Astronomy 401/Physics 903
Lecture 28
Observational Cosmology I: Type Ia Supernovae and the Accelerating Universe

Values of the various cosmological parameters (the density parameters for different components of the universe, the Hubble constant, etc) are measured in many different ways. We will discuss two that are particularly important: measurement of the acceleration of the universe from Type Ia supernovae, and measurement of anisotropies in the CMB.

1 Type Ia supernovae lightcurves

As we've already discussed, Type Ia supernovae can be used as a standard candle to measure very large extragalactic distances; Type Ia SNe have now been seen as far as redshifts$z \sim 2.5$ (e.g. Rodney et al. 2014, *AJ*, 148, 13). A Type Ia supernova is the explosion of a white dwarf star, caused by the merger of two white dwarf stars or a CO white dwarf that accretes material from a companion, causing it to explode.

Type Ia supernovae are useful because they are very bright and because their brightnesses and light curves (a plot of luminosity vs. time) are similar. Their luminosities aren't identical, however, and some corrections are required before they can be used as standard candles. What we actually measure is the brightness of the supernova at various points in time, and there is a well-defined inverse correlation between the maximum luminosity and the rate of decline of the light curve: brighter supernova take longer to decline. We can use this to determine the intrinsic peak luminosity. The light from the supernova is also affected by dust in the host galaxy, which can be understood and corrected for by observing the light curve in several filters. Once these corrections are made, the light curves become nearly identical, as shown in Figure 1.

2 Type Ia supernovae and the cosmological constant

Because Type Ia supernovae are visible to such large distances, they are useful in constraining the cosmological parameters Ω_m and Ω_Λ. To see how this works, we can look at how the luminosity distance changes for different cosmologies. Recall that the purpose of the luminosity distance is to preserve the usual relationship between flux and luminosity,

$$F = \frac{L}{4\pi d_L^2}. \tag{1}$$

In the last lecture we showed that the luminosity distance is

$$d_L(z) = x(z)(1+z), \tag{2}$$

where the coordinate distance $x(z)$ is given by

$$x(z) = \frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_{m,0}(1+z')^3 + \Omega_{\mathrm{rel},0}(1+z')^4 + \Omega_{\Lambda,0} + (1-\Omega_0)(1+z')^2}} \tag{3}$$

for a universe with total density $\Omega_0 = 1$ (and by more complicated expressions for $\Omega_0 \neq 1$). Because the luminosity distance depends on Ω_m and Ω_Λ, measuring it at high redshifts can constrain these parameters. The variation of luminosity distance with redshift is shown for different values of Ω_m and Ω_Λ in Figure 2.

We measure F and determine L by studying the light curve of the supernova, which means that we can measure the luminosity distance. If we have enough supernovae at high enough redshift, we can see which values of the cosmological parameters best matches the luminosity distances we measure. As redshift increases,

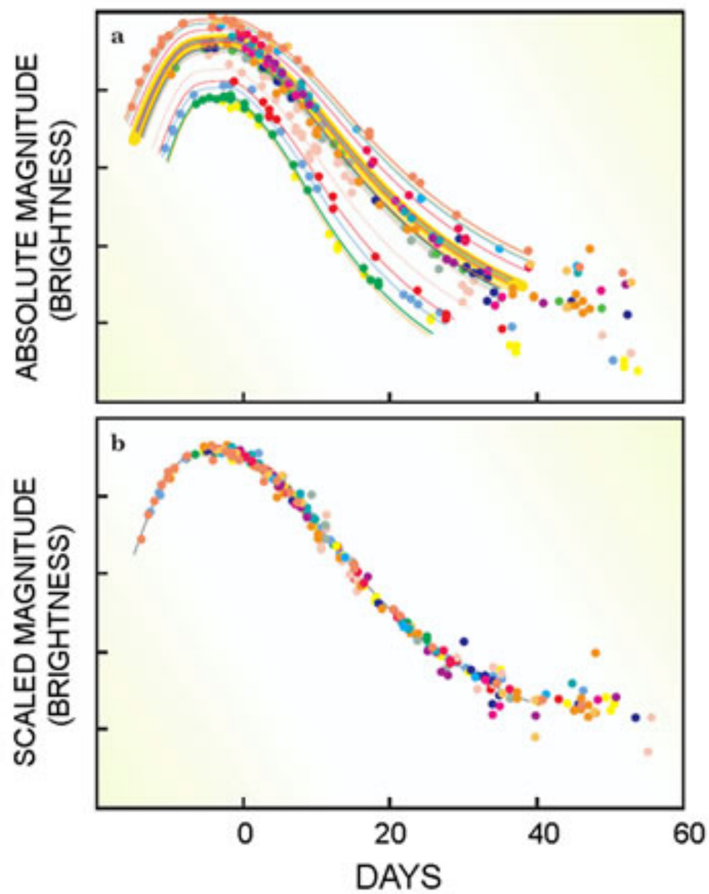

Figure 1: Top: Type Ia supernova light curves as observed. Bottom: The light curves after applying the time scale correction. The rate of decline depends on the luminosity (brighter supernovae decline more slowly), so by measuring the rate of decline we can determine the luminosity.

