Galaxy Formation
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Goal: understand origin and evolution of cosmic structures
- Review of standard Big Bang model
- Growth of small fluctuations (linear theory)
- Fluctuations in the microwave background radiation
- The formation of galaxies and clusters

Connection to three outstanding problems in 21st Physics:
- The identity of the dark matter
- The nature of the dark energy
- Origin of cosmic structure

You should be familiar with:
- Basic concepts in Big Bang theory
- The contents of the Universe
- The expansion properties of the Universe

Books:
- Cole & Lucchin: Cosmology — about the right level
- Peacock: Galaxy Formation — advanced
- Liddle: Cosmology — basic background

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http://star-www.dur.ac.uk/~csf/homepage/GalForm_lectures

The Big Bang Theory

What it is:
- Theory that the Universe as we know it began 10 – 15 billion years ago
- Initial state was a hot, dense, uniform sea of particles that filled space uniformly and was expanding

What it describes:
- How the universe expands and cools
- How the light chemical elements formed
- How matter congealed to form stars and galaxies

What it does not describe:
- What caused the expansion (expanding initial state assumed)
- Where did matter come from (energy assumed to be there from start)

Empirical evidence for the Big Bang

1. The expansion of the universe of galaxies
- Galaxies are receding from us with speed proportional to their distance
- Expansion is the same for all observers

2. The microwave background radiation
- Heat left over from Big Bang explosion
- Comes from everywhere in space (homogeneous and isotropic)
- It was emitted when the universe was 300000 years old

3. The abundance of the light elements
- BB theory predicts that 75% of mass is hydrogen, 24% is helium and 1% is the rest
- These are precisely the abundances observed in distant gas clouds!

(nc: elements heavier than H and He were produced billions of years later inside stars)
What is the Universe made of?

The content of our universe

![Diagram showing the composition of the universe]

**What is the universe made of?**

\[ \Omega = \frac{\rho}{\rho_{\text{crit}}} = \Omega_s + \Omega_b + \Omega_{\text{dm}} \]

- **Radiation (CMB, T=2.726±0.005 K)**: \( \Omega_b = 4.7 \times 10^{-5} \)
- **Massless neutrinos**: \( \Omega_{\nu} = 3 \times 10^{-5} \)
- **Baryons**: \( \Omega_b = 0.0023 \pm 0.0003 \)
- **Dark matter (cold dark matter)**: \( \Omega_{\text{dm}} \approx 0.26 \)
- **Dark energy (cosm. const. \( \Lambda \))**: \( \Omega_{\Lambda} \approx 0.7 \)

\[ \Omega_s + \Omega_b + \Omega_{\text{dm}} + \Omega_{\nu} + \Omega_{\Lambda} = 1 \]

Critical density: \( \Omega = 1 \) for a flat universe

**Galaxy rotation curves**

- Flat \( V_c \rightarrow M(<r) \propto r \)
- Dark halos around galaxy
Computer simulation of galaxy halo

Light rays are deflected by gravity (E=mc²)

Observer

Galaxy clusters (Gravitational lens)

Gravitational lensing

Light from distant galaxies is deflected by dark matter in cluster, distorting the galaxies’ images into arcs

The visible and dark sides of the universe

- There is ~5 times more dark matter than there is ordinary (baryonic) matter

(~90% of the mass of the Universe is dark matter)

- Most of the dark matter is NOT ordinary (baryonic) matter

- Weakly interacting massive particles (WIMPS)
Non-baryonic dark matter candidates

<table>
<thead>
<tr>
<th>Type</th>
<th>Candidate</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>hot</td>
<td>neutrino</td>
<td>a few eV</td>
</tr>
<tr>
<td>warm</td>
<td>sterile neutrino</td>
<td>keV-MeV</td>
</tr>
<tr>
<td>cold</td>
<td>axion neutralino</td>
<td>10^{-4} eV-100 GeV</td>
</tr>
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</table>

Looking for WIMPS

CERN
Geneva

The search for dark matter

Looking for dark matter ... down the mine (where cosmic rays can’t penetrate)
Looking for dark matter …
down the mine
(where cosmic rays can't penetrate)

Boulby mine
UK DM search

So, the Universe contains:

- Ordinary matter \((\Omega_b = 0.04)\)
- Dark matter \((\Omega_{dm} = 0.21)\)

Anything else?

