Fall 2019 UNIVERSITY OF MARYLAND, College Park

Physics 675/475 **Introduction to Relativity, Gravitation and Cosmology** Prof. B. L. Hu

Description: This is an introductory course on the basic principles of general relativity theory and quantitative description of the nature and dynamics of spacetime and matter. We shall introduce ideas and develop techniques toward the establishment and understanding of the Einstein equations, then explore their applications to gravitational waves, black holes, cosmology, with a glimpse of the early universe. Topics covered are described in the Contents (below). A Schedule will be provided as we move along.
Note: Advanced topics in gravitational physics are covered in Physics 776 and 879
Prerequisites: A good grade in classical mechanics and mathematical physics courses. Some knowledge of differential geometry would be helpful but not required. We will introduce the basic tools and concepts.

Lectures: Mon Wed 1:00pm - 2:15pm in PSC 3150, Discussion Sessions: Fridays 1-1:50pm in PSC 3150
Note attendance of both lectures and discussions are obligatory. *Tests are held in the Discussion sessions.*
Lecturer: Prof. B. L. Hu, Office: PSC3153, Phone: (301) 405-6029 -- you will get faster response via email blhu@umd.edu. Any important document you wish to give to me please do not hang it on or slip it under my door – it may get lost. Please leave it with our Faculty Assistant **Melanie Knouse** in PSC 3140 Phone (301) 405-6016 mknouse@umd.edu. Late homework upon my approval should be sent to your TA directly.
Office hours: MW 2:15 -3:15 pm (except for certain seminars on certain dates which I feel obliged to attend). Please email me ahead of time if/when you wish to come, to make sure I'll be there to receive you.
TA: **Yixu Wang**, Phone: (301)458 9889, (301)405 6149 Email: wangyixu@terpmail.umd.edu Office: PSC 3264 Office hours: Tu Th 2-3pm

Textbooks: "Required"
Bernard F. **Schutz**, *A First Course in General Relativity*, 2nd edition (Cambridge, 2009) - QC173.55 ISBN 0 521 27703 5 **ISBN-13:** 978-0521887052
http://202.38.64.11/~jmy/documents/ebooks/Schutz%20A%20First%20Course%20in%20General%20Relativity%28Second%20Edition%29.pdf– many beginning students find this book easier to read than Hartle's. It can be perceived as its strength (more pedagogical) or weakness (detailed derivations) depending on your taste and need. It is labeled as `required' largely because homework problems will be assigned from there.
"Recommended":
James B. **Hartle**, *Gravity, An Introduction to Einstein's General Relativity* (Addison-Wesley, Pearson, San Francisco 2003). QC173.6H38 2003 ISBN 0-8053-8662-9 A little more "professional", lesser derivations. Both books' materials are based on undergraduate courses the authors had taught for years.

Additional textbooks and monographs -- We divide them into Track 1 and 2:

Track 1 is at an elementary (Senior-1st year graduate) level and **Track 2** is at an intermediate (2nd – 3rd year graduate) level. Traditionally 675 is taught at a level in-between, to fulfill the dual needs of students seeking some general knowledge of general relativity and prepare those who wish to specialize in gravity research. The latter will find Phys 776 covering important topics useful for that purpose. For special themes, e.g., research in *gravitational wave* or *quantum gravity* research, you may find PHYS 879 useful.

TRACK 1: (suitable for undergraduate physics major students)

I highly recommend these two books to UG students -- read them for fun. They reflect on Wheeler's special interest and ability in making sophisticated topics accessible to an uninitiated yet inquisitive mind:
E. F. **Taylor** and J. A. **Wheeler**, *Spacetime Physics: Introduction to Special Relativity* (Freeman, New York, 1992) QC17.65T37 ISBN 0 7167 2327 1 Fun to read (for freshman/sophomore)
E. F. **Taylor** and J. A. **Wheeler**, *Exploring Black Holes: Introduction to General Relativity* (Freeman, New York, 2002) Fun to read (for junior/senior)

TRACK 2:
C. W. **Misner.** K. S. **Thorne** and John A. **Wheeler**, (MTW) *Gravitation* (Freeman, San Francisco. 1973) QC178.M57 ISBN 0 7167 0344 0
- Often regarded as The BOOK for gravitation theory. It has both Track 1 and Track 2 materials.

