# Addenda to Observational Cosmology, Chapter 3.

Dave 9/2/19 – 11/2/19

For meeting on 11/18/19:

## Chapter 3 The local universe

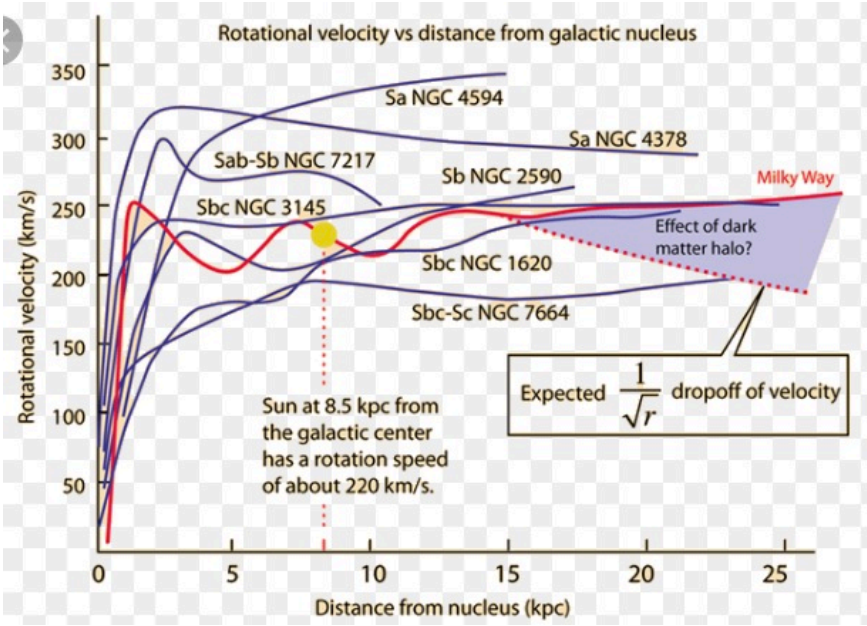


**Figure** Velocity curves for Spiral Galaxies {hyperphysics.phy-astr.gsu.edu}

**Galaxy Rotation Curves, v(r).**

The plot of rotational velocity versus radius from galaxy center shown in text rises more steeply than usual [Figure 3.1, p. 93]. Dark matter content varies from case to case, but "Most spiral galaxies show **flat rotation curves** out as far as we can trace them, even where no more stars are visible" (e.g., the Figure above). The rotation curve of our closest galaxy Andromeda M31(not shown above) is also very flat. The implication is that dark matter halos dominate and extend far beyond the visible disk of a galaxy.

The dark matter content of the Milky Way is about 90-95% which is higher than the 85% for the universe as a whole. The mass density for a general rotation curve can go roughly as $\rho(r)/\rho_o = 1/ [1+r^2/r_c^2]$ where $r_c$ is the radius of the galaxies central visible "core." So, for $r \gg r_c$, dark matter density $\rho \propto 1/r^2$ . If $\rho(r)$ is spherically symmetric (and that varies too), then outermost velocities will be flat, $v(r) \sim v_{flat}$.

Note that estimates of the size of our Milky Way galaxy recently doubled (Gaia and HST data) now out to a radius near 130,000 light years and a total mass near 1.5 trillion suns (out to the outermost globular clusters). The number of visible stars in the MW is about 200 billion (so roughly 90% of the mass is dark matter halo). Our mass is now competitive with that of Andromeda M31. The extent of the DM halo may be ten times wider than the visible galaxy. https://arxiv.org/pdf/1804.11348.pdf

**Neutrino Equation 3.1** presents a strange and curious little puzzle: why sum up the neutrino masses and what is the meaning of the 93.5 eV value in the denominator. Neutrino masses are not well known but there is an experimental constraint on the sum of the masses of the electron, muon and tau neutrinos (perhaps $\Sigma m < 0.72$ eV). There is no individual identity since neutrinos transmute into each other over distance and time depending on their energy. The mysterious 93.5 eV reference value in the equation seems to be like the energy of an imaginary particle such that the same density of them as the neutrino triplet density would close the universe (a replacement for critical density). It is estimated that the number density of individual neutrinos now is roughly $330/cm^3$ at a temperature near 1.9 K.

Section 3.3 p 96: For the simple but unreal case of all galaxy mass concentrated near the central bulge, the discussion on **Tully-Fisher** in the text could be a bit more transparent. Extremes of Doppler shifts come from the visible edges of the galaxy. If we see a spiral galaxy "edge on", then one side is speeding towards us with velocity v and the other side away from us (so $\Delta v \sim 2v$). Gravity force = centrifugal force, $mMG/R^2 = mv^2/R = (m/R)(\Delta v/2)^2$; so $M \propto R(\Delta v)^2$. Also notice that kinetic energy is – ½ times gravitational potential energy: $KE = mv^2/2 = mMG/2R = (-\frac{1}{2})(-mMG/R)$. This is the simplest example of the virial theorem for gravitationally bound systems (p 99). Note that the virial theorem also applies to much smaller systems such as the ground state kinetic and potential energy of atoms and molecules [Ruedenberg].

