Homework

1. **Hubble.**
   (a) What did Edwin Hubble observe in 1929 and how did he observe this. Be as specific as possible and sketch a graph of his data, with clearly labeled x and y axes and units given for both axes. Explain what the graph your means (especially the slope) and how it was measured. (Keep it brief. No BS please.)
   (b) How did Hubble determine that the spiral nebulae Andromeda was extragalactic?

2. Go to `http://www.atlasoftheuniverse.com`. What is the distances for the following things in light years.
   (a) The Barnard Star. (This star has the largest proper motion)
   (b) The Hyades Cluster. (Important for parallax measurements)
   (c) The Milky Way.
   (d) The Large Magellanic Cloud. (Important for calibration for Cepheids by Henrietta Swan Leavitt. Can see it by eye.)
   (e) The Andromeda galaxy. (Hubble showed that there were galaxies outside the milky way with this cluster)
   (f) The Coma Cluster. (Maximum distance Hubble measured)
   (g) The Pisces-Cetus Supercluster. (Read about this one online)
   (h) The end of greatness.

3. **Quasars and Reionization.** Quasars (Quasi-Stellar Objects) are believed to be nascent galaxies. These quasars are observed at redshifts $z \simeq 6$ and beyond. The observed emission spectrum from distant quasars changes dramatically around $z = 6$. This is thought to be due to the fact that at around $z = 6$ galaxies formed and merged creating hot ionized gas of electrons, protons, and photons, *i.e.* reionized plasma. Using the graphs for $a(t)$ and $r_*(t)$, determine when the light from a $z = 6$ Quasar was emitted. Determine the corresponding comoving distance $r_*(t)$ in light years. You will need to increase the magnification (with adobe acrobat) of Fig 3 to get a good read.

4. **Distances in the universe.** Using the distances determined in problems two and three (*i.e.* r_* in problem three), record all of these distances on a logarithmic plot in Fig 5, labelling each object.

5. **Supernovas.**
   (a) What is the progenitor of a Type Ia supernova? Explain how this progenitor turns into a supernova explosion.
   (b) Explain two features of Type Ia supernova's that make them excellent standard candles.

6. **Black Body Radiation.** A hot plasma (such as exists on the surface of the sun) is at a temperature of 3000^o K.

   (a) What is the typical kinetic energy of an electron in such a plasma in electron volts. Assuming that this energy is entirely kinetic determine the typical speed of an electron in m/s. Also give your answer in units of the speed of light, v/c, to verify that the electron is non-relativistic $v \ll c$. (Reminder: the kinetic energy is related to the mass and velocity by $E = \frac{1}{2}mv^2$.)

   (b) What is the typical value of the energy of a photon in the plasma (in electron volts!).

   (c) What is the wavelength of such a photon in nanometers.

7. **Recombination.** Assume that electrons and protons recombined at a temperature of 3000^o K, to make Hydrogen and Helium. After recombination, the black-body radiation flies freely until it is observed

   (a) What was the scale factor $a(t)$ at the moment of recombination. (Hint: What is the observed temperature today? How are the observed temperatures today related to the temperature at recombination.)

   (b) Fig 2 shows the scale factor as a function of time since the big bang on a logarithmic scale for both the x and y axes. From the graph, estimate the time after the big bang that recombination took place. Explain, how you arrived at this time estimate.

