HUMBOLDT UNIVERSITY BERLIN

BACHELOR THESIS

The effect of view direction on identifying correlated planes of satellite galaxies in cosmological simulations

---

Author:
Pouria SAMIEADEL

Gutachter/innen:
Prof. David Berge
Dr. Marcel PAWLOWSKI

Zur Erlangung des akademischen Grades
Bachelor of Science

Eingereicht am

Institut für Physik der Humboldt-Universität zu Berlin

July 26, 2021

HUMBOLDT UNIVERSITY BERLIN

Abstract

Faculty Name
Institut für Physik der Humboldt-Universität zu Berlin

Bachelor of Science

The effect of view direction on identifying correlated planes of satellite galaxies in cosmological simulations

by Pouria SAMIEADEL

While a significant amount of galaxies have been discovered until today, it has also been a great challenge to observe and analyse every single one of them to the fullest. As a matter of fact, there are only few neighboring galaxies optimal for observation. The Centaurus A galaxy is the reference galaxy used for this thesis, since it is one of the closer and well-observed galaxies.
Cen A is surrounded by a plane of satellite galaxies. While observing and calculating the velocity of these, a certain coherent pattern of movement can be recorded. The plane seems to be rotating around the host-galaxy.
This peculiar behavior has been set to test by using the $\Lambda-$ CDM model to simulate, in this case 180, galaxies.

Acknowledgements

The acknowledgments and the people to thank go here, don't forget to include your project advisor…

Contents

List of Figures

List of Tables

List of Abbreviations

LAH	**L**ist **A**bbreviations **H**ere
WSF	**W**hat (it) **S**tands **F**or

Physical Constants

Speed of Light $c_0 = 2.997\,924\,58 \times 10^8\ \mathrm{m\,s^{-1}}$ (exact)

List of Symbols

a	distance	m
P	power	W ($J\,s^{-1}$)
ω	angular frequency	rad

For/Dedicated to/To my…

Chapter 1

Chapter Title Here

1.1 Welcome and Thank You

Chapter 2

Physical and mathematical basis

2.1 The observed Galaxy, Centaurus A

Centaurus A, a giant elliptical radio galaxy, served as a reference for this project. In the centre of Cen A, there is a very compact but active core and it also possesses a rather visible disk of dust.[1]

2.1.1 Elliptical Galaxies

Astronomer Edwin Hubble divided every galaxy in the Universe into four categories: elliptical galaxies, spiral galaxies, irregular galaxies, and S0 galaxies.[2]

spiral galaxies look like what their name suggests. The disk of dusk has the shape of a spiral. Depending on certain properties, such as their brightness, these galaxies are subdivided into many other categories.

On the other hand, **irregular galaxies** don't have a recognizable shape. Moreover, they are also divided into at least two subgroups, since some have weak shapes and some don't take any shapes at all.

s0 galaxies, also called lentil-shaped galaxies, lie between elliptical and spiral galaxies. Their name is derived from their shape since they have a bump in their centre but around the edge, their shape fades, making them resemble lentils.

However, Cen A is an elliptical galaxy, which is the most common galaxy group in the Universe. In addition, this group has many sub-groups based on the ellipticity they possess. $'\epsilon = 1 - \frac{b}{a}'$[2] In general, elliptical galaxies are very massive and bright, with Cen A having a mass of 1 billion suns and a diameter of 60.000 light-years. Additionally, it has a brightness of around 6.6 mags. Moreover, Centaurus A has an active core emitting radio waves, thereby making it a radio galaxy.