Using the Virial Theorem, detected kinetic energies of stars in galaxies and of galaxies in galaxy clusters indicate what gravitational potential energy must be present. That in turn tells us the amount of unseen dark matter that must be present (e.g., page 115).

**"kSZ"** (bottom of page 101). "Evidence of Galaxy Cluster Motions with the Kinematic Sunyaev-Zel'dovich Effect," arXiv:1203.4219 (and Phys. Rev. Letters). "The Atacama Cosmology Telescope (ACT) performs the first statistical detection of the kinematic SZ effect." (This was in 2012, our book is dated 2010).

**HISTORY**: I was a bit appalled at the absence of human history in this book and in the development of the expanding universe and feel that some outside reading is desired to counterbalance that. For example, on Cepheid variable stars on page 105, it might have said: Henrieta Swan "Leavitt's discovery provided astronomers with the first 'standard candle' with which to measure the distance to faraway galaxies." This 1912 work was KEY to the great discoveries up to Hubble's law of 1929.
See Wikipedia: https://en.wikipedia.org/wiki/Cepheid_variable, and https://en.wikipedia.org/wiki/Henrietta_Swan_Leavitt,

**HUBBLE $H_o$ AND STANDARD CANDLE LIST: Red Giants** as Standard Candles (bottom of pg 105) and the **dilemma** of two different values for Hubble $H_o$: You've all heard that recent local Hubble estimates indicate that the universe is growing 10% faster than indicated by analysis of the cosmic micro-wave background radiation (CMB). https://www.quantamagazine.org/cosmologists-debate-how-fast-the-universe-is-expanding-20190808/ : Recent research by Wendy Freedman using **tip-of-the-red-giant-branch stars**, pegged the Hubble constant at 69.8—notably short of SH0ES' 74.0 measurement using cepheids, and H0LiCOW's 73.3 from quasars, and more than halfway back to the Planck Space Telescope team's 67.4 prediction.

**Time-delay cosmography** (multiple images near gravitational lens distance measure) – **a new method** not listed on p 105 Chapter 3. 10/23/19 "New measurement of Hubble constant adds to cosmic mystery," … looked at light from extremely distant galaxies that is distorted and split into multiple images by the lensing effect of galaxies (and their associated dark matter) between the source and Earth. {The source galaxies are far away, but the lenses are near – like z~0.3 to 0.34}. By measuring the time delay for light to make its way by different routes through the foreground lens, the team could estimate the Hubble constant ($H_o$ = 76.8 !, continually higher than Planck CMB ). In 2017, the H0LICOW team published an estimate of 71.9, using the same method. There is now a 4.4σ tension between Planck and other local measures.(‼)
https://www.sciencedaily.com/releases/2019/10/191023150327.htm, and also
https://academic.oup.com/mnras/article/490/2/1743/5568378

**Exercise 3.2** calculates the negative gravitational energy of a ball of matter (page 104). This alters gravitational mass and inertial mass to the same degree (absence of Nordtvedt effect). But, the gravitational mass is defined by the asymptotic Newtonian potential **at large distance** from the system—not close up. There is no real concept of close-up real gravitational potential energy in general relativity.

Pg 109 **Collision of Andromeda** with our Milky Way Galaxy, animation: **NEAT**‼
https://www.youtube.com/watch?v=fyQrdsTNuo0

109-112 The pictures of universe structure are very nice but are dated. There is a really nice 2019 picture of the huge local VOID on the web along with a great 4 minute movie animation of our **supercluster –Laniakea**.
https://www.universetoday.com/142923/meet-our-neighbour-the-local-void-gaze-into-it-puny-humans/

## And Comments on Last Month:

Question 1**. Inflation** as $H^2 = 8\pi G\rho_\Lambda/3$ doesn't look like a "ball falling through Earth" spring type problem, F = +kR – so is it the same physics? Well, the Friedman "acceleration" equation is $a''/a = -4\pi G(\rho + 3P/c^2)/3$. But, for an "only Lambda" universe with constant density, conservation of energy implies that we also have $P_\Lambda = -\rho_\Lambda c^2$ (effective negative pressure!), so $a''/a = +8\pi G\rho_\Lambda/3$ – same as for $H^2$. And note that $(d/dt)(H) = (d/dt)(da/adt) = (a\,a'' - a'^2)/a^2 = a''/a - H^2 = 0$, so $a''/a = H^2$ ! So, yes, the equations mean the same thing.

FYI: **The (nearly) Latest Astrophysical Constants** can be seen at:
http://pdg.lbl.gov/2017/reviews/rpp2017-rev-astrophysical-constants.pdf
[For interest: The Astronomical constants sheet says $\Omega_m = \Omega_r$ at z~3400 and adds that the z where universe acceleration = 0 is only $z_q \sim 0.65$. Compare that to $\Omega_m = \Omega_\Lambda$ at scale factor $a = (0.31/0.69)^{1/3} = 0.76$, (z~0.31, perhaps 3.5 billion years ago – see on-line calculator http://www.astro.ucla.edu/~wright/CosmoCalc.html ).]

Note: Friedman (1888-1925) was Russian with Cyrillic spelling, Фри́дман. Friedmann is a German form that is sometimes preferred in English (but not in spell-checker).