Galaxy Survey Cosmology

Introduction
Cosmology curriculum

- Cosmology I
  - FYS2081, period I
  - Bachelor’s (FYS)
  - Master’s (PAP)

- Cosmology II
  - PAP326, period II

- Galaxy Survey Cosmology
  - PAP341, period III-IV, 2019

- General Relativity
  - PAP335, period III-IV

- Cosmological Perturbation Theory
  - period III-IV, 2020?

- Galaxy Formation and Evolution
  - PAP 318, period I-II
Galaxy Survey Cosmology

- PAP341 Galaxy Survey Cosmology  14.1 – 2.5
  - Lecture notes
  - Homework problems
- Lecturer: Hannu Kurki-Suonio, C328 (office hour Mo 13-14)
  Assistant: Elina Keihänen, C329
- Lectures: Mo 10-12, Th 12-14, room A315
- Homework problem sets given out on Mondays
- Exercise session: Th 14-16, room A315
- The course is lectured in English (I take questions also in Finnish)
- No exam, grade 100% from homework
This is a new special course in cosmology, lectured now the second time; the first time was in spring 2017. While in the decades 2000-2020 the most important new cosmology data came from observations of the cosmic microwave background (CMB), especially by the WMAP (NASA) and Planck (ESA) satellites; the 2020s will be the decade of large galaxy surveys. These surveys include the ongoing ground-based surveys like KiDS (Kilo-Degree Survey) and DES (Dark Energy Survey), and the future LSST (Large Synoptic Survey Telescope); and the space-based surveys by the Euclid (ESA) and WFIRST (NASA) satellites.

The two main cosmological probes of these galaxy surveys are the distribution of galaxies and the distribution of all matter as measured by the gravitational lensing effect. The main statistical mathematical tools are correlation functions, both of galaxy positions and shear, i.e., the distortion of galaxy images due to (weak) lensing. These quantities can be used to constrain cosmological models. The main goal is to improve our understanding of what is commonly called Dark Energy, the cause of the acceleration of the expansion of universe; but a wealth of other astronomical and cosmological information is also obtained.

The course will cover the methods used in galaxy survey cosmology and what we already know about the Universe from them. The first part of the course is about the galaxy distribution and the second part about...
The course will cover the methods used in galaxy survey cosmology and what we already know about the Universe from them. The first part of the course is about the galaxy distribution and the second part about gravitational lensing. The course home page has now the lecture material from 2017 (the first time the course was lectured); but it will be updated with the latest results from KiDS and DES (and some parts of the course will be made lighter).

The lecturer and assistant are members of the Euclid Collaboration. There will be no exam; the grade will be based on homework. The course will be lectured in English, unless everyone speaks Finnish.

The first part of the course is partly based on Peacock, Chapter 16, and MBW, Chapter 6. The foundation of the field was laid by Peebles' 1980 textbook. The second part of the course, on gravitational lensing and especially on weak lensing surveys, will probably follow fairly directly Parts I and III of the Schneider et al 2006 book. Lecture notes will be provided and updated as the course progresses.

The course will be relatively mathematical in nature; we will use Fourier and spherical harmonic analysis, and special functions. Recommended background includes Cosmology I and II and Mathematical Methods of Physics (FYMM I and FYMM II).

MBW Sec. 2.7 gives a 4-page introduction to the field. I recommend reading it before the first lecture.

Lecture notes

I will update the lecture notes as the course progresses. Here is the current version for part 1: Galaxy Survey Cosmology, part 1, 11.1.2019 version

Handwritten lecture notes from 2017 for part 2:
Now and here (t = 14 Gyr)

Our past light cone

t = 0: primordial plasma

t = 380 000 yr: recombination, universe became transparent

CMB photons travel through the history and geometry of the universe

first galaxies, reionization
dark age
(no stars or galaxies)

the most distant galaxies observed

space

time
Sloan Digital Sky Survey
The CMB shows us the early universe at $t \approx 380\,000$ years.
Composition and fate of the universe

• Expansion of the universe appears to be accelerating
• This may eventually lead the universe to be very empty
• General relativity => energy component with negative pressure
• This is called “dark energy”:  $p = w \rho$,  $w < 0$ ($w = -1$ cosmological const.)
• Alternative explanation: modify general relativity (at very large scales)
Planck satellite

Launch 2009, observations 2009-13, final results 2018
Standard $\Lambda$CDM parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck 2018</th>
<th>+ other data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.02237±15</td>
<td>0.02242±14</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.1200±12</td>
<td>0.1193±9</td>
</tr>
<tr>
<td>$100\theta_*$</td>
<td>1.04110±31</td>
<td>1.04119±29</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.054±7</td>
<td>0.056±7</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9649±42</td>
<td>0.9665±38</td>
</tr>
<tr>
<td>$\ln(10^{10} A_s)$</td>
<td>3.044±14</td>
<td>3.047±14</td>
</tr>
</tbody>
</table>

(68% CL errors are for the least significant digits, $h = H_0$ in units of 100 km/s/Mpc)
Recipe for the universe

- Dark energy 68.5%
- Cold dark matter 26.7%
- Ordinary matter 4.8%
Limits to extended models

