# Galaxies: Structure, formation and evolution

## Lecture 3

Yogesh Wadadekar

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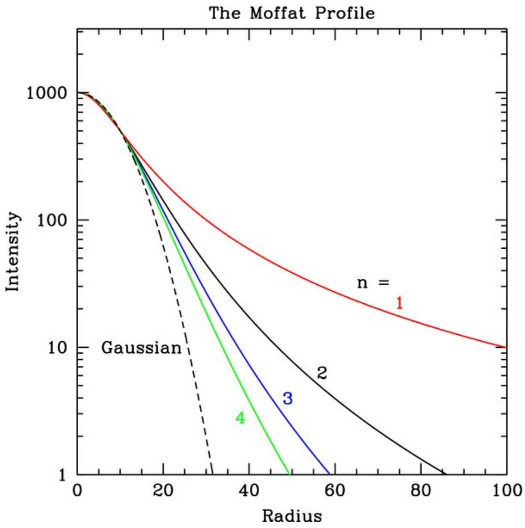
# Fitting a point source and convolution

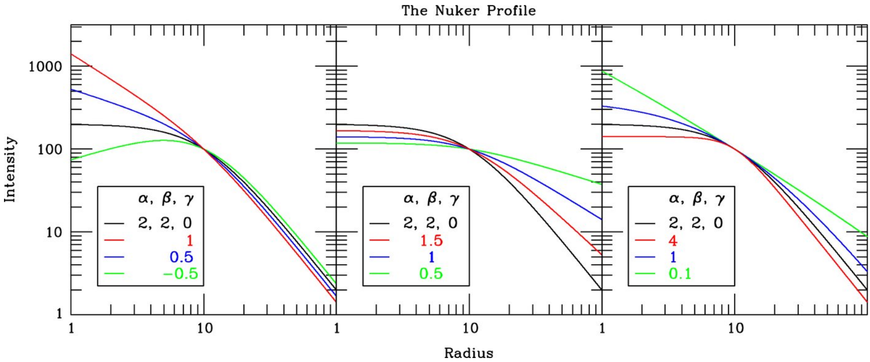


# The Nuker profile

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

Here $\beta$ is the outer power-law slope, $\gamma$ is the inner slope, and $\alpha$ controls the sharpness of the transition. The motivation for using this profile is that the nuclei of many galaxies appear to be fit well in 1D (see Lauer et al. 1995) by a double power law.

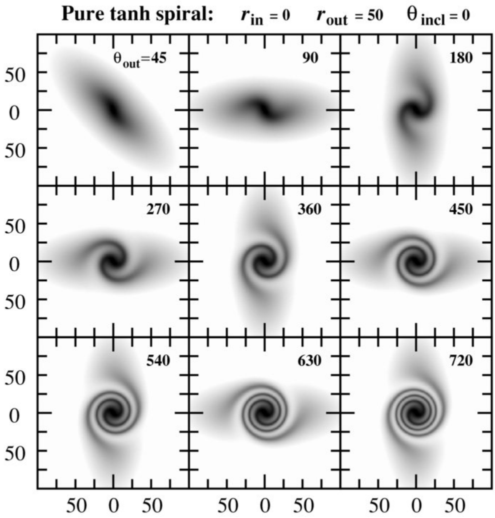
# Nuker profile



# Fitting spiral arms - why it is usually not a good idea

Why it is mostly not necessary.

# Spiral arm profiles



# Fainter galaxy components

such as shells and halos are too faint to fit but may be seen in the fit residuals.

# Fainter you go the more you see.....

Duc et al 2011

# Limitations of quantitative morphology

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# Limitations of quantitative morphology

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- If we add analytic forms for say, the spiral arms and the bar, the additional free parameters can introduce degeneracies in the fit.
- accuracy of parameter estimation is strongly dependent on the accuracy of PSF and sky estimation. A small error in one of these can lead to a large error in galaxy parameter estimates. (lazy person's solution - use HST data, Why?)
- Nevertheless, quantitative morphology is widely (but not always wisely!) used today in many studies of galaxy evolution.