S. **Weinberg**, *Gravitation and Cosmology* (Wiley, New York, 1972) QC6.W47 ISBN 0 471 92567 5
- An authoritative monograph, taking a field theorist/ particle physicist's approach. Special is its Chapter 13. Of historical importance is Chapter 15 which brought up generations of theoretical cosmologists.

Sean **Carroll**, *Spacetime and Geometry: An Introduction to General Relativity* (Pearson 2003)
ASIN**:** B01NH01PDS - A lucid, more tightly knit rendition of MTW.

Robert M. **Wald**, *General Relativity* (Chicago, 1984) QC173.6.W35 ISBN 0 226 87033 2
- Advanced monograph. Elegant treatment, more suitable for the mathematically minded.

Other useful books: (will expand this list as we cover more advanced topics):

Alan P. **Lightman** et al, *Problem Book in Relativity and Gravitation* (Princeton University Press, 1973)
QC173.55P76 ISBN 0 681 08162-X
-This book is useful for assisting you to work out problems (but don't copy from it for your homework!).

A **Liddle**, *An Introduction To Modern Cosmology*, Second Edition (Wiley 2003)

M. **Roos**, *Introduction To Cosmology*, Third Edition (Wiley 2003)
- The above two introductory books are suitable for UG students.

M. **Maggiore**, *Gravitational Waves*: Volume 1: Theory and Experiments (Oxford University Press, 2008),
Volume 2: Astrophysics and Cosmology (Oxford University Press, 2018)

P. J. E. **Peebles,** *Principles of Physical Cosmology* (Princeton, 1993)
QB981.P424 ISBN 0 691 01933 9 Intermediate
- I will recommend books on black holes and the early universe as we move closer to these subjects.

<u>Lectures</u> will be given at a level like Hartle, Schutz or Track 1 of MTW.
<u>Note:</u> my lectures do not adhere to any one book in its ordering of topics or emphasis, but are self-contained with their own logical consistency. The best way is to follow closely the lectures and consult the corresponding topics discussed in any one of these books which best suit your understanding.

<u>Course webpage</u>: Please check for new announcements, adjustment of topics or due dates in the course website at ELMS/CANVAS system: www.elms.umd.edu/page/student-support where you will also be able to access your exam grades. For questions call the Help Desk at 301.405.1500 or email elms@umd.edu.

Homework Assignments: Developing problem solving skills, both conceptual and technical, is the goal of many academic endeavors. Before you reach the PhD stage, you are usually given a problem and asked to find a solution. You may find out that one particular approach in reaching a solution may be better than the others. Regardless, when you get the right answer, the task is considered well done. For PhD research you are usually given a chain of problems or one bigger problem to solve, or you may not be given a problem at all. You have to formulate a meaningful problem, then solve it. When you become a professor the challenge shifts more to asking good questions which can address the important key issues in your field and seeking solutions to help make advances. Why am I saying all this, you may wonder? This is just to impress upon you that your wrestling with a problem and trying to find a solution on your own, elegantly and thoroughly, is absolutely necessary to gain **knowledge of,** and imperative to **mastering, a subject**.

The **search for information**, specifically finding the solutions to a problem, has become so much easier in the internet age. Comes with it is the temptation to consult, if not simply copying, the solutions, and hand in as your own work. There are two concerns: One, this is considered as *plagiarism*, with academic consequences. Two, without yourself thinking the problem through, the material will remain as external information, not **internalized knowledge**. Doing so will invariably lead to poor exam performances.

There will be <u>7 homework assignments</u>. A list of homework problems will be posted on the course website every 1-2 weeks. Homework handed in will be looked at by your TA, and a score of up to 20 points per HW will be assigned. *The best 2 sets of HW scores can be used to replace the worst 2 Test scores.* While you can choose to hand in your homework or not to, **everyone should take the 5 tests and the 2 exams.** If you do well in the HW you will be better prepared for the Tests and the Exams. [**A friendly advice:** if you think you can beef up your HW grade by copying or consulting the solutions, Don't! You will be wasting your TA's time reading it, and create a bad impression of yourself. Your time will be better spent working the problems out on your own, getting better grades in your tests and exams.]

