PHYS 598: Special Topics on General Relativity – Compact Binaries
Fall 2021

Class Time and Location: **T-Th 1230-1350 pm, Loomis 158**

Course website: https://courses.physics.illinois.edu/598

List of pre-requisite courses: PHY 515 (GR1) or equivalent.

Professor: Nico Yunes (Loomis 249), nyunes[at]illinois.edu.

Teaching Assistant 1: Yiqi Xie (Loomis 257), yiqixie2[at]illinois.edu.

Teaching Assistant 2: Alexander Deich (Loomis 257), adeich2[at]illinois.edu.

Professor's Office Hours: Infinite by appointment. Nico's Office (Loomis 249). If you can't find me, *email me*.

TA's Office Hours: By Appointment. Loomis 249. If you can't find them, *email them*.

What is this class about? This course will cover advanced topics in Einstein's theory of General Relativity, focusing on the dynamics of compact binaries. Emphasis will be put on widely separated binaries of comparable mass ratio, where the post-Newtonian approximation is valid. The topics discussed will include a subset of the following: orbital dynamics of binary systems, three-body interactions and the Kozai-Lidov mechanism, the radiation-reaction force, gravitational waves emitted during inspiral. This class is a very mathematically intensive, because it has to be to achieve its goals, and it will use technical language, as defined in GR I (see e.g. Carrol's textbook), which is heavily employed in the gravity and astrophysics scientific literature.

What is this class not? In short, this is not an easy class, because it has to be of a certain difficulty to achieve its main goal: to teach you all of the advanced tools you will need to make breakthroughs in your research. Therefore, this class is not a core course, or a superficial survey of advanced topics. Although the class is not easy, it is also not beyond the ability of intermediate or advanced graduate students, provided you devote the time required to do the work needed to learn the tools you will need to succeed.

Who should take this class? This course is intended for all intermediate or advanced graduate students with an interest in gravity, astrophysics, high energy physics or string theory. As such, it is assumed students have prior knowledge of Einstein's theory of *special* relativity, Newtonian gravitation and classical mechanics, Maxwell's theory of electrodynamics and advanced mathematics, including differential equations, advanced Calculus and advanced linear algebra, as well as knowledge of the basics of *general* relativity. The purpose of the class is to prepare students for research in (analytical or numerical) general relativity, relativistic astrophysics, gravitational waves, and cosmology, as well as black hole-related topics in high-energy physics and string theory. Other students with broader interests are welcomed to take this class, but they should be advised that there are other (perhaps less intensive) courses they can take to fulfill their elective requirements.

What is expected of students who take this class? Students are expected to attend class, complete all homework assignments and complete a final exam (see breakdown of topics below). In addition, students are expected to be mature enough to independently do some amount of self-learning outside of class, including reading the assigned book on their own (see below), reading papers mentioned in class, and doing homework discussed in the book but not explicitly solved in lecture (including optional assignments if depth is sought). Since this is a graduate course, readings will not be assigned weekly, but rather, students are expected to find the topics in the course's textbook that are being covered in class and read about them; in addition to the required class textbook, there are also other (recommended) textbooks that students can and should refer to if and when needed. Students will be required to do a very high amount of homework (much more than in their regular core classes), with assignments starting easy and light, but with the difficulty and the amount of homework increasing with the flow of class. Therefore, please expect the initial homework load to seem "easy," but rest assured that the more complicated homework that will really hone your research skills will come. Questions are always welcomed, either in class, or outside of class during office hours.

Textbooks:

- Required:

  - Gravity: Newtonian, Post-Newtonian, Relativistic (Cambridge U. Press, 2014) by Poisson and Will.
- Recommended:
  - Gravitational Waves (Oxford Press, 2008) by Maggiore
  - General Relativity, 1st Edition (University of Chicago Press, 1984) by Wald.
  - An Introduction to General Relativity, Spacetime and Geometry (Pearson Press) by Carroll.
  - Gravitation, 1st Edition (W. H. Freeman, 1973) by Misner Thorne and Wheeler.