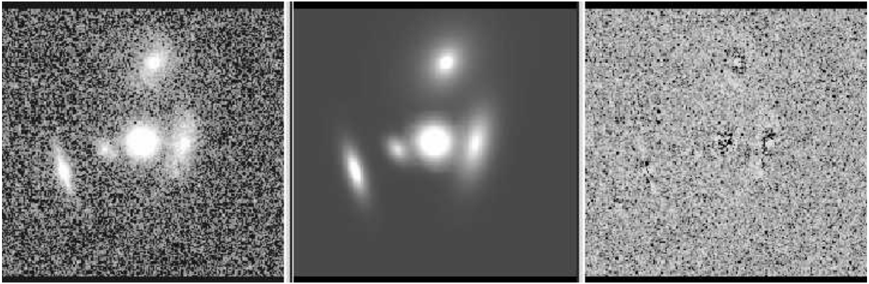
# Quality control for bulge disk decomposition

- the reduced $\chi^2$ is a quantitative goodness of fit indicator.
- in addition, the fit diagnostic plots were used to evaluate the quality of the fit
    1. are the residuals small and random?
    2. is the residual histogram approximately gaussian?
    3. does the radial profile pass through the azimuthally averaged data points?
    4. has the masking been done correctly?

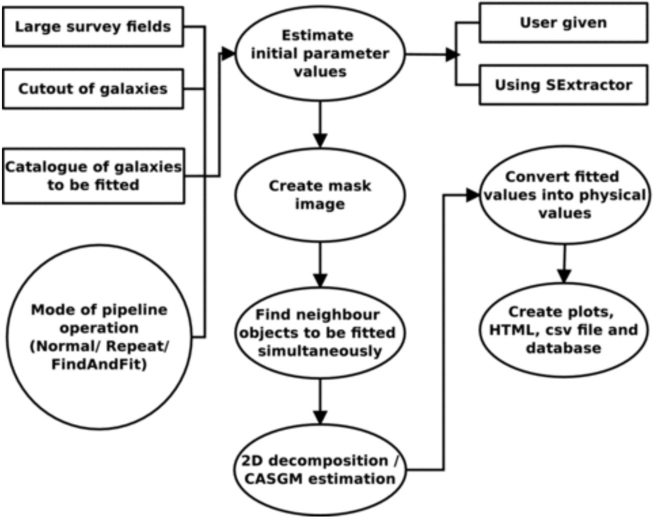
# Some Bulge disk decomposition codes

- **fitgal** Wadadekar, Robbason & Kembhavi (1999). One of the earliest 2D codes. Uses Davidon-Powell-Fletcher variable metric algorithm from Minuit. Very fast. Not maintained anymore
- **galfit** Peng et al. 2002. The most widely used code. Uses the simple Levenberg-Marquardt algorithm. Very fast.
- **gim2d** Simard et al. 2002 uses the Metropolis algorithm similar to simulated annealing. Very slow but can handle low S/N images well.
- **BUDDA** de Souza et al. 2004

# GALFIT can fit multiple galaxies simultaneously

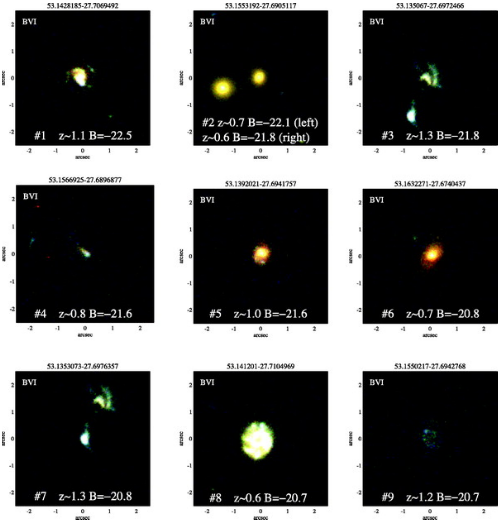


# PyMorph pipeline




Vikram, Wadadekar et al. (2010)

# When 2D decomposition does not work - use CAS or GM




de Mello et al 2006

# Concentration index ($C$)

Concentration is defined as the ratio of the radius of the galaxy which contains 80% of the total light ($r_{80}$) to the radius of the galaxy which contains 20% of the total light ($r_{20}$). i.e..,

$$C = 5\log\left(\frac{r_{80}}{r_{20}}\right) \tag{1}$$

How to measure or consistently define the “total light” of a galaxy?