Radio galaxies

The galaxies considered radio galaxies are all elliptical and are like Centaurus A in having an active core. Cygnus A is another example of a radio galaxy.[2] The galaxies in this group are divided by their radio emission, according to whether it is broad-line or narrow-line, providing insight into the properties of the gas and the activity of the galaxy. Cen A is a galaxy with a broad-line emission. Cen A is, therefore, a powerful source of radio, while its emission remains non-thermal synchrotron radiation. It has a radio luminosity of roughly $10^{33} - 10^{38}$ W, nearly as much as a regular

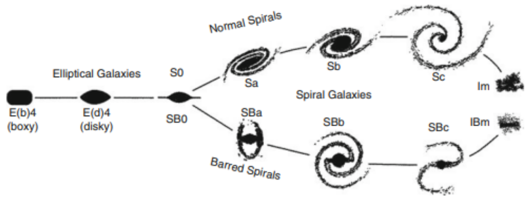


FIGURE 2.1: 'Hubble's 'tuning fork' for galaxy classification. Adapted from: J. Kormendy | & R. Bender 1996, A Proposed Revision of the Hubble Sequence for Elliptical Galaxies, ApJ 464, L119, Fig. 1.c AAS. Reproduced with permission'[2]

galaxy.

The main challenge is to discover an explanation for this radio emission. To be able to explain, we must understand the emergence of electrons and the magnetic field. Most importantly, there is a question around where these electrons gather the required energy.

A radio galaxy is characterized by two major radio emitting regions on the opposite side of the galaxy. (fig: 2.2) By looking at such a galaxy, you also recognize a fine line of the jet. This is the said radio emission line. The jet emitted by Cen A can be seen up to the edge of the galaxy. There is no other radio galaxy closer to Milkyway than Cen A.

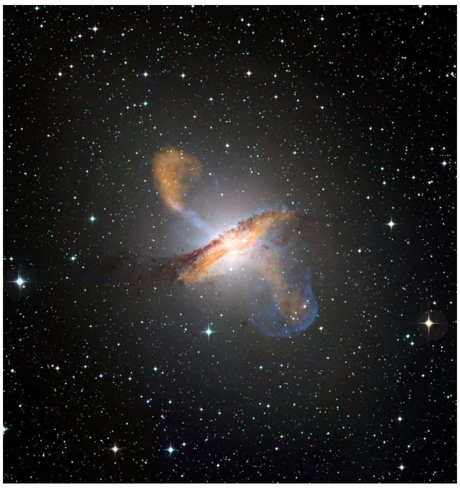


FIGURE 2.2: An illustration of Centaurus A[3]

However, in this study, we will make use of the size, position and velocity of 28 of Centaurus A's satellite galaxies. We compare the flatness and movement of the said satellite galaxies to that of the simulated one. This will be discussed in detail in Chapter 3.

2.2 ΛCDM Model and TNG-Project

Simulated galaxies are the core tool for this project. In this thesis, we measured the flatness of 180 systems, the positions of satellite galaxies and their velocities. We rely on data from the TNG-Project, which utilizes the standard model of cosmology in its simulations.[4]

2.2.1 The standard model of cosmology

The standard model of cosmology, also called the Λ -CDM model, is an attempt to explain the universe and its existence based on dark energy, the cosmological constant and cold dark matter.

the main statement of the model is about the density of mass energy and how it is dominated by the density of dark matter and dark energy, both being very unknown components. Galaxies don't always behave according to our current understanding of physical theories about gravity, so there are only hints that they exist. Therefore, a possible explanation is that the galaxy contains an unidentified mass, which cannot interact with light. The distribution of this mass is known as the 'cosmic web'.(fig: 2.3)

A **Cosmic web** is like a fabric that encloses our universe. There are fibres, knots, and holes in every fabric. It is the same with the cosmic web. Dark matter is distributed in fibres, that come together in certain spots to build a knot or 'halo'. Galaxies, in other words, visible matter, tends to take shape around those halos.

Therefore, TNG simulations first build a cosmic web and then let the galaxies simulate on top of this basis. Because of these simulations and their accuracy in replicating the galaxies in most cases, Λ CDM is considered as standard model of cosmology, however there are still some cases, like the one discussed in this thesis, where there are some incongruities.

