December ??, 2019   Name _____
                         Final Exam PHY 310/610

This test consists of five parts. In parts II and III, PHY 310 students can skip one question of
those offered, while PHY 610 students must answer all questions.

Part I: Multiple Choice (mixed new and review questions) [40 points] (2 points each)
PHY 310/610: For each question, choose the best answer

1. Our best guess is that in the future, the scale factor of the universe a will
    A) Increase exponentially forever
    B) Always increase, but at an ever slowing rate
    C) Asymptotically approach a finite value in the future
    D) Reach a maximum and then recollapse to $a = 0$
    E) Reach infinity in a finite time

2. Hubble's constant is probably closest to which of the following?
    A) 60 km/s/Mpc B) 70 km/s/Mpc C) 80 km/s/Mpc D) 90 km/s/Mpc E) 100 km/s/Mpc

3. Which of the following is <u>not</u> considered a force carrying particle?
    A) Neutrino   B) W boson   C) Z boson   D) Gluon   E) Photon

4. The hottest stars are of spectral type
    A) A   B) B   C) F   D) G   E) O

5. Homogenous means the same everywhere, isotropic means the same in all directions, and
    static means unchanging over time. Which of these three terms describes the universe on
    large scales?
    A) Homogenous (only)
    B) Isotropic (only)
    C) Static (only)
    D) Homogenous and isotropic, but not static
    E) Homogenous, isotropic, and static

6. According to modern particle physics, how many types (flavors) of quarks are there, total?
    A) Three   B) Four   C) Five   D) Six   E) Eight

7. At some point, the temperature dropped to the point where various quarks collided with anti-
    quarks and were annihilated. Why are there any quarks left over today, if this is the case?
    A) The quarks were generated after this annihilation through lepton decay
    B) There must have been a tiny excess of quarks over anti-quarks
    C) The density got so low that typical quarks couldn't find anti-quarks to annihilate with
    D) Various processes collected quarks in some parts of the universe and anti-quarks in others
    E) They did all annihilate; this is why there are no free quarks today.

8. The name of our galaxy supercluster, according to this class, is
   A) Milky Way   B) Andromeda   C) Local Group   D) Laniakea   E) Coma

9. A distant galaxy, is at a distance d and is moving away from us at a velocity v. Why can't we simply use the formula $t = d/v$ to deduce when it left us and find the age of the Universe?
   A) Galaxies were always moving <u>slower</u> in the past than they are now.
   B) Galaxies were always moving <u>faster</u> in the past than they are now
   C) Galaxies were moving <u>slower</u> at some times and <u>faster</u> at others in the past
   D) Peculiar velocities cause errors in this, which are particularly large for distant galaxies
   E) There is nothing wrong with this; this is how we get the age of the Universe

10. Which of the following coincidences was *not* mentioned as being crucial to the development of life in the Universe?
    A) The value of Ω at very early times was ridiculously close to 1
    B) Neutrino decoupling came almost exactly at the same time as neutron/proton freezeout
    C) There is a resonance in ^{12}C that makes it especially easy to synthesize
    D) The proton/neutron mass difference is remarkably small
    E) The cosmological constant is ridiculously tiny compared to the Planck scale prediction

11. Which of the following events is expected to be farthest in the future?
    A) Stars die B) Galaxies evaporate C) Matter decays   D) Isolated Universe E) Sun dies

12. Most of the mass of our galaxy is _____ and is located in the _____ .
    A) Dark matter, disk
    B) Dark matter, halo
    C) Dark matter, bulge
    D) Ordinary matter, disk
    E) Ordinary matter, halo

13. According to general relativity, when do objects follow geodesics, the longest proper time path between two events in space-time?
    A) Whenever there are no forces other than gravity acting on them
    B) Whenever there is no gravity acting on them, though there can be other forces
    C) Whenever there are no forces of any kind acting on them
    D) Only when there are no forces on them and spacetime has no curvature
    E) Always

14. What type of galaxy do we probably live in?
    A) Elliptical   B) Spiral   C) Barred Spiral   D) Irregular   E) None of these

15. When we look at the cosmic microwave background radiation (CMBR) we are seeing the universe at the era of
    A) Nucleosynthesis   B) Inflation C) Recombination D) GUT scale   E) Planck era

