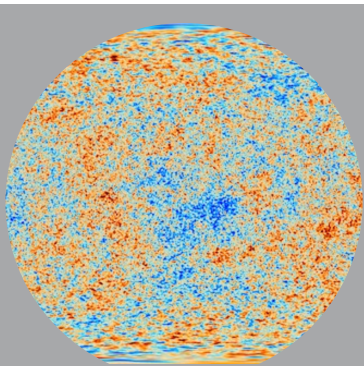

Cosmology

ASTR 425/525

Instructor Info

Prof. Francis-Yan Cyr-Racine

PAIS 3214

darkuniverse.unm.edu

fycr@unm.edu

Course Info

Prereq: Good knowledge of geometry, calculus, linear algebra, mechanics, and special relativity; some statistical and quantum mechanics; some knowledge of astronomy is an asset.

Mon & Wed

2-3:15pm

PAIS 1140

Course Website

Office Hours

Mon & Wed

3:30-4:30pm

PAIS 3214

TA Info

Fernando Garcia-Cortez

Thurs 12-1pm

3414

fgarcia02@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 $\sim 70\%$ 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

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

Useful References

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

Grading Scheme

25%	In-class worksheets
40%	6 homework assignments
20%	2 midterm quizzes (10% each)
15%	Final exam

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.

? 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.

? Do I need to know how to code to take this class?

! While there won't be coding assignments per se, there will be homework problems requiring you to perform numerical calculations, make plots, and analyze data. Familiarity with numerical tools (e.g. python) allowing you to do this is thus an important asset to have.

Graduate Student Expectations

Graduate students registered for the course will be expected to demonstrate a more thorough understanding of the material, especially for the topics involving thermodynamics, quantum mechanics, and field theory. To assess this, each homework assignment will contain additional questions that only graduate students are expected to answer. These questions will be optional for undergraduates, but can be attempted for bonus points. Graduate students are also expected to demonstrate a more substantial understanding of the material in the midterm and final exams.

Class Format

This will be face-to-face class held at the regular times outlined above. 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. 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.

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 and helium abundances during Big Bang Nucleosynthesis.
- Explain the meaning of the epoch of matter-radiation equality.
- Explain the physics of hydrogen recombination.
- Explain the origins of the cosmic microwave background.
- 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.
- Fit observational data to constrain the cosmological model of our Universe.

In-class worksheets

In almost every lecture, there will be an active-learning activity centered on a worksheet. Students will be expected to solve the problems on the worksheet in class in their pre-assigned group of 3-4 students. After 20-30 minutes, I will ask one group to volunteer and present their answers in front of the class. It is understood that each student will present for their group at least once during the semester. While the worksheet will not be graded, students will get the credits for the worksheet by actively participating in their group as they work through the worksheet. It is thus very important for all students to attend every classes. Students who are absent from class will not get credits for the worksheet, unless they have an excused absence with proper documentation. Even in this case, students will have one week from the missed lecture to complete the missing worksheet and hand it in to me.

Homework Assignments

There will be 6 homework assignments spread out over the course of the semester. They will be due every ∼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.

Course Material Access (relevant mostly to undergraduates)

Your digital course materials are directly available now on the My Shelf link in Canvas. To simplify your course materials access, you are automatically enrolled in a Complete option at a flat rate of $279 per semester. This will show up on your bursar bill. The Complete option covers all your required course materials for all your Albuquerque campus courses, including any graduate courses you may be taking. If you are interested in course materials access for only selected courses, or if you want to opt out entirely, you will need to select the option you want in the My Shelf link in Canvas. You can change your selected option in the My Shelf link in Canvas until the registrar's "Last Day to Drop Without a 'W' Grade and 100% Tuition Refund." Make sure that you review the video and information here to understand cost and the options for Complete (automatic enrollment), Select (take action), and Opt-out (take action).

