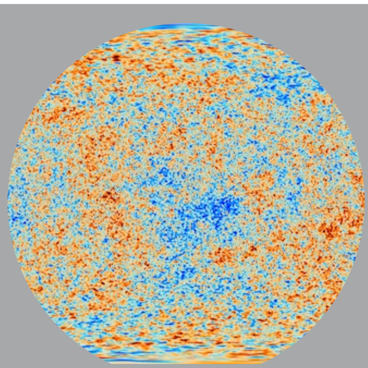

Cosmology

PHYS 480/581

Instructor Info

Prof. Francis-Yan Cyr-Racine

PAIS 3214

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fycr@unm.edu

Course Info

Prereq: Good knowledge of geometry, calculus, and mechanics; some statistical mechanics; some knowledge of astronomy is an asset.

Mon & Wed

10-11:15am

PAIS 1160

Course Website

Office Hours

Mon & Wed

11:30am-12:30pm

PAIS 3214

TA Info

Loc Ngo

Mon 11:30am-12:30pm

3414

ngophucducloc1995@unm.edu

Why Cosmology?

Cosmology is the study of the Universe as a whole. It aims to determine the fundamental laws governing its evolution on large scales, as well as how the multitude of objects populating it came to be. As such, cosmology aims to answer some of the most profound questions in all of science. Where do we come from? How did we get here? What is our place in the Universe? Where do we go from here? Due to the vast amount of observational data accumulated in the last two decades, cosmology is now a precision science which can accurately describe the evolution of our Universe over its 13.8 billion years of existence. In particular, detailed studies of the cosmic microwave background (CMB) reveal that the Universe was nearly homogeneous and isotropic in the distant past, with something mysterious called *dark matter* being about five times as abundant as regular baryonic matter. Moreover, measurements of the recent expansion history of the Universe indicate that ~ 70% of the energy density of the Universe is composed of something even more mysterious called *dark energy*. Determining the nature of these dark components require us to connect the behavior of the Universe on some of the largest imaginable scales with the fundamental physics governing the smallest length scales. As such, cosmology is about developing a holistic picture of the whole world we inhabit.

Overview

This course will cover the entire evolution of the Universe, from the early epoch of inflation to the formation of all the complex structure we observe around us today. We will start by exploring the fundamental assumptions underpinning our current cosmological model, and derive the key equations governing its evolution. We will also discuss the global geometry of the Universe and how to measure distances in an expanding Universe. We will then turn our attention to the thermal evolution, describing how the Universe went from a primordial hot plasma to a world dominated by dark matter and cold baryonic gas in the first million years of the Universe. Finally, we will study how structure forms in our Universe, from the quantum origins of primordial fluctuations in the inflationary epoch to the gravitational growth of perturbations in a matter-dominated Universe.

About Me

I am a practicing theoretical cosmologist/particle astrophysicist with a keen interest in the physics of the early Universe. My main interest is to use cosmological and astrophysical observations to discover new physics beyond the Standard Model.

Material

Required Text

Liddle, A. *An Introduction to Modern Cosmology*. 3rd Edition. Wiley. 2015. (ISBN: 978-1-118-50214-3)

Useful References

Dodelson, S. & Schmidt F. *Modern Cosmology*. 2nd Edition. Academic Press. 2020. (ISBN: 978-0-12-815948-4).

Baumann, D. *Cosmology*. 1st Edition. Cambridge University Press. 2022. (ISBN: 978-1-10-883807-8).

Grading Scheme

25%	Class participation and in-class worksheets
40%	6 Homework Assignments
35%	Research paper and final presentation

FAQs

What are the most important things I need to do to succeed in this class?

It's quite simple: Come to every class, work on the assigned in-class worksheets, and attempt every homework assignments. Do not wait until the last minute to begin writing your research paper!

Will there be a difference between the workload of undergraduate vs graduate students?

Yes, graduate students will be expected to hand in a more substantial research paper, and each homework will contain extra questions for graduate students. These questions will be optional for undergraduates, but can be attempted for bonus points.

What is the difference between *dark matter* and *dark energy*?

While often confused with each other, these two dark components could not be more different. As the name indicates, dark matter behaves like *matter*, which means it has no significant pressure. Its energy density is entirely dominated by its rest-mass energy. On the other hand, dark energy is characterized by a large *negative* pressure. This may sound mysterious, but negative pressure is like having a large number of stretched elastic bands that are allowed to relax to their natural state. As it does so, the system contracts instead of expanding as it would if it had positive pressure.