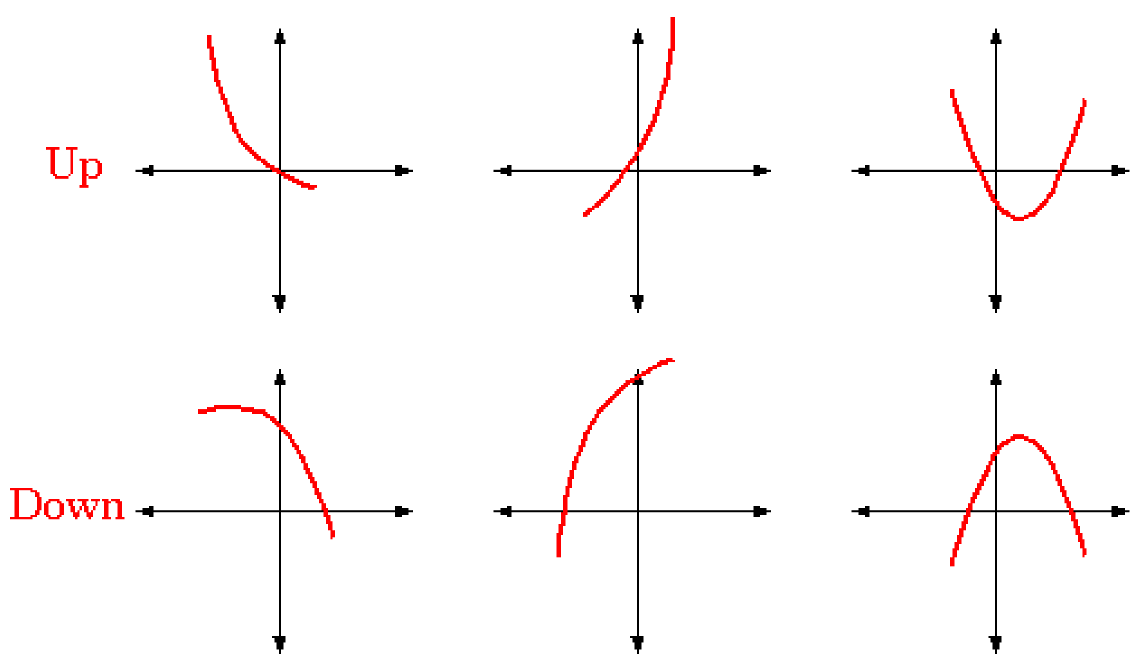
8. **The best fit cosmology.** Given the z of a supernova, and a theoretical model for the expansion history of the universe $a(t)$, one can predict the luminosity distance. This can be compared to experiment. If the $a(t)$ is correct then the result will agree with measured supernova data. In class we studied a decelerating $a(t)$. Here we will a more realistic $a(t)$.

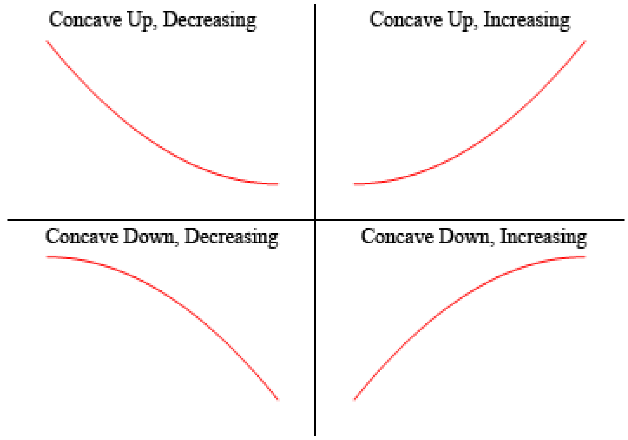
   (a) Given three supernova's observed at redshifts of $z = 0.5, 1.0$ and 1.4 (as in class) determine the quantities in this table, the scale factor at the time of emission, the time that the light was emitted, the distance from earth when it was emitted, the distance of the remains today (the coordinate distance), the luminosity distance and $\frac{H_o D_L}{c\,z}$, filling in this table. The attached graphs can be useful. Please work as accurately as possible.

z	0.5	1.0	1.4
$a(t_e)$			
t_e in Gy			
$d_*(t_e)$ in Gly			
$r_*(t_e)$ in Gly			
D_L^{th} in Gly			
$\frac{H_o D_L}{cz}$			

(b) Plot your three data points on the attached graph of luminosity distance $H_o D_L/cz$ versus distance in Fig 4.

(c) The $a(t)$ that can be extracted from supernova cosmology is shows a period of deceleration followed by a period of acceleration. On a graph of distance versus time, deceleration can be seen as a curve which is concave down ("mouth" of curve bending down), while acceleration can be seen as a graph which is concave up ("mouth" of curve bending up). To understand what concave up and down mean look at the following figures:





Examining the graph of distance versus time (the red lines in Fig 3), estimate how many years after the big bang, the universe switched from decelerating to accelerating.

