

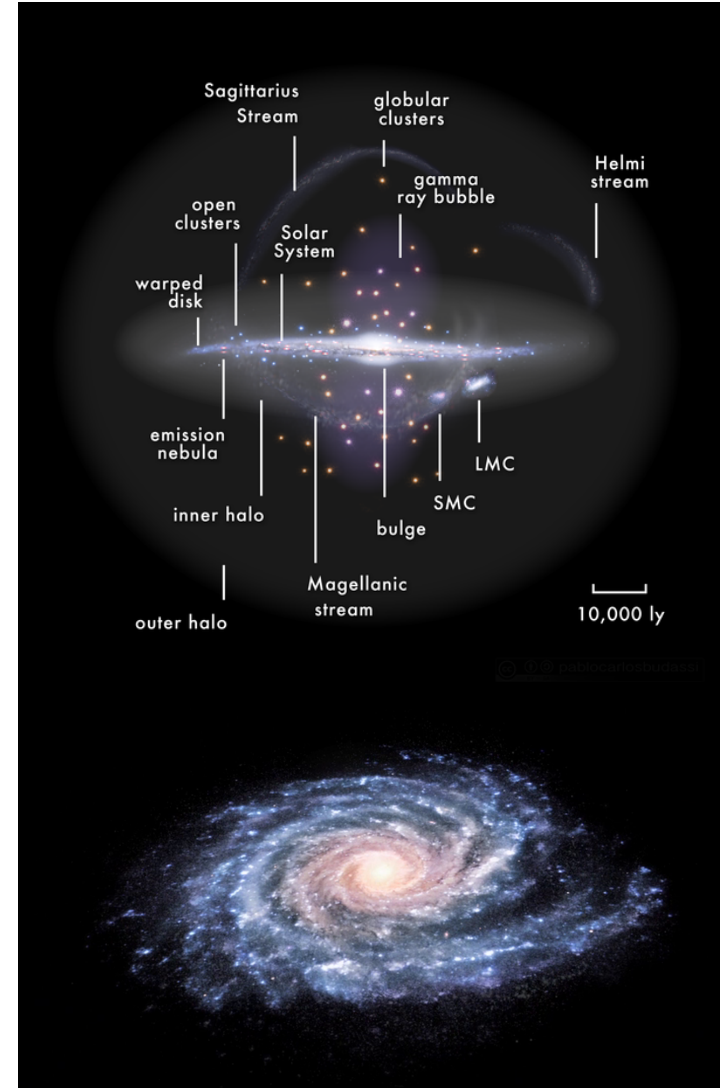


Galaxies: Hosts of dark matter

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Galaxies: Hosts of dark matter

- What do galaxies consist of?
 - How do we know?
 - How do we measure it?
 - How can you compute that?
-
- What is the mass of the Milky Way (MW)?



Milky Way Mass



$$\sim 10^{12} M_{\odot}$$

- How do we get there?

Milky Way components

- Bound system of bulge, disks, halo, clusters, gas, dust, black hole, ... dark matter
- How do we know that galaxies have dark matter?

M/L ratio – how do we get M and L? What contributes?

- How do we get the luminous mass → star count
- Thin disk – most dense → $6 \cdot 10^{10}$ stars + $0.5 \cdot 10^{10}$ gas/dust
→ lum ($L_B = 1.8 \cdot 10^{10} L_\odot$) → $M/L_{\text{thin_disk}} \sim 3$

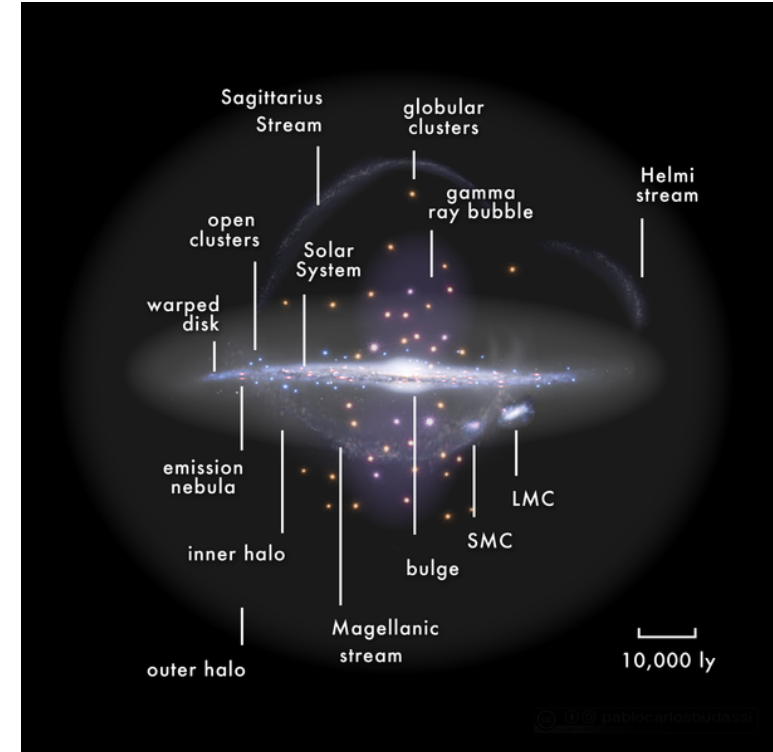
	Disks		
	Neutral Gas	Thin Disk	Thick Disk
M ($10^{10} M_\odot$)	0.5^a	6	0.2 to 0.4
L_B ($10^{10} L_\odot$) ^b	—	1.8	0.02
M/L_B (M_\odot/L_\odot)	—	3	—
Radius (kpc)	25	25	25
Form	e^{-z/h_z}	e^{-z/h_z}	e^{-z/h_z}
Scale height (kpc)	< 0.1	0.35	1
σ_w (km s ⁻¹)	5	16	35
[Fe/H]	> +0.1	-0.5 to +0.3	-2.2 to -0.5
Age (Gyr)	$\lesssim 10$	8 ^c	10 ^d

	Spheroids		
	Central Bulge ^e	Stellar Halo	Dark-Matter Halo
M ($10^{10} M_\odot$)	1	0.3	$190^{+360}_{-170}^f$
L_B ($10^{10} L_\odot$) ^b	0.3	0.1	0
M/L_B (M_\odot/L_\odot)	3	~ 1	—
Radius (kpc)	4	> 100	> 230
Form	boxy with bar	$r^{-3.5}$	$(r/a)^{-1} (1 + r/a)^{-2}$
Scale height (kpc)	0.1 to 0.5 ^g	3	170
σ_w (km s ⁻¹)	55 to 130 ^h	95	—
[Fe/H]	-2 to 0.5	< -5.4 to -0.5	—
Age (Gyr)	< 0.2 to 10	11 to 13	~ 13.5

Carroll & Ostlie, Tab. 24.1

Galactic Components

- Halo → Old stars – what does this mean?
 - Inner / outer stellar halo & DM halo
- Thin & thick disks → Gas – what does this mean?
- Bulge – a mix of stars – mainly old yet luminous
- Gas clouds
- Various stellar clusters
- System gravitationally bound



Mass-to-light ratio: M/L

- $L/L_{\odot} = (M/M_{\odot})^a$, where $a \sim 4$ for $M > 0.5M_{\odot}$, and ~ 2.3 for less massive stars
- Estimates average stellar mass

$$\langle M_{\text{thin disk}} \rangle = (M/L_{\text{thin disk}} = 3)^{1/(1-a)} M_{\odot} \rightarrow 0.7 M_{\odot}!$$

In agreement with IMF predicting more low-mass stars than high-mass stars and M-dwarfs being the most common type of stars.

- *Number of stars dominated by low-mass stars, luminosity by massive stars*

How are mass and light distributed?

- The thin disk is full of gas and forming stars – hosting a number of massive stars (luminous) – $6 * 10^{10}M_{\odot}$ and $1.8 * 10^{10}L_{\odot}$
- Thick disk has 1% of the luminosity, and 3% of mass wrt. thin disk, the halo contains $\sim 1\%$ of the MW total stellar mass
- Halo $\rightarrow 1 * 10^9M_{\odot}$ and $1 * 10^9L_{\odot}$ – a lot locked in globular clusters
- Bulge $\rightarrow 10^{10}M_{\odot}$, and $3 * 10^9L_{\odot}$
- Gas (e.g., H I) $\sim 10^9M_{\odot}$
- All luminous matter of the MW $\rightarrow 9 * 10^{10}M_{\odot}$
 \rightarrow This can explain the solar orbit – but not the orbits of more remote stars

Source: Carroll & Ostlie

Using stellar orbits to estimate mass....

Example 24.3.1. An estimate of the mass of the Milky Way Galaxy interior to the solar Galactocentric distance can be made using Kepler's third law, together with R_0 and Θ_0 . Using $R_0 = 8$ kpc and $\Theta_0 = 220 \text{ km s}^{-1}$, the orbital period of the LSR is

$$P_{\text{LSR}} = \frac{2\pi R_0}{\Theta_0} = 230 \text{ Myr.}$$

Assuming that the mass of the Galaxy within the solar circle is much greater than the mass of a test particle orbiting along with the LSR, and that the bulk of the Galaxy's mass is distributed spherically symmetrically, Kepler's third law (Eq. 2.37) gives

$$M_{\text{LSR}} = \frac{4\pi^2 R_0^3}{G P_{\text{LSR}}^2} = 8.8 \times 10^{10} M_{\odot}.$$

This value compares well with the estimate of the mass of luminous matter quoted on page 896, but it is much less than the total mass estimate of the Galaxy when the dark matter halo is included.

Source: Carroll & Ostlie

Milky Way Masses



$$M_{\text{total}} \sim 10^{12} M_{\odot}$$

$$M_{\text{luminous}} \sim 9 * 10^{10} M_{\odot}$$

Dark matter (DM) needed for this to add up!

