PHYS480/581 Cosmology
Research Project Topics

Due date: Wednesday 12/07/2022 by end of day

As part of this Cosmology course, I am asking you perform a short **research** project on a topic of your choice. The goal is to allow you to explore a cosmology topic in more depth than we can cover in a regular lecture while learning something new. The level should be such that you would feel comfortable presenting your research paper to your classmates (which you will do!). Your research paper **must contain**

1. a clearly identified research question,
2. at least one original plot that you made yourself,
3. a quantitative calculation supporting your research question,
4. a clear conclusion about the results of the research.

Obviously, this does not need to be *original* research, but I won't stop you if you want to pick a topic that is more at the forefront of research. The expected length is about 2500 words for undergraduate students, and 3000 words for graduate students. Note that these are purely indicative numbers, and the total length of your paper will depend on the number of figures and calculations that it contains. Your paper will be evaluated by the effort you have put in it, rather than the number of words it contains, with the expectation that graduate students should submit a more substantial research project than undergraduates to get the same grade. This research project will count for 35% of your final grade for this class.

Given the requirements above, simply reading a paper and summarizing it in an essay is **not sufficient**. Active calculations (including numerical ones) and plotting must be involved. All research articles that you might need for your project can be found on arXiv.org.

I. TIMELINE

- **Topics due (email me):** Wednesday October 26.
- **Outline + references due:** Monday November 14. Submit a brief bullet-point outline of your research paper, as well as at least 2 references that you are using to plan your research paper.
- **Research Project due:** Wednesday December 7, by end of day.

II. SUGGESTED TOPICS

I give below a selection of topics. You are encouraged to pursue other topics that interest you. Consult with me in advance. Once you've chosen a topic, please let me know by email. I won't allow 2 students to choose the exact same topic. First come, first serve.

1. **Dark Matter Candidates**
   Dark matter is about 5 times more abundant than regular baryonic matter, yet we do not know its nature and origins. Pick one potential dark matter candidate from the list below and describe why we think this is a reasonable dark matter candidate. How is their relic abundance set? What kind of observational signatures could we use to distinguish this candidate from other models? What experimental constraints do we have on this dark matter candidate?
   - QCD axion.
   - Ultra-light axion (fuzzy dark matter).
   - Lightest supersymmetric particle.
   - keV-scale sterile neutrino.
   - Primordial black holes.

2. **Impact of new physics on the Cosmic Microwave Background**
The cosmic microwave background (CMB) is our primary source of information about what happened in the early Universe. New physics beyond the Standard Model of particle physics can leave important imprints on the anisotropies of the CMB. Pick one example of new physics that can be probed with the CMB from the list below and quantitatively describe its impact on the temperature and polarization angular CMB power spectra. To do so, use the Boltzmann code `class` (which we can find here). See the file `explanatory.ini` within the code for references and to identify which parameters control the new physics of your choice. What are the current constraints on your chosen new physics? What about future constraints?

   - Additional free-streaming relativistic species beyond the standard neutrinos (parameterized through $N_{\rm eff}$)
   - Massive neutrinos
   - Dark matter decaying to dark radiation
   - Dark matter-dark radiation interactions
   - Dark matter-baryon interactions
   - B-mode polarization and inflationary gravitational waves

3. **Big Bang Nucleosynthesis**
Observations of the primordial abundances of helium and deuterium impose strict constraints on the baryon-to-photon ratio $\eta_{\rm b}$ and on the abundance of radiation (through $N_{\rm eff}$) in the early Universe. Study how changing these two parameters affect the predicted abundances of helium and deuterium (and other relevant light elements). How constraining are the current measurements of these abundance on $N_{\rm eff}$? You may find useful to use the codes `AlterBBN` or `PArthENoPE`. This paper is a good place to start.

4. **Impact of dark matter physics on structure formation**
Dark matter forms the gravitational backbone of all the structure we see around us in the Universe. As such, the microphysical properties of dark matter play an important role in both the abundance and internal properties of the structure around us. Pick one of the dark matter properties listed below and describe how it affects the abundance and inner properties of dark matter halos, and/or the large-scale structure of the Universe (if applicable). What is the key particle physics entering the problem? What kind of observations are used to constrain this dark matter property? What are the current constraints? You might want to use the Boltzmann code `class` (which we can find here) to compute the impact of your chosen dark matter physics on the large-scale structure of the Universe. See the file `explanatory.ini` within the code for references and to identify which parameters control your chosen dark matter physics.

   - Warm dark matter
   - Self-interacting dark matter (no need to use the `class` code)
   - Dark matter interacting with dark radiation the early Universe
   - Dark matter interacting with baryons

5. **Inflation and the primordial spectrum of fluctuations**
Inflation is a general paradigm that solves the horizon and flatness problems, among others. Many possible early-universe mechanisms have been proposed for inflation, each differing in their exact predictions for the properties of the initial primordial perturbations. Pick your favorite inflation model, and describe how they influence the primordial spectrum of curvature fluctuations. Does it predict a sizable gravitational wave signal? Are the predicted fluctuations Gaussian in nature, or are sizable non-Gaussianities present?

6. **Alternative to inflation**
Alternatives to inflation have been proposed in the literature. These include bouncing universes and the so-called ekpyrotic scenarios. Pick one of these alternatives and study their phenomenology, emphasizing how they differ from inflation. Which observations could be used to distinguish these scenarios from the standard inflationary scenario? Are these models even plausible?

7. **Local measurements of the Hubble rate**
We have multiple ways of inferring the Hubble constant in the local Universe. Pick one of the technique listed below and quantitatively study how these ultimately lead to a measurement of H_0. What is the fundamental anchor making this measurement possible? What are the assumptions made along the way? What are the main sources of systematic error? What are the future prospects for these measurements?

- Distance ladder: Type Ia supernovae calibrated using cepheid variables
- Distance ladder: Type Ia supernovae calibrated using the tip of the red giant branch
- Water masers in the Hubble flow
- Time-delay strong-lensing cosmography

8. **Baryon Acoustic Oscillation and the physics of the late Universe**
   The baryon acoustic oscillation (BAO) feature imprinted in the large-scale distribution of galaxies is an extremely useful standard ruler that can be used to measure the expansion of the Universe at low redshifts. Study the origin of the BAO feature and how we extract it from modern galaxy surveys. Then pick one of the following physical properties of the Universe, and study how BAO measurements can be used to constrain them:

   - Spatial curvature and neutrino masses (this is really two different scenarios, but they are both simple so I'm putting them together)
   - The equation of state of dark energy
   - The abundance of decaying dark matter

9. **General Relativity in Cosmology**
   General Relativity (GR) and the Einstein equation plays an important role in Cosmology, especially in the description of the growth of small inhomogeneities that eventually form all the structure we observe today. While it is relatively simple to derive the Friedmann, fluid, and acceleration equations in GR, it is more challenging to derive the evolution equations for the gravitational potentials and density fluctuations. Starting from the perturbed FLRW metric and perturbed energy momentum tensor, sketch the derivation of the relevant equations to study one of the problems listed below. Be mindful of gauge issues. What kind of observational signatures do these physical effects lead to? You may find this paper useful.

   - The difference between the evolution of cold dark matter and baryonic density fluctuations
   - The difference between the evolution of massless neutrino and photon density fluctuations
   - The evolution of the gravitational potentials in the radiation, matter, and dark energy dominated eras.