PHYS 598: Special Topics –
Neutron Stars: From nuclear theory to gravitational waves
Fall 2024

Class Time and Location: Tuesday-Thursday 11:00-12:20 am, Loomis 222.

Course website: https://courses.physics.illinois.edu/phys598nst/fa2024/index.html

List of preferred pre-requisite courses: PHY 515 (GR1), PHY 580 (QM1), and PHY 504 (Stat. Phys).

Professor: J. Noronha-Hostler (Loomis 427, jnorhos[at]illinois.edu), N. Yunes (Loomis 249, nyunes[at]illinois.edu).

Teaching Assistant 1: Jayana Antunes Saes (Loomis 257), jayanaa2[at]illinois.edu.

Teaching Assistant 2: Nikolas Cruz Camacho (Loomis 447), cnc6[at]illinois.edu.

Professors' Office Hours: Infinite by appointment. Jaki's or Nico's Office; if you can't find us, *email us.*

TA's Office Hours: Jayana on Wednesdays 3-4pm in Loomis 464, Nikolas on Fridays 2-3pm in Loomis 476.

What is this class about? This course will cover the advanced topic of neutron stars, focusing on the their interior composition and astrophysical observables. Emphasis will be put on (i) calculations of the equation of state of nuclear matter at high densities and low temperatures, and (ii) the modeling of the gravitational field of neutron stars. The topics discussed will include a subset of the following: Tolman-Oppenheimer-Snyder equation, mass-radius curves, Hartle-Thorne approximation, moment of inertia, quadrupole moment and tidal deformability, universal relations and gravitational waves, basics of thermodynamics, white dwarfs/crust, empirical mass formula, N-body interactions, liquid-gas phase transition/van der Waals, chiral effective field theory, chiral mean field model, NJL, (non)linear sigma model, MIT bag model, conserved charges, symmetry energy expansion.

This class is advanced because it will assume the student is well-versed in classical and quantum mechanics (at the level of Goldstein's and Baym's textbooks), and familiar with the basics of statistical mechanics (at the level of Reif's textbook) and general relativity (at the level of Carrol's textbook). The latter two are not pre-requisites for this class, but concepts drawn from these subjects will be employed. Some familiarity with basic particle or nuclear physics (at the level of Griffiths' textbook) would also be useful.

What is this class not? This will *not* be 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 nuclear physics, gravity, astrophysics, and high energy physics. 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, quantum mechanics and statistical mechanics, and advanced mathematics, including differential equations, advanced Calculus and advanced linear algebra, as well as knowledge of the basics of particle physics and *general* relativity. The purpose of the class is to prepare students for research in (analytical or numerical) general relativity, relativistic astrophysics, gravitational waves, and nuclear 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 (unless you are sick or have any symptoms of illness), complete all homework assignments and complete a final exam or final presentation (tbd). In addition, students are expected to be mature enough to independently do self-learning outside of class, including reading the suggested books and reviews on their own (see below), reading papers mentioned in class, and doing homework discussed in the books 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. As you will see below, there is no single required textbook, but rather a set of recommended books and reviews that students can and should refer to if and when needed. Students will be required to do a high amount of homework, with assignments starting easy and light, but with the difficulty and the amount of homework increasing with the flow of class. This should be manageable, but it won't be "easy" at all times. 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 later. Questions are always welcomed, either in class, or outside of class during office hours.

Textbooks: All textbooks below are recommended but not required. We will draw from most of them.