Brightness and density

- De Vaucouleurs law:

$$\log_{10} \left[\frac{I(r)}{I_e} \right] = -3.3307 \left[\left(\frac{r}{r_e} \right)^{1/4} - 1 \right],$$

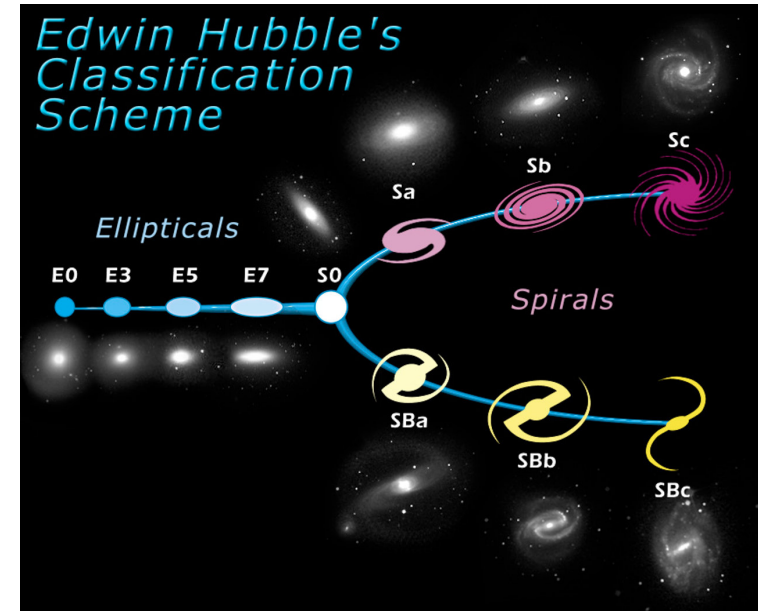
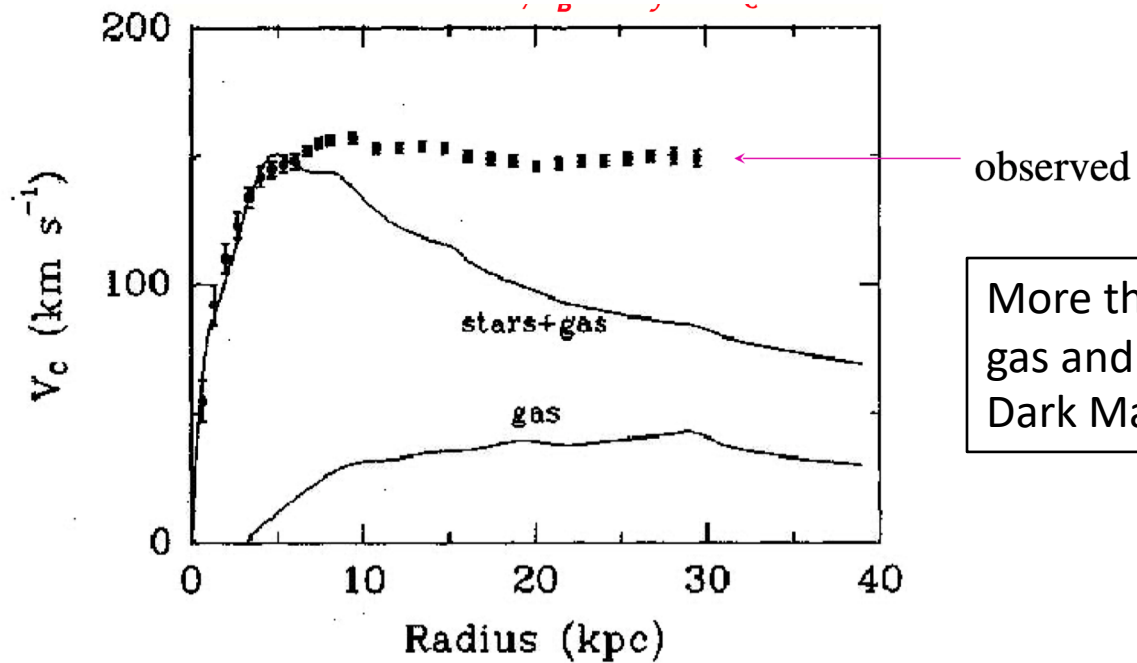
- r_e is the radius out to which $\frac{1}{2}$ of the light is emitted (cumulative),
 I = surface brightness in units [$L_{\odot} \text{ pc}^{-2}$] (I_e surface at r_e)

- Dark matter halo (to $\sim 230\text{kpc}$):

$$\rho(r) = \frac{\rho_0}{(r/a) (1 + r/a)^2},$$

- r is the radius, and a mass distribution constant from fit; at smaller distances $r \ll a \rightarrow 1/r$ ($M_{\text{DM}} \sim 10^{11} M_{\odot}$) and at large distances $r \gg a \rightarrow 1/r^3$ ($M_{\text{DM}} \sim 10^{12} M_{\odot}$)

Distribution of matter



Sa+Sb \rightarrow 50% DM, Sd \rightarrow 80-90% DM

Dark Matter

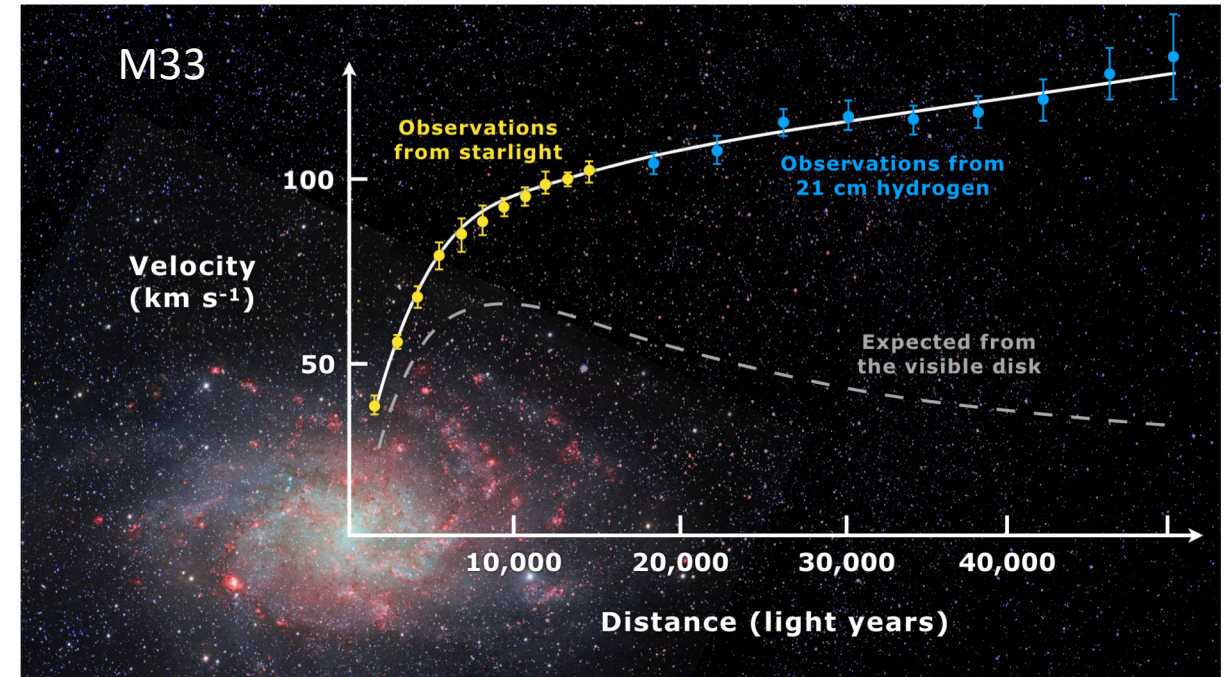
- DM makes up for 95% of the MW mass
(Weakly Interacting Massive Particles = WIMPs or MAssive Compact Halo Objects = MACHOs)
- How does it affect the Galaxy and objects we can see?
 - By adding mass to the Galaxy DM increases the potential which in turn affects the orbits (kinematics) of stars

Rotation curves

$$V_r = (\Omega - \Omega_0) * R_0 * \sin(l)$$

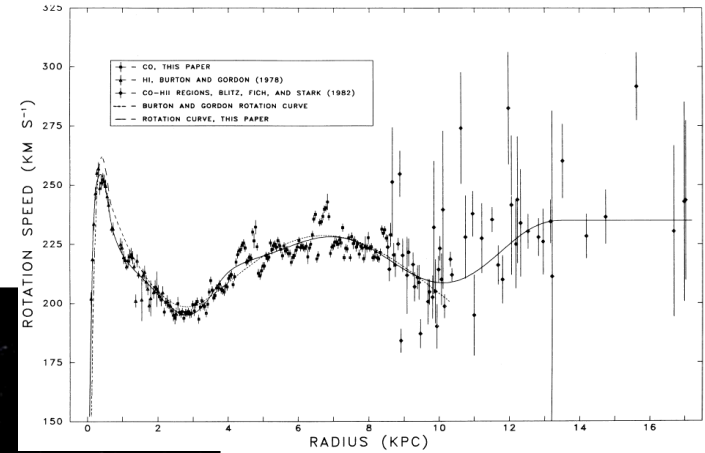
MW vs M33

Ω = angular velocity = orbital vel./R
R₀ = radius Sun – Gal centre,
l – Gal. longitude.
(assuming circular motion)