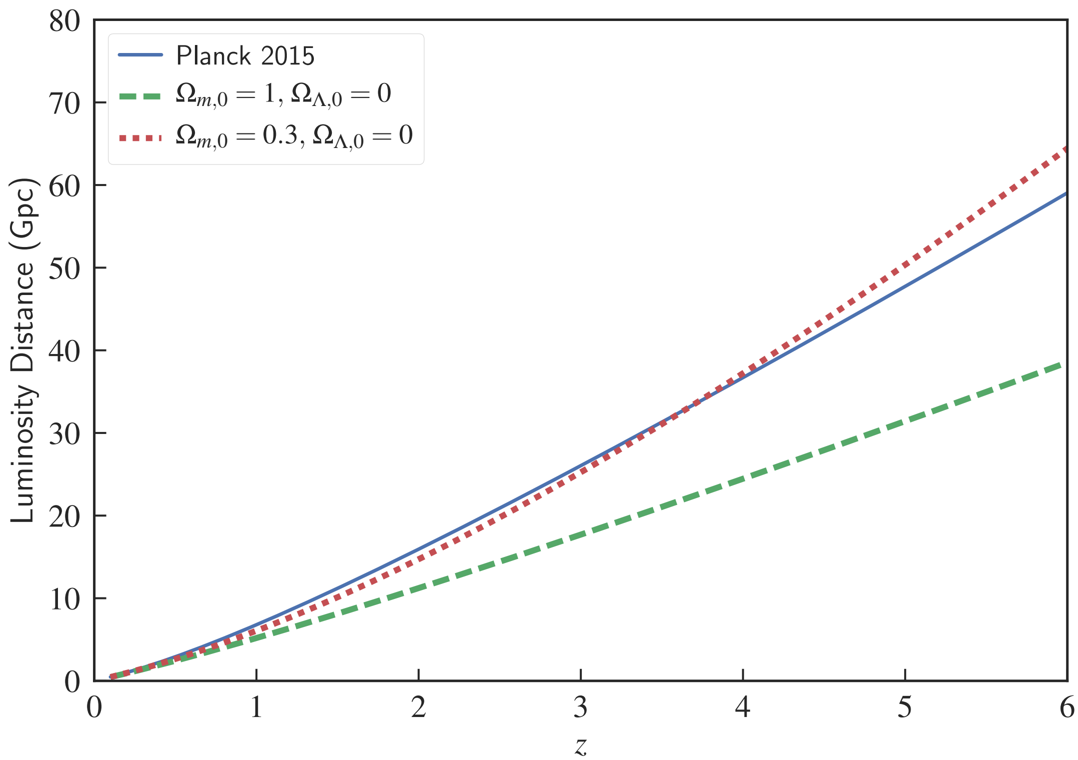

Figure 2: Luminosity distance for different values of the cosmological parameters Ω_m and Ω_Λ.

the luminosity distance becomes increasingly different for different values of the cosmological parameters. Note that for $z < 2.5$, where our current measurements are made, the luminosity distance is largest for the flat, Λ-dominated universe, and smaller for both of the matter-only models. Also note that at $z \sim 2$, the difference between the Planck 2015 model and the $\Omega_m = 0.3$, $\Omega_\Lambda = 0$ model is about 8%, so precise measurements are required.

The larger luminosity distance for the model with a cosmological constant means that the supernovae will appear fainter than they would in matter-only cosmologies: $F \propto d_L^{-2}$, so an increase in the luminosity distance leads to a decrease in flux. This is indeed what is observed; when the first high redshift SNe were detected, they were fainter than could be explained by any cosmological model without a cosmological constant.

In practice, astronomers usually plot the redshift-magnitude relation, i.e. the (extinction-corrected) distance modulus vs. redshift. Recall that the distance modulus is

$$m - M = 5 \log(d_L/10 \text{ pc}). \tag{4}$$

Writing the distance in units more convenient for cosmological measurements, we have

$$\mu = m - M = 5 \log d_L + 25, \tag{5}$$

where d_L is measured in Mpc.

A plot of the distance modulus vs. redshift for Type Ia supernovae is shown in Figure 3. This plot is taken from one of the key papers reporting on constraints on dark energy from Type Ia supernovae. Some important points regarding this figure:

- The dashed line on the main plot shows the best fit cosmological model, which has $\Omega_m = 0.29$ and $\Omega_\Lambda = 0.71$. The inset shows the differences between the binned data and various models (after an empty universe model with $\Omega = 0$ has been subtracted).

