December 15, 2023 Name ________________

Final Exam PHY 310/610

This test consists of three 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. The James Webb space telescope is focused on the infrared, and will probably be the best for observing extremely distant galaxies because
   A) These galaxies are often shrouded in dust, which infrared light will penetrate
   B) The stars in these galaxies are so cold they only emit infrared light
   C) We are unable to see stars at this distance, but we can detect H-I regions in infrared
   D) These galaxies are so red-shifted that their light will have shifted from visible to infrared
   E) We hope to see planets in these galaxies, and planets produce infrared light, not visible

2. Which force is responsible for holding the quarks together inside the protons and electrons?
   A) Weak B) Strong C) Gravity D) Electromagnetism E) Rubber bands

3. Which is believed to be the earliest stage in the evolution of the Universe?
   A) Planck era
   B) Nucelosynthesis
   C) Recombination
   D) Electron-positron annihilation
   E) Electroweak scale

4. The particle that carries the electromagnetic force is called the
   A) W boson B) Z boson C) Gluon D) Photon E) Graviton

5. Which process keeps neutrinos at the same temperature as everything else in the current universe?
   A) Collisions with photons
   B) Collisions with electrons
   C) Collisions with protons and neutrons
   D) The interactions with the Higgs field
   E) Nothing; they are not in thermal equilibrium with other particles

6. Our galaxy is probably of which classification?
   A) Elliptical B) Irregular C) Lenticular D) Spiral E) Barred spiral

7. The brightest main sequence stars have which spectral classification?
   A) A B) B C) F D) G E) O

8. At the center of our galaxy is a giant
A) Black hole B) Star C) Supernova D) Gas cloud E) Neutron star

9. The proton has baryon number +1, spin ½, and charge +1. The anti-proton has baryon number ___ spin ___ and charge ___
A) –1, –½, –1 B) –1, ½, –1 C) +1, –½, –1 D) –1, ½, +1 E) –1, –½, +1

10. Which of the following quarks might be found in a proton or neutron?
A) Top B) Bottom C) Charm D) Strange E) Down

11. The name of the galaxy cluster or group we live in is the
A) Andromeda B) Local group C) Laniakeia D) Coma E) Virgo

12. The largest galaxies are which classification?
A) Elliptical B) Irregular C) Lenticular D) Spiral E) Barred spiral

13. Which of the following was not one of the scenarios discussed as the reason why there is more matter than anti-matter in the universe?
A) GUT scale baryon violation
B) Supersymmetry combined with sphaleron conversions
C) Neutrino effects combined with sphaleron conversions
D) Left over baryons from the previous cycle of the universe
E) Actually, all of these were discussed

14. In the distant future, what is believed will be the largest contribution to the energy density of the universe?
A) Baryons B) Dark matter C) Dark energy D) Radiation E) None of these

15. If we knew both the angular size α (in radians) and the physical size s of an object, how could we find the distance d?
A) $d = \alpha s$ B) $d = \frac{\alpha}{s}$ C) $d = \frac{s}{\alpha}$ D) $d = \frac{1}{\alpha s}$ E) None of these

16. For small red-shifts, the relationship between radial velocity and red-shift is
A) $\frac{v_r}{c} = z + 1$ B) $v_r = \frac{z+1}{c}$ C) $\frac{v_r}{c} = z - 1$ D) $v_r = \frac{z-1}{c}$ E) $\frac{v_r}{c} = z$

17. Which of the following is a reason it might make sense to believe in multiple universes?
A) In chaotic inflation, a "universe" appears as a bubble, and it could happen again (only)
B) If the universe could be created from nothing, it could happen again (only)
C) In the many worlds interpretation of quantum mechanics, the universe can "split" into many different alternative realities that coexist simultaneously (only)
D) All of the above were discussed
E) None of the above were discussed

18. According to our best estimate, the current universe is about ___ billion years old
   A) 12.8 B) 13.8 C) 14.8 D) 15.8 E) 16.8

19. Inflation explains all of the following except
   A) Why the universe is so flat
   B) Why the universe is so similar everywhere (isotropic and homogeneous)
   C) Why there are more baryons than anti-baryons in the universe
   D) What the origin of the small fluctuations in the universe is
   E) Actually, it accounts for all of these

20. Photons are bosons with spin $g = 2$. But for some reason, I kept using $g_{\text{eff}} = 3.36$ when discussing recent events in the universe. What other particle is contributing to g_{eff}?
   A) Neutrinos B) Electrons C) Protons D) Gluons E) Higgs field

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. Qualitatively, list at least three aspects of how the Sun moves around our galaxy. For example, your answer might be, "It moves approximately in a square, but it goes a little faster on the top and bottom sides, and the corners are a little bit rounded, and it's tilted slightly compared to the galactic plane."

22. List the following five ingredients in order of contribution to the current mass/energy density of the universe, from largest contribution to smallest:

ordinary matter, dark energy, dark matter, electromagnetic radiation, neutrinos

23. Primordial nucleosynthesis is the buildup of simple nuclei from protons and neutrons. Why didn't this process occur much earlier, say just after quark confinement? Why weren't all the protons and neutrons incorporated into helium? Why didn't it go all the way to making heavy elements, ultimately ending in iron?

24. Suppose you are an up quark that existed from the beginning of time and you are lucky enough to survive all the way to the present day as helium. For each of the events listed below, tell me what you would become part of. Be careful to distinguish between nuclei and atoms as necessary. Some entries might have more than one correct answer; simply give one of the options.