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 (including AI); 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 2025 semester. Please plan for a minimum of six hours of out-of-class work (or homework, study, assignment completion, and class preparation) each week.

Respectful behavior and absences

I am committed to building with you a positive classroom environment in which everyone can learn. I reserve the right to intervene and enforce standards of respectful behavior when classroom conduct is inconsistent with University expectations. Interventions and enforcement may include but are not limited to required meetings to discuss classroom expectations, written notification of expectations, and/or removal from a class meeting. Removal from a class meeting will result in an unexcused absence. Three or more unexcused absences may result in permanent removal and a drop from the course (see attendance policy). The University of New Mexico ensures freedom of academic inquiry, free expression and open debate, and a respectful campus through adherence to the following policies.

UAP 2720 and 2740

Our classroom and our university should foster mutual respect, kindness, and support. If you have concerns about discrimination, harassment, or violence, please seek support and reports incidents. Find confidential services at the LoboRESPECT Advocacy Center, the Women's Ressource Center, and the LGBTQ Ressource Center. UNM prohibits discrimination on the basis of sex (including gender, sex stereotyping, gender expression, and gender identity). All instructors are "responsible employees" who must communicate reports of sexual harassment, sexual misconduct and sexual violence to Compliance, Ethics, and Equal Opportunity. For more information, please see UAP 2720 and UAP 2740.

Accommodations

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 the Accessibility Resource Center at arcsrvs@unm.edu or by phone at 505-277-3506.

Tentative Class Schedule

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

Week 1	Overview of the Universe and of cosmological history; the cosmological principle; comoving coordinates and the metric	Baumann Ch. 1, 2.1
Week 2	FRLW metric, curvature and the spatial geometry of the Universe, the Hubble parameter, cosmological redshifts, Hubble's law.	Baumann Ch. 2.1, 2.2.2
Week 3	The fluid equation, the evolution of matter, radiation, and dark energy densities in an expanding Universe	Baumann Ch. 2.3.1-2.3.3
Week 4	Friedmann Equation and its solutions, critical density and the density parameters, Hubble constant, age of the Universe	Baumann 2.3.4-2.3.6
Week 5	Distances in an expanding Universe: The comoving, luminosity, and angular diameter distances	Baumann 2.2.3
Week 6	Detailed energy content of the Universe: baryons, dark matter, photons, neutrinos, and dark energy. ΛCDM model	Baumann 2.4

MODULE 2: Thermal evolution of the Universe

Week 7	Statistical mechanics: Distribution function, number density, energy density, and pressure in the relativistic limit	Baumann Ch. 3.1.1-3.1.2,
Week 8	The number density, energy density, and pressure of non-relativistic particles; chemical potential; The effective number of relativistic species after the Big Bang in an adiabatically cooling Universe	Baumann Ch. 3.1.2
Week 9	Entropy conservation and the temperature of neutrinos after e^+e^- annihilation	Baumann 3.1.3-3.1.4
Week 10	Big Bang Nucleosynthesis: Neutron, helium and deuterium abundances	Baumann Ch. 3.2.4
Week 11	The Universe becomes transparent: The epoch of recombination; Out-of-equilibrium hydrogen recombination; the cosmic microwave background (CMB) and its blackbody spectrum	Baumann Ch. 3.1.5, 3.2.5
Week 12	Observation and characterization of the CMB, photon-baryon sound horizon, Silk damping; two-point correlation functions and power spectra	Baumann 7.1, 7.4.1, 7.5

MODULE 3: Structure formation in our Universe

Week 13	The horizon and flatness problems; Inflation as a solution; Simple models of inflation; reheating	Baumann Ch. 4.1-4.3
Week 14	What is dark matter? What is dark energy?	
Week 15	The growth of matter structure and radiation and matter domination	Baumann 5.1-5.2
Week 16	Matter power spectrum; From matter density fluctuations to galaxies; galaxy clustering and observations	Baumann 5.3-5.4