Section A (69 points)

1. C	2. B	3. A	4. B	5. A	6. D
7. B	8. A	9. B	10. A	11. D	12. B
13. D	14. B	15. C	16. D	17. B	18. A
19. C	20. B	21. A	22. B	23. D	24. D
25. B	26. C	27. A	28. B	29. A	30. B
31. D	32. B	33. C	34. A	35. C	36. A
37. A	38. C	39. D	40. A	41. C	42. B
43. C	44. A	45. A	46. B	47. B	48. B
49. B	50. B	51. C	52. D	53. A	54. B
55. A	56. A	57. D	58. A	59. A	60. B
61. A	62. C	63. C	64. C	65. B	66. D

Section B (66 points)

1. C 2. D 3. B 4. A 5. C 6. B

7. A 8. D 9. D 10. A 11. D 12. A

13. 1.6×10^{47} J

14. C 15. A

16. There are absorption lines for various elements in the spectrum of H2356-309 (at the same redshift as the Sculptor Wall), meaning the light had to mass through some structure on its way to earth.

17. B 18. A 19. C 20. D

21. The cluster environment has a powerful role in galaxy quenching.

22. D 23. C

24. There might be previously unknown dust and gas that obscures this light. However, the results of this survey match other studies, which would not be affected by this gas and dust.

25. Bullet Cluster (IE 0657-56)

26. Image 2 (X-ray), Image 10 (Optical)

27. The highlights show where most of the mass is. This was measured by observing gravitational lensing.

28. Two galaxies collided with each other. Most baryonic/normal mass was slowed down by interacting with the mass from the other galaxy and thus is in the middle of the cluster. Because dark matter only interacts with baryonic/normal matter gravitationally, its velocity was not slowed as much, so the dark matter from both galaxies continued past the center. Most of the observable radiation is produced in the center, near the baryonic/normal matter.

29. Because a large amount of the mass of the cluster is spatially separated from where most of the radiation (and thus luminous matter) is coming from, we know there must be a large amount of nonluminous matter (aka dark matter).

Section C (158 points)

1. (a) 8 AU
   (b) 8 $M_\odot$
   (c) 6 $M_\odot$
   (d) 2.3×10^5 $\mathrm{m\,s^{-1}}$
   (e) 0.5

2. (a) It explained that the viewing angle of the AGN would result in a different observation.
   (b) At the center of the AGN is a supermassive black hole which accretes matter from an accretion disk surrounding it. Further out is a large dust torus which obscures the SMBH, absorbing its radiation and radiating it out in infrared. Perpendicular to the dust torus is a jet which shoots out relativistic particles accelerated by synchrotron radiation.
   (c) A: jet, B: dust torus
   (d) E
   (e) $535 \in [450, 650]$ pc

3. (a) A
   (b) A (1 pt). The linear regression is easy to spot, so we're left between A and C. We note the differing behavior at $x = 0$. For a power regression, we first notice that $b < 0$, as the function levels out as t increases. The equation is thus $M = at^{-|b|} + c$, which clearly goes to infinity as $t \to 0$. For the exponential though, we have $M = ae^{b \cdot 0} + c = a + c$. Most crucially, the slope near $t = 0$ is always finite, and so the graph with the steeper slope there must be the power regression. 2 points for having the right idea with the explanation.
   (c) The linear regression only has two parameters, whereas the power and exponential ones have three. Thus, the linear regression has fewer degrees of freedom, and thus would have more difficulty fitting a given set of data.

4. (a) C
   (b) 24.3 Mpc
   (c) A
   (d) 1.1×10^{55}
   (e) 32 %
   (f) 2.0×10^{42} J

5. (a) 3.9×10^{-4} $R_\odot$
   (b) 8.4×10^{35} Pa
   (c) As mass increases, gravity eventually dominates over neutron degeneracy pressure. The pressure required to support the object would result in a violation of the Pauli Exclusion Principle.
   (d) The centrifugal force assists neutron degeneracy in countering gravity.

Section C cont. (158 points)

6. (a) The cosmic censorship hypothesis essentially states that singularities must always be cloaked by event horizons, while the "no hair" theorem states that the only three observable properties of black holes are mass, charge, and spin (angular momentum).
   (b) 10^{-8} kg
   (c) 8.8×10^{41} $\mathrm{kg\,m^2\,s^{-1}}$
   (d) Disk-shaped; outward pressure due to centrifugal force of rotation exceeds inward gravitational pull; something falling in would need to add enough angular momentum.

7. (a) B
   (b) B
   (c) 40 Mpc
   (d) 2.74 $\mathrm{km\,s^{-1}}$
   (e) B
   (f) A: 40 Mpc B: 8.4 Mpc
   (g) $\alpha = 4.5$, $\beta = -9.6$

8. (a) 500 Mpc
   (b) 500 Mpc
   (c) 500 Mpc
   (d) 1000 Mpc
   (e) $z = \frac{1}{a(t_e)} - 1$
   (f) 12.09
   (g) $H(t) = \frac{da/dt}{a}$
   (h) $\frac{2}{3H}$
   (i) 9.3 Gyr Not consistent.
   (j) No, it is dark energy dominated.