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Notes for USRP M vs. L Project

**Milky Way Mass**

* Halo masses for the Milky Way
* Gives masses for M100
  + *1.84 (+ 0.80, -0.60) \*1012 Msol* 
    - (Boylan-Kolchin et al. 5/2013)
    - From Leo I proper motion, assuming the galaxy is bound
  + *1.84 (+ 0.19, -0.21) \*1012 Msol* 
    - (Patel et al. 3/2018)
    - Instantaneous velocity of MW dwarf galaxy satellites as measured by Gaia Data Release 2
    - As further away galaxies were included, the mass estimate increased
  + *0.96 (+0.29, -0.28) \*1012 Msol* 
    - (Patel et al. 3/2018)
    - Angular momentum of MW dwarf galaxy satellites as measured by Gaia Data Release 2
    - As further away galaxies were included, the mass estimate increased
  + *2.05 (+0.97, -0.79) \*1012 Msol*
    - (Sohn et al. 6/2018)
    - From proper motion of globular clusters as measured by Hubble Space Telescope
  + *1.84 (No errors given) \*1012 Msol*
    - (Fritz et al. 8/2018)
    - From proper motion of dwarf galaxies up to an orbital distance of 420 kpc as measured by Gaia
  + *1.30 (±0.30) \*1012 Msol*
    - (Posti et Helmi 12/2018)
    - From proper motion of globular clusters not associated with the Sagittarius Stream
    - Data from HST and Gaia DR2
  + *1.28 (+0.97, –0.48) \*1012 Msol*
    - (Watkins et al 2/2019)
    - 6D proper motion with Gaia DR2
    - Objects out to 21 kpc, estimated out to R200
  + *1.54 (+0.75, –0.44) \*1012 Msol*
    - (Watkins et al 2/2019)
    - 6D proper motion with Gaia DR2 and HST
    - Objects out to 21 kpc, estimated out to R200
  + *0.94 (+1.50, –0.50) \*1012 Msol*
    - (Vasiliev 4/2019)
    - Proper motion and dynamical Modelling
    - Says this is an extrapolated value and makes little sense to compare it to other masses
* **From this, it seems we should pick a value of Mhalo(MW)=1.5 \*1012 Msol**
  + **We can also discuss what happens at 1.0 \* 1012 and 2.0 \* 1012**

**Andromeda Mass**

* Halo Masses for M31
* Again, masses are M100
  + *1.5 \* 1012 Msol*
    - (Shiavi et al 6/2019)
    - Given as a parameter, but doesn’t ever justify
    - References are lacking
  + *1.5\* 1012 Msol*
    - (Van der Marel et al. 2/2019)
    - From rotation and proper motions of the Andromeda system
    - Gives two models, each with different virial mass for M31
  + *2.0 \* 1012 Msol*
    - (Van der Marel et al. 2/2019)
    - From rotation and proper motions of the Andromeda system
    - Gives two models, each with different virial mass for M31
  + *1.0 \* 1012 Msol*
    - (Solomon et al. 7/15)
    - Says a slightly higher value would make more of the satellites they measured bound
  + 1.2 \* 1012  Msol
    - (Evans et al. 2000)
    - Argues MW is probably the highest mass object in the Milky Way
  + *3.5 (±1.0) \* 1012 Msol*
    - (Bahcall and Kulier [and references therein] 1/2014)
* Although these measurements vary, it is often cited that Andromeda does have a higher mass than the Milky Way
  + **We thus adopt a value of Mhalo(M31) = 2.0 \* 1012 Msol**

**Magnitude of the Milky Way**

* Absolute magnitudes of the Milky Way
* Magnitudes are given in various bands, converted when possible
  + *M­V = –20.9*
    - (Courteau and van den Bergh 1999)
  + *MV = –20.5 🡪 –21.3*
    - McGill website
    - Not an extremely credible source, but gives some sort of idea of the range
* Bahcall + Kulier (2014) cite Courteau 1999 in their paper. Because this seems fairly reasonable, I believe it’s reasonable to just take their absolute magnitude (and their calculation of the i-band luminosity) **MV(MW) = -20.9 magnitudes**
* Find another credible source for this

