

December 11, 2021

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. The value of the Ω at very early times (at least after inflation) is closest to which number?
A) 0.003 B) 0.999 C) 1.000 D) 1.001 E) 1.953
2. The particle that carries the strong force between quarks is called a
A) W boson B) Z boson C) Gluon D) Photon E) Graviton
3. When we look at the cosmic microwave background, we are seeing the universe at the time of what event?
A) Nucleosynthesis B) Big bang C) Inflation D) First structure E) Recombination
4. Which of the following spectral classes of stars would be coolest?
A) A B) B C) F D) O E) M
5. Galaxies that have undergone recent collisions are most likely to be
A) Elliptical B) Spiral C) Barred Spiral D) Irregular E) None of these
6. The name of the galaxy we live in is
A) Milky Way B) Andromeda C) Local group D) Laniakea E) Virgo
7. The largest contribution to the mass density today is _____ and second largest is _____.
A) Dark matter, baryons
B) Dark energy, dark matter
C) Dark energy, baryons
D) Dark matter, dark energy
E) Baryons, dark matter
8. A very reliable method to measure the distance to some of the nearest stars is
A) Radar distancing
B) Parallax
C) Cepheid variable stars
D) Type Ia supernovae
E) Hubble's law
9. Active galaxies are believed to have which object generating the energy at the center?
A) Supernova B) Star C) Globular cluster D) Hot nebula E) Black Hole

10. Which of the following is important for something to make an ideal standard candle?
- A) It must be consistently the same luminosity (only)
 - B) It must be bright enough to see at long distances (only)
 - C) It must always be at the same distance from us (only)
 - D) A and B are correct, but not C
 - E) A, B, and C are all correct
11. From our perspective, almost all galaxies seem to be moving away from us with a speed proportional to their velocity. If we were looking at things sitting on a distant galaxy we would see almost all the galaxies moving
- A) Away from us
 - B) Towards us
 - C) Past us
 - D) Not moving
 - E) None of these
12. Gravity should become as strong as other forces at approximately the time of
- A) Planck scale
 - B) Electroweak scale
 - C) GUT scale
 - D) Quark confinement
 - E) Recombination
13. The Sun, in addition to going around the galaxy in a circle, also does which of the following?
- A) Moves alternately inwards/outwards from its current position (only)
 - B) Occasionally reverses its direction, going around the other way (only)
 - C) Bobs up and down compared to the galactic plane (only)
 - D) A and B are correct, but not C
 - E) A and C are correct, but not B
14. 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
15. Which of the following is *not* explained by inflation?
- A) Why the universe is almost perfectly flat
 - B) Why there is more matter than anti-matter in the universe
 - C) Why the universe is approximately the same in all directions (isotropic)
 - D) Why the universe is approximately the same at all locations (homogenous)
 - E) Where the small fluctuations in the density come from
16. Shortly after the time of quark confinement, the quarks and anti-quarks annihilated. How come there are any leftover quarks today?
- A) The quarks and anti-quarks became segregated, so other places have anti-quarks
 - B) The annihilation was not equal, so more anti-quarks were destroyed than quarks
 - C) They *were* all annihilated, but later processes made more quarks
 - D) There must have been a tiny excess of quarks over anti-quarks at the time
 - E) Santa Clause used his magic bag to deliver more quarks for Christmas

17. About how old was the universe when electrons and positrons annihilated?
A) 10^{-42} s B) 10^{-6} s C) 20 s D) 57,000 y E) 6×10^8 y
18. What method can sometimes be used to determine the mass of a cluster of galaxies?
A) Gravitational lensing; observing how it bends light from objects behind the cluster
B) Estimating the mass of each galaxy from rotation curves and adding them up
C) Calculating the orbital speed of galaxies circling the cluster
D) Counting the number of black holes and multiplying by the mass of one black hole
E) Measuring the gravitational red shift from galaxies near the center of the cluster
19. Which of the following was suggested as a possible reason to believe in multiple universes?
A) Many Worlds interpretation of quantum mechanics (only)
B) Spontaneous creation of the universe (only)
C) Chaotic/Eternal inflation with “pockets” resulting in multiple universes (only)
D) All of the above
E) None of the above
20. Which force is *not* currently explained by particle physics
A) Weak force
B) Gravity
C) Strong force
D) Electromagnetism
E) Actually, all of them are explained by particle physics

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 how measuring rotational velocities of spiral galaxies can be used to indicate the existence of dark matter in galaxies. In particular, how would these rotational velocities look different if there were no dark matter?

22. Explain at least two reasons why Hubble's Law $v = H_0 d$ does not work very well at very *high* red-shifts/velocities

23. There were lots of protons and neutrons present in the early universe. Why didn't they just immediately bond together to make heavier nuclei? Once they did bond together, what isotope did they mostly combine to make? Why was there any hydrogen left over at the end?

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

electroweak scale, first structure, matter/radiation equality, nucleosynthesis, Planck era

25. Give a list of five significant events that are expected to happen in the distant future (more than ten billion years from now).