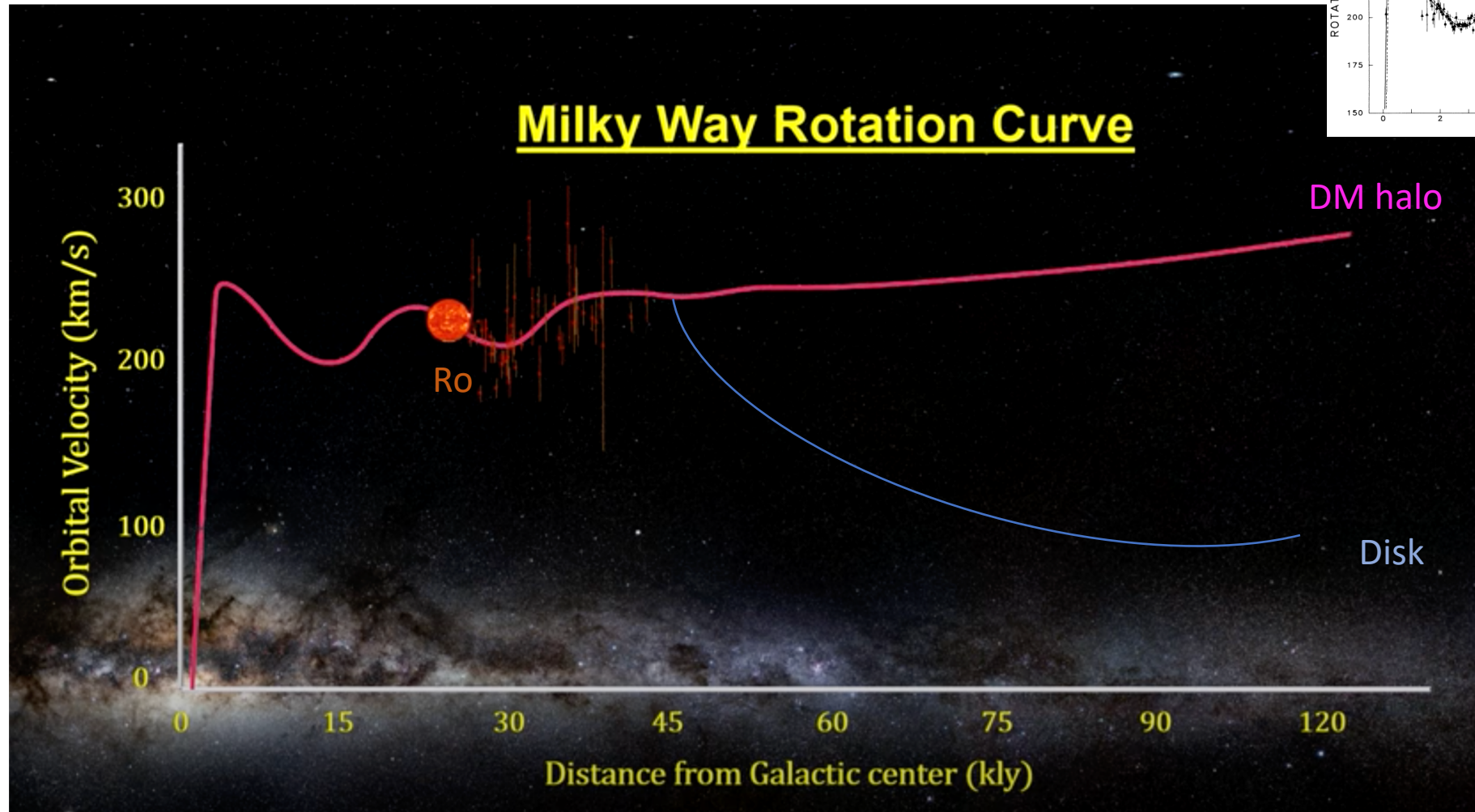


- The inner parts of the Galaxy can be well-traced using gas clouds – rotational/orbital velocities and distances (HI – radio observations → 21 cm lines) – further out more uncertain
- HI 21cm – can penetrate the entire galaxy – good to measure galactic structure
- HI 21cm – emission line giving the intensity along the line of sight - useful in e.g., De Vaucouleurs formula (intensity as a function of r)
- At larger distances $R \gg R_0$ – variable stars (Cepheids/RR Lyr) can be used as their distances can be calculated from period-luminosity relations

Rotation curve of the Milky Way



Clemens 1985



Camilla J. Hansen, IAP, Frankfurt

<https://www.youtube.com/watch?v=1aZ0Vujb08o>

If most matter inside R_o (in disk) then from Newton+Kepler \rightarrow

$$V_{orb} \sim R^{-1/2}$$

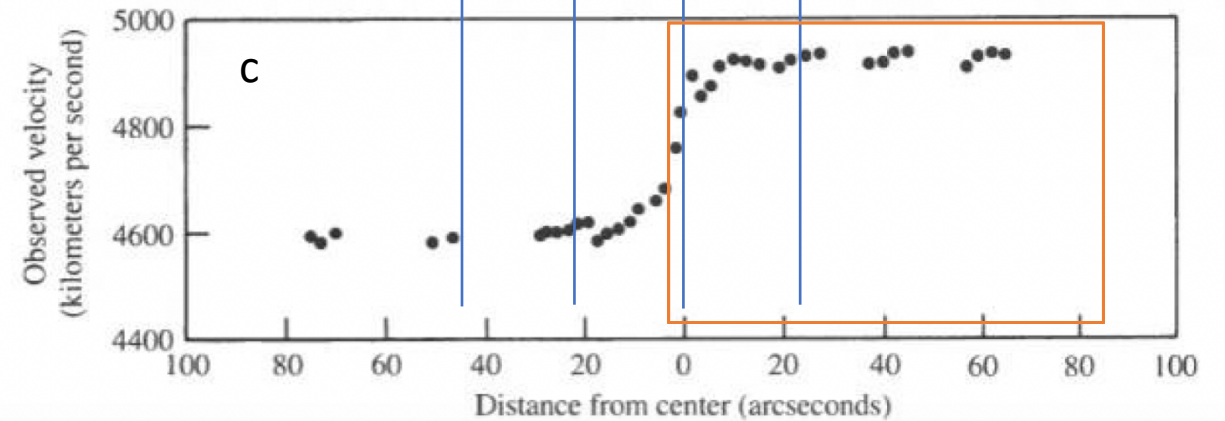
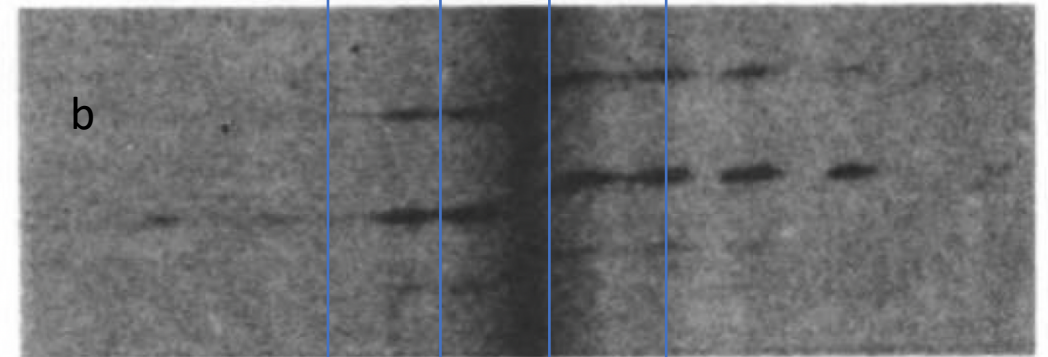
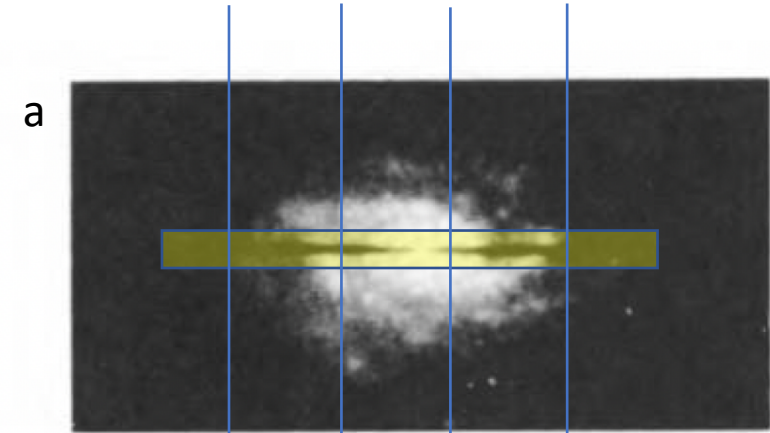
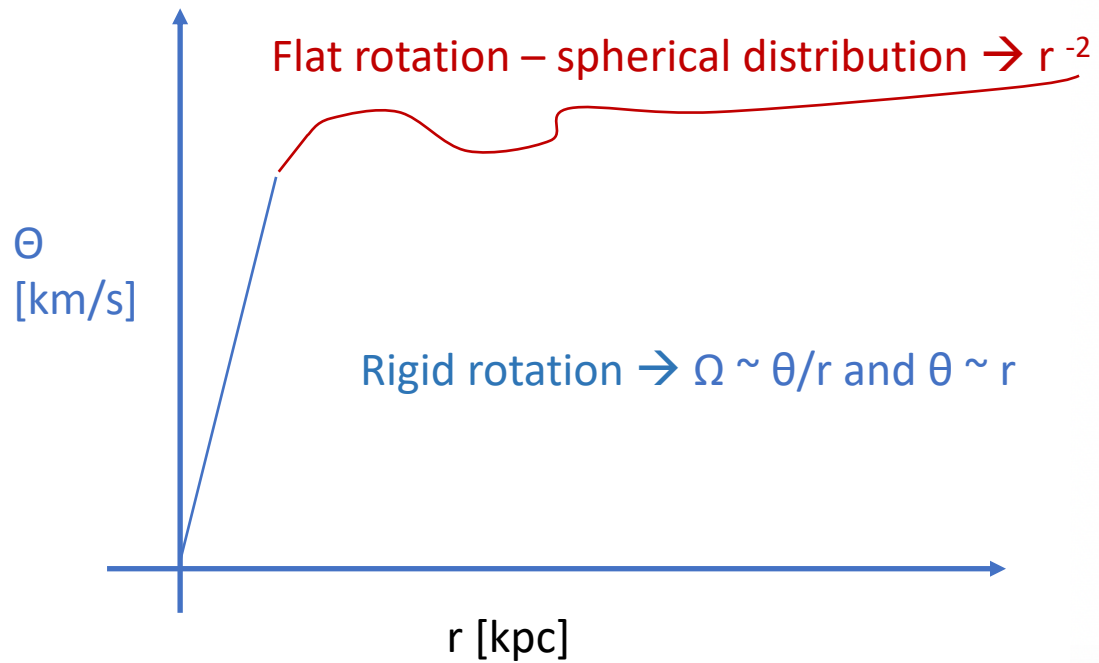
Not the case! = a lot of mass outside R_o