# Petrosian radius

The Petrosian radius $r_p$ is the radius of the galaxy at which the Petrosian parameter $\eta$ takes a value of 0.2. The Petrosian parameter is defined as follows:

$$\eta = \frac{\langle I_r \rangle}{\langle I \rangle_r} \tag{2}$$

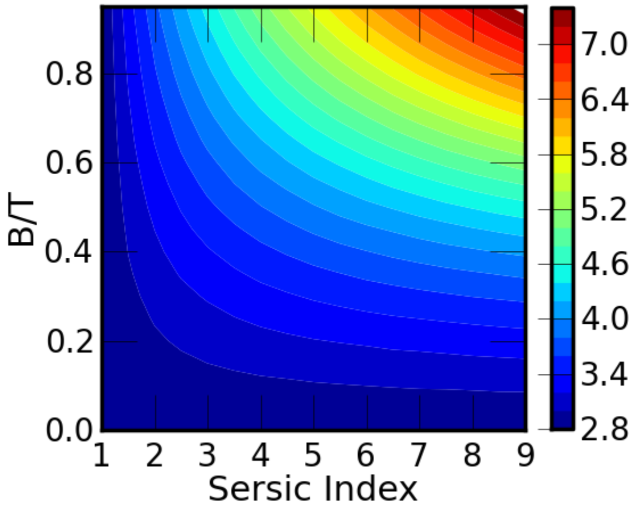
where $\langle I_r \rangle$ is the average light at the radius $r$ and $\langle I \rangle_r$ is the average light inside $r$.

The total light of the galaxy is defined to be the light within $R_T$ which is defined to be 1.5 times of the Petrosian radius $r_p$

# What is the connection between concentration index and morphology?

The theoretical value of concentration of an elliptical galaxy which follows $r^{1/4}$ law is 5.3 and that of a pure disk galaxy is 2.8. Therefore, the concentration is directly related to the $B/T$ of the galaxy. Also it can be shown that the concentration parameter is related to the Sérsic index as the ellipticals have larger value of the index than disk galaxies. These correlations make the concentration a useful **non-parametric** quantity to classify galaxies. The three way analytical relation between these quantities, i.e. $B/T$, Sérsic index and concentration, can be derived.

# Relation between $C$,$B/T$ and $n$



# Asymmetry

We rotate the galaxy through 180 degrees using bilinear interpolation about its centre which is taken to be the centroid (first image moment) of the galaxy pixels. In the next step, we subtract the rotated image from the original image of the galaxy. From the residual image we estimate the total residual flux inside the extraction radius. This is then normalised by the total flux of the galaxy. This step can be represented as follows:

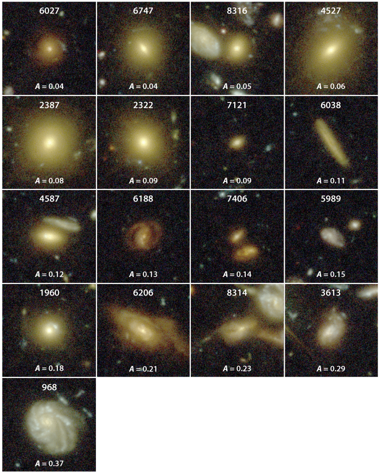
$$A_O = \frac{\sum |I_0 - I_R|}{\sum I_0} \tag{3}$$

where $I_0$ and $I_R$ are original image and the rotated image respectively and the summation is over all pixels, inside the radius $R_T$.

# Question

How is asymmetry connected with morphology?