- Gravity: Newtonian, Post-Newtonian, Relativistic (Cambridge U. Press, 2014) by Poisson and Will.
- Gravitational Waves (Oxford Press, 2008) by Maggiore
- An Introduction to General Relativity, Spacetime and Geometry (Pearson Press, 2004) by Carroll.
- Black Holes, White Dwarfs and Neutron Stars: The Physics of Compact Objects (Wiley, 1983) by Shapiro and Teukolsky
- Compact Stars: Nuclear Physics, Particle Physics, and General Relativity (Springer, 2000) by Glendenning.
- Gravitational Waves in Physics and Astrophyscs: An Artisan's Guide (IOP Press, 2022) by Miller and Yunes.
- Compact Star Physics (Cambridge University Press, 2020) by Juergen Schaffner-Bielich
- Finite-Temperature Field Theory: Principles and Applications (Cambridge University Press, 2011) by Joseph I. Kapusta and Charles Gale

Reviews: All reviews below are recommended but not required. We will draw from most of them. Note, most of the material on the equation of state at large densities is found only in reviews, not in textbooks.

- Volker Koch, "Aspects of chiral symmetry", Int.J.Mod.Phys.E 6 (1997) 203-250
- V. Somà, "From the liquid drop model to lattice QCD: A brief history of nuclear interactions," Eur. Phys. J. Plus 133, no.10, 434 (2018)
- R. Machleidt and D. R. Entem, "Chiral effective field theory and nuclear forces," Phys. Rept. **503**, 1-75 (2011)
- M. Buballa, "NJL model analysis of quark matter at large density," Phys. Rept. **407**, 205-376 (2005)

Topics: (27 or 28 Lectures of 75 minutes each)

- (J+N) *Preliminaries* [4 lectures]
  - (J) Units Rule! (0.5 lecture)
  - (J&N) General Overview of NS Structure a(0.5 lecture)
    - Layers of a neutron star
    - particles+quantum numbers
    - GW observables
  - (N) Relativity Review [1 lecture]
    - Spacetime and the metric tensor
    - The Einstein equations and energy conservation
    - Perfect and not-so-perfect fluids
  - (J) Stat Mech Review (2 lectures)
    - EOS, p/e, c_s^2 etc
    - phase transitions/matching conditions
    - Conserved charges
    - Grand canonical ensemble (μ_B)
    - minimizing energy
- (N) *Introduction to Compact Stars I* [1.5 lectures]
  - White dwarfs [1.5 lectures]

        * Formation
        * Discovery
        * Composition and Structure
        * Chandrasekhar mass
        * Properties

- (J) *Outer and Inner Crusts: From White Dwarfs to BPS* [3 lectures]
    - Empirical mass spectrum, continuous EOS
    - Nuclei (BPS)
    - Electrostatic corrections
    - Neutron drip line
- (N) *Introduction to Compact Stars II* [1.5 lectures]
    - Neutron stars [1.5 lectures]
        * Discovery
        * Formation
        * History
        * Magnetic Breaking
- (J) *Outer Core: N-body interactions* [3 lectures]
    - Liquid-gas phase transition
    - N-body interactions
    - Symmetric vs. asymmetric matter
    - Symmetry energy expansion derivation
    - Chiral Effective field theory
- (N) *Newtonian, Non-rotating Neutron Stars* [3 lectures]
    - Newtonian Structure of Compact Objects [1.5 lectures]
        * Equations of structure
        * A bit on radiative transport
        * Properties of equations
    - Solutions to Newtonian Structure Equations [1.5 lectures]
        * Polytropes and spectral representation of the EoS
        * Lane-Emden Equation
        * Properties of solutions
- (J) *Inner Core: Nucleons, hyperons, and quarks: Simple Methods* [3 lectures]
    - MIT Bag model
    - Baby Lagrangian
    - Linear sigma model
- (N) [OPTIONAL: *Newtonian Stability of Neutron Stars* [4 lectures]]
    - Lagrangian and Eulerian perturbations
    - Perturbed Euler and Poisson equations
    - Perturbed Hamiltonian
    - Stability Criteria
- (N) *General Relativistic, Non-rotating Neutron Stars* [2 lectures]
    - TOV Equations of structure