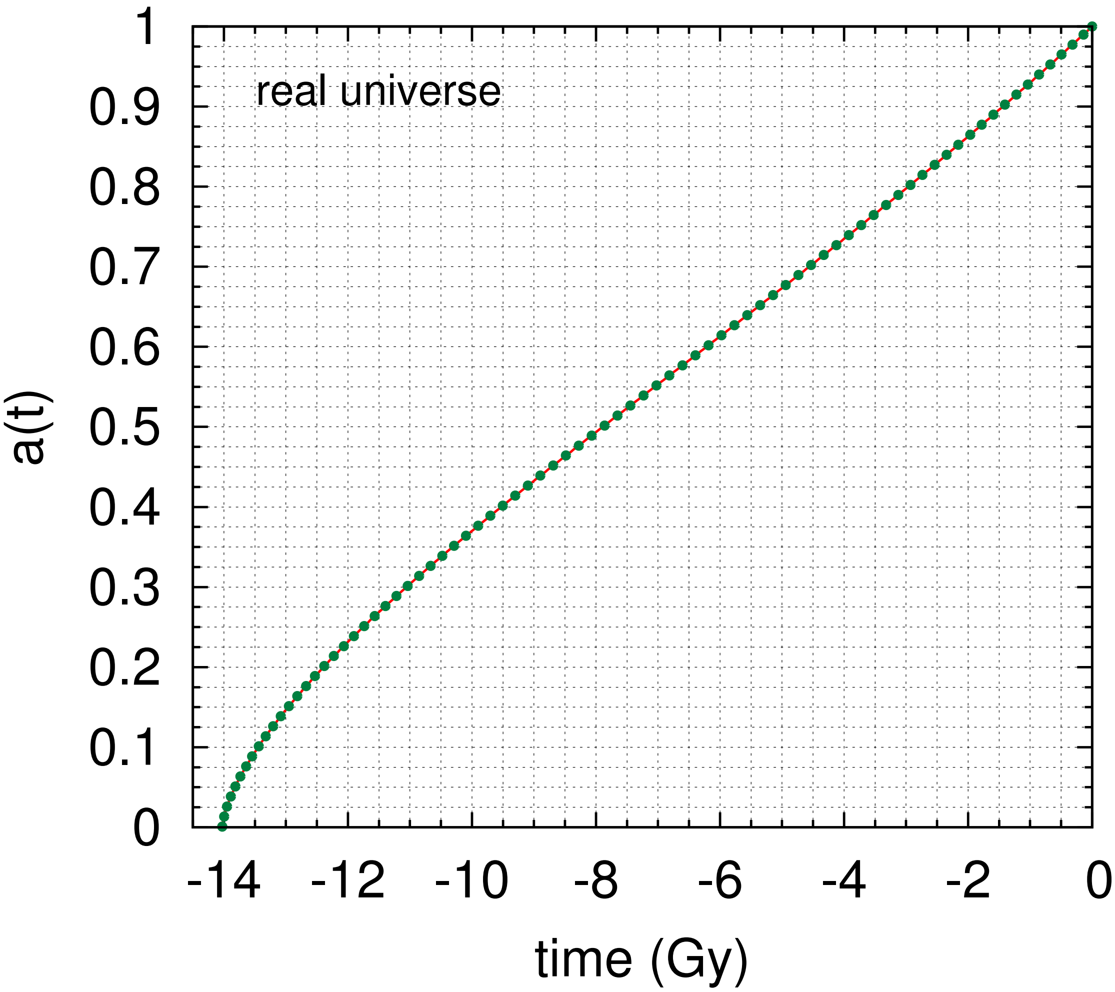


Figure 1: $a(t)$ for the real universe given current best estimates from the Supernova data and the cosmic microwave background

