2.3.2. *What are the properties of these neutral H clouds? Can they form galaxies?*

We deduce the size of the intergalactic clouds by comparing the Ly-α forest in the spectra of pairs of lensed quasars. Many of the absorption lines are seen in both spectra, but some are not. This indicates that the clouds are, on average, about the size of the lensing galaxy. From the total calculated column density of hydrogen (ionized plus neutral), the mass of atypical cloud is somewhere around 10^7 M$_\odot$. At the temperate estimated for a typical cloud ($T \sim 3 \times 10^4$ K, its self-gravity would be too weak to keep it from dispersing. It may be held together by the pressure of less dense (but hotter) external IGM or by the presence of DM within the cloud.

The clouds are placed into three categories. The low column density Ly-α forest absorbers ($\Sigma_{HI} < 10^{16}$ cm^{-2}) are associated with the diffuse IGM. These systems probe low-density, highly ionized gas and are thought to trace the dark matter distribution throughout the IGM as well as contain the bulk of the baryons at high redshift and a significant amount of the baryons even today. At the other end, the high column density damped Ly-α absorbers (DLAs, $\Sigma_{HI} > 10^{20}$ cm^{-2}) appear associated with the main bodies of galaxies. These high-density, predominantly neutral systems serve as neutral gas reservoirs for high redshift star formation. The intermediate column density systems, known as Lyman Limit Systems, mark the transition from the optically thin Ly-α forest to the optically thick absorbers found in and around the extended regions of galaxies. Typically these absorbers are easy to identify in QSO spectra due to the characteristic attenuation of QSO flux by the Lyman limit at ~ 912 Å in the rest frame. In addition, they are optically thick enough to be harbouring neutral hydrogen cores.

2.4. *Question 4*

QUESTION: Describe as many steps of the distance ladder and the involved techniques as you can. What are the rough distances to the Magellanic Clouds, Andromeda, and the Virgo Cluster?

This is mostly from my own notes.

The cosmic distance ladder consists of a large number of means to determine (luminosity, for the most part) distances to objects. They are listed below, and extragalactic ones in Fig. 32. The differing techniques are generally calibrated to one another (to provide consistency), and therefore it is highly advantageous for differing rungs of the ladders to overlap.

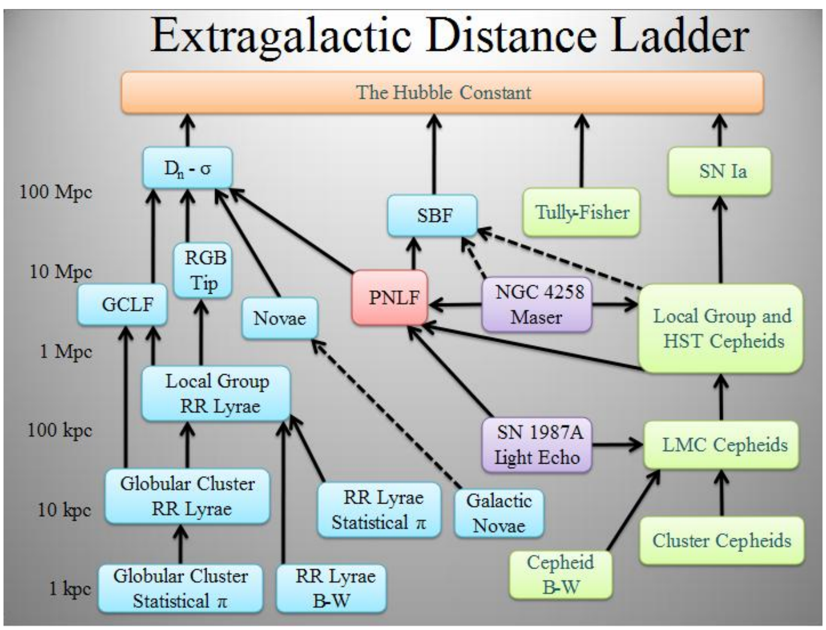

Fig. 32.— Plot of various extragalactic distance-determining techniques, with their maximum effective luminosity distance measures located to the left. The various colours represent applicability to different classes of object (but can effectively be ignored). Solid black lines indicate good calibration between two steps on the ladder; dashed lines indicate poor calibration. "GCLF" is the globular cluster luminosity function, "PNLF" is planetary nebula luminosity function, and "SBF" is surface brightness function. From Wikipedia (2011a).