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

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 top quark is the heaviest particle in the standard model, with a mass of $m = 173 \text{ GeV}/c^2$.
- What was the approximate temperature $k_B T$ at the time when the top quark disappeared? Would this have been in the matter or radiation dominated era?
 - The fermions that were around at this time would have been the other quarks (12 spin states each for up, down ...) and the leptons (18 total spin states). The bosons would have been the Higgs, W^{\pm} , Z , gluons, and photon (28 total). What was the value of g_{eff} ?
 - How old was the universe at this time? The top quark decays at a rate $\Gamma = 2.0 \times 10^{24} \text{ s}^{-1}$. Would this decay have kept the top quark in thermal equilibrium?
27. In class we assumed that matter was gathered into galaxies at a late event, but could it have happened at the time of nucleosynthesis, $t = 200 \text{ s}$?
- Would this have been during the matter or radiation dominated eras? What was the temperature at this time? If you need it, assume the current value of $g_{\text{eff}} = 3.36$.
 - By what factor has the universe grown since this time?
 - The Andromeda galaxy is currently approximately 760 kpc away. How far away would it have been at this time, in m, if it existed then?
 - Assume that at nucleosynthesis, the baryons were somehow gathered together at the speed of light. How far could they have traveled at the time of nucleosynthesis? Comparing with answer (c), could baryons have separated on the scale necessary to form galaxies at this time?
28. The current mass density of radiation, matter, and cosmological constant (in atomic mass units u) are roughly

$$\rho_{m0} = 1.599 \text{ u}/\text{m}^3, \quad \rho_{\Lambda 0} = 3.593 \text{ u}/\text{m}^3, \quad \rho_{r0} = 4.697 \times 10^{-4} \text{ u}/\text{m}^3$$

The neutrinos have been included in the radiation in an appropriate manner.

- Write a formula for the density of these three concentrations ρ_m , ρ_{Λ} and ρ_r at all times in terms of the red-shift factor $z+1$.
- Find the value of $z+1$ when the radiation equals the cosmological constant. At that time, find the density of the matter, cosmological constant, and radiation. What dominated the universe?
- How old was the universe at this time?

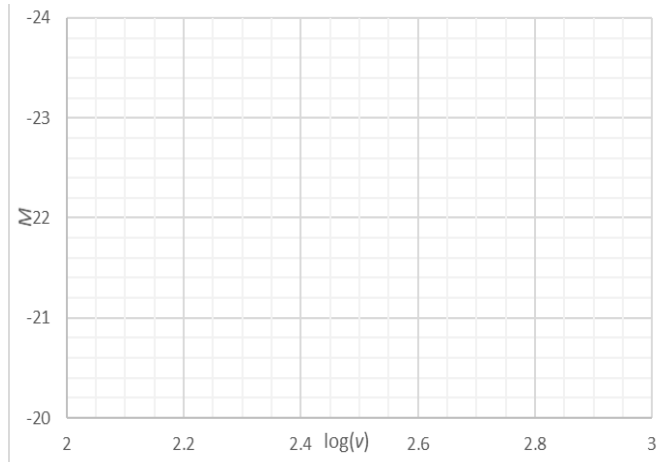
29. Are the primordial neutrinos currently in thermal equilibrium? Assume neutrinos are massless, have a number density of $3.36 \times 10^8 \text{ m}^{-3}$, and a temperature of $T_\nu = 1.945 \text{ K}$. The cross section for two particles to interact weakly are typically given by $\sigma = AE_1E_2$ where $A = 4.85 \times 10^{-60} \text{ m}^2 \cdot \text{eV}^{-2}$ and E_1 and E_2 are the energies of the two particles.

- What is the typical energy of a neutrino at this temperature?
- Find a typical cross-section for neutrino-neutrino scattering.
- Since we assumed neutrinos are massless, what is their velocity? Find the rate for neutrino-neutrino scattering today. You can use any appropriate approximation for the relative velocity $|\Delta v|$.
- Based on the approximate age of the universe today, how many scatterings of this type will a typical neutrino have undergone? Will this process keep it in equilibrium?

Galaxy	v km/s	$\log(v)$	M
A	123		-20.64
B	332		-23.66
C	275		-23.03
D	191		-21.93

30. The Tully-Fisher relationship is a relationship for spiral galaxies between the asymptotic rotational velocity v and the absolute magnitude M of the galaxy.

- Calculate $\log(v)$ for each of the galaxies listed. Then plot $\log(v)$ vs. absolute magnitude M . You may put your answers directly on the provided table and chart.
- Explain roughly why the Tully Fisher relationship might be a good distance indicator. A trend line on the graph might help.
- Galaxy X is a spiral galaxy with rotational velocity $v = 250 \text{ km/s}$ and apparent magnitude $m = 12.03$. Estimate the distance to galaxy X .



31. The Σ^0 baryon almost always decays to two neutral particles chosen from the following list:

$$\bar{K}^0 \pi^0, \Lambda^0 \nu, \Lambda^0 \gamma, n^0 \gamma, n^0 \bar{K}^0$$

- Which of these are impossible? For those that are possible, classify them as strong, weak, or electromagnetic.
- Which one is probably the most likely to occur?
- All of the baryons and mesons listed have only up, down and strange quarks and/or their anti-quarks. Which quarks or anti-quarks make up the Σ^0 ?

	Mass (MeV/c ²)	spin	strange	type
Σ^0	1192	$\frac{1}{2}$	-1	baryon
Λ^0	1116	$\frac{1}{2}$	-1	baryon
n^0	938	$\frac{1}{2}$	0	baryon
π^0	135	0	0	meson
\bar{K}^0	498	0	-1	meson
ν	0	$\frac{1}{2}$	0	neutrino
γ	0	1	0	photon