Nanyang Technological University
Division of Physics and Applied Physics

Academic Year	2019/20	**Semester**	1
Course Coordinator	Dr. Tan Hai Siong		
Course Code	PH3403		
Course Title	Cosmology		
Pre-requisites	PH1107, PH2101, PH2103		
No of AUs	3 AU		
Contact Hours	2 hr – lecture; 1 hr – tutorial		
Proposal Date	3 March 2019		

Course Aims

This is a first course in cosmology which covers various fundamental aspects of standard cosmology and background tools to understand some active research topics in this area. The topics to be covered include inflation theory, structure formation, cosmic microwave background and gravitational waves. We will also discuss some aspects of geometry of the universe including the Robertson-Walker metrics and Friedmann equations. The course will conclude via touching on currently open problems in cosmology such as dark matter, dark energy and primordial gravitational waves.

Intended Learning Outcomes (ILO)

Upon the successful completion of this course, you (as a student) would be **able to**:

1. state and explain how the cosmological principle leads to the FRW metric.
2. derive the cosmological redshift factor by considering light rays traveling on an FRW metric
3. derive the luminosity distance's dependence on the cosmological redshift
4. distinguish between FRW line elements corresponding to different spatial curvature sections
5. use Hubble diagram to estimate the age of the universe
6. derive the luminosity distance as an expansion in redshift for low redshift.
7. use Friedmann equations to solve for the geometry of the universe assuming various forms of matter and energy content
8. compute the age of the universe as a function of cosmological parameters
9. recognize when a cosmological solution admits big bang and big crunch in its time evolution
10. differentiate between particle and cosmological event horizon
11. state the motivations for considering inflation as a possible era in the cosmic history
12. derive the mechanism for slow-roll inflation and solve for the time-evolution of the inflaton in simple scenarios
13. qualitatively relate between inflation and primordial gravitational waves
14. describe how cosmic microwave background radiation contains useful data relevant to our cosmic history
15. derive the gravitational wave equation on Minkowski and FRW backgrounds
16. state and explain the motivations for various candidates for dark matter

Some general comments
You will be equipped with a repertoire of basic quantitative skills necessary to understand important ideas in cosmology. You will understand how physicists have pieced together various events in the history of our universe and the process of structure formation. Through this course, you will also appreciate the multi-disciplinary nature of this subject.

Course Content

FRW geometry
Cosmological principle
Luminosity distance
Cosmological redshift
Cosmic expansion and big bang theory
Friedmann equations
Age of the universe
Cosmological parameters
Inflation
The horizon problem
Gravitational waves on various backgrounds
Dark matter
Gravitational lensing
Cosmic microwave background radiation

Assessment (includes both continuous and summative assessment)

Component	Course LO Tested	Related Programme LO or Graduate Attributes	Weighting	Team / Individual	Assessment Rubrics
1. Final Examination	All	Competence 1,2,3,4,5 Communication 1	40%	Individual	Point-based marking (not rubric-based)
2. Midterm I	Range 1-9	Competence 1,2,3,4,5 Communication 1	20%	Individual	Point-based marking (not rubric-based)
3. Midterm II	Range 10-15	Competence 1,2,3,4,5 Communication 1	20%	Individual	Point-based marking (not rubric-based)
4. Homework (5 problem sets)	All	Competence 1,2,3,4,5 Creativity 2 Communication 1	20%	Individual	Point-based marking (not rubric-based) Open-ended marking scheme[1]
Total			100%		

Formative feedback

Formative feedback is given through discussion within tutorial lessons, a discussion after the midterm, and an examiner's report for the final exam.

[1] There are homework questions in which you are expected to synthesize various concepts you encounter in the course to present solutions to modern problems in cosmology.

Learning and Teaching approach

Approach	**How does this approach support students in achieving the learning outcomes?**
Problem solving (tutorial and lecture)	Develop competence and perseverance in solving physics problems
Peer Instruction (during lecture)	Develop communication skills and competence in physics.
Lectures	Warm-up questions will be raised first, followed by lectures that further explain the physics based on the questions. Then wrap-up questions will also be provided.
Tutorial	You will review main concepts learned in lectures. This helps them to digest and understand better.
Homework	The homework comprises standard textbook practice questions that are covered during tutorial.

Reading and References

a. Kolb E.W. and Turner M.S., *The Early Universe*, Perseus 1994, ISBN: 0201626748

b. Linde A., *Particle Physics and Inflationary Cosmology*, Taylor and Francis, 1990, ISBN: 3718604906

c. Peebles P.J.E., *Principles of Physical Cosmology*, Princeton, 1993, ISBN: 0691019339

d. Peacock J.A., *Cosmological Physics*, Cambridge, 2015, ISBN: 0521422701

e. Ryden B.S., *An introduction to cosmology*, Addison-Wesley, 2003, ISBN: 0805389121

f. Dodelson S., *Modern Cosmology*, Academic Press, 2003, ISBN: 0122191412

g. Trodden M. and Carroll S.M., *TASI lectures: Introduction to Cosmology*, http://arxiv.org/abs/astro-ph/0401547, 2004.

h. Baumann D., *TASI lectures: On cosmology*, http://arxiv.org/abs/0907.5424, 2009.