**Magnitude of Andromeda**

* Absolute magnitudes of the Milky Way
* Magnitudes are given in various bands, converted when possible
  + *M­V = –21.2*
    - (Courteau and van den Bergh 1999)
  + *MV* = –21.5; (B–V) = 0.63
    - (Ribas et al 2/2018)
    - From a spectroscopic analysis of eclipsing binaries in M31
  + *MV = -21.8* 
    - (NASA/IPAC extragalactic database [NED])
* Again, these all seem around the same place, so we can just use Bahcall + Kulier’s analysis
* **M­V(M31) = –21.2**

**Other Isolated Spirals**

* Some masses and magnitudes for other isolated spirals (i.e. those not in clusters)
* Conversion from Mould I-band to Gunn i-band is approximated by
  + i = I + 0.75
    - (Windhorst, R. W., et al. 1991, ApJ, 380, 362)
  + **NGC 5523**
    - M\* = ~1 \* 1010 Msol
      * Fulmer et al. (10/2018)
        + Assumes MO/LO = 1
    - MI = –20.5 🡪 Mi = –19.75
      * NASA/IPAC extragalactic database
  + **NGC 4414** 
    - M\* = 1.67 (±0.39) \* 1010 Msol
      * (Martinez-Garcia et al 1/2017)
        + h = 0.678 km/s/Mpc
    - M\* = 6.26 \* 1010 Msol
      * (Vallejo et al. 2002)
      * See calculation in the mass to light notebook on github
      * Not perfect, done with some subtraction
    - I like the second value of M\*, mostly because it seems like more thought went into it (it was calculated piece by piece)
    - MI = –22.4 🡪 Mi = –21.65
      * NASA/IPAC extragalactic database
  + **MW** (included for reference)
    - M\* = 6.08 (±1.14) \* 1010 Msol
      * (Licquia et al. 8/2015)
        + Assumes a Kroupa IMF and an exponential disk profile
    - M\* = 4.5 \* 1010 Msol
      * (Bahcall + Kulier, 2014)
  + **M31** (included for reference)
    - M\* = 10.3 (+2.3, –1.70) \* 1010 Msol
      * (Sick, Courteau et al. 10/2014)
    - M\* = 13.10 (+2.0, –2.1) \* 1010 Msol
      * Tamm et al. 2012
        + Overestimates stellar mass
* If we look at a plot of M\* / Li vs. M\*, we see that the stellar mass / luminosity ratio is roughly constant for spiral galaxies at 1.5 in solar units. The main exception to this is M31, which is known to have a redder (i.e. older) stellar population, and therefore lower luminosity per unit mass. (Plot is in github / jupyter notebook)