Yes! Dark energy

Dark energy is a property of space itself.
It has the opposite effect to gravity

Evidence for \(\Lambda\) from high-z supernovae

SN type Ia (standard candles) at
\(z \approx 0.5\) are fainter than expected even if
the Universe were empty

The cosmic expansion must have been accelerating since the light was emitted

Friedmann equations

\[
\begin{align*}
\frac{d^2 a}{d \tau^2} &= \frac{8\pi G}{3} \rho_c \left(3w + 1\right) \Rightarrow 3w + 1 > 0 \Rightarrow \ddot{a} > 0 \Rightarrow \text{expansion accelerates} \\
\rho_{\text{tot}} &= \rho_{\text{mass}} + \rho_{\text{rel}} + \rho_{\text{vac}} \\
\rho_{\text{rel}} &= \frac{\rho_{\text{mass}}}{3c^2} + \frac{\rho_{\text{rel}}}{3c^2} + \rho_{\text{vac}} \\
\rho_{\text{vac}} &= \text{cosmological constant} \\
p &= \rho - \rho_{0} \Rightarrow p = \rho^w \Rightarrow \text{quintessence}
\end{align*}
\]
**Evolution of Cosmic Scale Factor in FRW Model**

\[ \rho = \rho_{\text{mass}} + \rho_{\text{rel}} + \rho_{\text{vac}} \]

\[ a^{-3} + a^{-4} \approx \text{const} \]

**Inflation**

- Initially, Universe is trapped in false vacuum
- Universe decays to true vacuum keeping \( \rho_{\text{vac}} \) constant
- Universe oscillates converting energy into particles
Friedmann equations

\[
\dot{a}^2 + k a^2 = \frac{8}{3} \rho G c^2
\]

If \( k = 0 \) and \( w = -1 \),

\[
\left( \frac{\dot{a}}{a} \right)^2 = \frac{8}{3} \rho G
\]

\[\Rightarrow a \propto t^{3/(8 \rho G)} \]

\[\Rightarrow \text{Universe expands exponentially}\]
The evolution of density fluctuations

If the universe expands rapidly, difficult for fluctuations to collapse
Or pressure forces dominate inside the perturbation.

How fluctuations evolve

Key time: epoch of matter/radiation equality

Radiation dominated: $\delta \sim \rho^2$
Matter dominated: $\delta \propto \rho$

Key concept: is the fluctuation inside the horizon?

Inside horizon scale: DAMPING

Evolution of a density perturbation (dark matter)

T_1: horizon has expanded to enclose fluctuation
T_2: epoch of matter-radiation equality
T_1<T_2 fluctuations in radiation density and expansion of universe

Evolution of a density perturbation (baryons)

T_1: horizon has expanded to enclose fluctuation
T_2: epoch of recombination, atoms form, photon pressure drops
The origin of cosmic structure

Quantum fluctuations:

\[ P(k) = A_k T^2(k,t) \]

Damping (nature of dark matter)

- Hot DM (eg. ~30 eV neutrino)
- Top-down formation
- Cold DM (eg. neutralino)
- Bottom-up (hierarchical)

Transfer function

The microwave background radiation

John Mather 2006 Nobel laureate
The cosmic microwave background radiation (CMB) provides a window to the universe at $t \approx 3 \times 10^5$ yrs.

In 1992 COBE discovered temperature fluctuations ($\delta T / T \approx 10^{-5}$) consistent with inflation predictions.

George Smoot - Nobel Prize 2006
The amplitude of the CMB ripples is exactly as predicted by inflationary cold dark matter theory.