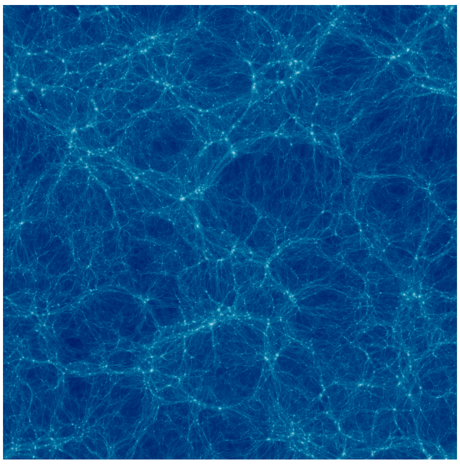


FIGURE 2.3: an Illustration of a simulated cosmic web [5]

2.2.2 TNG-Project

'The IllustrisTNG project' is a variety of simulations of galaxies. The model is based on the standard model of cosmology.
A total of 18 simulations are included in the project. Each has its advantages. They differ in size, resolution, and complexity. There are three main simulations, the TNG-50, TNG-100 and TNG-300, with their primary difference being their size. It's important to know the advantages of each simulation before deciding which to use since their use cases differ widely.

For instance, **TNG-50** has a size of 50 Mpc. An advantage of a smaller simulation is its significantly higher resolution. However, the smaller size creates the disadvantage of the scarcity of rare objects or host galaxies, which are very important for our project.

In contrast, **TNG-300** has a lot more detail, more rare objects, and more samples, while lacking the high resolution of TNG-50.

Therefore, for our purposes of using simulations, thus counting satellite galaxies, **TNG-100** would be the most beneficial. There is enough detail for a reasonable number of galaxy hosts as well as a decent enough resolution for the required precision.

Each three groups of TNG-simulations have further properties to customize the simulation for the user. for example each has three levels of resolution and each nine simulation has its 'dark matter only' and 'baryonic physics', making an overall amount of 18 different simulations. However, these properties are not used for this thesis. The table below shows a more detailed information on each simulation group.

		TNG50	TNG100	TNG300
Volume	[Mpc^3]	51.7^3	110.7^3	302.6^3
L_{box}	[Mpc/h]	35	75	205
N_{GAS}	-	2160^3	1820^3	2500^3
N_{DM}	-	2160^3	1820^3	2500^3
N_{TR}	-	2160^3	2×1820^3	2500^3
m_{baryon}	[$\mathrm{M}_\odot$]	8.5×10^4	1.4×10^6	1.1×10^7
m_{DM}	[$\mathrm{M}_\odot$]	4.5×10^5	7.5×10^6	5.9×10^7
$\epsilon_{\mathrm{gas,min}}$	[pc]	74	185	370
$\epsilon_{\mathrm{DM},\star}$	[pc]	288	740	1480

FIGURE 2.4: more detail and information regarding every simulation. [4]

2.3 Creating a random System

The Data used is compared with randomly generated systems to ensure its plausibility. Therefore, we need a galaxy host and enough satellite galaxies. We use simulated systems and reposition the satellites randomly to make the process fail-proof.

The first step is to place the host in the centre of the coordinate system. This gives us the satellites' position in relation to the host, and we can now reposition them randomly in a sphere. The radius of the sphere represents the distance between the satellite and the host. To reposition the satellite, we first create three components:

$$\begin{aligned} \phi &\in [0, 2\pi) \\ cos(\theta) &\in [-1, 1) \\ r &= \sqrt{x_{pos}^2 + y_{pos}^2 + z_{pos}^2} \end{aligned} \tag{2.1}$$

the angle ϕ and $cos(\theta)$ are created randomly, while r is the radius of the sphere. these components are spherical coordinates which we now transfer back into Cartesian, using:

$$\begin{aligned} x &= r \cdot sin(\theta) \cdot cos(\phi) \\ y &= r \cdot sin(\theta) \cdot sin(\phi) \\ z &= r \cdot cos(\theta) \end{aligned} \tag{2.2}$$

In addition to randomizing the positions, we also randomly redirect the movement of the same satellite galaxy without altering its velocity, analogous to the distance.

2.4 Tensor of Inertia

The moment of inertia of a rotating rigid body is the most relevant physical property.[6] Despite the fact that technically a galaxy is not a rigid body, but rather a rotating system, in order to determine how flat a simulated galaxy is, we need to understand the moment of inertia or the Tensor of inertia.