Topics: (Approximately 29 Lectures of 75 minutes each)

- *Newtonian Orbital Mechanics*
  - Newtonian Gravity (PW 1) – Super-fast Review
    - Foundations (PW 1.1, 1.2, 1.3)
    - Hydrodynamics (PW 1.4)
    - Spherical Bodies (PW 1.5)
    - Motion (PW 1.6)
  - Newtonian Dynamics (PW 3)
    - The 2-Body Problem (PW 3.1, 3.2)
    - The Perturbed Kepler Problem (PW 3.3)
    - Osculating Orbits (PW 3.3, 3.4)
    - Examples: Restricted 3-body, Kozai, oblateness, tides (PW 3.4)
- *Relativistic Orbital Mechanics*
  - Toward Relativity (PW 4 and 5)
    - Linearized Theory and Irreps (PW 5.5)
    - Perihelion Precession of Mercury (PW 5.6)
    - Relativistic Fluid Dynamics and ToV (PW 5.6)
  - Post-Minkowskian Theory and Implementation (PW 6 and 7)
    - Landau-Lifshitz Formulation (PW 6.1)
    - Direct Integration of the Relaxed Einstein Equations (PW 6.2)
    - Near Zone Metric (PW 7.3)
    - Far Zone Metric (PW 7.4)
- *Relativistic Dynamics and Gravitational Waves*
  - Post-Newtonian Theory and Implementation (PW 8, 9 and 10)
    - Post-Newtonian Fundamentals (PW 8)
    - Isolated Bodies (PW 9)
    - Equations of Motion (PW 9)
    - Compact Objects (PW 9)
    - Regularization (PW 9)
    - Applications: Binary Pulsars (PW 10)
  - Gravitational Waves (PW 11)
    - Review
    - Quadrupole Formula
    - Applications: Binary Systems
    - Applications: Mountains on Neutron Stars
    - Beyond Newtonian Waves: Tails and Memory.
  - Radiation Reaction (PW 12)
    - Short Wave Approximation
    - Fluxes
    - Radiation-Reaction Force

    - Orbital Evolution

- **Final Exam [Very Non-Trivial Take Home. Be Prepared!!!]**

No Class On: November 11th (Midwest Relativity Meeting), November 16th and 18th (Berkeley talk).

Office Hours/Presentation Hours. Every week and for two hours, we will meet in a room (TBD) in which one student in the class will present the results of 1 hw problem (for the set due the previous week). The TAs will evaluate the presentation and the solution, and then there will be opportunity to ask questions. Attendance is not optional.

Credit Points: Everyone starts with 0 credit points (CPs). You gain CPs by doing homework, doing the final exam and participating in class (asking or answering questions). There will be 12–14 homework sets and in total they will be worth $\sim 70\%$ of your grade. There will be one final exam, worth $\sim 20\%$ of your grade. The remaining $\sim 10\%$ of your final grade can be earned by doing a good job during the presentations (as judged by the TAs), by asking and answering questions *in class*.

Grade Scale: Your overall grade is correlated with your overall CP, as given by the following ranking table:

- Wizard
    - ★ $>$ 970 CPs correlates with an A+.
    - ★ $>$ 930 CPs and $<$ 970 CPs correlates with an A.
    - ★ $>$ 890 CPs and $<$ 930 CPs correlates with an A-.
- Sorcerer
    - ★ $>$ 850 CPs and $<$ 890 CPs correlates with an B+.
    - ★ $>$ 810 CPs and $<$ 850 CPs correlates with an B.
    - ★ $>$ 770 CPs and $<$ 810 CPs correlates with an B-.
- Mage
    - ★ $>$ 730 CPs and $<$ 770 CPs correlates with an C+.
    - ★ $>$ 690 CPs and $<$ 730 CPs correlates with an C.
    - ★ $>$ 650 CPs and $<$ 690 CPs correlates with an C-.
- Enchanter
    - ★ $>$ 600 CPs and $<$ 690 CPs correlates with an D+.
    - ★ $>$ 550 CPs and $<$ 6000 CPs correlates with an D.
    - ★ $>$ 500 CPs and $<$ 550 CPs correlates with an D-.
- N/A
    - ★ $<$ 500CPs correlates with an F.