The position of the first peak:
- FLAT UNIVERSE

Hinshaw et al. '06

The origin of cosmic structure:

1. FLAT GEOMETRY
2. QUANTUM FLUCTUATIONS

Cold dark matter

Structure $\sim 3x10^{13}$ Mpc

WMAP temp anisotropies in CMB

The WMAP survey observed the CMB and detected temperature fluctuations on various scales.

The amplitude of fluctuations is consistent with the predictions of inflationary cold dark matter theory.

Survey complete and catalogue released in July '03

A collaboration between (primarily) UK and Australia

250 nights at the AAT
The 2dF galaxy redshift survey

- 1997-2003: 250 nights at 500 IAT
- 221,000 redshifts to date

Evolution of spherical perturbations

Calculating the evolution of cosmic structure
### Non-baryonic dark matter candidates

- **Axions**
- **Neutrinos**
- **Neutralinos (SUSY)**
- **Primordial black holes**

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<tr>
<td>Neutrino (hot) DM</td>
<td>$30$ eV</td>
</tr>
<tr>
<td>Cold DM</td>
<td>$&gt;20$ GeV</td>
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#### Neutrino (hot) dark matter

- Free-streaming length is so large that superclusters form first and galaxies are too young.
- Neutrinos cannot make an appreciable contribution to $\Omega$ and $m_{\nu} < 30$ eV.

#### Cold dark matter

- In CDM structure forms hierarchically.
- Early CDM N-body simulations gave promising results.

- Davis, Efstathiou, Frenk & White 85
The Millennium simulation

Springel et al. Nature June/06

Helly & Frenk 06

Dependence of ΔT/T on cosmological params

Springel, Frenk & White
Nature, May '06

Institute for Computational Cosmology
University of Durham

1 Mpc

2dF survey
SDSS
CfA

Δ

T/T on cosmological params

Max Tegmark
CMB
Galaxies
Cosmological parameters from WMAP+2dFGRS
Spergel et al '03

Accelerated expansion

The cosmic power spectrum: from the CMB to the 2dFGRS

ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06

Conclusions
The origin of cosmic structure

1. FLAT geometry:
2. Small (quantum) ripples

Recent measurements of fluctuations in the temperature of the microwave background confirm this paradigm.
Open questions

• What is the dark matter?
• What is the dark energy?
• What happened in the first $10^{-35}$ s after the Big Bang?
• How, in detail, did stars and galaxies form?
• How much farther will the simulations go?

Tools:
• Satellites to study the CMB & distant galaxies
• Large telescopes
• Direct dark matter searches
• Particle accelerators (CERN)
• Supercomputer simulations

Ideas:
• Theoretical physics & mathematics

Our implausible Universe

If the Lord Almighty had consulted me before embarking upon creation, I would have recommended something simpler. At least, the Learned.

The paradigm of structure formation

$\Lambda$CDM

• Material content: Cold dark matter, baryons, $\Lambda$
• Initial conditions: From quantum fluctuations during inflation: $\delta^2 \propto k^2$; Gaussian ampl.
• Growth processes: Gravitational instability; gas (cooling, star formation, etc)
• Parameters: $\Omega_{\text{CDM}} = 0.26$, $\Omega_{\Lambda} = 0.74$, $h = 0.70$, $\Omega_{\text{baryons}} = 0.04$, $\Omega_{\text{dark matter}} = 0.7$, $\Omega_{\Lambda} = 0.9$

Galaxies form hierarchically
Conclusions: open questions

- Detection (or manufacture) dark matter
- The origin of the dark energy?
- The astrophysics of galaxy formation?

UK DM search (Boulby mine)

Open questions:
- Direct searches for CDM (Boulby, CDMS, G Sasso)
- Constraints on w (high-z SN, lensing, high-z clustering)
- Surveys of galaxies at high-z (VLT, SIRTF, ALMA, NGST)
- Supercomputers simulations
- New ideas on w

The future of cosmology