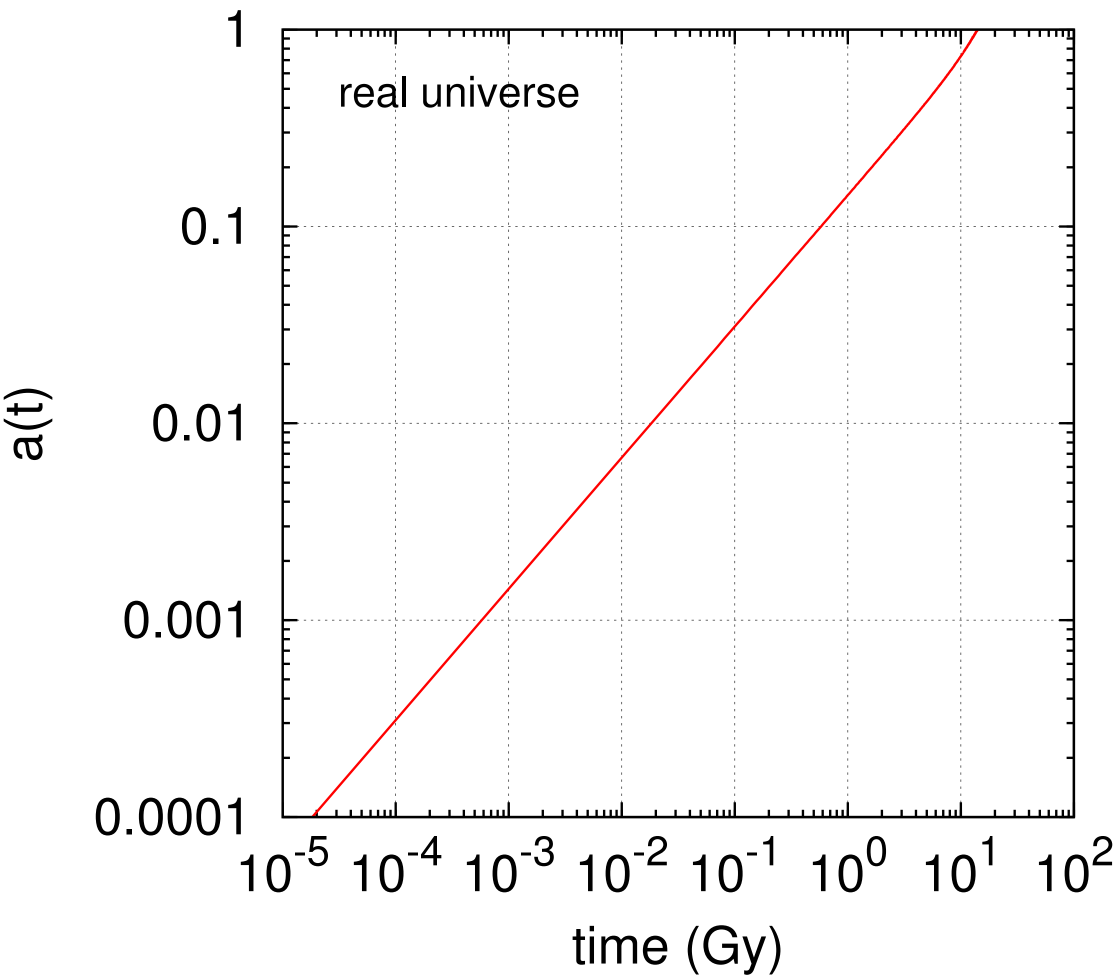


Figure 2: This is the same graph of $a(t)$ for the real universe given current best estimates from the Supernova data and the cosmic microwave background, but plotted using a logscale for the y and x axes.