16. The luminosity distance is defined as $d_L^2 = L/(4\pi b)$, where L is the power it is putting out and b is the power per unit area we receive. This corresponds to the physical distance in an unchanging, flat universe. Why are things more complicated in the real universe?
A) The distances are changing with time, since the Universe is expanding (only)
B) The objects are moving away, causing them to be red-shifted to lower energy (only)
C) Space might be curved, meaning the formula is basically wrong (only)
D) All of the above are correct
E) None of the above are correct

17. Which of the following ingredients contributes approximately 26% of the total density of the Universe?
A) Baryons   B) Cosmological constant C) Neutrinos   D) Photons   E) Dark matter

18. Which of the following isotopes is believed to <u>not</u> have been produced primordially, even in small quantities
A) ^{2}H   B) ^{4}He   C) ^{3}He   D) ^{7}Li   E) ^{12}C

19. The velocity of a distant object towards or away from us is normally measured by
A) Doppler shift
B) Measuring how the object's apparent size changes with time
C) Using radar distancing to measure its distance over time
D) Noting how the parallax angle changes with time
E) Seeing how the apparent brightness changes over time

20. If particles are colliding with a cross section σ, have a number density n, and are moving relative to each other at a speed Δv, which formula gives us the rate for collisions Γ?
A) $\Gamma = \dfrac{n\sigma}{\Delta v}$ B) $\Gamma = \dfrac{n\Delta v}{\sigma}$ C) $\Gamma = \dfrac{\sigma\Delta v}{n}$ D) $\Gamma = \dfrac{\Delta v}{n\sigma}$ E) $\Gamma = n\sigma\Delta v$

Part II Short Answer [40 points/50 points] (10 points each)
PHY 310: Choose **four** of the following five questions and give a short answer (1-3 sentences)
PHY 610: Answer **all five** questions

21. Explain qualitatively how one can use Cepheid variable starts to measure distances.

22. Explain how our observations of white dwarf supernovae at high redshift radically changed our understanding of the Universe.

23. What problems of the standard ΛCDM cosmological model are inflation supposed to fix?

24. List the five events below in order from earliest to latest:

e^+/e^- annihilation, first structure, inflation starts, quarks confined, recombination

25. Give at least two reasons there might effectively be multiple universes. Would the low-energy physics in these multiple universes necessarily be the same?

Units and Constants	Physical Constants	Age of Universe	Temperature
$pc = 3.086 \times 10^{16}$ m	$k_B = 8.617 \times 10^{-5}$ eV/K	**Matter**	$T_0 = 2.725$ K
$eV = 1.602 \times 10^{-19}$ J	$k_B = 1.381 \times 10^{-23}$ J/K	$t = \dfrac{17.3 \text{ Gyr}}{(z+1)^{3/2}}$	**Mass Density**
$M_\odot = 1.989 \times 10^{30}$ kg	$\hbar = 6.582 \times 10^{-16}$ eV·s	**Radiation**	$\rho = g_{\text{eff}} \dfrac{\pi^2 (k_B T)^4}{30(\hbar c)^3 c^2}$
$y = 3.156 \times 10^7$ s	$\hbar = 1.055 \times 10^{-34}$ J·s	$t = \dfrac{2.42 \text{ s}}{\sqrt{g_{\text{eff}}}} \left(\dfrac{\text{MeV}}{k_B T} \right)^2$	
$G = 6.674 \times 10^{-11}$ m³/kg/s²	$\hbar c = 1.973 \times 10^{-7}$ eV·m		**Friedman Equation ($\Omega = 1$)**
			$H^2 = \frac{8}{3}\pi G \rho$

Part III: Calculation [100/120 points] (20 each)
PHY 310: Answer **five** of the following six problems
PHY 610: Answer **all six** of the following problems