2.4.1 The moment of inertia

Rotating rigid bodies have only one degree of freedom. it rotates around one axis with the rotating angle ϕ. To calculate the Equation of Motion, we need the law of conservation of energy, angular momentum, and the centre of mass. In physics, the moment of inertia is the fundamental quantity that forms all of these equations, which you can calculate as follows: [7][6]:

It is assumed that the forces acting on the body or in our case, the galaxy, from the outside are conservative. Therefore, we know there is a potential and the conversation of energy applies. A rigid body's kinetic energy thus becomes our focus.

$$T = \sum_i \frac{m_i}{2} \dot{\mathbf{r}}_i^2 \tag{2.3}$$

The mass point in the body is m_i, and the position of that mass point is $/textbf[r]_i$. We now need to define $\mathbf{r}_i$ and to do so we look at the angular speed of the rotating body. The rotation axis doesn't move, so we can set the z-axis of the coordinate system so, that

$$\boldsymbol{\omega} = (0, 0, \omega) \tag{2.4}$$

The angular speed is $/omega$ in this case, and with that we can calculate $\mathbf{r}_i$, since

$$\dot{\mathbf{r}}_i = (\boldsymbol{\omega} \times \boldsymbol{r_i}) = \omega(-y_i, x_i, 0) \tag{2.5}$$

As a result, we can re-state the kinetic energy as follows:

$$T = \frac{1}{2} \sum_i m_i (x_i^2 + y_i^2) \omega^2 \tag{2.6}$$

This allowed us to define the moment of inertia as

$$J = \sum_i m_i (x_i^2 + y_i^2) \tag{2.7}$$

2.4.2 The tensor of inertia

Moment of inertia can only be calculated for rotations around a fixed axis. Things become more complicated if the direction of the axis changes over time.[6]

$$\mathbf{n}(t) = \frac{\boldsymbol{\omega}(t)}{\omega(t)} \tag{2.8}$$

In order to solve this problem, we need to define **the tensor of inertia**. In order to do that, we need to explore the general motion of a rigid body.

The motion is divided into two parts,

- 1. **Translation**, for that we select one particular point S and define the translating motion of the body through that point
- 2. **Rotation**, Although the rotation axis changes direction, it always passes through the same point S.

We must first establish two Inertial frame of references in order to arrive at a formula stating both motions.

- $\sum'$: the first one has the origin of its coordinate-system somewhere in the room. $\vec{0}$ is always fixed at the same point.
- $\sum$: the second ones origin is in S.(fig: 2.5)

looking at both systems, it is clear that

$$\boldsymbol{r}'(t) = \boldsymbol{r}_0(t) + \boldsymbol{r}_i(t) \tag{2.9}$$

now we look again at the kinetic energy (eq. 2.3). to calculate the term we need to calculate the velocities. According to [6]

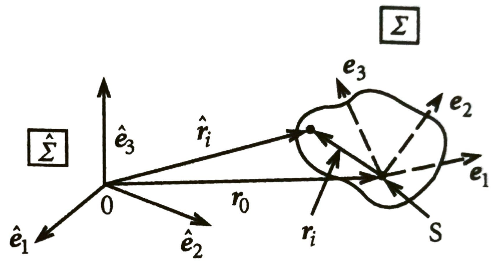


FIGURE 2.5: [6]

$$\begin{aligned}\dot{\mathbf{r}}_i &= (\boldsymbol{\omega} \times \boldsymbol{r_i}) \\ \dot{\mathbf{r}}_i' &= \dot{\mathbf{r}}_0 + (\boldsymbol{\omega} \times \boldsymbol{r_i})\end{aligned} \tag{2.10}$$

putting eq. 2.10 into eq. 2.3 givs us

$$T = \frac{1}{2}\sum_i m_i \dot{\mathbf{r}}_0^2 + \frac{1}{2}\sum_i m_i (\boldsymbol{\omega} \times \boldsymbol{r_i})^2 + \sum_i m_i (\boldsymbol{\omega} \times \boldsymbol{r_i}) \cdot \dot{\mathbf{r}}_0 \tag{2.11}$$

there are 2 plausible cases to discuss now.