Rotation curves - shape

NGC2998

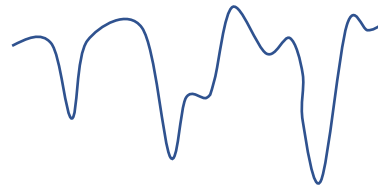
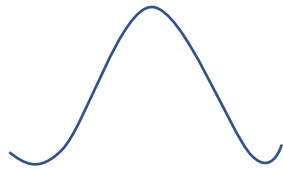
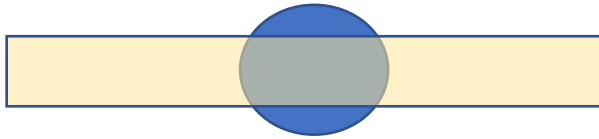
a) observed with slit \rightarrow radial velocity \rightarrow rotational velocity

b+c) Left side blueshifted – right side redshifted

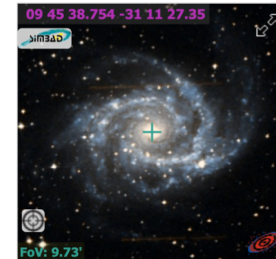
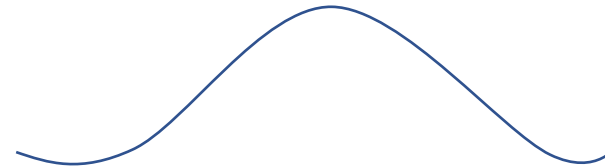
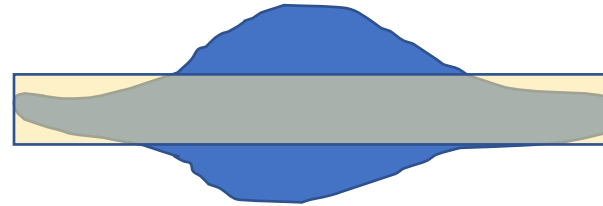


Imaging vs spectroscopy

- Stars



- Galaxies



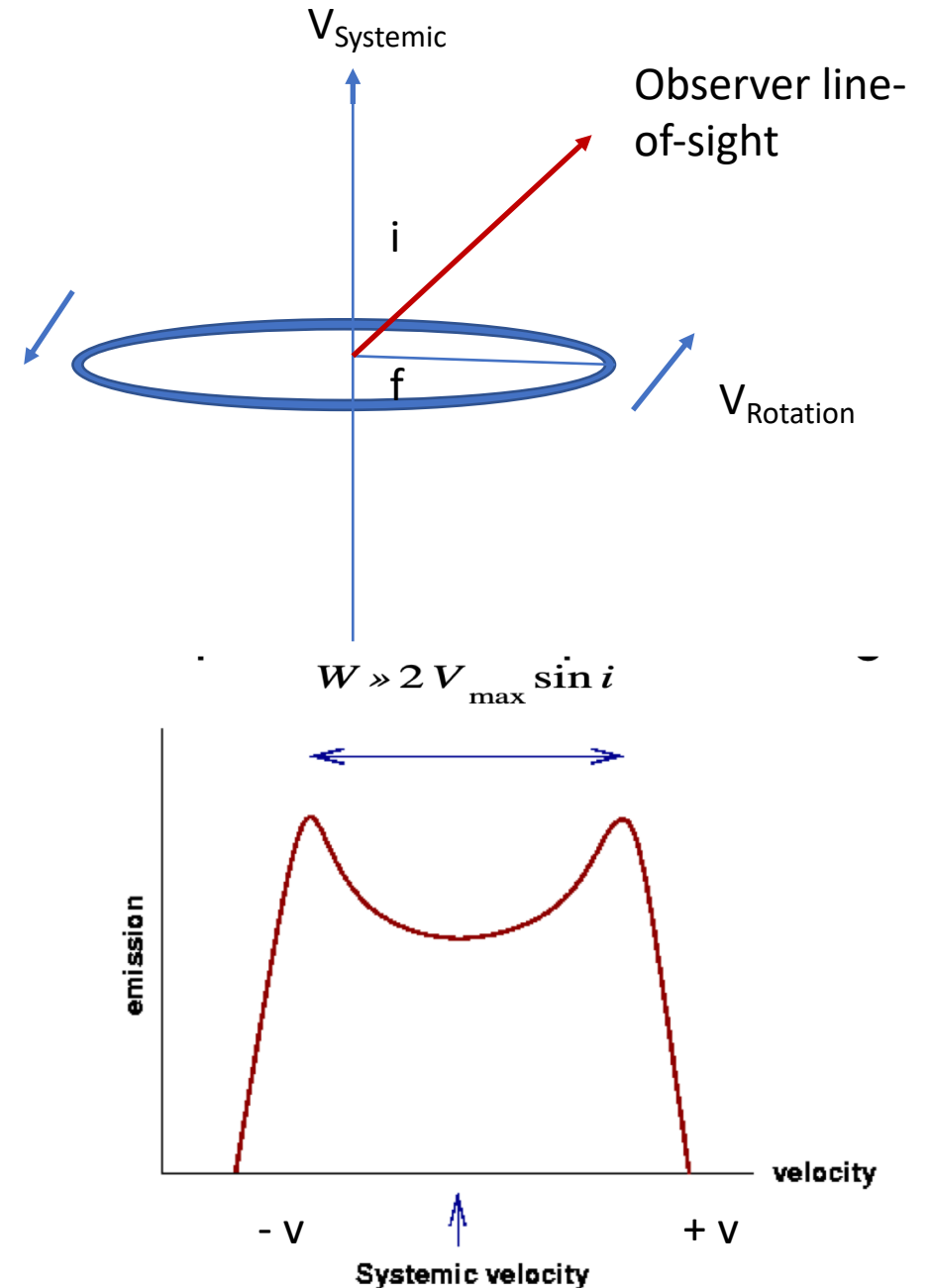
Object on slit

Point Spread Function (PSF)

Image & spectra – notice difference in number of lines and width of lines

What can we measure?

- Consider a galaxy with pure rotation
→ $V_{\text{rad}}(R) = V_{\text{sys}} + V_{\text{rot}}(R) \cdot \sin(i) \cos(f)$
- If possible we measure V_{rad} across the galaxy
→ $V_{\text{rad}}(R)$
 - Optical (nearby/remote gal.) → Ha / oxygen
 - Radio → HI 21cm
 - advantage = gas disk extends further out than stellar disk!
- Not resolved galaxy → measure emission as function V – use Doppler shift ($\lambda/\lambda_0 = v/c$) of spectral lines to get V_{rad}
 - Separation of the peaks yields the inclination (i) if $V_{\text{max,rot}}$ known



Rotation curves – shape

- Rotation curves depend on the distribution of mass
 - The rigid body rotation $\rightarrow \sim$ spherical mass distribution & density \sim constant
 - Flat curves \rightarrow outer part spherical distribution & density $\sim r^{-2}$
- Assuming spherical symmetry, $\theta \sim V = \text{const.}$, and $M(r) = \frac{4}{3} \pi r^3 \rho$ for a mass enclosed within radius r in a sphere,
Equating $F_{\text{centripetal}}$ and $F_{\text{Newton, grav.}}$

$$\frac{mV^2}{r} = \frac{GM_r m}{r^2}, \quad \rightarrow \quad M_r = \frac{V^2 r}{G},$$

Density profiles

- Using Kepler's 3rd law for velocity: $P = 2\pi r / V$ inserting into $M(r)$
→ $M(r) = 4\pi^2 r^3 / GP^2$

Differentiating and using mass conservation in spherical systems.

$$\frac{dM_r}{dr} = 4\pi r^2 \rho, \quad \& \quad \frac{dM_r}{dr} = \frac{V^2}{G}. \quad \longrightarrow \quad \rho(r) = \frac{V^2}{4\pi Gr^2}.$$

The density is proportional to r^{-2} (theory) and from star counts $r^{-3.5}$

$$\rho(r) = \frac{\rho_0}{1 + (r/a)^2},$$

Density in outer regions
- central density and a
scale radius from fit

$$n_{\text{halo}}(r) = n_{0,\text{halo}}(r/a)^{-3.5},$$

Number density
from star count in
halo (GC+field)

Density – dark matter halo

- To fit the central parts $r \ll a$ (constant density) and rigid body rotation, outer parts $r \gg a \rightarrow r^{-2}$ behaviour \rightarrow
 - Only valid to finite r ($M \propto r$) – or $M \rightarrow \infty$, (no galaxy has infinite mass)

$$\rho(r) = \frac{\rho_0}{1 + (r/a)^2}, \quad \rho_0 \text{ and } a \text{ galaxy specific}$$

- Navarro, Frenk, White cold dark matter halo based on simulations – valid to larger r !