Course Policies and Student Responsibilities

Absence Due to Medical or Other Reasons

If you are sick and unable to attend your class / Mid-terms, you have to:

1. Send an email to the instructor regarding the absence and request for a replacement class and make-up mid-terms.
2. Submit the original Medical Certificate* or official letter of excuse to administrator.
3. Attend the assigned replacement class (*subject to availability*) and make-up mid-terms.

* The medical certificate mentioned above should be issued in Singapore by a medical practitioner registered with the Singapore Medical Association.

Academic Integrity

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values.

As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Course Instructors

Instructor	Office Location	Phone	Email
Dr. Tan Hai Siong		+65 6316 2962	hs.tan@ntu.edu.sg

Planned Weekly Schedule

Week	Topic	Course LO	Readings/ Activities
1	Introduction and course overview Preview and motivations: introducing the general paradigm of cosmology, the cosmological principle, cosmic history and fate, the cosmic microwave background radiation, etc.	All	References and lecture notes, videos
2	Refining the notion of distance – the metric tensor The cosmological principle and the FRW metric	1, 4	References and lecture notes, videos
3	On the scale factor, cosmological redshift and luminosity distance Hubble diagram and Hubble's law from linearized relations	2, 3, 5, 6	References and lecture notes, videos
4	Prelude to Friedmann equations: introduction to tensor analysis	7	References and lecture notes, videos
5	On Friedmann equations, simple classes of solutions, and conservation laws in cosmology	7, 8, 9	References and lecture notes, videos
6	On the energy-matter distribution of the universe and computation of the age of the universe from cosmological parameters	7, 8, 9	References and lecture notes, videos Midterm Test 1

7	On dark matter: motivations from galaxy curves and gravitational lensing	7, 16	References and lecture notes, videos
8	Cosmic microwave background radiation – homogeneity and anisotropies	14	References and lecture notes, videos
9	Aspects of inflation I: slow-roll conditions, reheating, slow-roll potentials	10, 11, 12, 13	References and lecture notes, videos
10	Aspects of inflation II: horizon problem, initial conditions, primordial gravitational waves	10, 11, 12, 13, 14	References and lecture notes, videos
11	Gravitational waves I: Perturbation theory and gravitational waves propagating on Minkowski background	15	References and lecture notes, videos Midterm Test 2
12	Gravitational waves II: waves from binary star systems, recent LIGO observations, cosmological gravitational waves	15	References and lecture notes, videos
13	Conclusion and review of course content	All	References and lecture notes, videos

Graduate Attributes
What we want our graduates from Physics and Applied Physics to be able to do:

Upon the successful completion of the PHY, APHY and PHMA programs, graduates should be able to:

Competency	1	demonstrate a rigorous understanding of the core theories and principles of physics involving (but not limited to) areas such as classical mechanics, electromagnetism, thermal physics and quantum mechanics [PHMA only] demonstrate a rigorous understanding of the core theories and principles of mathematical sciences involving (but not limited to) areas such as analysis, algebra and statistical analysis
	2	read and understand undergraduate level physics content independently;
	3	make educated guesses / estimations of physical quantities in general;
	4	apply fundamental physics knowledge, logical reasoning, mathematical and computational skills to analyse, model and solve problems;
	5	develop theoretical descriptions of physical phenomena with an understanding of the underlying assumptions and limitations;
	6	critically evaluate and distinguish sources of scientific/non-scientific information and to recommend appropriate decisions and choices when needed;
	7	demonstrate the ability to design and conduct experiments in a Physics laboratory, to make measurements, analyse and interpret data to draw valid conclusions.

Creativity	1	propose valid approaches to tackle open-ended problems in unexplored domains;
	2	offer valid alternative perspectives/approaches to a given situation or problem.

Communication	1	describe physical phenomena with scientifically sound principles;
	2	communicate (in writing and speaking) scientific and non-scientific ideas effectively to professional scientists and to the general public;
	3	communicate effectively with team members when working in a group.

Character	1	uphold absolute integrity when conducting scientific experiments, reporting and using the scientific results;
	2	readily pick up new skills, particularly technology related ones, to tackle new problems;
	3	contribute as a valued team member when working in a group.

Civic Mindedness	1	put together the skills and knowledge into their work in an effective, responsible and ethical manner for the benefits of society.