- 1. the body is fixed at one particular point in space. S is the best choice for this. Therefore, $\mathbf{r}_0 = \mathbf{0}$, $\dot{\mathbf{r}}_0 = \mathbf{0}$
- 2. the body is not fixed, so we choose S to be the center of mass of the body. Therefore, $\sum_i m_i \mathbf{r}_i = \mathbf{0}$

in both cases the third term in eq. 2.11 is equal to zero. Thus, reaching our goal.

$$T = \frac{1}{2}\sum_i m_i \dot{\mathbf{r}}_0^2 + \frac{1}{2}\sum_i m_i (\boldsymbol{\omega} \times \boldsymbol{r_i})^2 = T_T + T_R \tag{2.12}$$

we now have an equation describing the energy, divided into two parts. **Translation** T_T and **Rotation** T_R. With that and with

$$(\boldsymbol{\omega} \times \boldsymbol{r_i})^2 = \omega^2 r_i^2 - (\boldsymbol{\omega} \cdot \boldsymbol{r})^2 = (\omega_1^2 + \omega_2^2 + \omega_3^2)(x_1^2 + x_2^2 + x_3^2) - (\omega_1 x_{i1} + \omega_2 x_{i2} + \omega_3 x_{i3})^2 \tag{2.13}$$

which helps us defining the tensor of inertia as

$$J_{lm} = \sum_i m_i (r_i^2 \delta_{lm} - x_{il} x_{im}); l, m = 1, 2, 3 \tag{2.14}$$

by calculating the eigen-vectors and eigen-value of the tensor, we can determine the flatness of the galaxies. the calculations for that are described in chapter 3.

2.5 Tip of the red-giant branch

TRGB is a method used to assess distances in astrophysics. It uses the luminosity of a star, that reached the red-giant branch stage. The stellar evolution stage provides us with the information we need to determine our distance from the galaxy.[8]

for this project, the distances were already provided and there were no calculations necessary. However, they were calculated using this method and it is important to note, that the calculations come with an uncertainty of estimated 5%.

Chapter 3

Data and methods

This chapter discusses every data used and every step taken to get the results, beginning with the data used for the reference galaxy Centaurus A [9]. We then continue to look at the methods used to calculate the results step by step. This chapter is in the same order as the written Python-Code and describes how the code is written.

3.1 Centaurus A

Galaxy group Centaurus A is the largest collection of galaxies next to our galaxy, the Milky Way. It is within a distance of 10 Mpc. The largest galaxy inside this group is Centaurus A. for this project we focus on the galaxies bound to Cen A by gravity. Those satellite galaxies are collected in a plane of galaxies with a small-scale RMS (root-mean-square) thickness of 69 kpc and a major axis RMS length of 309 kpc. [9]

Observing the Centaurus A galaxy from earth, the plane of galaxy appears to be in an inclined position of 14.6°. The distances of most of the satellite galaxies have been calculated, using the tip of the red giant branch method, discussed in chapter 2. Overall we include 28 satellite galaxies of Cen A in our project.

Therefore, every simulated galaxy should also have around 28 satellite galaxies for a plausible comparison. In addition, they also are required to have a combined mass of 4 to 12 $\times 10^{12}$ $M_{\odot}$. Each galaxy has one single host isolated inside of a radius of 1.2 Mpc, which is the distance of Centaurus A to the next biggest Galaxy, M83, in the Centaurus A Group. Any galaxy with a mass of 0.5 $\times 10^{12}$ $M_{\odot}$ can be considered as a co-host and should be outside of the said sphere. Since the observed satellite plane is within a radius of 800 kpc, we also consider every galaxy in that range as a satellite galaxy of the host. [10]

The most important Data for our project however, are the flatness of the galaxy $b/a = 0.52$ and "the number $N_{corr} = 21$ of satellite galaxies with coherent line-of-sight velocities along the major axis dividing the on-sky satellite distribution along the minor axis." [10]

We are looking for simulated galaxies being as flat or flatter than 0.52 and have a higher N_{corr} than 21.

