Particle Physics in the Early Universe: typical exam questions

These are typical questions, not necessarily the exact questions you will be given at the exam. But if you have good answers for all these you will do well.

1. What is neutrino decoupling? At which temperature, approximately, did it happen? What happens to neutrinos after that?
2. Before nucleosynthesis starts protons and neutrons are in equilibrium. What reactions are responsible for this equilibrium? What happens after neutrinos decouple and the temperature drops? What prevents the elimination of all neutrons?
3. What is the temperature during recombination? Why is it not 13.6eV?
4. What is the Cosmic Microwave Background? What does it tell us about the early Universe¿ What is the source of the dipole anisotropy of the CMB?
5. What is Baryogenesis and why is it necessary? Describe the Shakharov conditions for succesful Baryogenesis.
6. What is Leptogenesis and how can we get Baryogenesis from Leptogenesis?
7. What kind of evidence do we have today that Dark Matter exists?
8. What is hot Dark Matter and why is it disfavored?
9. What are WIMPs and what is the "WIMP miracle"?
10. In a Beyond-the-Standard-Model theory of your choice, describe what particle would be a Dark Matter candidate.
11. In which ways can we detect DM WIMP-type particles?
12. What is the Horizon problem in classical Big Bang theory? How does inflation solve it?
13. What is the flatness problem in classical Big Bang theory and how does inflation solve it?
14. What is the cosmological constant puzzle?
15. From the Friedmann equation
$$\frac{\dot{a}^2}{a^2} + \frac{\tilde{\kappa}}{a^2} = \frac{8\pi G}{3}\rho \tag{1}$$
define the critical densities Ω_M, Ω_R, Ω_Λ, Ω_κ. Show that ${}_i\Omega_i = 1$. Are the Ω_i time-dependent?
16. For an expanding, relativistic perfect fluid, the continuity equation is $\frac{d}{dt}(\rho a^3) = -P\frac{d}{dt}(a^3)$. Derive this from the energy-momentum tensor of the fluid, $T^{\mu\nu}$.
17. What is the relation between energy and pressure (i.e. the equation of state) for non-relativistic matter?
18. What is the relation between energy and pressure (i.e. the equation of state) for relativistic matter?
19. How does the energy density depend on $a(t)$ for relativistic and non-relativistic matter? Derive this from the continuity equation and the equation of state, in each case.

20. Given that in matter-dominated Universe, $\rho \sim 1/a^3$, how does ρ evolve with time, assuming flat Universe?

21. Given that in radiation-dominated Universe, $\rho \sim 1/a^4$, how does ρ evolve with time?

22. Show that a flat Universe with a cosmological constant and nothing else is an exponentially expanding Universe.

23. Show that the equation of state for the cosmological constant is $P = -\rho$.

24. Consider a system in thermal equilibrium with negligible chemical potentials. How do we compute the energy density of a fermion field as a function of the temperature?

25. If the Universe is dominated by relativistic particles and is flat, what is the relation between the Hubble parameter and the temperature T?

26. The reaction through which deuteron is destroyed, $d + \gamma \to p + n$ has a threshold of 2.22MeV (i.e. the photon needs to have energy more than 2.22 MeV at the rest frame of the deuteron, for the reaction to take place). Does this mean that once the temperature of the Universe falls below 2.22MeV, the deuteron stops being destroyed?

27. What are CMB anisotropies? How are the multipole anisotropies defined?

28. What does the location of the first accoustic peak of the CMB tell us?

29. What are necessary features for a Dark Matter candidate?

30. Discuss the possibility that the DM is baryonic. What kind of objects would make up baryoic Dark Matter and why are they disfavored?

31. How do we hope to detect WIMP-like DM directly in the laboratory?

32. Describe the Seesaw mechanism. Why would a Majorana mass term generated by a Yukawa coupling of the Higgs to Majorana neutrina, induce Lepton number violation?

33. What is neutrinoless double beta decay and why is it important for cosmology?

34. What caused the baryon to photon ratio to be so small?

35. Do we have a source of CP violation in the classical Standard Model?

36. What is Electroweak baryogenesis?

37. What is the Electroweak Phase Transition?

38. What is the difference between a first and a second order phase transition in the context of electroweak symmetry breaking? Which one is most likely to have happened, according to current knowledge?

39. What are the conditions for slow roll inflation?

40. Derive the height of the sphaleron potential for intermediate temperatures. (Just joking - this would be entirely out of the scope of the exam).