Fall 2020 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. **Discussion Sessions** (held by TA): Fridays 1-1:50pm.
This Friday tutorial hour is added to help students in 475 who may need some catch up, and supplementary topics for the enrichment of students in 675. Please plan on attending all lectures and discussions.
Lecturer: Prof. B. L. Hu, Office: PSC3153, Phone: (301) 405-6029 [not in use during pandemic] -- you will get faster response via email blhu@umd.edu. I'll hold discussions with you via skype. ***See note on p.4***
Faculty Assistant **Melanie Knouse** in PSC 3140 Phone (301) 405-6016 mknouse@umd.edu.
Office hours: I plan to use ~ 2-2:15 MW in class to entertain any questions you may have. At other times, for questions related to the lectures and conceptual issues, please email me for an appointment. For problems related to homework you can ask them in the Friday discussion sessions or the TA's office hours.
TA: Das, Saurav Office: 0104 Toll Bldg. Phone: x58577 (cell) 240-758-4917 sauutsab@terpmail.umd.edu, Office hours: flexible by appointment for Skype or Zoom discussions.

Textbooks: "Required" -- largely because homework problems will be assigned therefrom.
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(Second%20Edition).pdf – many beginning students find this book easier to read than Hartle's. It can be perceived as its strength (more readable, user-friendly) or weakness (too much emphasis in derivations) depending on your taste and need.
"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 both 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.

Lectures will be given at a level of Hartle, Schutz or Track 1 of MTW.
Note: 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.

Course webpage: 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: There will be 7 homework assignments. A list of homework problems will be posted on the course website every 1-2 weeks. Homework should be submitted on time to ELMS. Late HW please get my permission with a good reason.

Each HW has a full score of 25 points. *Your lowest scored set will be dropped.* 6 HWs add to 150 points max. [Details in assigning scores: Each set has 5 problems. I shall select two problems to be graded in detail, each worth 8 points. The remaining 3 problems will be looked at and assigned 1-3 points depending on whether you have got it right (3), used the correct strategy (2) or made an effort (1).]

Always do the homework in all seriousness! If you feel like working out some more, by all means. Try those from the two textbooks, select some from Lightman et al's *Problem Book*.

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**.

Please note: 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. I suggest the following **weekly routine:**

a) **Study the lecture notes before** attending the lectures (you may get lost quickly if not attending classes consistently) accompanied by the corresponding material from **the textbook**(s) b) Review the lectures and the textbook materials c) **work on the assigned homework**, one problem after another in a continuous manner, in parallel to the lectures. d) Attend regularly the Friday **discussion sessions**. e) if you find some of 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.

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 participation will be recorded by the TA. It may make a difference in borderline grades.

<u>Exams</u>: Two 75-minute **closed book exams** are planned, to be <u>held in class</u>. <u>Please mark down on your calendar</u>: Exam 1 will be on **Wed October 28**, covering materials up to the end of the lecture a week before. Exam 2 will be on **Monday December 14**, 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 150 points in your course score**. These are closed book exams, but you are allowed to bring one 8x11 formula sheet to each exam – formulas only, sketches of solutions to problems are forbidden. 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: Homework 150 points max plus 2 Exams, each counting 150 points max = total 450 points max.

<u>A Request</u>**:** 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 and the Homework assignments* will be posted on the course website about every 2-3 weeks.
1. <u>Special Relativity</u> Review: Spacetime approach, 4 vectors, Relativistic dynamics: use of invariants. Introduction to <u>General Relativity</u>: Gravitational redshift; Principle of Equivalence; Matter and spacetime curvature.
2. <u>Curved Spacetime</u>: 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. <u>Einstein's Equation</u>: Vacuum solutions; Relativistic matter; Dynamics of spacetime and matter.
4. <u>Linearized Theory</u>: Gravitational radiation; Einstein's equation for weak fields; Generation, propagation and detection of gravitational waves; Conservation of energy momentum and angular momentum
5. <u>Relativistic Astrophysics</u>: Spherically symmetric spacetimes; Schwarzschild metric; Trajectories around a compact object. How does a black hole look like?
6. <u>Relativistic Cosmology</u>: 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.

Special note for online instruction:

Some of you may have experienced online instruction in the last two months of the spring semester. It is surely very different from traditional learning –e.g., we cannot gather around the blackboard and work on the equations or argue points out, which are the valuable parts of in-person teaching/learning. These are obvious drawbacks but we can compensate for some of this. There are also small advantages, e.g., the lectures will be recorded and you can watch them anytime, for as many times as you wish. Because of these changes I'd like to call your attention to <u>a few practices important for online learning</u>:

1) Keep the habit of **attending classes at the scheduled times** albeit via Zoom. In principle you can watch the recorded lectures at any time of convenience, but you'll lose out on the active participatory parts which are of special value. The routine provided by the class schedules is useful for you to keep pace with the procession of the course materials-- lectures, readings, homework -- in an orderly manner. Reviewing the recorded lectures after classes is good, but try not to lag behind by more than one week. Not attending classes but relying on studying the recorded lectures on your own could lead to disorganization quickly. It is not easy to catch up on your own in a course like this, where the subject matter is not so familiar or easy.

2) The lecture notes for the two classes will be posted in the week before. Please **study the lecture notes carefully before the lectures**. <u>Better yet, read the corresponding parts in the textbooks.</u> In this way when we go over the derivations you can stop me wherever it is not clear to you. I will try to respond to your individual requests, even minute details, or repeat the parts which you find unclear. I may allot the last 10-15min of each lecture for the continuation of questions and/or discussions, kind of like a group office hour. This exchange-enabled interruption-permitted mode makes it livelier than just yourself watching passively a video-lecture, as in most of the online courses. I need you to study the lecture notes beforehand so there will be meaningful questions and discussions. In this way we can avoid excessive back and forth and still have enough time to cover the planned rather heavily loaded course materials.

3) Please bear with any inconvenience in this new mode of teaching and learning. We are still exploring ways to get better results. We value your feedback and will make necessary adjustments to improve.

Welcome to a New Semester and Happy Learning!

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Lecture 1 & 2*:* ***Review of Special Relativity*** *with emphasis which eases us into General Relativity*

Aug 31 *1. Relativistic Kinematics: Spacetime Interval, Spacetime diagram: preparing for* ***Geometry***

Sept 2 2. Relativistic Dynamics: Spacetime Invariants, 4 vectors: preparing for ***Tensor Analysis***