**Isolated Elliptical Galaxies**

* Masses and some magnitudes of isolated elliptical galaxies
* Conversion from r-band to i-band found in a plot in (Chang et al. 9/2005)
  + Found on page 6, plot in the top left corner
    - r – i vs. M­r
  + **CIG 0189**
    - Mr = -19.436
    - z = 0.0105
      * [UNAM-KIAS Catalog (Hernandez-Toledo et al. 5/2010)]
    - We don’t have a mass for this, so we probably won’t end up using this galaxy anyway.
    - Mr = -20.58
      * Hernandez-Toledo 11/2018
  + **UGC 03960**
    - **Mr** = -18.178
      * [UNAM-KIAS Catalog (Hernandez-Toledo et al. 5/2010)]
    - **z** = 0.0075
      * NASA/IPAC
    - **r – i** = 0.38
      * (Chang et al. 9/2005)
    - **M\*** = 1 \* 1010.09 Msol
      * (Boardman et al 7/2017)
    - **Mhalo** not found
  + **UK 0613**
    - **Mr**= -19.731
    - z = 0.0272
      * UNAM-KIAS, h = 0.70
    - r – i = 0.37
      * (Chang et al. 9/2005)
    - **M\***= 1010.35 / h2 Msol
    - = 4.66 \* 1010 Msol (for h = 0.7)
    - **M180**= 1012.0 / h Msol
    - = 1.44 \* 1012 Msol (for h = 0.7)
      * **M­100 = 9.53 \* 1011 / h Msol = 1.38 \* 1012 Msol**
      * (Lacerna et al. 9/2014)
        + They leave everything in terms of h, I plugged in our value
  + **UK 1197** 
    - **Mr**= -19.876
    - **z** = 0.0318
      * UNAM-KIAS, h = 0.70
    - **r – i** = 0.37
      * (Chang et al. 9/2005)
    - **M\***= 1010.15 / h2 Msol
    - =2.94 \* 1010 Msol (for h = 0.7)
    - **Mhalo**= 1011.78 / h Msol
    - =9.10 \* 1011 Msol (for h = 0.7)
      * **M­100 = 6.75 \* 1011 / h Msol = 9.74 \* 1011 Msol**
      * (Lacerna et al. 9/2014)
        + They leave everything in terms of h, I plugged in our value
  + **UK 1394**
    - **Mr**= -18.178
    - **z** = 0.0347
      * UNAM-KIAS, h = 0.70
    - **r – i** = 0.38
      * (Chang et al. 9/2005)
    - **M\***= 1010.13 / h2 Msol
    - = 2.81 \* 1010 Msol (for h = 0.7)
    - **M180**= 1011.75 / h Msol
    - = 8.11 \* 1011 Msol (for h = 0.7)
      * **M­100 = 6.30 \* 1011 / h Msol = 9.09 \* 1011 Msol**
      * (Lacerna et al. 9/2014)
        + They leave everything in terms of h, I plugged in our value
* If we do the same thing as for the spirals, we see that the stellar mass to light ratios are almost always larger than the spirals by at least a factor of 2. There are examples which are about a factor of 4 larger (e.g. UGC 03960). **We could use an estimate of roughly 4 in solar units for elliptical galaxies.**
* If we plot halo mass to light vs. halo mass, we get a value ranging from 70 – 162 in solar units. Andromeda and the Milky Way hover at roughly 50. **I propose we use an estimate of 100 in solar units for halo mass to light for elliptical galaxies. This result does not really change when keeping everything in terms of h.** We have some data that are below 100 and above. Also, our calibration of the Milky Way and Andromeda is independent of redshift (and therefore h) and thus we can use the argument of 50 for spirals and double that for ellipticals.

**References**

* Unam-Kias Catalog
  + (Hernandez-Toledo et al. 5/2010)]
  + HO= 70 km/s/Mpc
  + No Initial Mass Function
  + All the elliptical magnitudes came from this source. It was also a good source for redshifts of the same galaxies
* NASA/IPAC Extragalactic Database
  + HO= 67.8 km/s/Mpc
  + No Initial Mass Function
  + I used this as a reference for redshifts and absolute magnitudes of spiral galaxies, as well as UGC 03960. It contains information from photometry, redshift, images, distances, etc.
* Lacerna et al. 9/2014
  + h = 0.73
  + Kroupa IMF used for the stellar masses
  + Defines haloes with an over density of 180 (so gives M180)
  + I used this as a reference to get the stellar masses and halo masses of the UK galaxies. The useful graphs are: Figure 7 for Stellar Masses; Figure 9 for halo masses. There’s also a good table on page 14 (Table 2) that has the data for the galaxies I was looking at.
* Boardman et al 7/2017
  + HO= 72.0 km/s/Mpc
    - I found this in a reference within the paper. They cite this paper when putting the data in for the distance, so I inferred they are probably using this paper (i.e. the same h value) for their paper (from Capellari et al. 2011a)
  + Uses the KS- band luminosity to get the stellar mass
    - (from Cappellari et al 2012)
  + I used this source for the stellar mass of UGC 03960. They also have other galaxies if we want to go back and look at others.
* Fulmer et al. (10/2018)
  + Photometric analysis of 3.6 μm SST image
  + I used this to get the stellar mass of NGC 5523
* Martinez-Garcia et al 1/2017
  + h = 0.678
  + Gives a less biased stellar mass of NGC 4414. Uses NED
  + I used this to get one estimate of the stellar mass of NGC 4414. The value it gives, however, is a factor of 6 smaller than the other estimate I have for it, which gives a value much more similar to other spirals.
* Licquia et al. 8/2015
  + Assumes a Kroupa IMF and an exponential disk profile
  + I used this as a reference to get a stellar mass for the Milky Way. It seems like a higher estimate compared to other sources. It is only used to compare to some of the other spiral galaxies
* Sick, Courteau et al. 10/2014
  + I used this as a reference for the stellar mass of Andromeda. It derives the mass through an optical and infrared disk survey.
* Tamm et al. 2012
  + I used this as a reference for the stellar mass of Andromeda. The author says himself that it is likely an overestimate (and it has huge error bars to begin with).
* Hernandez-Toledo 11/2018
  + I used this as another data point for the r-band magnitude of CIG 0189. It ends up being irrelevant because we don’t have a mass for that galaxy, but it suggests that the magnitudes of these ellipticals are around here.
* Vallejo et al. 2002
  + I used this for the stellar mass of NGC 4414. This is the source that gave the total baryonic mass, and I had to subtract the gas components. Because this, there might be a lot of propagating uncertainty / I may have missed a factor in my calculation. I’ll go back and check this.
* Chang et al. 2005
  + This was used to find the color vs. absolute magnitude. There’s a function on page six, top left corner (figure 3). It graphs r-i vs. Mr. Thus, I was able to get the i-band magnitude by extrapolation.