# Galaxies in order of increasing asymmetry




Conselice CJ. 2014.
Annu. Rev. Astron. Astrophys. 52:291–337

# Clumpiness

To find $S$ we convolve the galaxy image with a boxcar function of width $0.25r_p$ where $r_p$ is the Petrosian radius of the galaxy. This smoothed image is then subtracted from the original image and the residual is summed within the extraction radius. The output of this process is the sum of the clumpiness of the object and background. The whole process can be summarised in the following equation:

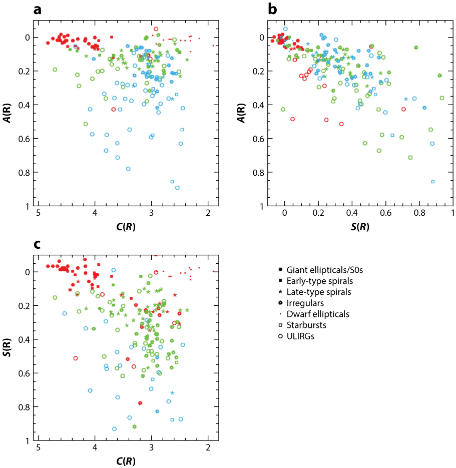
$$S = 10\left[\frac{\sum I_0 - I_S}{\sum I_0}\right] \tag{4}$$

where $I_0$ is the original image, $I_S$ is the smoothed image and the summation is over all the positive pixels of residual image with the annular region of width $0.2R_T \leq r \leq R_T$.

# Question

How is clumpiness related to morphology?

# Galaxies separated by CAS parameters

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for more details on CAS: Conselice (2014)

# Gini coefficient

To get $G$ we first find the pixels in the image which belong to the galaxy, i.e. obtain the **segmentation map** of the galaxy. For this, we convolve the galaxy image with a boxcar filter of size $r_p/5$. This process will increase the signal to noise ratio in the outer parts of the galaxy. Then we measure the intensity $I_p$ at $r_p$. We assign all the pixels in image with $I_p \leq I \leq 10\sigma$ to the galaxy where $\sigma$ is the standard deviation of the sky. The upper limit ensures that no cosmic rays or spurious pixels are included in the segmentation map. Then the pixels belonging to the segmentation map are sorted according to their photon count $I_i$ and $G$ is calculated using the equation:

$$G = \frac{1}{\bar{I}_i n(n-1)} \sum_{i=1}^{n} (2i - n - 1)|I_i| \tag{5}$$

where $I_i$ is the photon count in the pixel $i$ which belongs to the segmentation map, $\bar{I}_i$ is the mean of all the pixel values $I_i$ and $n$ is the total number of pixels (Lotz et al 2004). G=0, implies complete equality.

# Question

How will Gini be affected if we get the segmentation map wrong? Will the Gini coefficient be higher in ellipticals compared to spirals?

# Second order moment of the brightest pixels ($M20$)

This quantity measures of how the brightest pixels are distributed over the galaxy segmentation map. To compute $M20$ we use the segmentation map generated to estimate the Gini coefficient. We start by computing the flux weighted second order moment of the galaxy $M_T$ as

$$M_T = \sum M_i = \sum I_i \left[ (x_i - x_c)^2 + (y_i - y_c)^2 \right] \tag{6}$$

where $I_i$, $x_i$, $y_i$ are the flux value and x and y coordinates of the $i^{th}$ pixel in the segmentation map and $x_c$ and $y_c$ are the initial centre of the galaxy. We then minimize $M_T$ with respect to the centre of the galaxy as the initial value of the centre is the centroid of the galaxy.