Homework: New homework sheets will be uploaded on Tuesdays before class and they will be typically due to be handed in online on the Tuesday in the week thereafter until 11:59pm CST. Small modifications of the due deadline may occur if a particular homework set is too difficult or lengthy to be completed in 1 week. The due date of the homework will be announced in class. Late homework will not be accepted. In general, you are allowed to use computer algebra software, like Maple or Mathematica, unless stated otherwise. If you do use computer algebra software, you must then hand in a well-formatted print out of your code.

Optional Homework: Some homework problems may be labeled "optional." This means that the homework will not be graded and it will not count toward your final grade. However, we include this homework for the more ambitious student that wishes to have a more solid foundation on general relativity.

Exams: The final exam will be both open-book and take-home. The exam will be due in class, 2-5 days after being given out. The only book you are allowed to use during exams is the required textbook for the course.

Do's and Don'ts:

- Do sit as close as possible to the blackboard. My handwriting is not the best.
- Do come to class prepared to take notes. Lectures draw from material outside the class' textbook.
- Do put your cell phone on vibrate and, if it rings and you have to answer, do so outside.
- Do ask questions and feel free to interrupt or point out typos on the board or in the book.
- Do work in groups if you want to, but Do Not copy from a classmate; that's cheating.
- Do not bring a newspaper, magazine, iPod, iPad, or other pads or other sources of entertainment to class.
- If you need to use the bathroom, do so *before* or *after* class. Leaving the classroom while a lecture is going on disrupts the flow of the class' chi.

CoVid-19-Specific Recommendations by the University

Following University policy, all students are required to engage in appropriate behavior to protect the health and safety of the community, including wearing a facial covering properly, maintaining social distance (at least 6 feet from others at all times), disinfecting the immediate seating area, and using hand sanitizer. Students are also required to follow the campus COVID-19 testing protocol.

Students who feel ill must not come to class. In addition, students who test positive for COVID-19 or have had an exposure that requires testing and/or quarantine must not attend class. The University will provide information to the instructor, in a manner that complies with privacy laws, about students in these latter categories. These students are judged to have excused absences for the class period and should contact the instructor via email about making up the work.

Students who fail to abide by these rules will first be asked to comply; if they refuse, they will be required to leave the classroom immediately. If a student is asked to leave the classroom, the non-compliant student will be judged to have an unexcused absence and reported to the Office for Student Conflict Resolution for disciplinary action. Cumulation of non-compliance complaints against a student may result in dismissal from the University. If said student refuses to leave the classroom, then I will be forced to dismiss the class and report the student to the Office for Student Conflict Resolution for disciplinary action.

CoVid-19-Specific Modifications to our Course Structure

- **Do we have to come to class?** Ideally, if possible, yes. Class will be in-person but socially-distanced, while this remains safe at UIUC. What this means is the following:
  - Only a certain number of seats will be available for you to occupy in the classroom, because they have been designated to be 6 feet apart from each other. Please occupy the allowed seats only.
  - Feel free to clean your desk before you sit down at it at the beginning of class, and after class is over. There will be cleaning wipes available throughout the building, or you can bring your own.
  - **Always wear a mask inside the building and in the classroom**. Wearing a mask is defined as having the mask cover your mouth and nose. Students not wearing a mask will be asked to leave the classroom. If the student refuses to comply, then I will be forced to dismiss the class and report the student to the Office for Student Conflict Resolution for disciplinary action per university policy.
  - If you test positive for Covid-19, do not come to class, and follow university guidelines.
- **What do I do if I can't attend class for whatever reason?**
  - If you can't attend class in person, we expect you will attend the lectures in the following ways:
    - If you are in a nearby time-zone, you can attend the lecture synchronously via Zoom. We will create a Zoom session that will be managed by the TAs.
    - If you are not in a nearby time-zone, you will view the recorded lectures we will generate after the class is over, whenever you are able to. We will post or link to the lectures through the course website, but they will probably be hosted through a channel in mediaspace.
  - If you can't attend class in person, we expect you will still do the homework assignments and hand them in through the internet.