**References for Faint Galaxies**

* Hashimoto et al, 6/2019
  + HO = 70 km/s/Mpc
    - From Greco et al 4/2018 (and 11/2018)
  + Looking at low surface brightness galaxies
  + Looking for γ-ray emission from dark matter annihilations
    - Constrains DM mass
  + Good tables / figures:
    - Table 1 (page 4)
      * Objects, redshifts, distances, i-band apparent magnitude
    - Table 2 (page 9)
      * Objects, stellar mass, halo mass
        + Estimates from Monte Carlo
        + Errors

Log(stellar) ± 0.2

Log(halo) ± 0.4

* + Not extremely useful, but is a good sanity check.
* Kovacs et al., 6/2019
  + HO = 70 km/s/Mpc
    - From Greco et al 4/2018 (and 11/2018)
  + Looks at x-ray emissions from gas to constrain DM mass
    - Detected very little in the range of 0.3 – 1.2 keV
  + Concludes that UDGs have Dwarf-sized DM haloes [M200< 3\*1010]
  + Good Table:
    - Table 2 (page 6, appendix)
      * Has galaxies, coordinates, effective radius, i-band central surface brightness, g-i color
  + Doesn’t give a ton of data, but at least it’s something to compare the other masses to.
* Honey et al., 3/2018
  + HO = 70 km/s/Mpc
  + D = v / HO
  + Looks at HI regions in LSBGs
    - Splits them into different morphologies
  + Gives red band absolute magnitudes, stellar masses, and (g-r) colors
  + Not extremely relevant
  + best info probably in table 1 (page 4490)
* Prole et al., 1/2019
  + DFornax = 20 Mpc
    - Blakeslee et al. 3/2009
      * Gets the absolute magnitude of Fornax from color comparison / calibration with the population of Virgo
      * Can’t see a major need for HO, except where it was probably used to find the distance to Virgo
  + Estimates Halo masses of LSBGs from the number of Globular clusters in the galaxies
    - (previously found to have some [imperfect] correlation)
  + Estimates stellar masses of LSBGs from photometry g and i bands
  + good graph on page 11 (figure 8)
  + table of all their data in appendix E (page 16, table E1)
    - note: halo masses are upper limits
    - errors
      * MV ± 0.2 mag
      * M\*/Msol ± 0.3 dex
  + I used this for two things:
    - 1) this was a consistency check with Leuthaud et al. It shows that for the extremely faint galaxies (in this case, Low Surface brightness galaxies) the stellar fraction continues to decrease.
    - 2) Less importantly, I also took the first page of the data they provide in the appendix and took some data for the very small stellar masses (106.0)
* Leuthaud et al. 1/2012
  + Gives constraints on stellar to DM fraction
  + Ωm = 0.258, ΩΛ =0.742
  + HO=72 km/s/Mpc
  + Gives M200b values (aka M50)
    - I converted the values to what they should be
  + Combines g-g lensing, spacial clustering, and galaxy number density to get estimates for halo mass
  + Stellar masses estimated using Bayesian methods
    - Uses Chabrier IMF
  + Finds:
    - 1) Mh α M\*0.46
    - 2) figure 10 on page 16
      * Gives stellar mass vs. M200b/M\* and M200b vs. M\*
  + Uses:
    - I used this mainly for the figure on page 16. I used the WebPlotDigitizer website in order to extract the data for three bins (Lstar, middle, and low) for the low end of the stellar mass region, and took the average stellar fraction.