$\Lambda$CDM + one extra feature (parameter):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck 2018</th>
<th>+ other data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_K = 1 - \Omega$</td>
<td>-0.011±13</td>
<td>0.001±4</td>
</tr>
<tr>
<td>$\sum m_\nu$ [eV]</td>
<td>&lt; 0.241</td>
<td>&lt; 0.120</td>
</tr>
<tr>
<td>$N_{\text{eff}}$</td>
<td>2.89±0.38</td>
<td>2.99±0.34</td>
</tr>
<tr>
<td>$r = T/S$</td>
<td>&lt; 0.101</td>
<td>&lt; 0.065</td>
</tr>
<tr>
<td>$w = \text{DE } \rho/\rho$</td>
<td>-1.57±0.50</td>
<td>-1.04±0.10</td>
</tr>
<tr>
<td>nonG $f_{\text{NL}}$ (2015)</td>
<td>2.5±11.4</td>
<td></td>
</tr>
<tr>
<td>$\alpha_T$ (matter)</td>
<td>&lt; 1.3%</td>
<td></td>
</tr>
<tr>
<td>$\alpha_T$ (neutrinos)</td>
<td>&lt; 1.7%</td>
<td></td>
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</table>

(95% confidence limits)
Flatness of the universe

- Planck data agrees with a flat universe
- No sign of background curvature
- Deviation from critical density < 0.5%
- Curvature radius > 5.9 x distance to the horizon (from where CMB comes)

Smallest allowed closed (3-sphere) universe
Lensing of the CMB

\[ T(\hat{n}) = T^{\text{unl}}(\hat{n} + \nabla \phi(\hat{n})), \]
Lensing Potential $\approx$ Distribution of Dark Matter

Lighter color = more dark matter

Planck 2015
Summary

• We have a working cosmological model that agrees with observations:
  – The universe is flat ($\Omega = 1$)
  – Expands according to the laws of general relativity
  – Energy content:
    • $\approx 69\%$ dark energy (cosmological constant, vacuum energy)
    • $\approx 26\%$ cold dark matter
    • $\approx 5\%$ ordinary (“baryonic”) matter
    • $< 0.6 \%$ neutrinos
    • $0.005\%$ photons
  – Structure (galaxies, their clustering) formed by gravitational attraction starting from small primordial seed density variations,
  – which were created by some random process in the very early universe (consistent with quantum fluctuations during inflation)
• Primordial perturbations:
  – almost scale invariant ( \( n = 0.965 \pm 0.004 \) )
  – no gravitational waves observed so far ( \( r < 6.5\% \) )
  – no deviations from Gaussianity observed so far ( \( f_{NL} < 14(\approx 0.2\%) \) )
  – no deviations from adiabaticity observed so far ( \( \alpha_T < 1.7\% \) )
  – agrees with predictions from the simplest inflation models
    • but we would like to observe primordial gravitational waves

• Open questions:
  – Nature of dark energy ? (New ESA mission Euclid, launch 2022)
  – What is the cold dark matter particle ? (LHC)
Galaxy survey cosmology

• Current observational information on cosmology is dominated by the cosmic microwave background (z ~ 1000)
  – WMAP and Planck space missions
• Focus on the early universe
• Constraints on evolution from then to now are weak
• Attention now turning to large galaxy surveys
• Focus on the evolution during the last ¾ of the history
  – z ~ 2 to 0
Ground-based surveys

• Current
  – Sloan Digital Sky Survey (SDSS)
    • Baryon Oscillation Spectroscopic Survey (BOSS)
  – Kilo-Degree Survey (KiDS)
  – Dark Energy Survey (DES): 1st year results published

• Future
  – Large Synoptic Survey Telescope (LSST)
Space missions

- Euclid (ESA), launch 2022
- WFIRST (NASA), launch after 2025
Two-point correlation function $\xi$

- Measure of clustering of galaxies
- $\xi(r) = \text{excess probability of finding another galaxy a separation } r \text{ from a randomly chosen galaxy}$

Fig. 2.37. The two-point correlation function of galaxies in redshift space (left) and real space (right). The straight line is a power law, $\xi(r) = (r/r_0)^{-\gamma}$, with $r_0 = 5.05 h^{-1}\text{Mpc}$ and $\gamma = 1.67$. [Based on data published in Hawkins et al. (2003)] [MBW p. 83]
Redshift-space distortions (RSD)

- Distance to the galaxy determined from redshift
  - Affected by peculiar velocity
- Affects radial component of position
  - Transverse component (position on sky) not affected

Baryon Acoustic Oscillation scale

- Distance scale (~ 140 Mpc) imprinted on matter distribution in the early universe by oscillation of the baryon-photon fluid
- Prominent in the CMB anisotropy (z = 1090)
- Faint in galaxy distribution, can be measured at different redshifts z
- A standard ruler to measure expansion
Ross et al. arXiv:1607.03415
Two-parameter dark energy equation of state:  \[ p = [w_0 + w_a (a-a_0)] \rho \]

Dark energy vs modified gravity

• Both can give the same expansion history
• But they affect growth of structure (formation of galaxies and galaxy clusters) differently
• Expansion slows down formation of structure
• Modifying gravity has an additional effect
• Most of the structure is in the distribution of dark matter; galaxies provide only a crude measurement
• How to see dark matter structures?
  – Gravitational lensing
Gravitational lensing
Abell 2218: strong gravitational lens
All galaxies are lensed

- For most galaxies the effect is small (weak lensing)
  - Image stretched by a few %
- But large enough to be measured
- If we only knew the true shape of the galaxy!
- Statistical method
  - Fit an ellipse to each galaxy image
  - Assume galaxies oriented randomly
  - If galaxies in the same small region of sky appear elongated in the same direction on average; conclude this is due to lensing
Shear (lensing) field

Gravitational lensing maps dark matter

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>No lensing</td>
<td></td>
</tr>
<tr>
<td>Weak lensing</td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>Large-scale structure</td>
</tr>
<tr>
<td>Strong lensing</td>
<td>Substructure, outskirts of halos</td>
</tr>
<tr>
<td></td>
<td>Cluster and galaxy cores</td>
</tr>
</tbody>
</table>
Structure in dark matter
HST COSMOS survey of 2 square deg
THE END