    - Homework assignments will be posted through the class website gradescope on a given day and at a given GMT time, and the assignment will be announced in class and via email.
    - **What is Gradescope?** Excellent question. It's a website (https://https://www.gradescope.com/) that the university wants us to use to interact online about homework. This website respects the privacy rules of students, meaning that you and only you (and the TAs and me) are able to see your grades and your graded homework. Once you create a student account on gradescope (it is free with your illinois email address), you should be able to search for PHYS 598 at UIUC (eventually, i.e. if this option is deployed due to CoVid requirements).
    - Once you complete the homework assignment, take a picture of it and upload it through gradescope by the required GMT time and date.
    - The graded homework assignment will be returned to you again via gradescope as soon as possible.

- **What do we do about Office Hours?**
  - Office hours will be done all via Zoom, and not in person. As stated above, and given the size of this class, we will start with office hours being infinite but scheduled only upon request. Please let us know 24 hours in advance if you would like to have an office hour.
  - In addition to office hours, we have created a webpage for this course on Piazza (www.piazza.com). In this webpage, you can pose questions that all students in this class can see. The course TAs will answer quick questions via piazza, and you can also have discussions among yourselves via piazza. Please do not email the TAs with questions, but rather ask your questions via piazza (you can even do so through piazza's anonymous feature), so that all students can benefit from the answer to your question.

- **What's the plan if things get worse?** If the Covid-19 situation worsens, and we are forced to move instruction online, we will do so. What this means is the following:
  - All lectures will be delivered on Zoom on the usual days and at the usual time. The Zoom lectures will be recorded and distributed *upon email request to the TAs*.
  - All homework will continue to be assigned, handed in and returned through gradescope (see above).
  - All office hours will continue to be done via Zoom.
  - The piazza website will continue to be used for quick questions and answers.

  So essentially we will do the same we would do normally, except that the lectures would all be done via Zoom. More details on this will be provided via Zoom and/or via email if this option is acted on.

Academic Integrity

All activities in this course are subject to the Academic Integrity rules as described in Article 1, Part 4, Academic Integrity, of the Student Code. Infractions include, but are not limited to:

- cheating, plagiarism, fabrication,
- facilitating infractions of academic integrity,
- academic interference,
- computer-related infractions,
- unauthorized use of university resources,
- sale of class materials or notes.

Violations of any of these rules will be prosecuted and reported to the student's home college in compliance with the Student Code: Article 1, Part 4, Academic Integrity, of the Student Code.

All aspects of the course are covered by these rules.

Disability Access

https://www.disability.illinois.edu/academic-support/instructor-information/examples-disability-statements-syllabus

The Department of Physics is committed to being an open and welcoming environment for all of our students. We are committed to helping all of our students succeed in our courses.

To obtain disability-related academic adjustments and/or auxiliary aids, students with disabilities must contact the course instructor and the Disability Resources and Educational Services (DRES) as soon as possible. To contact DRES, you may visit 1207 S. Oak St., Champaign, call 333-4603, e-mail disability@illinois.edu or go to the DRES website. If you are concerned you have a disability-related condition that is impacting your academic progress, there are academic screening appointments available on campus that can help diagnosis a previously undiagnosed disability by visiting the DRES website and selecting ÒSign-Up for an Academic ScreeningÓ at the bottom of the page.

If you are interested in obtaining information to improve writing, study skills, time management or organization, the following campus resources are available to all students:

- *Writer's Workshop*, Undergrad Library, 217-333-8796,

  http://www.cws.illinois.edu/workshop

  https://www.disability.illinois.edu/strategies,

  http://www.counselingcenter.illinois.edu/self-help-brochures/

  Also, most college offices and academic deans provide academic skills support and assistance for academically related and personal problems. Links to the appropriate college contact can be found by going to this website and selecting your college or school:

  http://illinois.edu/colleges/colleges.html

  If you are experiencing symptoms of anxiety or depression or are feeling overwhelmed, stressed, or in crisis, you can seek help through the following campus resources:

- *Counseling Center*, 206 Fred H. Turner Student Services Building, 7:50 a.m.-5:00 p.m., Monday through Friday Phone: 333-3704,

- *McKinley Mental Health*, 313 McKinley Health Center, 8:00 a.m.-5:00 p.m., Monday through Friday Phone: 333-2705, McKinley Health Education offers individual consultations for students interested in learning relaxation and other stress/time management skills, call 333-2714.