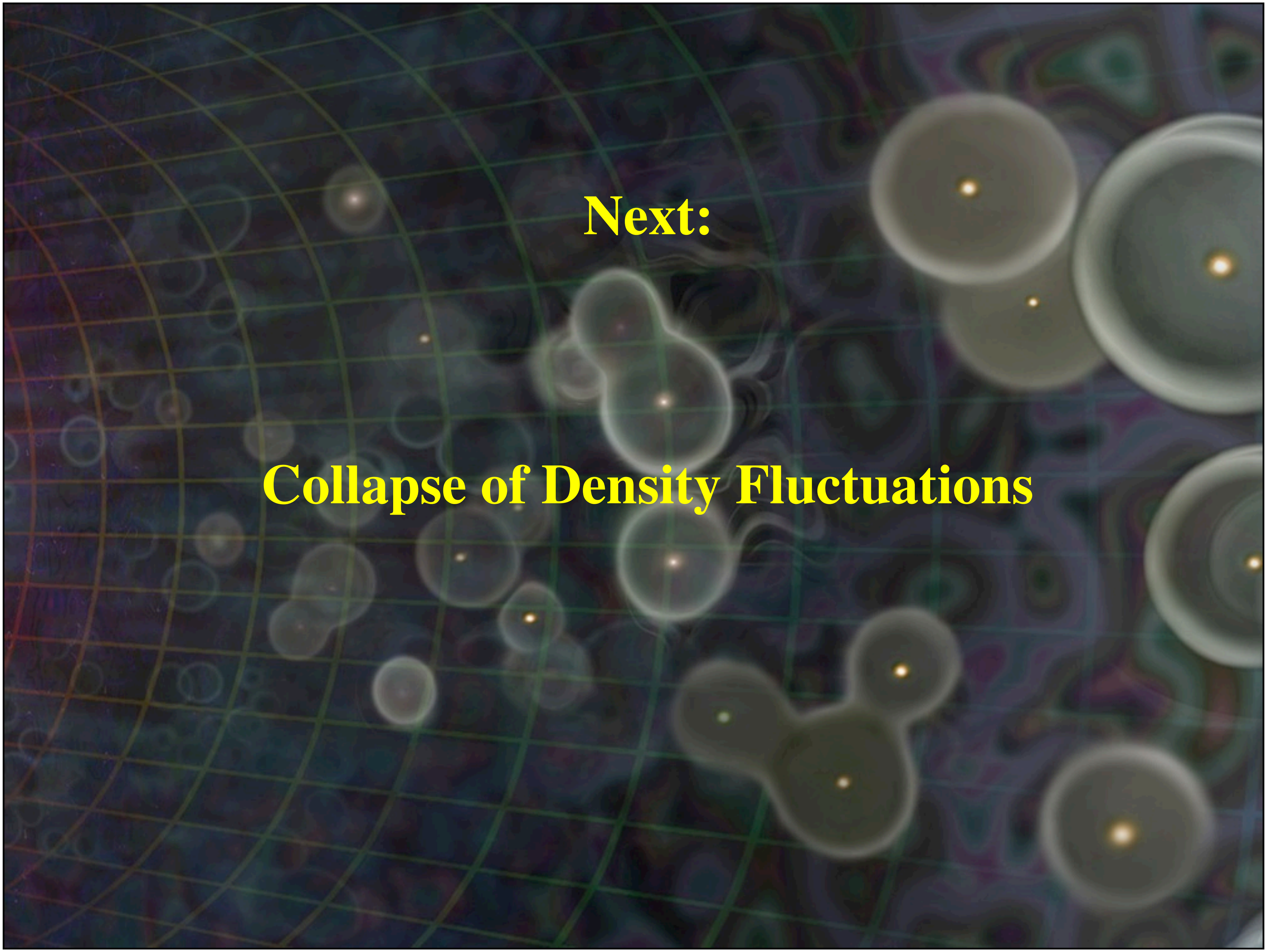
Let's try it from recombination to $z = 5$:

$$\delta_f = 10^{-5}\left(\frac{1+1000}{1+5}\right) \sim 0.002$$

Oops! It should be ~ 10^6 - now what?

We need to start with larger fluctuations to get galaxies, etc.
We neglected the effects of ***non-baryonic dark matter***. Before recombination, the radiation prevented the baryonic fluctuations of collapsing, but fluctuations in non-baryonic dark matter can start growing much earlier!

The fluctuations we see in the CMB (in the baryonic matter) are sitting on top of much stronger fluctuations in the non-baryonic matter. Once recombination occurs, the baryons can fall into the dark matter concentrations to form galaxies …


Next:
Collapse of Density Fluctuations