26. Galaxy Carlsonii is edge on to us, and the velocity of the
    stars away from us is measured at various distances from
    the center, as shown at right.
    (a) How fast, approximately, is this galaxy moving away
        from us? What are the rotational velocities of the
        stars at distances of 5 kpc and 20 kpc from the
        center, relative to the center of the galaxy?
    (b) Find the total enclosed mass in $M_\odot$ within a radius
        of 5 kpc. Repeat at 20 kpc.
    (c) Does this galaxy show evidence of dark matter?
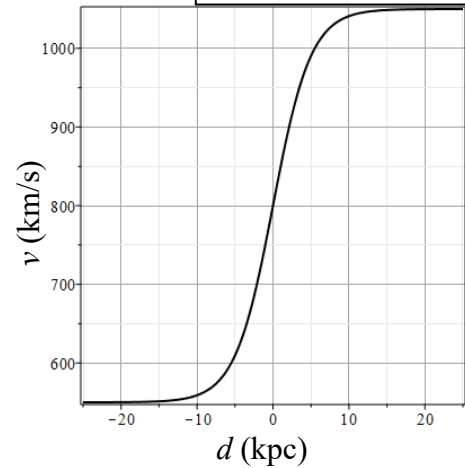
27. A muon is a particle with a mass of $mc^2 = 105.7$ MeV.
    One of the processes by which it can disappear in the early universe is decay $\mu^- \to e^- \nu \bar{\nu}$,
    which occurs at a rate $\Gamma = 4.55 \times 10^5 \text{ s}^{-1}$. This process can also occur in reverse.
    (a) At approximately what temperature $k_B T$ would we expect this particle to disappear, if it
        stays in thermal equilibrium? Is this in the radiation or matter-dominated era?
    (b) Not counting the muons, what is g_{eff} at this time? Include photons (boson with 2 spin
        states), electrons (fermions with 4 spin states) and neutrinos (fermions with 6 spin states).
    (c) What is the approximate time at this temperature? Use the g_{eff} you computed in part (b).
    (d) Is this process fast enough to keep it in thermal equilibrium with everything else?

28. The boiling point of liquid nitrogen is 77.36 K, and the density is 808 kg/m³.
    (a) What was the red-shift z at the time when the universe was at the temperature of the
        boiling point of liquid nitrogen? Was the universe matter or radiation dominated?
        Calculate the age of the universe at this time.
    (b) What was the temperature $k_B T$ in eV at the time the density of the radiation matched that
        of liquid nitrogen? Assume $g_{\text{eff}} = 3.36$ at this time. Was the universe matter or radiation
        dominated? Calculate the age of the universe at this time.

29. A long time ago in a galaxy far away, Han Solo measured the distance and red-shift to several galaxies. The values he found can be found at right
    (a) For all five galaxies, find the velocity in km/s.
    (b) Estimate the value of Hubble's constant using galaxies A–D in km/s/Mpc. One of the data points does not work very well; what probably went wrong for this galaxy?
    (c) Estimate the unknown distance to galaxy E.

Gal.	z	d (Mpc)	v (km/s)
A	0.0006	0.75	
B	0.0096	24.1	
C	0.0147	36.4	
D	0.0187	46.4	
E	0.0213		

30. In a certain fictitious universe, which is homogenous, expanding and flat like ours, astronomers measure the concentration of baryons, cosmological constant, and radiation as

$$\rho_{b0} = 9.60 \times 10^{-22} \text{ kg/m}^3, \quad \rho_{\Lambda 0} = 1.50 \times 10^{-23} \text{ kg/m}^3, \quad \rho_{r0} = 4.00 \times 10^{-24} \text{ kg/m}^3$$

In this universe, there are no neutrinos, and no dark matter.
    (a) Write a formula for the density of these three concentrations ρ_b, ρ_Λ and ρ_r at all times in terms of the red-shift factor $z+1$.
    (b) Find the value of z when (i) radiation equals baryons, (ii) baryons equals cosmological constant. In each case, did this occur in the past or in the future?
    (c) What is the Hubble constant H_0 and inverse Hubble time H_0^{-1} in y^{-1} and y respectively?

31. One way to make the $\Xi^?$ particle is to collide two protons head on with energy 1800 MeV each in the reaction $p^+ + p^+ \to \Xi^? + p^+ + K^+ + K^+$. This is a strong reaction, and all particles are made of combinations of up, down, and strange quarks or their anti-particles.

	Mass (MeV/c^2)	spin	strange	type
p^+	938	½	0	baryon
K^+	494	0	+1	meson

    (a) What is the baryon number, charge and strangeness of the $\Xi^?$? Is it a fermion or boson?
    (b) What is the maximum possible mass that the $\Xi^?$ particle could have in MeV/c^2?
    (c) What is the quark content of the $\Xi^?$?