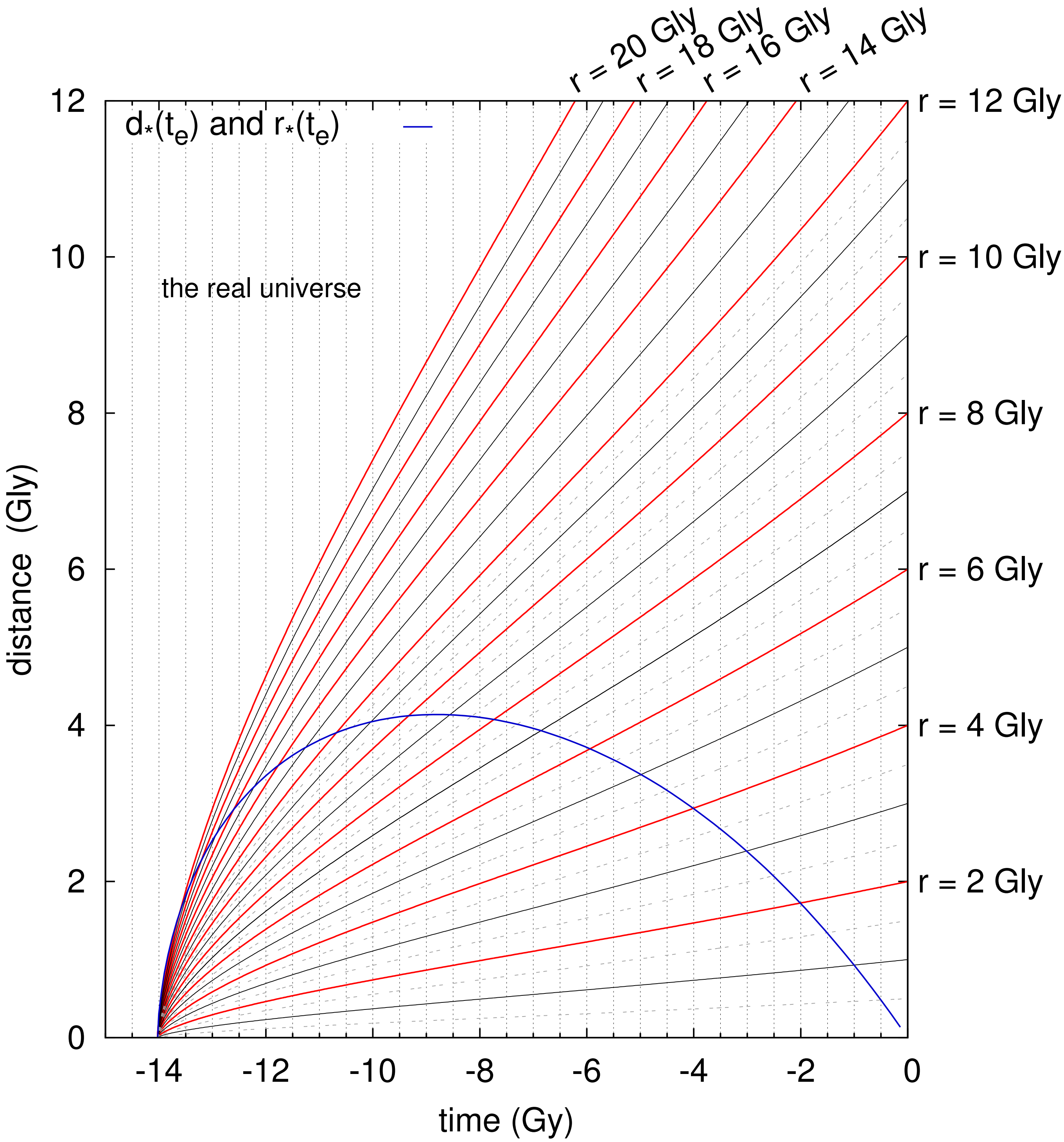


Figure 3: A graph of $r_*(t_e)$ for a realistic expansion

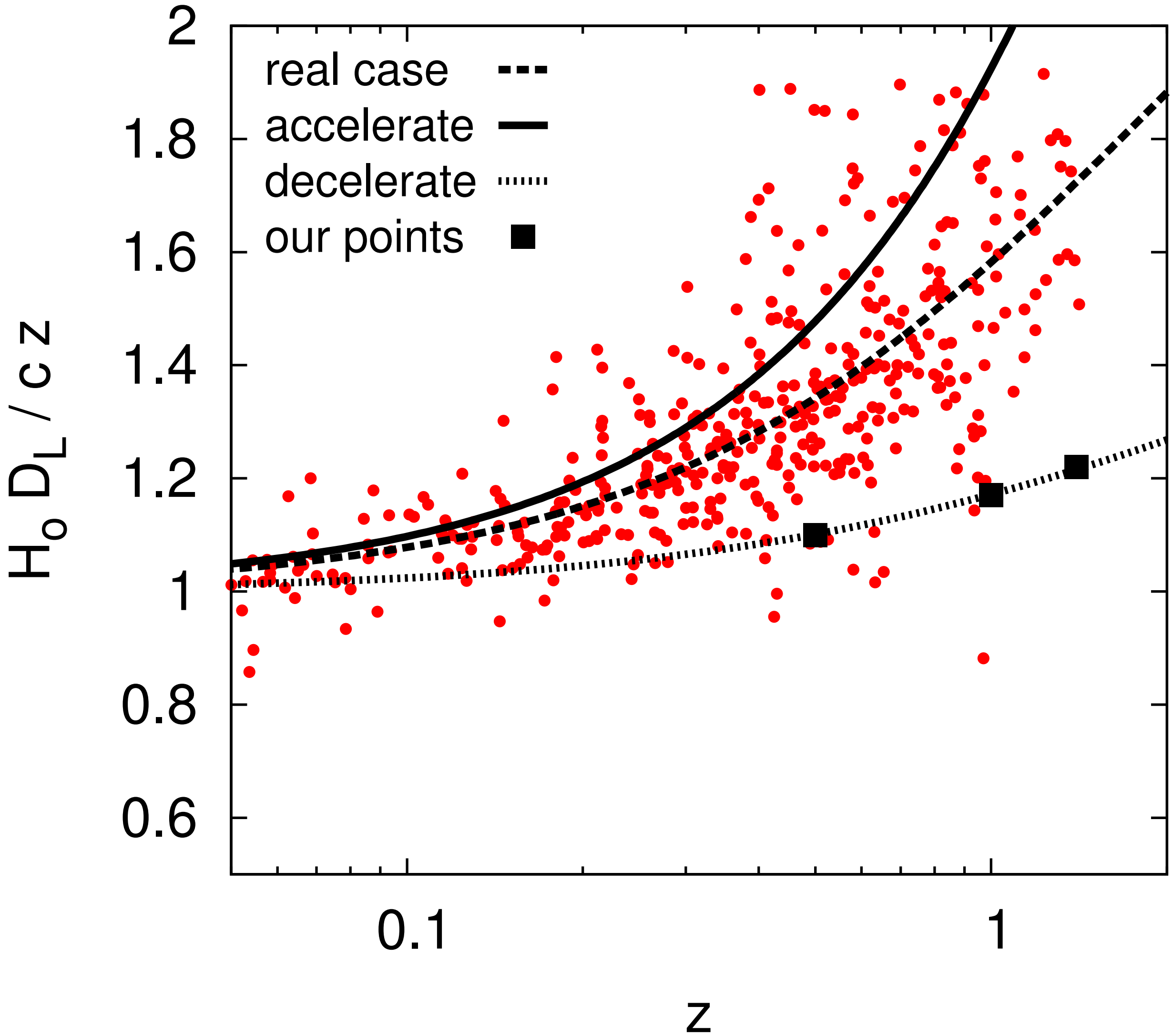


Figure 4: A graph of supernova data for $H_o D_L/(cz)$ vs. z. Note that the x axis is on a log