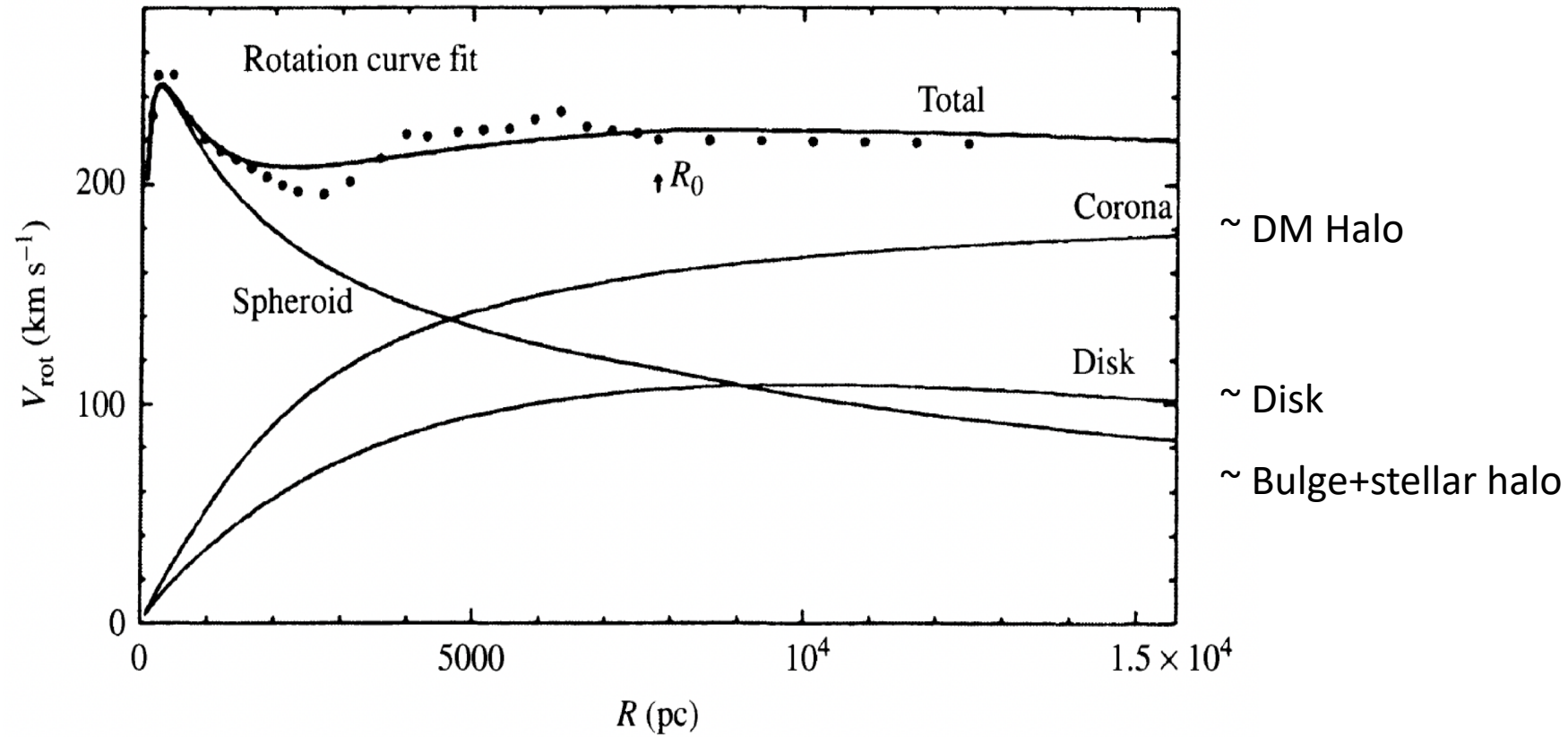
$$\rho_{\text{NFW}}(r) = \frac{\rho_0}{(r/a)(1 + r/a)^2}$$

Central density $\sim 1/r$

Halo $1/r^2$

Outer DM Halo $\sim 1/r^3$

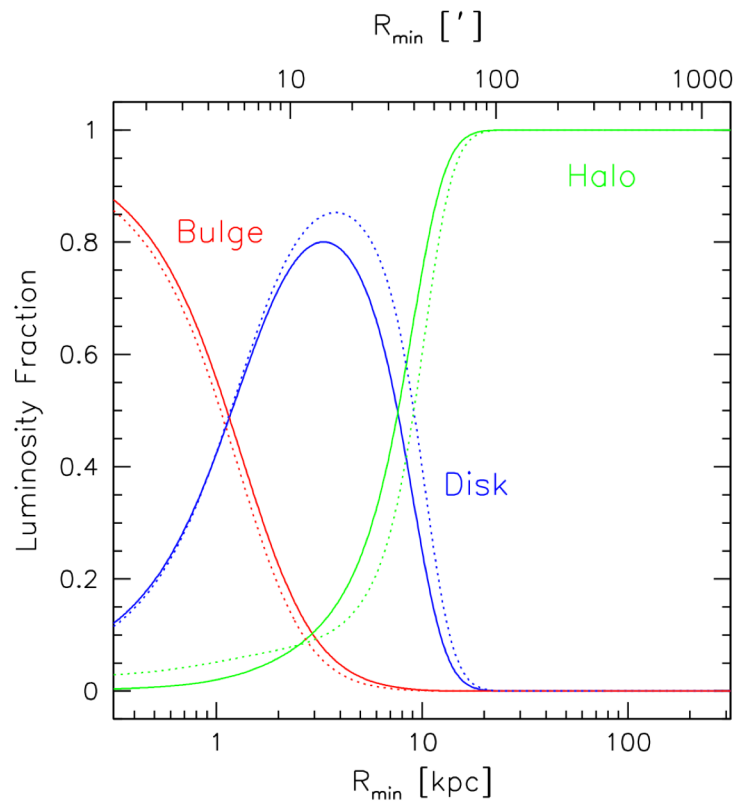
Model of Galactic components (MW)



Recall R_0 – solar distance to Galactic centre (in MW)

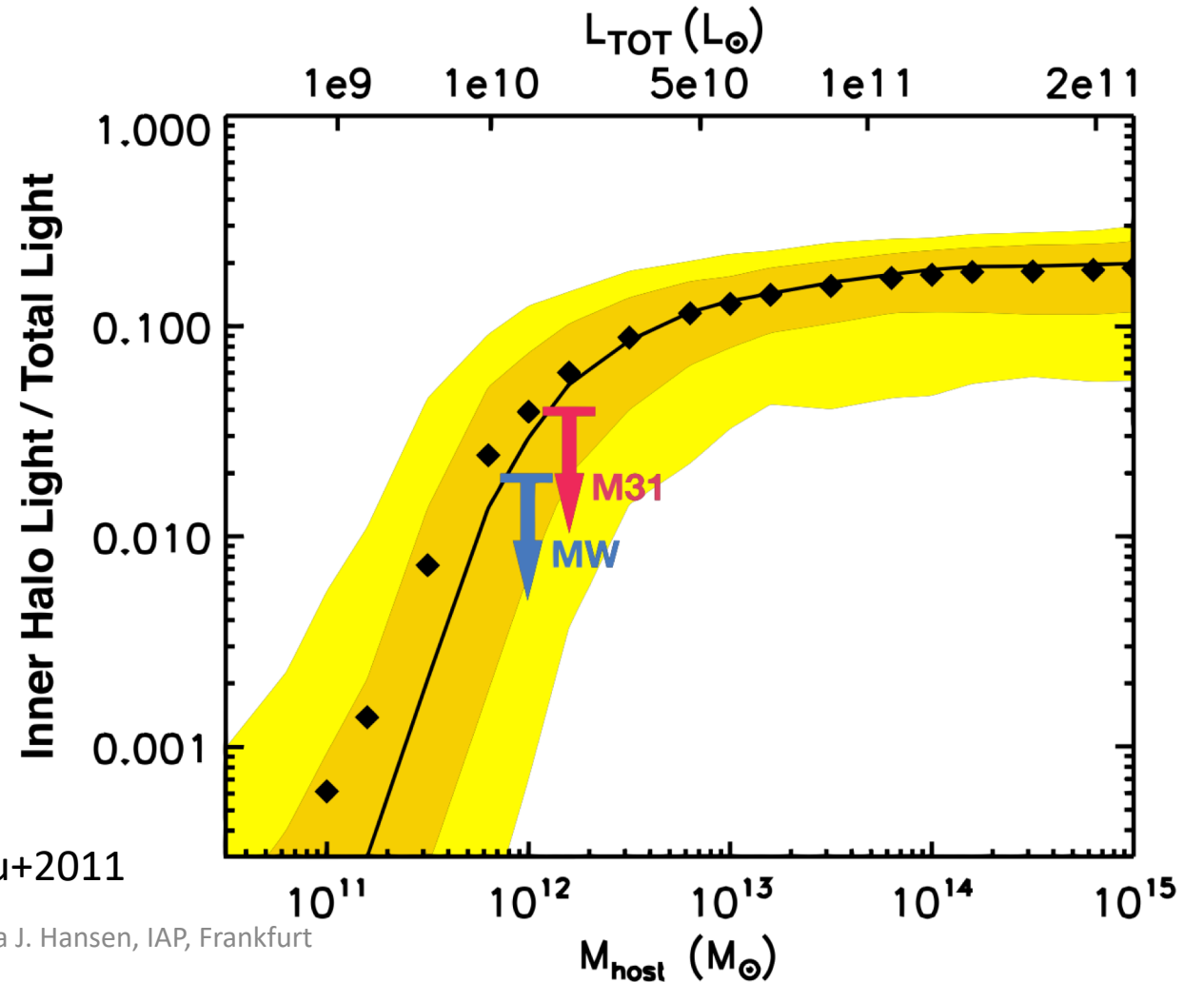
Luminosity from Galactic components

- Massive spiral galaxies (M31)