Always do the homework in all seriousness! -- whether you wish to hand it in or not. Try out extras from these textbooks plus those in Lightman et al's *Problem Book*. Attend the Friday problem discussion sessions: you can contribute to the collective wisdom in problem solving.

I suggest the following **weekly routine:**

a) **attend the lectures** (you may get lost quickly if not attending classes consistently) b) **study the textbook**(s) c) **work on the assigned homework**, by yourself, one problem after another in a continuous manner, in parallel to the lectures. d) if you find the class materials hard to understand or the problems difficult to solve, **after** you have made some serious attempts, **consult me** for conceptual & technical issues, and **the TA** for problem solving specifics. e) Attend regularly the **problem discussion sessions**.

Friday Discussion sessions conducted by the TA are devoted to problem solving. You are encouraged to raise questions of how to, why so, what for, and share your thoughts with your fellow students. A score of A B or C for discussion participation will be recorded by the TA, and considered in borderline grades.

Tests: There will be 5 tests given in the **Discussion Sessions**, on a problem related to the assigned homework or from the lectures. Tests are meant to help you gauge your understanding of the materials taught and learned. They are **open book tests** – you can bring one book of your choice. Each test will last 20min. The dates of the 5 tests are tentatively set on: **Sept 20, Oct. 4, Oct 18, Nov 8, Nov 22.** Please make sure you can come to all of these tests, since *there will not be make-up tests or make-up exams given*.

Exams: Two 75-minute **closed book exams** are planned, to be held in class. Please mark down on your calendar: Exam 1 will be on **Wed October 30**, covering materials up to the end of the lecture a week before. Exam 2 will be on **Monday December 9**, covering the material since Exam 1 (There will be no exam given on the official final exam date of this course.) Please make all necessary preparations and arrangements to ensure you can take these exams because **no make-up exam will be given**. **Each exam counts 100 points (**out of a total of 300 points) **in your course score**. These are closed book exams, but you are allowed to bring one 8x11 formula sheet – only formulas, sketches of solutions to problems are forbidden -- to each exam. Please turn it in with your exam paper.

Academic dishonesty is a serious violation and will be dealt with strictly according to University policy.

Your course grade will be determined according to your total course score: Test score 100 points max (with adjustment from HW score) plus 2 Exams, each counting 100 points max = total 300 points max.

A Request**:** Because this course serves both graduate and undergraduates I ask that graduate students be a bit tolerant, especially at the beginning, for the extra time it may take for Q&A in class. Toward the end of the course, I ask the UGs in this course to be more understanding if the material gets more challenging. I would be happy to explain to you in more details after class. Since many of you may be taking this course for enrichment or cultural purposes, I'd be happy to discuss with you any topic you find exciting or interesting in gravitation physics or in relation to other fields.

Course Contents:
A logbook of *Topics covered in the Lectures* will be posted on the course website about every 3 weeks.

1. Special Relativity Review: Spacetime approach, 4 vectors, Relativistic dynamics: use of invariants. Introduction to General Relativity: Gravitational redshift; Principle of Equivalence; Matter and spacetime curvature.
2. Curved Spacetime: Principle of Covariance, coordinate transformations; Tensor Analysis, geometry of curved space. Cartan calculus: Differential, Affine and Riemann geometry. Connection and geodesic equations. Particle motion. Curvature and geodesic deviation equation.
3. Einstein's Equation: Vacuum solutions; Relativistic matter; Dynamics of spacetime and matter.
4. Linearized Theory: Gravitational radiation; Einstein's equation for weak fields; Generation, propagation and detection of gravitational waves; Conservation of energy momentum and angular momentum

5. Relativistic Astrophysics: Spherically symmetric spacetimes; Schwarzschild metric; Trajectories around a compact object. How does a black hole look like?
6. Relativistic Cosmology: Cosmological principles; Standard Model: Robertson-Walker metrics, Friedmann-Lemaitre solutions; De Sitter spacetime and inflationary cosmology; The early universe: Bianchi and Kaluza-Klein cosmology. Quantum effects.