Overview

Problems

Inflation

Epochs

Distance ladder, expansion

CMB

Acoustic peaks

Dark matter

BICEP2
Overview

1. Overview
2. Some problems with a simple expanding universe
3. Inflation
4. Epochs
5. Distance ladder, expansion
6. CMB
7. Acoustic peaks
8. Dark matter
9. BICEP2

Credit many pictures: ESA, NASA, WMAP, Planck, Scientific American
Problems I: Flatness problem

- Rewrite Friedman-Lemaître equation as
  \[
  \frac{3H^2}{8\pi} = -\frac{3k^2}{8\pi R^2} + \rho \quad H = \frac{\dot{R}}{R}
  \]

- \( k = 0 \) or flat defines critical density \( \rho_c \equiv \frac{3H^2}{8\pi} \)

- measure all components of \( \rho \) in units of \( \rho_c \): \( \Omega_i = \frac{\rho_i}{\rho_c} \)

- Time evolution
  \[
  \frac{k}{R(t)^2} = H(t)^2 (\Omega(t) - 1)
  \]

  e.g. Matterdominated \( (\Omega(t) - 1) \propto kt^{2/3} \)

  \( \Omega \approx 1 \) does not stay there

  Flatness problem: close to 1 now, really close to 1 in early universe

  For cosmological constant dominated:
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Problems II

- We see the universe as the same from all directions
- Not all these spots have had time to talk to each other
- Homogeneity problem

- Many phase transitions possible
- Create defects: vortices (cosmic strings), domain walls, ... 
- All of these contain large amounts of energy
- None seen, so either no phase transitions or they have had time to align
- Monopole problem
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Problems III

- The early universe was very smooth
- Where does the observed structure come from?
- Much structure seen: galaxies, voids, sheets, the great wall,
- How are these formed?
- **Structure formation problem**
Inflation

- At some point very early in the universe we had a period dominated by $\Lambda$
- This is not the present $\Lambda$ or dark energy
- Blow up a small region that had fully homogeneized to enormous size
  - Solves homogeneity problem
  - Solves monopole problem (for earlier first order phase transitions)
- That bit also gets really flat
  - Solves flatness problem
- During the blowup: quantum fluctuations get very big, become real
- Possible seeds of structure
  - Can solve structure problem
Inflation solves the Horizon Problem
Epochs

- Matter $\rho_M \propto R^{-3}$, radiation $\rho_R \propto R^{-4}$
- In addition all momenta were bigger earlier since $\lambda \propto \frac{1}{p} \propto R(t)$
- Early universe dominated by radiation

- Present: Matter + cosmological constant (dark energy)
- $t \approx 300000$ years or $T \approx 1$ eV: decoupling/recombination
- Accident: becomes radiation dominated at about the same time
- $t \approx$ a few minutes or $T \approx 1$ MeV: Primordial nucleosynthesis (BBN)
- Much earlier $T \gg 100$ GeV: Inflation
Distance ladder

Main problem in cosmology: **Measuring distances**

**Distance ladder:**

- **Parallax:** triangulation
  - easy in principle
  - take base: Earth orbit
  - main problem: how accurate to measure the angles
  - Note old debate: if earth moves around sun, why don’t the stars move?
  - Now dominated by satellite: Hipparchos, Hubble, Gaia (to come)

- **Redshift distance:** simply take the redshift as a measure of distance

- **Luminosity distance**
Distance ladder

- Luminosity distance
  - Flux (in flat space) goes like $1/d^2$
  - Know Luminosity at source, measure luminosity at earth ⇒ know the distance
  - Small correction: if curvature take into account (example all the light emitted in a sphere surface from Southpole arrives at Northpole)

- Essentially start close by and then work further out
- Cepheid variables: period ⇒ Luminosity
- ...
- Supernovae Ia: Luminosity decay period ⇒ Luminosity
Three main satellites

- WMAP: up 2001-2010 Final data 2012
- Planck: up 2009-2013 Final data ???
  (3rd batch February 2015)

Also many ground based measurements, galaxy surveys,...
Perfect black body radiation
Perfect black body radiation

![FIRAS Residual Spectrum](image-url)
CMB: homogeneity/isotropy

This is data, not a uniform picture

Note: CMB discovered 1960s, Nobel Prize 1978 Penzias Wilson
CMB: homogeneity/isotropy

So \( v \approx 600 \text{ km/s} \)

Originally discovered in 1970s
CMB: homogeneity/isotropy

Nobel Prize 2006 Mather Smoot

$\Delta T = 18 \, \mu K$
CMB: homogeneity/isotropy
WMAP/Planck

- More frequencies (COBE 3, WMAP 5, Planck 9)
- Much better angular resolution
- Much better sensitivity
- Polarization
- Note: all-sky pictures have a fit of the foreground removed and a simulated spectrum across the galaxy
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BICEP2
Planck Nine months
Planck 2 years
Angular spectrum of fluctuations