scale. "our points" were worked out in class. and have redshits (z) of $0.5, 1, 1.4$, which can help you place your points on the x axis appropriately.

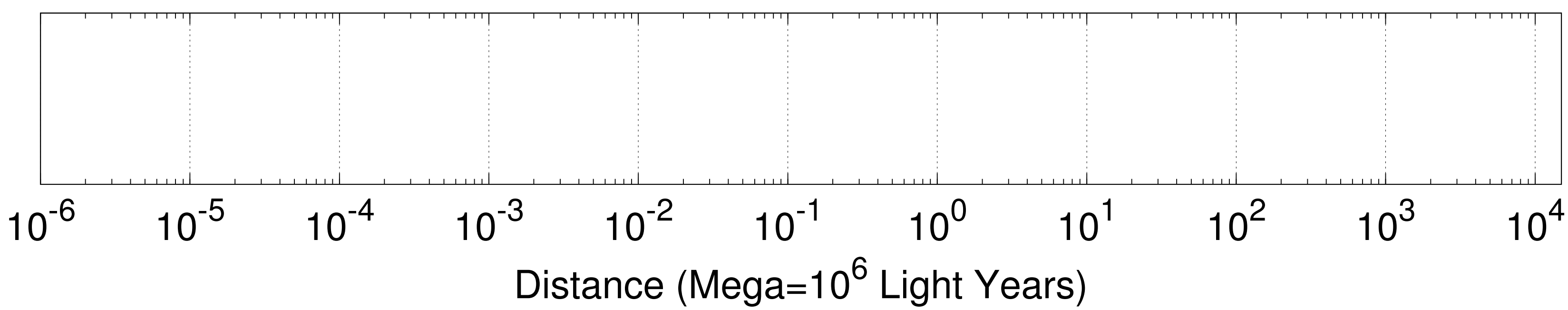


Figure 5: Do your homework on this graph!