3.2 Preprocessing the simulation files

The simulation files are from the TNG-project which are discussed in Chapter 2 [4]. The Data for every simulated System is given in a .csv file. They provide us with a large amount of information. The most important ones for our project is the positions of the galaxies and their velocities.

First, we need to know which galaxy is the host-galaxy by looking for the required properties as described above. We need the position of every satellite galaxy relative to the host. Therefore, we reposition the origin of the coordinate system to where the host is. Then we randomly rotate every system as often as required. After every rotation we save the x, y and z coordinates of the position, then the velocity of each satellite galaxy and then the ones of the host galaxy. The original positioning of the system without any rotation is also saved in its own file.

We now have the information on the host properties, and the n+1 files, describing the positions and direction of every galaxy from another point of view. n in this case is the number of rotation applied.

3.3 Calculating the desired values

now we look at every file in isolation. The goal is to calculate the flatness of the Galaxy the N_{corr} from that point of view.

For that we first want to look at our System and compare it to the reference galaxy, Centaurus A. The properties of the host galaxy have to be as described in chapter 3.1. However, we need also to make sure, there are enough satellite galaxies in the simulation and all of them are inside the same radius as the ones of Cen A.

3.3.1 flatness

After making sure that the simulation matches the requirements, we project the positions on a two dimensional image of the galaxy from the specific point of view. For that, we first calculate two different angles. First one called ξ (xi) is the angle between the position of Cen A and the position of the satellite projected on the x-z level, while η (eta) is the angle between Cen A and the position projected on the y-z level. These two angles are the x and y components of the vector used to create a tensor of inertia.

Tensor of inertia

We already discussed the mathematical theory behind Tensor of inertia in chapter 2. now we have a list of two dimensional vectors. Each belong to another satellite galaxy. using this list and the formula [11]

$$T = \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}^2 \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} - \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} \cdot \begin{pmatrix} x_i & y_i & z_i \end{pmatrix} \tag{3.1}$$

afterwards, we calculate the eigenvectors and eigenvalues of the Tensor. The projected long axis is the eigenvector belonging to the smallest eigenvalue, v_S. Afterwards, we want to determine the direction this vector is showing towards, if projected onto the x-y level. We name this rotation angle, α

$$\alpha = tan^{-2}\left(\frac{v_{S,1}}{v_{S,2}}\right) \tag{3.2}$$

the new position of each satellite is calculated by

$$\boldsymbol{x}_{new} = \begin{pmatrix} x_{old,1} \cdot cos(\alpha) - x_{old,2} \cdot sin(\alpha) \\ x_{old,1} \cdot sin(\alpha) + x_{old,2} \cdot cos(\alpha) \\ 0 \end{pmatrix} \tag{3.3}$$

the first component of the vector $\boldsymbol{x}_{new}$ is perpendicular and the second one parallel to the major axis direction. We calculate the root-mean-square (RMS) of each. The ratio of these two values is the flatness we are looking for.

$$b/a = \frac{RMS_{per}}{RMS_{par}} \tag{3.4}$$

3D Tensor of inertia

for the three dimensional flattening things are a little different. First, we use a list of the positions of the satellites. Then, we calculate the Tensor of inertia just as described in 3.1 and again determine their eigenvector and eigenvalues and with that the largest and smallest eigenvalues. From now on we use the eigenvectors belonging to the largest eigenvalue, $\boldsymbol{v}_L$ and the one belonging to the smallest, $\boldsymbol{v}_S$.

What we do next is called **Scalar projection**. We project every satellite onto $\boldsymbol{v}_L$ and $\boldsymbol{v}_S$,

$$s = ||x_{sat}||cos(\theta) = \boldsymbol{x}_{sat} \cdot \boldsymbol{v}_i^{'} \tag{3.5}$$

with x_{sat} being the position of each satellite, and $\boldsymbol{v}_i^{'}$ being the unite vector showing in the same direction as the eigenvectors. To simplify the calculation we use

$$cos(\theta) = \frac{\boldsymbol{x}_{sat} \cdot \boldsymbol{v}_i}{||\boldsymbol{x}_{sat}||\ ||\boldsymbol{v}_i||} \tag{3.6}$$

and with that we get

$$s = \frac{\boldsymbol{x}_{sat} \cdot \boldsymbol{v}_i}{||\boldsymbol{v}_i||} \tag{3.7}$$

now having a list of projected scalars, we calculated their root-mean-square (RMS), leaving us with two values. the RMS along the direction of $\boldsymbol{v}_L$ and the one along the direction of $\boldsymbol{v}_S$. the ratio of these two values is the three dimensional flatness we are looking for.