# M20 index

We sort the pixels according to their flux value and find the moment of the 20% brightest pixels of the galaxy using the equation

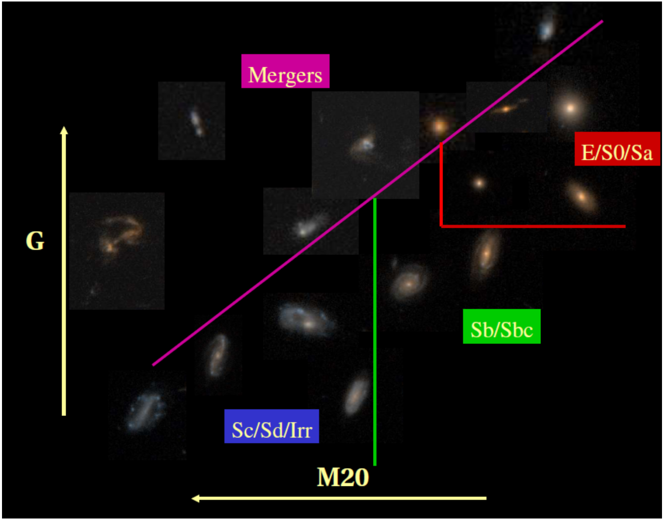
$$M20 = \log \left( \frac{\sum M_i}{M_T} \right) \tag{7}$$

where the summation continues until it satisfies $\sum I_i \leq 0.2 I_T$ where $i$ is the pixel in the sorted array of the segmentation map and $I_T$ is the total light of galaxy.

# Question

If you observe the same spiral galaxy in a blue and red filter where will the M20 be higher and why? Is M20 similar to the concentration parameter?

# Gini+M20 and galaxy morphology



# Large scale structure of galaxies

So far, we have looked at galaxies and their components from a structural point of view. The physical scale is a few 10s of kiloparsecs.

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So far, we have looked at galaxies and their components from a structural point of view. The physical scale is a few 10s of kiloparsecs. Now we look at the large scale structure of baryons in the universe on Mpc scales. Just as stars are the individual building blocks of galaxies, galaxies are building blocks of the *cosmic web* of large scale structure. Remember, however, that galaxies are *biased* tracers of the underlying DM distribution i.e. $M/L$ ratio is not constant!

# Why conduct galaxy redshift surveys?

- Density fluctuations evolve into structures we observe: galaxies, clusters, etc.
- On scales $>$ galaxies, we talk about the Large Scale Structure (LSS); groups, clusters, filaments, walls, voids, superclusters are the elements of LSS
- To map and quantify the LSS (and compare with the theoretical predictions of cosmological models), we need redshift surveys: mapping the 3-D distribution of galaxies
- Today we have redshifts measured for $>$ 2 million galaxies
- While the existence of clusters was recognized early on, it took a while to recognize that galaxies are not distributed in space uniformly randomly, but in coherent structures.

# Galaxy imaging surveys

| | | |
|---|---|---|
| 1970 | Lick (Shane-Wirtanen) | 1 M galaxies |

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| 2005 | SDSS | 200 M |

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| 2005 | SDSS | 200 M |
| 2024 | Rubin/LSST | 10000 M |

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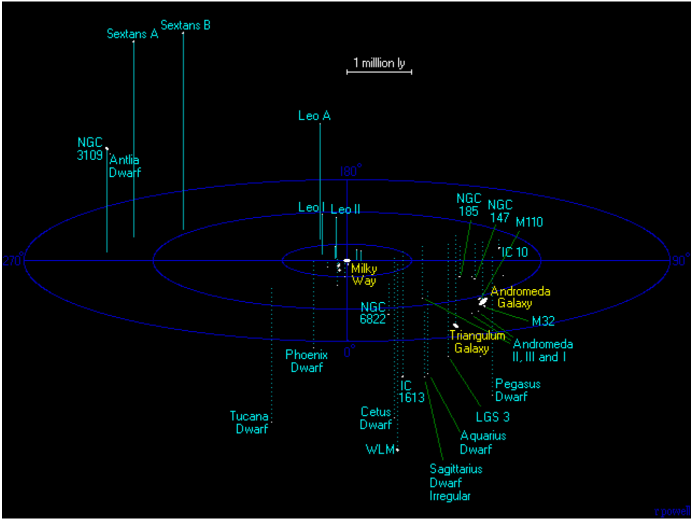
| 1996 | LCRS | 23000 |
| 2003 | 2dF | 250k |
| 2005 | SDSS | 800k |
| 2021 | SDSS DR17 | 3m |
| 2023 | DESI EDR | 1.2m |
| 2027 | DESI | $\sim$30m |