Solely Galactic distance determining techniques:

- **Geometric parallax** is the measurement of the position of a distant objects from two different observation points separated by some physical distance called a "baseline". The baseline divided by the angle by which the objects shifts when moving between the two points of observation gives a distance estimate. The technique is usually only applicable to nearby stars (the Gaia satellite will change this). Commonly the baseline used is the diameter of the Earth's orbit around the Sun, but the proper motion of the Sun can be used to create longer baselines.

- **The moving cluster method** uses the proper motion of cluster members, as well as cluster member radial velocities, to determine distance to the cluster.

- **Dynamical parallax** uses measurements of the period (or a related orbital value) and angular semi-major axis of binary stars to determine their distance. By plugging in the period, angular semi-major axis and a mass-luminosity relation into Kepler's Third Law, one obtains an equation solvable for the distance to the binary.

- **Main sequence fitting*** of stars in a cluster onto an HR diagram, and comparison of that fit with a similar fit to the Hyades cluster, can be used to determine open cluster distances up to 7 kpc.

- **Spectroscopic parallax** is the determination of the luminosity of a star from a combination of spectral class and line-broadening (the 2-dimensional Morgan-Keenan luminosity class). Combined with the apparent magnitude, this can be used to determine a distance modulus to the star. Technically spectroscopic parallax is useful up to 10 Mpc, but in practice it is only used up to 10^5 pc.

- **Expansion velocities of SNe ejecta** proper motion measurements, combined with measurements of radial velocity from Doppler shifts and the assumption that expansion is spherically symmetric can be combined to obtain distances.

Extragalactic distance determining techniques (some can also be used in our own Galaxy):

- **The Wilson-Bappu effect** (up to 0.1 Mpc) is a spectroscopic parallax effect where the width of a small emission line housed in the K absorption line of calcium is correlated to absolute magnitude for G, K and M stars. Calibrated to geometric parallax, the Wilson-Bappu effect is mostly used for distances up to the LMC.

- **Bright red supergiants** (up to 7 Mpc) which appear to have the same absolute V and bolometric magnitude. Requires distingishing individual stars, giving it the same range as spectroscopic parallax.

- **Tip of the RGB** (up to 7 Mpc) is a similar method that uses the tip of the red giant branch star luminosity function. Stars travelling up the RGB will eventually experience an He flash and transition off the RGB to the zero-age horizontal branch. An He flash occurs when the He core of an RGB reaches ~ 0.5 M$_\odot$, and the luminosity prior is dependent on properties of the H-burning shell, which in turn is dependent on the He core; this means that the most luminous a red giant can get is an almost constant value. A distance, then, can be estimated from the brightest RGB stars in a galaxy (since they will be very near the RGB tip).

- **Novae** (up to 20 Mpc) have, like their SNe Ia cousins, a luminosity vs. light curve decline time relationship that allows them to be calibrated into standard candles using $M_V^{max} = -9.96 - 2.31 log_{10}\dot{m}$, where $\dot{m}$ is the average rate of decline over the first 2 mag in magnitudes per day. This relationship comes from the fact that more massive WDs tend to accrete smaller amounts of matter before a nuclear runaway occurs (i.e. producing less bright an explosion), and this thinner layer is ejected more easily.

- **Variables** (up to 29 Mpc) have a correlation between pulsation and luminosity[8], allowing determination of a distance modulus (assuming extinction is also known). Classical Cephids have been seen up to 29 Mpc away, while RR Lyrae and W Virginis stars are generally fainter and therefore can only be used for closer distances.

- **Globular clusters*** (up to 50 Mpc) follow an empirical luminosity function. Because the function has a turnover, fitting a sampling of globular clusters around a distant galaxy with the luminosity function can be used to derive a relative distance.

- **Planetary nebulae*** (up to 50 Mpc) also appear to follow a luminosity function[9] with a rapid cutoff at around -4.6 mag. Fitting, and comparing to a fit with a known distance, provides a distance measure; alternatively, finding the brightest PN in a galaxy and assuming they reside near the cutoff also gives a distance. As the cutoff method uses brighter PN, it can be to larger distances (the fitting method only goes up to 20 Mpc).

- **The surface brightness method*** (up to 50 Mpc) is based on the fact that the number of bright stars (which contribute the majority of the brightness) per area element in a galaxy fluctuates by Poisson noise. Since a galaxy further away will subtend a smaller area on the sky, there will be more bright stars per angular area, and therefore less fluctuation in the surface brightness (since the fluctuation goes like $\sqrt{N}/N$).

[8] $M_V = -3.53 log_{10}(P_d) - 2.13 + 2.13(B - V)$.

[9] Here the measured luminosity is L_λ at $\lambda = 5007$ Å.