Faint Galaxies

* Three Bins:
  + Lstar 🡪 8 \* 109 Msol ≤ M\* ≤ 4 \* 1010 Msol
    - Av. M\* / M100 = 3.71 %
    - WHEN TAKING POINTS FROM above the line
    - Av. M\* / M100 = 1.88 %
  + Mid 🡪 8 \* 108 Msol ≤ M\* ≤ 8 \* 109 Msol
    - Av. M\* / M100 = 1.45 %
    - WHEN TAKING POINTS FROM above the line
    - Av. M\* / M100 = 0.878 %
  + Low 🡪 8 \* 107 Msol ≤ M\* ≤ 8 \* 108 Msol
    - Av. M\* / M100 = 0.357%
    - WHEN TAKING POINTS FROM above the line
    - Av. M\* / M100 = 0.217 %
  + (Leuthaud et al. 1/2012)
  + Data extracted using WebPlotDigitizer
  + At 0.2 L\*:
    - Av. M\* / M100 = 1.55 %
  + At 0.6 L\*:
    - Av. M\* / M100 = 2.1%
* For much fainter LSBGs
  + Av. M\* / M100 = 0.042 %
  + (Prole et al. 1/2019)
* From analysis of Prole data, it seems that Mh α M\*0.64
  + This is a small dataset, so it makes sense that it varies a little

**Mass to light calculations**

* Estimates for M/Li using the formula:
  + M/Li = 50 \* (Li / L\*)-0.54
  + At L\*:
    - = 50
  + At 0.6 L\*:
    - = 65.88
  + At 0.2 L\*:
    - = 119.24
  + At 0.1 L\*:
    - = 173.37
  + At 0.01 L\*:
    - = 601.13

**Mass to Light Ratio (averages)**

* Based on formula:
  + - = 1.16
  + NOTE: there are terms of no and L\* that pop out of these integrals, but they all cancel
    - Also, by integrating to 0 on all integrals we are implicitly assuming that the Schechter Luminosity function continues on the same power law all the way down to 0
* **For %[E] - *bright* = 0.90, %[E] - *faint* = 0.50**
  + This represents the high density of central regions of groups and clusters
  + Conservative estimate for faint galaxies
  + Mbright = 81.7
  + Mfaint =180.0
  + = 225.6 + [15 % gas] = **259.4**
* **For %[E] - *bright* = 0.90, %[E] - *faint* = 0.75**
  + This represents the high density of central regions of groups and clusters BUT…
  + This time, we take a percentage that assumes the Density-morphology relation down to faint galaxies
  + Mbright = 81.7
  + Mfaint =210.0
  + = 251.5 + [15 % gas] = **289.2**
* **For %[E] - *bright* = 0.30, %[E] - *faint* = 0.20**
  + This represents the low density of larger scale structure
  + Gives a slightly higher elliptical proportion for bright galaxies than for faint
  + Mbright = 55.9
  + Mfaint =144.0
  + = 172.3 + [15 % gas] = **198.2**
* **For %[E] - *bright* = 0.20, %[E] - *faint* = 0.20**
  + This represents the low density of larger scale structure
  + Gives same percentage for both bright and faint galaxies
  + Mbright = 51.6
  + Mfaint =144.0
  + = 168.6 + [15 % gas] = **193.9**

**Width of Band**

* + In Bahcall + Kulier, they have a band centered at about 310 Msol / Lsol \* h, **with a spread of 30 units** in either direction. I can’t find much explanation for this band with, but I think it’s just a conservative estimate of possible uncertainty in this (admittedly unspecific) calculation.
  + Considering low scale structure first (aka where we’re gonna have more ellipticals by a good margin
    - Our calculation above likely overestimates the actual ratio. We could center it at around 320, again with a **spread of 20 or 30 units in either direction (or 10-15%)**