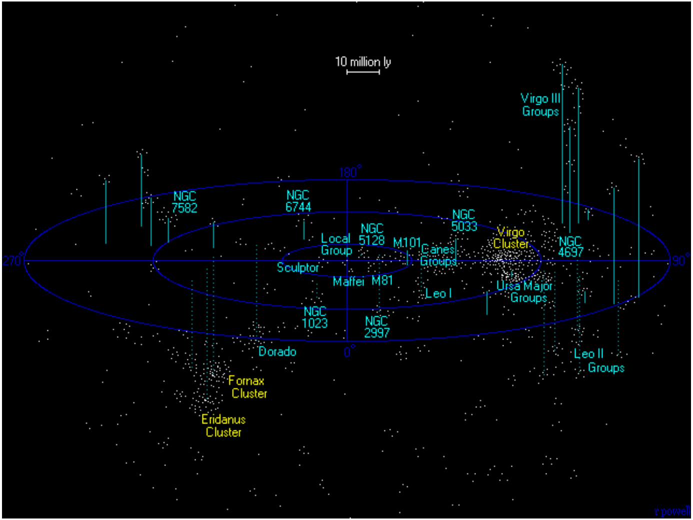
# DESI EDR fly through

https://www.eurekalert.org/multimedia/987945

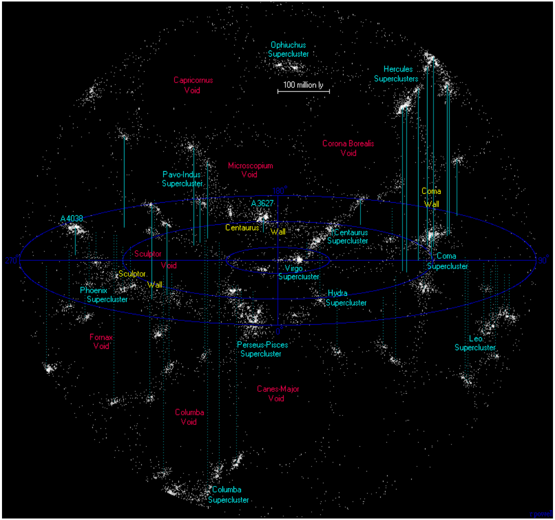
# The Local group



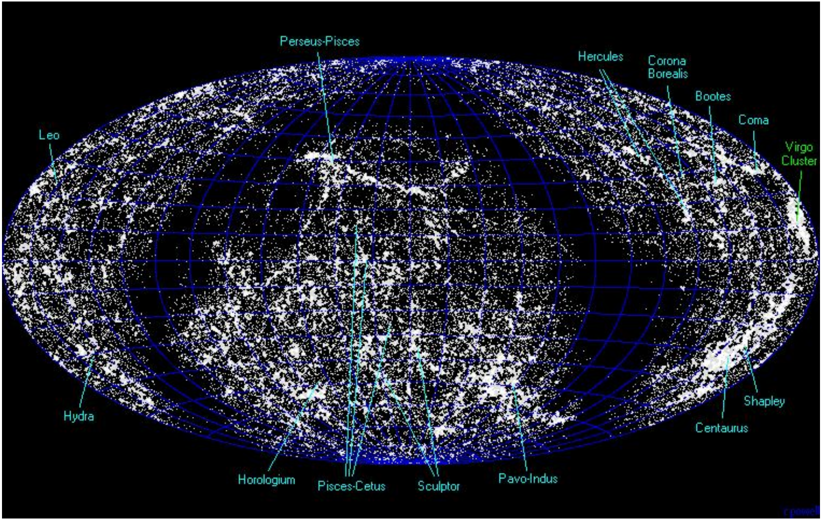
# The local supercluster



# Nearby superclusters



# 6000 Brightest galaxies




Where would the 6000 brightest stars lie?