General Relativity Ph236c
Problem Set 5
Due: In class, May 15, 2007

Suggested Reading: Sections 8 and 9 in astro-ph/0403392. Also, read through "Anisotropies in the cosmic microwave background: an analytic approach," by W. Hu and N. Sugiyama, Astrophys. J. 444, 489 (1995) [arXiv:astro-ph/9407093].

1. Exercise 13 in the suggested reading (astro-ph/0403392).

2. In the first quarter, we showed that the Einstein angle (the angular size of the Einstein ring) for lensing by a point mass is

$$\theta_E = \sqrt{\frac{4GMd_{LS}}{d_S d_L \theta}},$$

where M is the mass of the deflector, and d_S and d_L are the distances to the source and lens, respectively, and the lens-source distance is d_{LS}. In quarter 1, we considered only lensing in a background Minkowski spacetime. Show that in a FRW Universe, the Einstein ring radius is the same, except that the distances are now angular-diameter distances.

3. For this problem, you will find, download, compile, run, and play around with publicly available software to produce CMB temperature and polarization power spectra (the C_l's). There are two packages available to produce these power spectra. They are called `CAMB` and `CMBFAST`. Although CMBFAST came first, I think that CAMB might be now more widely used.
   a. Using google or anything else you can think of, find, download, and compile one of these programs.
   b. Figure out how to run the program to produce temperature and polarization power spectra for both density perturbations and gravitational waves.
   c. See if you can reproduce (more or less) curves that look like those in Figs. 7 and 8 in astro-ph/0403392—i.e., you should be able to produce temperature ($C_\ell^{\rm TT}$) power spectra for density perturbations and for gravitational waves; gradient polarization power spectra ($C_\ell^{\rm GG}$ or $C_\ell^{\rm EE}$) for density perturbations and for gravitational waves; and a curl polarization power spectrum ($C_\ell^{\rm CC}$ or $C_\ell^{\rm BB}$) for gravitational waves.
   d. Search for a 2006 WMAP paper by Spergel et al. for the best values of the cosmological parameters from WMAP 3-year data, and then produce a density-perturbation temperature power spectrum for these best-fit models.
   e. Now re-run CMBFAST or CAMB, changing slightly each of the following parameters, one by one, holding all other parameters fixed: (i) $\Omega_{\rm cdm}h^2$, the dark-matter density; (ii) $\Omega_b h^2$, the baryon density; (iii) h the Hubble parameter; (iv) $\Omega_{\rm total}$, the total density; (v) n_s, the scalar spectral index; and (vi) τ, the optical depth to the surface of last scatter. Try to understand why the temperature power spectrum changes

as it does as you change each of these parameters. The Hu-Sugiyama article listed above may help.