Structure Formation

From Inflaton to Milky Way

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Recap of last week....
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- What is dark matter?
- What is dark energy?
- What is origin of perturbations?
- Why is Universe flat?
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- What is dark energy?
- What is origin of perturbations?
- Why is Universe flat?
The Inflationary Universe
Inflation

Inflaton acts like dark energy and causes exponential expansion. Inflation stops when inflaton `decays' to true vacuum state. Energy of inflaton converted to particles & photons.

Postulate

Shortly after Big Bang (~$10^{-35}$s), energy density of Universe is dominated by false vacuum state of a scalar field (the inflaton).

Inflation is envisioned to lasts for at least ~60 e-foldings, during which size of Universe increased by a factor $\sim 10^{26}$.
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Inflation stops when inflaton `decays' to true vacuum state.

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Inflation is envisioned to lasts for at least \(~60\) e-foldings,
during which size of Universe increased by a factor \(\sim10^{26}\).

For comparison, since CMB Universe has expanded by factor \(10^3\).
Because of huge expansion, any pre-existing curvature is inflated away
--> post-inflationary Universe is flat
Quantum physics dictates that on very small scales, energy density associated with inflaton fluctuates...

Because of exponential expansion, these quantum fluctuations are inflated to fluctuations in energy density of Universe.
During inflation, a patch the size of a human hair (width) is inflated to patch larger than our Milky Way, in less than $10^{-33}$ s.

Inflation solves the flatness problem in that it inflates away any pre-existing curvature.

Because of quantum fluctuations, inflation also automatically predicts generation of density perturbations on wide range of scales.
The Inflationary Universe

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What gave rise to this bewildering variety of structures?
The Milky Way and more than 1.5 million galaxies from 2MASS, color coded according to redshift (blue = near, red = far)
Sloan Digital Sky Survey

Apache Point Observatory, New Mexico
Galaxy distribution is sponge-like; strong clustering
Massive clusters are the largest structures in the Universe, and contain hundreds of (mainly elliptical) galaxies.
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At recombination: $|\delta| < 10^{-5}$

13 Gyr

Today, within Solar radius of MW: $\delta \simeq 10^5$

Dynamical time at Solar radius $\sim 250$ Myr

$$\delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}}$$
At recombination: \(|\delta| < 10^{-5}\)

Today, within Solar radius of MW: \(\delta \approx 10^5\)

Dynamical time at Solar radius \(\sim 250\) Myr

Perturbations have grown by more than 10 orders of magnitude in less than 50 dynamical times

\[ \delta(x) = \frac{\rho(x) - \bar{\rho}}{\bar{\rho}} \]
At recombination:

|δ| < 10^{-5}

Today, within Solar radius of MW:

δ ≃ 10^5

13 Gyr

Dynamical time at Solar radius ~ 250 Myr

Perturbations have grown by more than 10 orders of magnitude in less than 50 dynamical times

HOW??

δ(x) = \frac{ρ(x) - \bar{ρ}}{\bar{ρ}}
Gravitational Instability: slightly denser regions attract matter thus becoming even denser, etc.

Evolution of overdensities...
Gravitational Instability: slightly denser regions attract matter thus becoming even denser, etc.

This process continues until overdensities are of order unity.

At that point, overdensities `turn around' (stop expanding) and start to collapse...
The Collapse of Perturbations

Evolution after turn-around depends on nature of matter

Dark Matter = collisionless \rightarrow shell crossing

Baryonic Matter = collisional \rightarrow shock heating
Onion Model

you can think of overdensity as consisting of many individual thin mass shells

Evolution of shell of Cold Dark Matter
Because dark matter has no pressure, shell crosses itself and starts to oscillate.

Onion Model

you can think of overdensity as consisting of many individual thin mass shells
The Formation of a Dark Matter Halo
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Individual oscillating shells interact gravitationally, exchanging energy (virializing), giving rise to a relaxed dark matter halo.
Onion Model

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individual thin mass shells
Because of pressure a shock develops, which heats the gas and makes it expand.

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Evolution of shell of Baryonic Matter

The End Result

A dark matter halo filled with hot gas.
The Hierarchical Growth of Dark Matter Haloes
A region in space in which 5 dark matter haloes have formed
Dark matter haloes attract each other gravitationally...
consequently, they move towards each other....
and merge together, to form bigger haloes....
with substructure
Numerical Simulations

Start with box with many particles, whose spatial distribution reveals tiny fluctuations (as in CMB)

Let box `expand' (as Universe), and compute gravitational force between all particles

Propagate all particles according to the gravitational acceleration

Repeat this procedure for as many time steps as needed
Distribution of dark matter with tiny fluctuations in initial density
Millennium Simulation
10,077,696,000 particles

(z = 0)
A Close-Up View of a Dark Matter Halo
Flying Faster than the Speed of Light...
Flying Faster than the Speed of Light...
The Formation of Galaxies
Because of angular momentum conservation, the cooling baryons spin up and form a thin disk inside the disk the density gets very high, causing fragmentation and star formation: a disk galaxy is born...

Hot gas radiates, emits photons which carry away energy: the gas cools due to pressure loss, gas starts to contract because of angular momentum conservation, the cooling baryons spin up and form a thin disk inside the disk the density gets very high, causing fragmentation and star formation: a disk galaxy is born...
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Hot gas radiates, emits photons which carry away energy: the gas cools.

Due to pressure loss, gas starts to contract.

Because of angular momentum conservation, the cooling baryons spin up and form a thin disk.

Note that dark matter does NOT cool.

Inside the disk the density gets very high, causing fragmentation and star formation: a disk galaxy is born...
If dark matter haloes host galaxies, clusters are a natural outcome of hierarchical formation in CDM Universe.
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But what happens when two galaxies collide??
When two disks collide...
When two disks collide...

...an elliptical emerges
Small perturbations, due to quantum fluctuations, grow and collapse to form dark matter haloes.

Baryonic gas is shock heated to high temperatures.

Baryonic gas cools and settles in center of halo; angular momentum conservation → disk galaxy.

Disks merge giving rise to population of ellipticals especially in denser environments (clusters).
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Where are the other 90%?

- Hot gas in clusters (observed)
- Warm-hot gas in filaments (elusive)
Outstanding Problems: Some Feedback Please...

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Why so few stars?
- Feedback from supernovae & AGN?
- We do NOT understand this process...
Thank you for believing...
Remember me?