Event	**Is part of**
Beginning	Up quark
Quark confinement	
Nucleosynthesis	
Recombination	
Structure formation	

25. List the following five events in the future in the correct order from first to last:

black holes evaporate, death of the Sun, killer asteroid, last stars born, matter decays

Units and Constants	**Physical Constants**	**Age of Universe**	**Distance / Magnitudes**
$\text{pc} = 3.086\times10^{16}\ \text{m}$	$k_B = 8.617\times10^{-5}\ \text{eV/K}$	Matter: $t = \dfrac{17.3\ \text{Gyr}}{(z+1)^{3/2}}$	$d = 10^{1+\frac{m-M}{5}}\ \text{pc}$
$\text{eV} = 1.602\times10^{-19}\ \text{J}$	$k_B = 1.381\times10^{-23}\ \text{J/K}$	Radiation: $t = \dfrac{2.42\ \text{s}}{\sqrt{g_{\text{eff}}}}\left(\dfrac{\text{MeV}}{k_B T}\right)^2$	$m - M = 5\log(d) - 5$
$M_\odot = 1.989\times10^{30}\ \text{kg}$	$\hbar = 6.582\times10^{-16}\ \text{eV}\cdot\text{s}$	**Temperature**	**Quark Charges**
$\text{y} = 3.156\times10^{7}\ \text{s}$	$\hbar = 1.055\times10^{-34}\ \text{J}\cdot\text{s}$	$T_0 = 2.725\ \text{K}$	Up: $\frac{2}{3}$, Down: $-\frac{1}{3}$
$G = 6.674\times10^{-11}\ \text{m}^3/\text{kg/s}^2$	$\hbar c = 1.973\times10^{-7}\ \text{eV}\cdot\text{m}$		Strange: $-\frac{1}{3}$

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. The muon is a spin ½ particle with four total spin states with a mass of 105.7 MeV/c^2.
    (a) What was the approximate temperature $k_B T$ at the time when the muon disappeared? Would this have been in the matter or radiation dominated era?
    (b) The other particles around at this time were the electrons (spin ½, 4 spin states), the neutrinos (spin ½, 6 spin states) and the photons (spin 1, 2 spin states). What was the value of g_{eff}, if we also include the muon?
    (c) How old was the universe at this time? The muon decays at a rate $\Gamma = 4.55\times10^{5}\ \text{s}^{-1}$. Would this decay have kept the muon in thermal equilibrium?

27. You might think the universe is transparent to *all* photons, but this is not necessarily the case. A pair of photons colliding head-on can create an electron/positron pair, $\gamma\gamma \to e^+e^-$, if the energy of the two photons satisfies the inequality $E_1 E_2 > (m_e c^2)^2$, where $m_e c^2 = 0.511\ \text{MeV}$.
    (a) The universe has a thermal bath of photons at temperature $T = 2.725$ K and a number density of $n = 4.11\times10^{8}\ \text{m}^{-3}$. What is the typical energy of a CMBR photon in eV?
    (b) What is the minimum energy E_2 such that a photon of this energy can pair create by hitting a cosmic ray photon?
    (c) For the purpose of this problem, assume the cross-section is $\sigma = 7.94\times10^{-30}\ \text{m}^2$. What is the rate at which a high energy photon will collide with a background photon, in s^{-1}?
    (d) On what time scale t in years will such a photon undergo on average one collision? Compare with the time it takes photons to cross our galaxy, about 10^5 y.

28. I don't know about you, but I like temperatures around $T = 295$ K. What was the universe like when it was at this temperature?
    (a) Is this during the radiation or matter dominated eras? What was the value of the red-shift z at this time? What was the average energy of a photon, in eV?
    (b) How old was the universe at this time?
    (c) At present there are about 0.250 baryons/m^3. What was the density of baryons then? Assume each baryon corresponds to a hydrogen atom with mass 1.674×10^{-27} kg. What was the mass density of baryons at that time?

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29. One of the isotopes that is produced in primordial nucleosynthesis is ^{7}Be. **In the laboratory**, ^{7}Be decays to ^{7}Li with a mean lifetime of 76.78 days (day = 86,400 s).
   (a) Is 76.78 days after the era of nucleosynthesis? When the universe was 76.78 days old, was this in the matter or radiation dominated era?
   (b) What is the temperature $k_B T$ at this time in eV? If you need it, use $g_{eff} = 3.36$.
   (c) The binding energy of a single electron in a beryllium atom is about 218 eV. Would a typical photon have enough energy to dissociate a beryllium atom by removing the electron?
   (d) In the laboratory, the decay occurs via electron capture, where a **bound** electron is captured by the nucleus, so $^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu$. Explain why it is likely that ^{7}Be lasts longer in the early universe than in the laboratory.

30. Several rich galaxy clusters are measured, and the apparent magnitude of the brightest galaxy is also measured, as shown in the table. In some cases the distance is known.
   (a) For clusters *A*, *B*, and *C*, find the absolute magnitude of the brightest galaxy.
   (b) Is the brightest galaxy in a galaxy cluster a standard candle? Why or why not?
   (c) Estimate the distance to cluster *D*.

Clus-ter	*d* (Mpc)	*m*	*M*
A	35	10.22	
B	137	13.18	
C	1200	17.90	
D		21.53	

31. The Ω^- is a baryon with mass 1672 MeV/c^2 and strangeness –3. Its most common decay is $\Omega^- \rightarrow \Lambda^0 K^?$, where Λ^0 and $K^?$ each have strangeness -1, the Λ^0 has a mass of 1116 MeV/c^2, and the $K^?$ is a meson.
   (a) Is the Λ^0 a baryon, an anti-baryon, or a meson?
   (b) What is the charge of the $K^?$? What is its maximum possible mass?
   (c) Is this interaction, strong, weak, or electromagnetic?
   (d) Only up, down, and strange quarks (or their anti-quarks) are found in these three particles. What is the quark composition of each of these particles?