$$c/a = \frac{RMS_L}{RMS_S} \tag{3.8}$$

3.3.2 Movement around the host

After calculating the flatness of the galaxy we use the determined long axis vector to determine N_{corr}. We want to look at every single satellite galaxy and analyse them as following

```
countvel = 0
for j in range(len(positions)):
    angle = angleBetween(positions[j], Long_vec) / numpy.pi * 180.0
    if angle < 90.0:
        if velLosList[satindexlist[j]] > 0.0:
            countvel = countvel + 1
        else:
            countvel = countvel - 1
    else:
        if velLosList[satindexlist[j]] > 0.0:
            countvel = countvel - 1
        else:
            countvel = countvel + 1
countvel = (Nsat + abs(countvel)) // 2.0
```

First, the loop has the range of the number of satellites. For each satellite in the loop we calculate the angle between said satellite (positions[j]) and the long major axis (Long_vec) calculated with the help of the tensor of inertia.

if the angle is smaller than 90° then it means, that the satellite is on one side of the small major axis and if it is larger than 90°, it is on the other side. Since we are looking for a rotation around the host, the satellite galaxies on one side of the galaxy have to move in the same direction, while the ones on the other side move in the opposite direction.

Therefore, we look at the velocity of the satellite galaxy in relation to the observed galaxy.

$$v_{los} = \frac{v_{sat} \cdot (x_{sat} + x_{CenA})}{||x_{sat} + x_{CenA}||} \tag{3.9}$$

The calculated velocities are gathered in the list called, velLosList. If the velocity under 90° is positive we add one count to 'countvel', if it is negative we subtract one count. If the velocity over 90° is negative we add one count to 'countvel', if it is positive we subtract one count. At the end we add the count with the amount of satellite galaxies and divide by two.

Example

To make this more clear, we use an example. We assume a total amount of 20 satellite galaxies. 13 of them are from our point of view above the small major axis and 7 underneath it. out of the 13, 8 move away from us and 5 towards us. so if we add 1 to the count for every galaxy moving away from us and then subtract every galaxy that moves towards us, we then have a total count of 3.

now we look underneath the axis and out of 7 galaxies, 5 move towards us, the opposite direction of the ones above. so the count would be 5 - 2 = 3. over all we have a count of 6.

adding these 6 to the total number of galaxies, we have 26, which divided by 2 is 13. Therefore, $N_{corr} = 13$

Basically, we have 8 galaxies above moving away and 5 below moving towards us making a total of 13 galaxies rotating the host. The calculation chosen here, is designed to avoid mistaken counts.

3.4 plotting the results

After calculating the 2 values we are looking for, we want to illustrate our results. for that we first simply plot every calculated b/a in relation to its N_{corr} from the same point of view.