Class Format

This will be face-to-face class held at the regular times outlined above. Feel free to wear a mask if you wish (see UNM information below about that). In terms of the actual format for the class itself, it will usually (but not always) consist of a brief lecture at the beginning of class about the topic of the day, followed by active problem solving in small groups made up of 3-4 students. It is very important that you attend every class and do the worksheets (it counts for participation points!). Groups will be asked often to share their solutions with the rest of the class.

Since students in this class have many different levels of expertise (ranging from undergraduates to senior graduate students), I will be assigning students to the different small group to ensure a balance of expertise. To ensure fairness, groups will be rotated on a regular basis.

Homework Assignment

There will be 6 homework assignments spread out over the course of the semester. They will be due every $\sim$15 days. They will be posted on the course webpage. Homeworks are to be submitted directly to me during class on the due date. Late Homework assignments will be accepted but with a 25% penalty for each day past the deadline. So a homework handed-in within 24 hrs of the deadline will carry a 25% penalty, one handed-in within 48 hrs will carry a 50% penalty, as so on. Let me know if you are planning on submitting your homework late such that I can delay the posting of the solutions. It is very important that you attempt every assignment as they count for a sizable fraction of the final grade. While I strongly encourage you to discuss the homework assignments with your classmates, the work you hand in must be entirely yours.

Research Project

Each student will choose a topic from a list of possible projects (to be provided at a later date) and write a ~ 2500-word (~ 3000 for graduate students) research paper on that topic. Your paper must have a quantitative cosmological element and be supported by the relevant calculations. During the last week of classes, you will be asked to do a short presentation ($\sim$10 mins) summarizing the content of your research paper.

Student Learning Outcomes

Upon successful completion of this course, students will be able to . . .

- Explain the cosmological principle and describe at least one way to test it observationally.
- Explain the physical content of the Friedmann equation and be able to solve it for simple cases.
- Explain how the global geometry of the Universe is related to its energy density.
- Compute the comoving, angular diameter, and luminosity distances in an expanding Universe.
- Compute the evolution of the energy density, pressure, number density, and entropy in an expanding Universe.
- Explain the chronology of the thermal history of the Universe.
- Quantitatively explain the physics setting up the neutron abundance during Big Bang Nucleosynthesis.
- Explain how the Helium abundance is essentially set by the relic neutron abundance.
- Explain the meaning of the epoch of matter-radiation equality.
- Explain the physics of hydrogen recombination.
- Describe the problems that inflation automatically solves.
- Describe the main properties that dark matter must have.
- Describe the main properties that dark energy must have.
- Compute the evolution of matter fluctuations and the gravitational potential in a radiation- or matter-dominated Universe.
- Describe the key physics giving rise to the anisotropies of the cosmic microwave background.

Academic Integrity

Each student is expected to maintain the highest standards of honesty and integrity in academic and professional matters. The University reserves the right to take disciplinary action, up to and including dismissal, against any student who is found guilty of academic dishonesty or otherwise fails to meet the standards. Any student judged to have engaged in academic dishonesty in course work may receive a reduced or failing grade for the work in question and/or for the course. Academic dishonesty includes, but is not limited to, dishonesty in quizzes, tests, or assignments; claiming credit for work not done or done by others; hindering the academic work of other students; misrepresenting academic or professional qualifications within or without the University; and nondisclosure or misrepresentation in filling out applications or other University records.

Credit-hour statement

This is a three credit-hour course. Class meets for two 75-minute sessions of direct instruction for fifteen weeks during the Fall 2022 semester. Please plan for a minimum of six hours of out-of-class work (or homework, study, assignment completion, and class preparation) each week.

Diversity and Inclusion Statements

I consider this classroom to be a place where you will be treated with respect, and I welcome individuals of all ages, backgrounds, beliefs, ethnicities, genders, gender identities, gender expressions, national origins, religious affiliations, sexual orientations, ability - and other visible and non-visible differences. All members of this class are expected to contribute to a respectful, welcoming and inclusive environment for every other member of the class.

Citizenship and/or Immigration Status: All students are welcome in this class regardless of citizenship, residency, or immigration status. Your professor will respect your privacy if you choose to disclose your status. UNM as an institution has made a core commitment to the success of all our students, including members of our undocumented community. The Administration's welcome is found on our website.