- **The Tully-Fisher relation*** (> 100 Mpc) is a relation between a spiral galaxy's luminosity and its maximum rotational velocity described in Sec. 2.1. The analagous relation for ellipticals is the Faber-Jackson relation, and is much noisier and more difficult to use as a standard ruler. Physically, the Tully-Fisher relation means that the mass-to-light ratio and mean surface brightness of spirals is fairly constant. In fact, due to the changing fraction of baryons in gas instead of stars for lower mass spirals, the mass-to-light ratio does change - adding a correction term to the Tully-Fisher relation results in a much tighter relationship.

- **The $D - \sigma$ relation*** (> 100 Mpc) is a relation between an elliptical galaxy's angular diameter D out to a constant surface brightness (20.75 B-mag per arcsec) and its velocity dispersion. Since surface brightness is independent of distance, D is inversely proportional to the distance to the elliptical galaxy. Physically, this relation is a natural outcome of the fundamental plane and the (fairly good) assumption that all ellipticals are self-similar.

- **Masers** (> 1000 Mpc) are amplified microwave emissions coming from regions of interstellar media where populations (due to very low densities) can become inverted. Cosmic masers exist around some galactic nuclear regions with line luminosities up to 10^4 $L_\odot$; these maser sources orbit the supermassive black hole, and observations of both the radial and proper motions of these sources can be made. If we assume circular orbits, these two values can be combined to give a distance. Source radial velocities can also be combined with an independent measure of the black hole mass to determine distances.

- **Supernovae Ia** (> 1000 Mpc) have (or at least a sub-class of them have) a strong relation between light curve decay time and peak luminosity, the Phillips relation (Sec. 1.9). While most optical and infrared observations can be used, this relation is has the smallest spread in the infrared. Other supernovae have similar relationships that could be used to determine luminosity (ex. SNe IIP plateau longevity is correlated with maximum luminosity), though these relationships are generally not as well defined and/or studied, and SNe Ia are brighter in the optical and IR and other SNe.

- **Brightest galaxies in clusters*** (> 1000 Mpc) fits a luminosity function to the galaxy cluster, and determines a distance modulus from the fit. It assumes that the luminosity function of galaxies remains fixed over time.

- **Cosmological redshift** (> 1000 Mpc) requires finding characteristic spectral features (lines, bumps, etc.). Redshift can be made to correspond to a physical distance through Hubble's Law ($v = H_0 d$) at low redshifts, and to d_c (assuming a cosmological model) at large redshift. Use of this measure must take into account peculiar velocities of objects.

All techniques denoted with a * are secondary distance indicators, which only give distance scaling, and therefore require a calibration galaxy with a distance known by other means (primary distance indicators can be used on their own because they give absolute luminosity distances).

The distance to the LMC can be determined from the Wilson-Bappu, RGB tip/supergiants, and variable star methods, giving a distance of ~ 48 kpc (the same answer can be obtained by "going backwards" by taking the NGC 4258 maser distance as a baseline for other distance measures). The most accurate distance for an object, however, was found using the light echo of SN1987A off of a nearly perfectly circular ring of material (ejected during the SN progenitor's AGB phase) to determine a distance. The ring is inclined to us, and so while light from the SN should impact all sections of the ring at the same time, due to the inclination and light delay we see different sections of the ring light up at different times. The light delay can be used to determine the physical size of the ring, while its angular size is easily observed, and from these two measurements we can obtain a distance of 51.8 ± 3 kpc to the SNR.

The distance to Andromeda has been measured with variable stars, surface brightness fluctuations, RGB tip/supergiants, the Wilson-Bappu effect and measurements of eclipsing binaries; the current accepted distance is ~ 770 kpc.

The distance to the Virgo Cluster can be determined by using a large number of these methods, including variable stars, novae, luminosity function methods, surface brightness fluctuations, the Tully-Fisher and $D - \sigma$ relations and Type Ia supernovae, applied to its component galaxies; all methods agree that it is ~ 17 Mpc away.

2.5. *Question 5*

QUESTION: What evidence is there that most galaxies contain nuclear black holes? How do those black holes interact with their host galaxies?

For most observational purposes, a black hole (BH) is defined as a mass-concentration whose radius is smaller than the Schwarzschild radius r_S of its corresponding mass. This value is about $r_S \sim 10^7$ km ~ 15 $R_\odot$ for the SMBH in the Galactic centre (GC). Since we cannot even resolve the supermassive black hole (SMBH) in our own galactic centre (which spans 10^{-5}") in order to show that other galaxies contain SMBHs we must find indirect evidence of a massive compact object at the centres of galaxies.