Courteau+2011

Camilla J. Hansen, IAP, Frankfurt



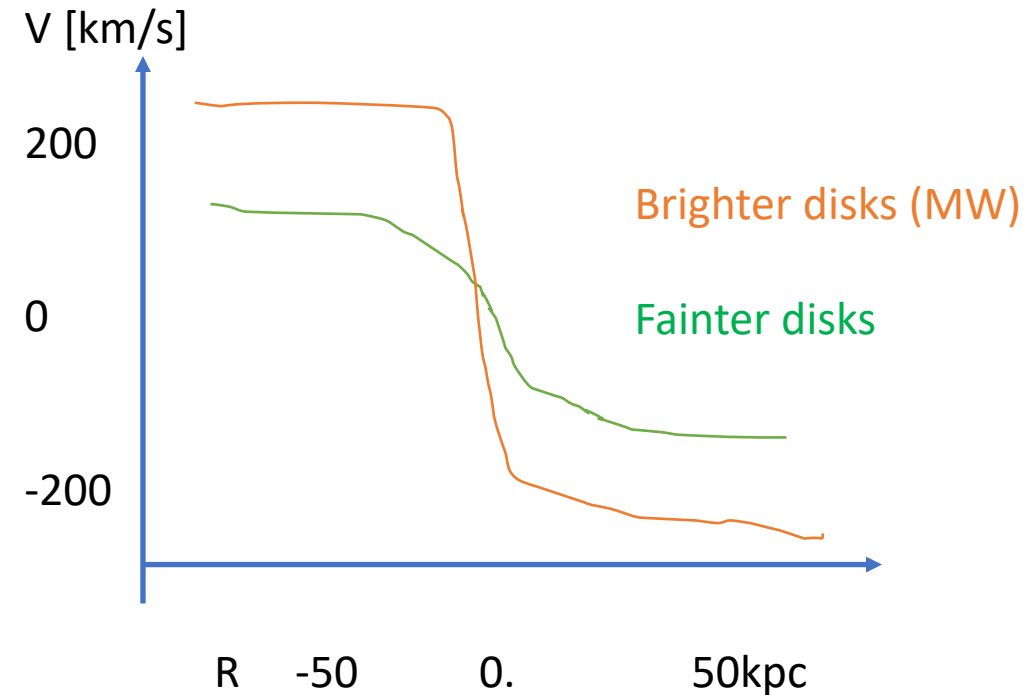
Brightness

- The disk is kept in place by $F_{\text{centripetal}} (V_{\text{rot}})$ and by gravity F_{grav} (see above)

- Disk Intensity: $I(R) = I(0) e^{-R/h_R}$

where h is the scale length, and $I(0)$ is the central surface brightness (dominated by the bulge)

- For most spirals $I(0)$ is constant at $I_B \sim 21.65 \text{ mag/arcsec}^2$ (Freeman law)



Brightness profiles

- Various realisations of de Vaucouleurs $r^{1/4}$ law which is good for ellipticals – and for different galaxy components

$$I(R) \propto e^{-bR^{1/n=4}}$$

While for spiral galaxy disks $n=1$ is a good approximation

$$I(R) \propto e^{-bR^{1/n=1}}$$

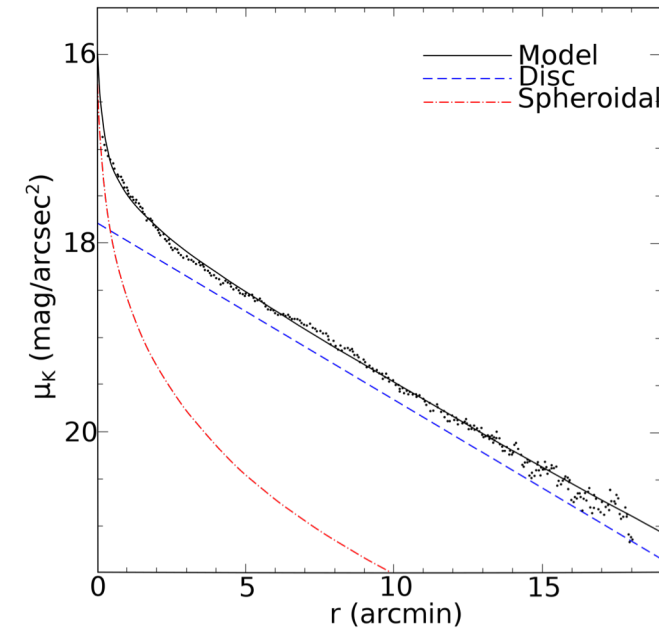
- **Sersic profile**

$$I(R) = I_e \exp \left\{ -b_n \left[\left(\frac{R}{R_e} \right)^{1/n} - 1 \right] \right\}$$

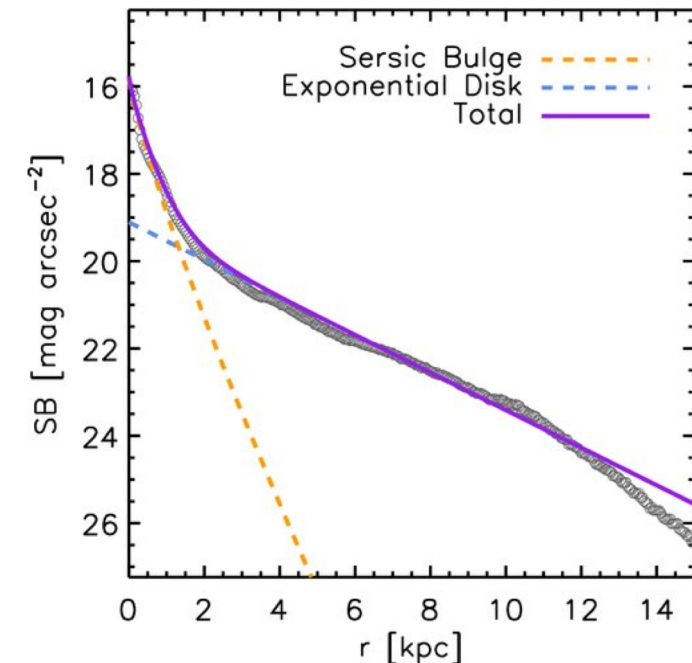
where b_n is approximately $2n - 1/3$ for $n > 8$.

'e' indicates half light radius (R_e) or intensity (I_e)

M 33 surface brightness profile

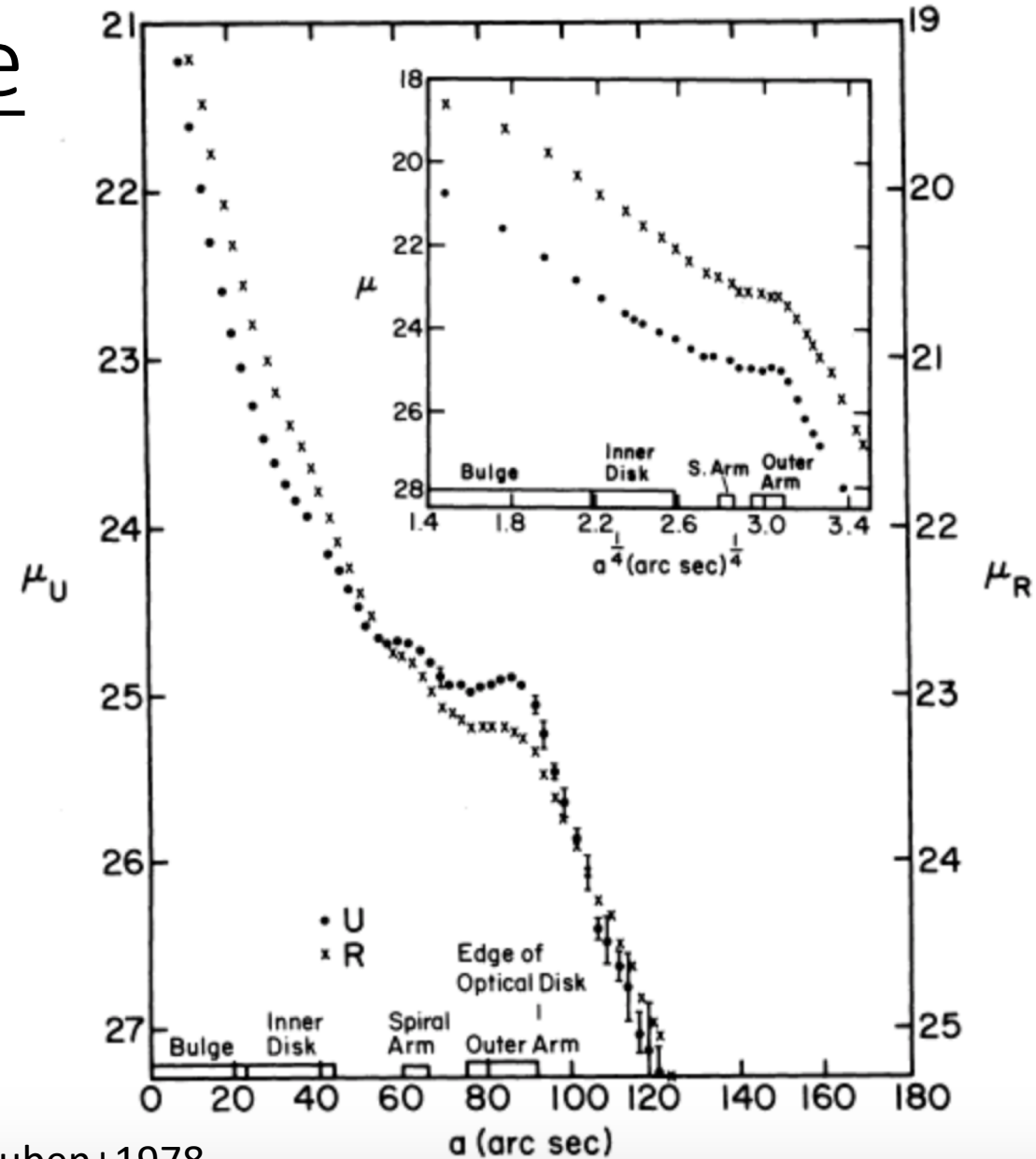


Spheroidal
~ bulge



Shape of brightness profile

- What does the shape of the brightness profile tell us?
- Direct information of Galactic structure
 - Bumps = arms/ rings in outer parts
 - Inner parts → Bulge