Angular Scale

\[
\frac{\ell(\ell+1)C_\ell}{2\pi} \text{ [\mu K}^2]\]

Multipole moment \( \ell \)

TT

TE
Plot temperature or intensity as a function of $I(\theta, \phi)$

$$I(\theta, \phi) = \sum_{lm} C_{lm} Y_l^m(\theta, \phi)$$

- For each $l$ average the power over $m$: $C_l$
- So we have an angular measure and fluctuations
- Ground based ones add at high $l$
Planck Two years

Angular scale

Note: SEVEN peaks now visible
Can fit to nine peaks
The source of the fluctuations

- Small quantum fluctuations do exist
- Inflation blows them up so they cannot disappear again
- Expected power spectrum \( P_s = A_s \left( \frac{k}{k_0} \right)^{n_s} \)
- Tensor spectrum can come from primordial gravitational waves \( P_t = A_t \left( \frac{k}{k_0} \right)^{n_t} \)
- Inflation predicts \( n_s \approx 1 \) (scale invariant) and usually a little below 1.
- So then inflation stops, what now?
Growing and oscillating

- Very long wavelength: frozen in, no time to interact
- As soon as within horizon (i.e. time to interact)
  Fluctuations grow: denser spots grow denser, rarer spots
grow rarer (gravity is attractive)
- Then however: universe is dominated by radiation: we
  know the photon gas
- If too dense, pressure counteracts the compression by
  gravity, like sound waves (hence acoustic oscillations)
- Matter reacts much slower and in first hand only normal
  matter reacts with the photons
- So height first peak depends on photon density, we know
  that one, so get information on total matter and from the
different sizes first second peak also on baryonic matter
How big is the first peak

- We know the real size of the first peak plus the age, so the angle of view tells us flat, open (hyperbolical) or closed (spherical) from the shape of the triangles.
- If neutrinos had mass: streaming kills of those peaks so upper limit on neutrino mass.
- CMB fluctuations should hook on to those measured from galaxy distributions (surveys).
- Number of neutrinos: how many radiation species: affects rate of expansion also visible.
### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 - \Omega$</td>
<td>$-0.0008 \pm 0.0040$</td>
</tr>
<tr>
<td>$\Omega_\Lambda$</td>
<td>$0.6911 \pm 0.0062$</td>
</tr>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02230 \pm 0.00014$</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>$0.1188 \pm 0.0010$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$67.74 \pm 0.46 \text{ km/s/Mpc}$</td>
</tr>
<tr>
<td>$h$</td>
<td>$0.6774 \pm 0.0046$</td>
</tr>
<tr>
<td>Age</td>
<td>$13.799 \pm 0.021 \text{ Gyr}$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9667 \pm 0.0040$</td>
</tr>
<tr>
<td>$\sum_{\nu} m_{\nu}$</td>
<td>$&lt; 0.194 \text{ eV}$</td>
</tr>
<tr>
<td>$w$</td>
<td>$-1.006 \pm 0.045$</td>
</tr>
</tbody>
</table>

![Graph showing $H_0$ vs. $\Omega_\Lambda$ values from various experiments.](image-url)
Universe content (WMAP)

\[ \Omega_{\Lambda} \]
\[ \Omega_M \]

No Big Bang

Supernovae

CMB: Spergel et al. (2003)

Clusters: Allen et al. (2002)

expands forever

recollapses eventually

open

closed

flat

−1

0

1

2

3

Ω_{\Lambda}

Ω_M
Universe content (WMAP)

- Dark Energy: 72%
- Dark Matter: 23%
- Atoms: 4.6%

13.7 BILLION YEARS AGO (Universe 380,000 years old)
Dark matter

Galaxy rotation curves: flat???
Dark matter

- Globular clusters: also more matter needed than visible to bound them
- Seen in essentially all galaxies
- Clusters of galaxies
- Dark matter needed for galaxy formation
- Weigh galaxies by gravitational lensing: see directly dark matter
- Colliding galaxies: dust interacts strongly, starsless, dark matter even less
Dark matter

Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.
Gravitational waves

Big Bang

- Big Bang plus $10^{-33}$ seconds?
- Big Bang plus $10^{-43}$ seconds
- Big Bang plus 380,000 years
- Big Bang plus 14 billion years

Quantum-gravity era

Inflation

Cosmic microwave background

Gravitational waves

Light

Now

Copyright: Physics World IOP
BICEP2

Density Wave

E-Mode Polarization Pattern

Gravitational Wave

B-Mode Polarization Pattern

Credit: BICEP collaboration
BICEP2

Credit: BICEP collaboration
BICEP2

Credit: Wikipedia commons
BICEP2

Credit: BICEP collaboration
BICEP2 B–mode signal

Credit: BICEP collaboration
**BICEP2**

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