This problem set will contain General questions and questions based on the two papers:


1. General question 1

(a) How and when was the accelerated expansion of the Universe discovered? What is meant with Einstein’s cosmological constant $\Lambda$ and how does its energy density evolve with time? The vacuum energy model is the simplest and most plausible model, but at the same time the most puzzling dark energy candidate, explain why.

(b) How can the cosmic microwave background (CMB) be used to measure dark energy? Why is the CMB on its own not particularly sensitive to dark energy? What is the role of large-scale structure in measuring dark energy? Roughly speaking in which redshift range should the efforts on measuring the effect of dark energy be concentrated and explain why this is the case.

(c) Were there hints for $\Omega_\Lambda \neq 0$ even before the discovery of dark energy? How does dark energy help to reconcile the measured matter density of $\Omega_m \sim 0.3$ with the theory of cosmic inflation, i.e. what is the inflationary prediction for $\Omega_{\text{tot}}$ and the geometry of the Universe? How did dark energy help to reconcile the age discrepancy between old stars in globular clusters and the age of the Universe?

2. General question 2

(a) Apart from the cosmological constant what type of dark energy models have been proposed? Why do scalar field provide an attractive solution to the dark energy problem? Could dark energy and dark matter be connected? Could modifications to the gravitational theory help explain dark energy? Could the assumption of a homogeneous Universe assumed in the Friedmann models potentially break down and how would this influence our interpretation of dark energy?

(b) Explain very briefly how observations of supernovae, galaxy clusters, baryonic acoustic oscillations and weak lensing could help to probe the cosmic acceleration of the Universe. Why is it important to use a combination of several methods? If the cosmological constant is the correct dark energy model, what is going to happen to the local galactic neighbourhood in the far future? What is the big rip?

(c) Go on the internet and find out what the Euclid space telescope is. When will this mission be launched and what are the main science goals of this mission and how will they be achieved? In your opinion is it worth spending billions of dollars/euros on studying dark energy? Why are so many people so excited about dark energy?
3. Based on **Paper 1** answer the following questions:

(a) What is the main aim of the paper? What is the redshift $z_{da}$ that they are trying to measure? What type of observational data are they using? What is the baryonic acoustic oscillation (BAO) peak and what is the Ly$\alpha$ forest?

(b) Describe briefly which three cosmological dark energy models they are testing in this paper? Based on their observational data are they able to tell which model best fits the data? Why would observational data at very high redshifts of $z \gtrsim 5$ be of almost no use for the present study?

(c) What is shown in Figs. 1-3? Why are there both a filled circle and open circle in all three plots? What is meant by a prior in the analysis and how is the prior affecting the final results based on Figs. 1-3? What is the final result for $z_{da}$ and what cosmic time does this correspond to? Did the solar system exist at $z_{da}$?

4. Based on **Paper 2** answer the following questions:

(a) What is the author of this paper attempting to do? How can radio measurements of the HI 21 cm line be used in cosmology and what physical process is causing the HI 21 cm line? Why is this type of measurement independent of the assumed cosmological model and why is this quality especially valuable when studying the expansion history of the Universe?

(b) What values are found for the $\dot{z}$ and $\Delta v/\Delta t_0$ variables and what do these variables describe? Studying Fig 3. has the expansion of the Universe been directly detected? How does the measured value compare with the theoretical expectation value? How long would it take to detect the expansion using the Green Bank Telescope employed in this study? What is the Square Kilometer Array and how would it make this measurement possible?

(c) In addition, the author is studying the evolution of the quantity $\alpha^2 g_p m_e/m_p$, what is this quantity and how can it be studied with absorption-line spectroscopy? Studying Fig 4. what is the result, does this quantity evolve with redshift? If it did, what would it mean for the Universe and especially the constancy of the laws of nature in time and space?