Shape of rotation curve

- Different rotation curves for spirals

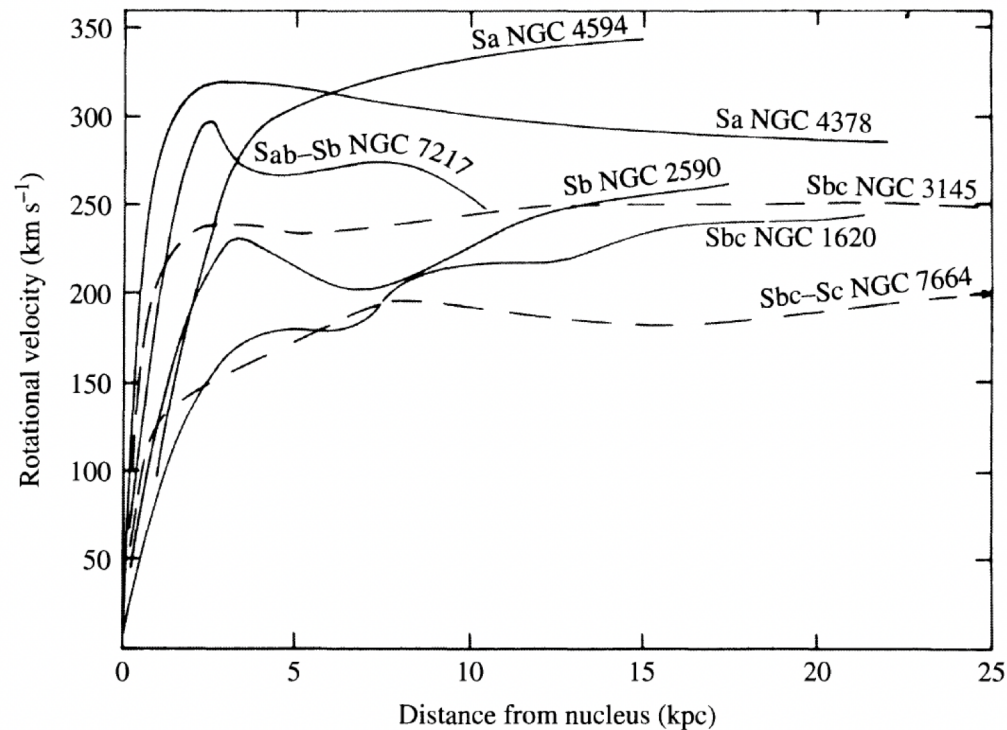


FIGURE 24.27 A series of rotation curves for spiral galaxies. (Figure adapted from Rubin, Ford, and Thonnard, *Ap. J. Lett.*, 225, L107, 1978.)

What is needed?

Distance to/in object

Zero point for absolute magnitude

Point spread function

Different light profiles

- King – isothermal sphere ~ bulge or GC

$$\Sigma(r) = \Sigma_0 \left[1 - \frac{1}{(1 + (r_t/r_c)^2)^{1/\alpha}} \right]^{-\alpha} \times \left[\frac{1}{(1 + (r/r_c)^2)^{1/\alpha}} - \frac{1}{(1 + (r_t/r_c)^2)^{1/\alpha}} \right]^{\alpha}$$

- Nuker – fit nuclear profile of nearby galaxies

$$I(r) = I_b 2^{\frac{\beta-\gamma}{\alpha}} \left(\frac{r}{r_b} \right)^{-\gamma} \left[1 + \left(\frac{r}{r_b} \right)^{\alpha} \right]^{\frac{\gamma-\beta}{\alpha}}$$

- Exp. Disk - fit disks

$$\Sigma(r) = \Sigma_0 \exp\left(-\frac{r}{r_s}\right) \quad \Sigma = \text{surface brightness}$$

For more profiles and descriptions – see Peng's Galfit manual

Camilla J. Hansen, IAP, Frankfurt

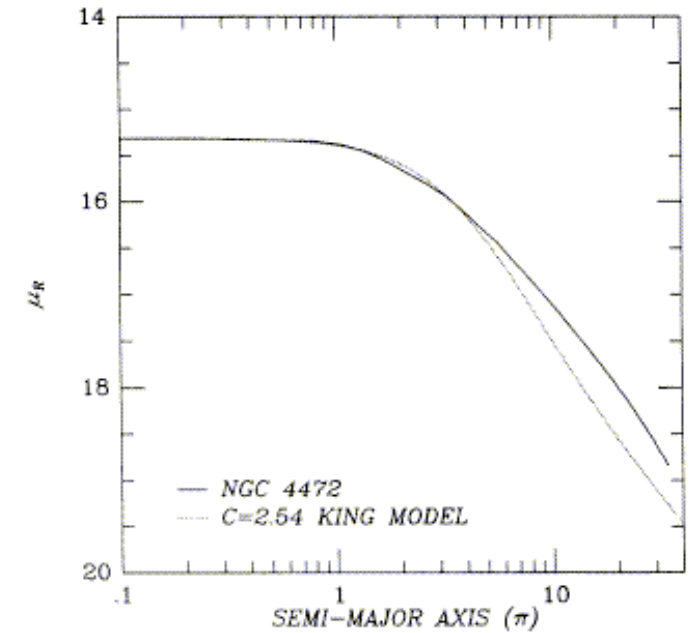
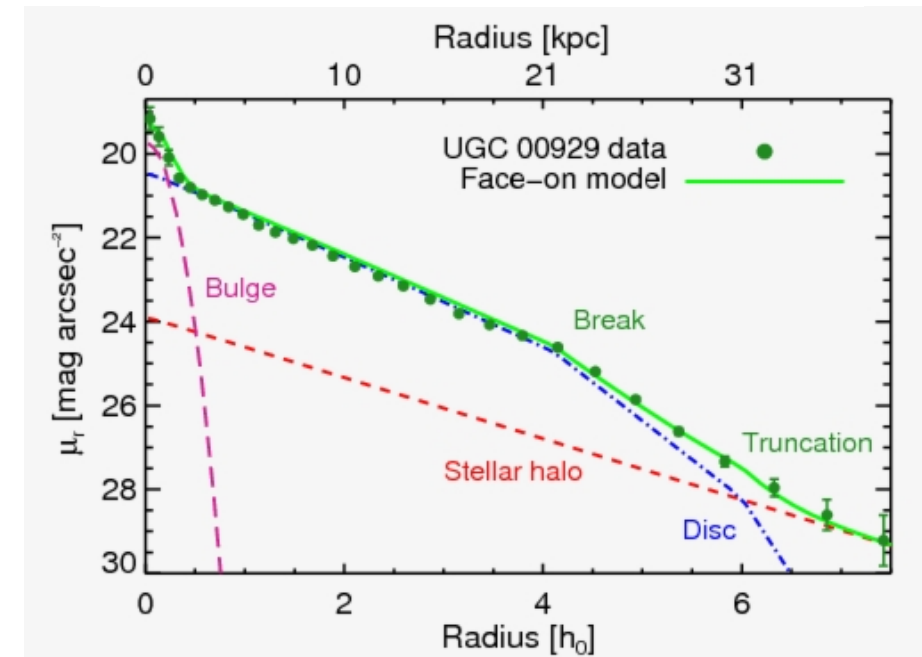


FIG. 6.—Concentration 2.54 King model fitted to the deconvolved core of NGC 4472.



Questions and break

- What do rotation curves (and their shape) tell us?
- What can we learn from brightness profiles
- Which density (halo) profile provides a good description and why?
- What does the M/L tell us? How was that conclusion reached?

Background information

- http://legacy.ifa.hawaii.edu/~cowie/ast626_dir/gal_lec17.pdf
- Carroll & Ostlie
- Pixel -> coordinate: https://nova.astrometry.net/user_images/5512030#annotated
- DS9: <http://www.adamgginsburg.com/ds9tips.htm#body8>
- Galfit: <https://users.obs.carnegiescience.edu/peng/work/galfit/README.pdf>
- <https://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html>

A quick guide

STEP ①

Extract/convert pixel to coordinate →
https://nova.astrometry.net/user_images (Tab → upload)

STEP ②

Measure the PSF → IRAF: task = psfmeasure or imexam+imcopy
<https://iraf.net/irafhelp.php?val=obsutil.psfmeasure&help=Help+Page>

STEP ③

Measure the magnitude zero point → DS9 (use >10s stars)
<http://www.adamgginsburg.com/ds9tips.htm#body8>

STEP ④

Run Galfit on your object – try different ways
<https://users.obs.carnegiescience.edu/peng/work/galfit/README.pdf>

Results: Intensity curves, (rotation profiles), and M/L-ratio

Download Data

- Download data - for one or both galaxies
- <https://hessenbox-a10.rz.uni-frankfurt.de/dl/fiRT1WSQuuZvj3rWAFkrSP/.dir>

Convert pixel to RA,DEC

- After downloading your image go to www.nova.astrometry.net/upload
- Upload your image and have the conversion done for you
- Download “new-image.fits” → this is your input galaxy image w coordinates – copy it over to galaxy_input.fits where galaxy is to be replaced by e.g., M31
- What do you see on screen?