Our classroom and our university should always be spaces of mutual respect, kindness, and support, without fear of discrimination, harassment, or violence. Should you ever need assistance or have concerns about incidents that violate this principle, please access the resources available to you on campus, especially the LoboRESPECT Advocacy Center and the support services listed on its website. Please note that, because UNM faculty, TAs, and GAs are considered "responsible employees" by the Department of Education, any disclosure of gender discrimination (including sexual harassment, sexual misconduct, and sexual violence) made to a faculty member, TA, or GA must be reported by that faculty member, TA, or GA to the university's Title IX coordinator at the Office of Compliance, Ethics, and Equal Opportunity. For more information on the campus policy regarding sexual misconduct, please see this link.

Accommodations for Students with Disabilities

UNM is committed to providing equitable access to learning opportunities for students with documented disabilities. As your instructor, it is my objective to facilitate an inclusive classroom setting, in which students have full access and opportunity to participate. To engage in a confidential conversation about the process for requesting reasonable accommodations for this class and/or program, please contact Accessibility Resource Center at arcsrvs@unm.edu or by phone at 505-277-3506. Support: Contact me at fycr@unm.edu or at my office hours, and also contact the Accessibility Resource Center.

COVID-19 Health and Awareness

UNM is a mask friendly, but not a mask required, community. To be registered or employed at UNM, Students, faculty, and staff must all meet UNM's Administrative Mandate on Required COVID-19 vaccination. If you are experiencing COVID-19 symptoms, please do not come to class. If you have a positive COVID-19 test, please stay home for five days and isolate yourself from others, per the Centers for Disease Control (CDC) guidelines. If you do need to stay home, please communicate with me at fycr@unm.edu; I can work with you to provide alternatives for course participation and completion. UNM faculty and staff know that these are challenging times. Please let us know that you need support so that we can connect you to the right resources and please be aware that UNM will publish information on websites and email about any changes to our public health status and community response.

Tentative Class Schedule

MODULE 1: The cosmological principle, geometry, and the expansion of the Universe

Week 1	Overview of cosmological history, the cosmological principle, and the metric	Liddle Ch. 1, 2.1-2.4
Week 2	Comoving coordinates and the FRLW metric, the Friedmann Equation and its solution in the presence of a cosmological constant	Liddle Advanced Topic 1, Ch. 3.1-3.3
Week 3	The fluid equation, and the evolution of matter and radiation densities in an expanding Universe	Liddle Ch. 3.4, 5.3
Week 4	Curvature and the spatial geometry of the Universe. Critical density and the density parameters, Hubble constant, age of the Universe	Liddle Ch. 4.1-4.6, 5.5, 6.1-6.2, 8
Week 5	Cosmological redshifts, Hubble's law, Distances in an expanding Universe: The comoving and angular diameter distances	Liddle Ch. 5.1-5.2, Advanced Topic 2
Week 6	Distances in an expanding Universe: The luminosity distance. Detailed energy content of the Universe: baryons, dark matter, photons, neutrinos, and dark energy. Acceleration.	Liddle Advanced Topic 2, Chap. 7, Advanced topic 6.4

MODULE 2: Thermal evolution of the Universe

Week 7	Statistical mechanics: Distribution function, number density, energy density, and pressure in the relativistic limit; chemical potential	Liddle Ch. 2.5, 5.4,
Week 8	The number density, energy density, and pressure of non-relativistic particles; The effective number of relativistic species after the Big Bang in an adiabatically cooling Universe	
Week 9	Entropy conservation and the temperature of neutrinos after e^+e^- annihilation; Big Bang Nucleosynthesis: the early neutron abundance	Liddle Ch. 12, Ad. Topic 3
Week 10	Big Bang Nucleosynthesis: Helium and deuterium abundances	Liddle Ch. 12
Week 11	The Universe after nucleosynthesis, matter-radiation equality and the epoch of recombination	Liddle Ch. 10, 11
Week 12	Out-of-equilibrium hydrogen recombination, photon last-scattering and the cosmic microwave background	Liddle Ch. 10, 11

MODULE 3: Structure formation in our Universe

Week 13	The horizon and flatness problems; Inflation as a solution; Simple models of inflation; reheating	Liddle Ch. 13
Week 14	What is dark matter? The linear growth of matter structure	Ch. 9, Advanced Topic 5
Week 15	Cosmic Microwave Background: Sound waves and diffusion	Advanced Topics 5, 6
Week 16	Final presentations	