- **Gray dust.** We won't discuss all of the models shown on the inset plot, but one that is important to note is the high-z gray dust model. An important initial concern with the supernova data, when the SNe were found to be fainter than expected, was that there might be some sort of "gray" dust in the way, absorbing the light equally at all wavelengths and making the SNe fainter. Normal dust affects blue light more than red light, so we can see that it changes the color of objects; gray dust would be very difficult to detect because it would make objects fainter without changing their color. We don't actually know of any gray dust, but it didn't seem to be any less plausible than the cosmological constant when the fainter-than-expected supernovae were initially discovered. However, if gray dust were making the SNe fainter, they would continue to be fainter than expected as they got farther and farther away, and that's not what happened as more distant SNe were discovered. As can be seen from the solid black (best-fit) line in the inset panel, the supernovae do indeed get fainter than expected with redshift, but then they turn over and start getting brighter again, at about the redshift when the universe changed from being matter-dominated to being Λ-dominated. This trend rules out the gray dust. In other words, *the supernovae strongly favor a model with recent acceleration and previous deceleration.*

- **Evolution.** Another early counter-argument to the accelerating universe was that the Type Ia supernovae might not actually be standard candles: there might be something different about high redshift supernovae which makes them intrinsically fainter—lower metallicity, for example. However, like the gray dust case, if the intrinsic brightness of the SNe were evolving with redshift we would expect them to continually get fainter with distance, and they don't. The turnover in observed brightness also makes such evolutionary effects very unlikely. This is the "evolution $\sim z$" model on the plot.

- There were a lot of doubts about the SNe results when they first started coming out about 20 years ago, but subsequent data has made the accelerating universe model much more robust. There are also other, independent lines of evidence that support the dark energy/accelerating universe model, as we'll discuss later.

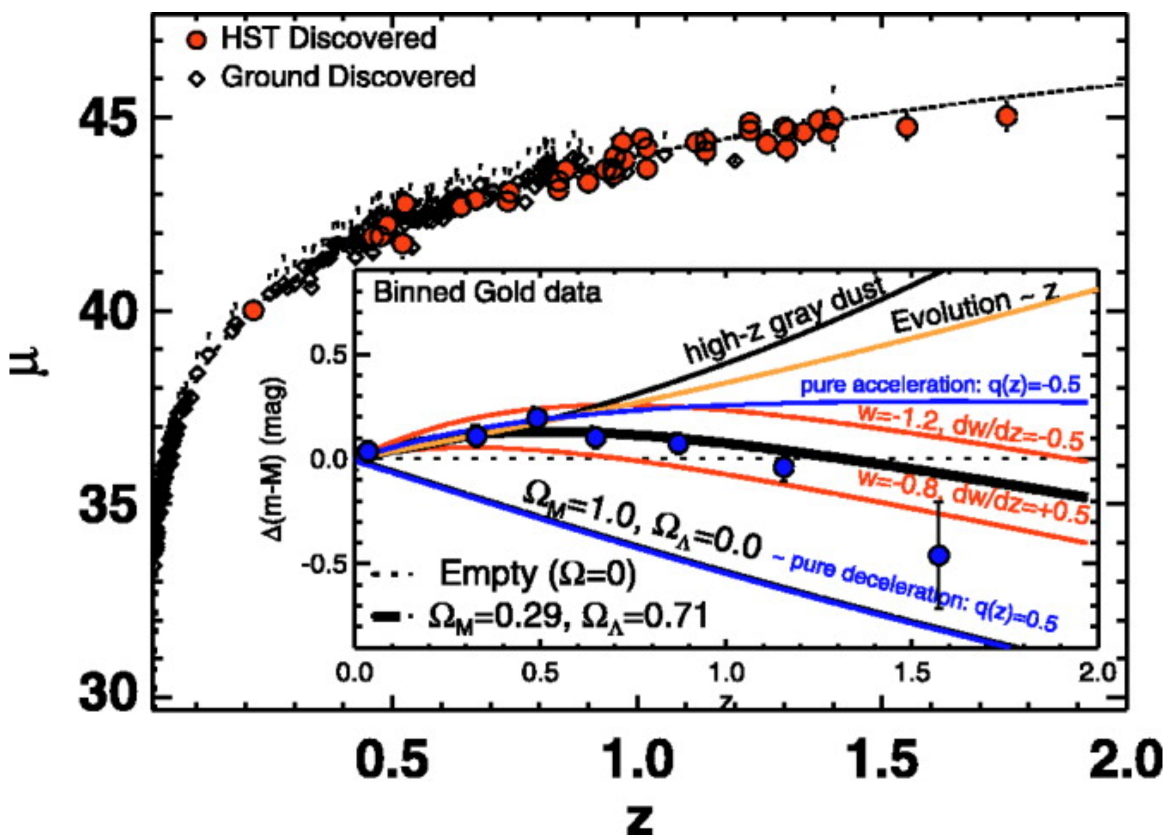

Figure 3: Distance modulus vs. redshift for Type Ia supernovae (Riess et al. 2007). The best-fit model for a flat cosmology ($\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$) is shown by the dashed line in the main panel. The inset panel shows the binned supernova data and several models after subtracting an empty universe model.