IRAF & DS9

- For a quick inspection use **psfmeasure** & load the image in DS9
- In IRAF (epar psfmeasure) give input_image and set coords=mark1 & GFWHM and execute using “:g”
- Alternatively use **imexam + imcopy + imstat + imarith + imcombine** → PSF image
- Before starting imexam load the Astrometry.net downloaded image in DS9

IRAF packages

- Preload following packages:
 - NOAO
 - Images , tv
 - Obsutil
 - Digiphot, daophot

IRAF & DS9

- **Imexam**: this task logs the stellar flux and the Full Width Half Maximum (FWHM) of the stars on the Galaxy image
 - In the IRAF command line: `imexam M31_input.fits logfile=M31.log keeplog=yes`
 - In DS9 - zoom in on different regions away from the Galaxy to find field stars – place cursor on top and click and press `r` → the star has been measured and logged in the logfile
 - Cover different parts of the image (sensitivity) and stars of different brightness – use several tens of stars (>50) – this can help with setting the zeropoint magnitude as well
- Inspect what you see on screen – and once you are done hit ‘`q`’ to exit
- Open the logfile and understand what has been recorded

IRAF & DS9

- Now you define regions around the stars to be cut out and used for the final PSF image
- Copy the logfile and cut out the central x,y coordinates (in pixels) – define a region around central x,y so that all of the stars are in with some background – e.g., ± 20 pixels on each side of x,y
- **Imcopy**
- IRAF Command line: `imcopy M31_input.fits[x1:x2,y1:y2] star1_out`
 - Make a full list (ascii) with all stars you measured – one line per star as shown above – `stars2_out`, `stars3_out` etc.
 - Execute ascii: `cl < ascii_starlist.cl`
 - This generates a new image for all stars you measured with those stars in

IRAF & DS9

- You measured stars with different brightness – this needs to be normalised before you can co-add your stellar images
- **Imstat**
 - `Imstat stars***.fits fields=image, mid`
 - This measures the median value of each of the stellar images
- Now compute the normalised image by dividing with the median value
- **Imarith**
 - IRAF command line: `imarith stars1***fits / #value outputname`
 - Here the value comes from `imstat` (e.g., 350) and the outputname should indicate that the new image is normalised – e.g., `stars1_out_norm.fits`
 - Make a script – a list that includes all stars and execute the script: `cl < norm_imarith.cl`

IRAF & DS9

- Now stack/co-add the normalised stellar images
- **Imcombine**
 - `Imcombine stars*_out_norm.fits output comb=median`
 - The output is now the normalised, combined stellar image = PSF image!
- Now inspect and measure on the PSF image – use either `psfmeasure` or `imexam`.
 - In **imexam** – try clicking on r, s, e, l and understand what is plotted

IRAF & DS9

- Zeropoint magnitude
- Use output ascii file from imexam that contains flux and magnitudes
- Now we need to go from pixels to coordinates and look up the real magnitudes for our stars to understand the zeropoint offset in our observations
- Cut useless lines from our ascii
 - Grep -v COL central_out.reg
 - This gives us a file with central regions (x,y) of the stars measured and update this file: line 1 should read "image", line 2 "global color=gree"
 - Line 3 – xx: circle(x,y,10) - or if in Ra and dec circle(x,y,10")

DS9

- If you view one of your newly cut stellar images in DS9 – you see that it has “image x,y” but also the old galaxy image “physical x,y” as well as Ra and Dec.
- Open M31_input.fits (the astrometry.net image) in DS9
- Go to “Region” in the top bar – choose “load regions” and load your central_out.reg file you just generated
- Now all the measured stars have a small green circle around them
- In “Region” you can play with shape and ruler and finally save the image “save regions” – NB: **select fk5! (You might have to save twice)..**

DS9 & command line

- In the now generated regions file (stars.reg) that contains
- Circle(Ra,Dec,arcsec) we need to convert the hms format to degrees to do a crossmatch in order to get the magnitudes from a catalogue

- For many stars:

```
awk '{n+=1};{print n, 15*($1+$2/60+$3/3600), $4+$5/60+$6/3600}'  
stars.reg > stars_degrees.reg
```

- To the top of stars_degrees.reg add a small header with: 'name ra dec'

Cross match with SDSS

- Go to <http://skyserver.sdss.org/dr17/CrossMatchTools/ObjectCrossID>
- Set following:
 - Images → photometry, search scope radius → nearest primary obj, and RA&Dec
 - Search radius = 0.1-0.2 arcmin
 - Browse and load file stars_degrees.deg (incl. the header) & submit
- From this file you cut out galaxies and other things so that it only contains stars – it turns out that you might have measures bright spots that were galaxies instead of stars.
- From this file you need running ID (n), ra, dec, mag_r put this in “calib_stars”

Awk

- The last file you make will then help you get the zeropoint magnitude
- Awk '{print, \$1, ... \$flux_column,....\$r_mag, -2.5log(\$flux)/log(10)}'
calib_stars > my_zeropoint
- The last $-2.5\log(F)$ is the computed magnitudes
- If you are in a hurry – take the mean of the (r_mag-comp_mag)
- Better way: make a linear fit to r_mag (x) and comp_mag (y) and read off the intersection with y → your zeropoint magnitude

- Now you can run galfit to get intensity and luminosity

A few conversions!

- A few things to pay attention to:

- Gain is set to 0 in the fit(s) files → hedit them (in IRAF) to a non-zero value (~0.1)
- Resolution must be computed:
 - How many pixels does the image have in x and y – and what field of view (fov) is covered (degrees). E.g., 0.5x0.5 degrees fov and 4800 x 3200 pixels – then use **1 degree = 3600 arcsec**
→ 0.38 x 0.56 "/pixel

- Arcsec → parsec

- **Tan (A) = r/dist** – if in arcsec convert to degrees (see above) first – and if in radians: arcsec * $\pi/(3600*180)$



Galfit

- <https://users.obs.carnegiescience.edu/peng/work/galfit/README.pdf>
- Update the galfit.feedme file and then run galfit: `./galfit galfit.feedme`
- **Sersic**
 - **Input:** A) – K) – read off centre of the galaxy in DS9 and use conversions from previous slide. The Convolution box should be $20 \times \text{PSF}$ value ($\sim 50-100$)
 - **Output:** x[pixel], y[pixel], m_{tot} , re[pixel], n, b/a (axis ratio), pos. angle
- If Galfit will not run – go to IRAF and update Gain from 0 to 0.1 using 'hedit'
- Galfit output – inspect in DS9 using: “open as” \rightarrow “Multiple .. frames”
- If the model does not look good (i.e., like the galaxy try running again with a different model or more models)

Last steps to M/L-ratio - Luminosity

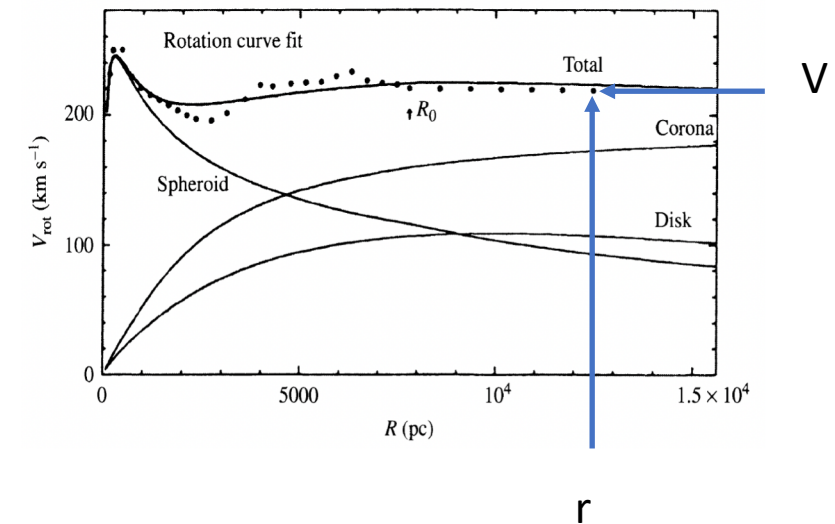
- Galfit gives you m_{tot} – which is the total apparent magnitude – to get the luminosity you need the absolute magnitude

$$m_{tot} = -2.5 \log_{10} \left(\frac{F_{tot}}{t_{exp}} \right) + \text{mag zpt},$$

- Distance modulus: $d = 10^{(m - M + 5)/5}$ - to convert mag to absolute mag – the distance you look up in the literature
- Intensity/Flux – luminosity – magnitude: $L/L_o = 10^{0.4(M_{bol,o} - M_{bol})}$
 - You may skip extinction and bolometric corrections and assume $M = M_{bol}$

Last steps to M/L-ratio - Mass

- The mass can either be looked up in literature directly – or estimated from rotation curves – where you read-off V and r
- Now using: $M(r) = 4 \pi^2 r^3 / G(2 \pi r / V)^2$
- where $P = 2 \pi r / V$
- Make $I(r)$ plots
- Finally – compare your M/L with literature



Extra files

- <https://hessenbox-a10.rz.uni-frankfurt.de/getlink/fiRT1WSQuuZvj3rWAFkrSP/>