  - Properties of equations
  - Solutions and Mass-Radius curves
  - Stability

- (J) *Inner Core: Nucleons, hyperons, and quarks: Advanced Methods I* [1.5 lectures]
  - Nambu-Jona-Lasinio (NJL) model
- (N) *General Relativistic, Rotating and Perturbed Neutron Stars* [3 lectures]
  - Hartle-Thorne approximation
  - Moment of Inertia
  - Quadrupole Moment
  - Tidal Love numbers
- (J) *Inner Core: Nucleons, hyperons, and quarks: Advanced Methods II* [1.5 lectures]
  - Chiral mean field model
- (N) *Some astrophysical observables* [2 lectures]
  - Gravitational Wave observables
  - I-Love-Q relations
  - Binary Love relations
- **Take home final exam**

No Class On: Sept 2 (Labor Day), Nov 23-Dec 1 (Fall break)

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 7–9 homework sets and in total they will be worth $\sim 70\%$ of your grade. There will be one final exam or presentation, worth $\sim 25\%$ of your grade. The remaining $\sim 5\%$ of your grade is based on class participation.

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: Assignments will be uploaded on Tuesday before class, and they will be typically due 7–10 days later. Submission of homework solutions via email to the TAs will be allowed, provided they are sent **before** the due date. The due date of the homework will be announced in class every week. Late homework will **not** be accepted, unless due to a documented extraordinary circumstance. 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 may include this homework for the more ambitious students that wish to have a more solid foundation on the subject matter.

Do not upload homework problems or solutions online: Websites that store homework solutions and/or does homework problems for you, such as Chegg, are **NOT** to be used. In particular, it is strictly forbidden to upload your homework solutions to Chegg or other equivalent websites. Violation to this policy will result in disciplinary actions.

Do not search for solutions to homework problems online: The use of the internet is allowed to search for general physics information, but it is not allowed to search for solutions to homework problems or exams. This violates the university's academic integrity policy, which, if violated, carries severe consequences (please see below).

Final Take home Exam: The final exam will be both open-book, open-notes, and take-home. The exam will be due in class, 3-5 days after being given out, and the due date will be announced in class. The only book you are allowed to use during exams are the recommended ones for the course. You may not use the internet, but you may use symbolic manipulation software (like Mathematica or Maple), as well as any numerical codes you developed in the course.

Do's and Don'ts:

- Do sit as close as possible to the blackboard if you are attending in person. Our handwriting is not the best.
- Do come to class prepared to take notes. Lectures draw from material outside the class' textbook and they will *not* be powerpoint.
- 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. But you are allowed to use an electronic note-taking device if you prefer. You are also allowed to record the lecture and take pictures of the board if you'd like.

On the use of Artificial-Intelligence and other Machine-Learning tools: It will be considered cheating if students upload howmework sheets or the takehome exam to chatGPT (or equivalent) and ask these software tool to answer scientific questions for them. Note that AI tooks, such as chatGPT, do not work well on advanced physics problems in general, so it will not be to your benefit to use them. We are ok with students using these tools to check English grammar or ask questions to optimize code (but not to create code from scratch).

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 Sign-Up for an Academic Screening 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.

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[1] L. Adamczyk *et al.* (STAR), Phys. Rev. C **96**, 044904 (2017), arXiv:1701.07065 [nucl-ex] .
[2] V. Vovchenko, D. V. Anchishkin, and M. I. Gorenstein, J. Phys. A **48**, 305001 (2015), arXiv:1501.03785 [nucl-th] .
[3] V. Vovchenko, D. V. Anchishkin, and M. I. Gorenstein, Phys. Rev. C **91**, 064314 (2015), arXiv:1504.01363 [nucl-th] .
[4] V. Vovchenko, A. Motornenko, P. Alba, M. I. Gorenstein, L. M. Satarov, and H. Stoecker, Phys. Rev. C **96**, 045202 (2017), arXiv:1707.09215 [nucl-th] .
[5] J. Walecka, Annals of Physics **83**, 491 (1974).