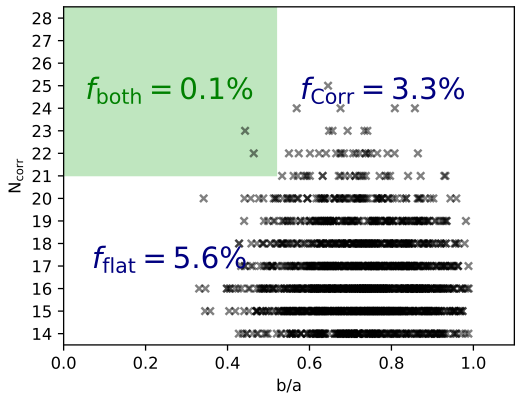
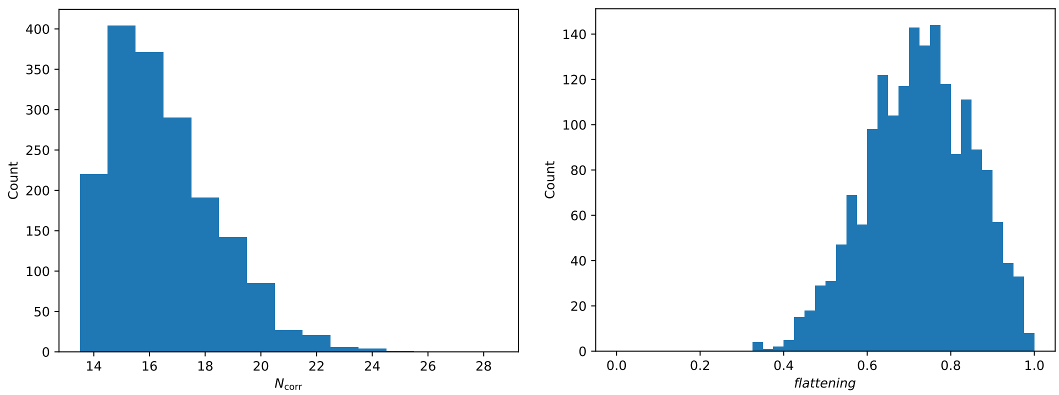


FIGURE 3.1: Example plot of all calculated values for flatness on the x-axis and N_{corr} on the y-axis. We used 180 simulations and a certain number of rotations to change the POV

the systems in the green area are the ones we are looking for. the point of views in this area are showing a system as flat or flatter with a N_{corr} as big or bigger than Centaurus A.

After that we check the distribution of the flatness and N_{corr} illustrated in a histogram.



(A) Distribution of N_{corr}

(B) Distribution of the flatness

FIGURE 3.2: Example plot of all calculated values. x-axis shows the calculated flatness or N_{corr}, while the y-axis shows from how many points of view we get the same value

Afterwards, we look at one simulation at a time. every system has been rotated and looked at for a particular amount of times that we call n. Thus, we have n number of values for flatness and N_{corr}. We now want to find the minimum flatness and maximum N_{corr}. After doing so with

```
mindFlattening = flatteningList[i][0]
sumFlat = 0.0
for j in range(len(flatteningList[i])):
    sumFlat = sumFlat + flatteningList[i][j]
    if flatteningList[i][j] <= mindFlattening:
        mindFlattening = flatteningList[i][j]
        mindFID = SysIDnameList[i][j]
        mindFcoorbit = coorbitList[i][j]
```

for minimum flatness and analogue to this code for maximum N_{corr}, we plot the results.

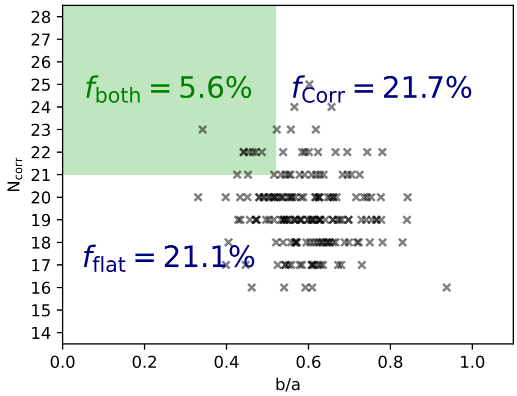
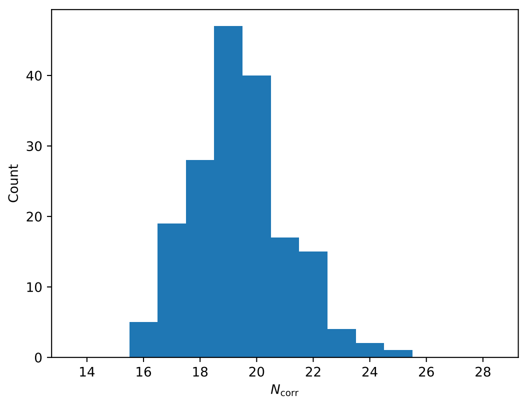
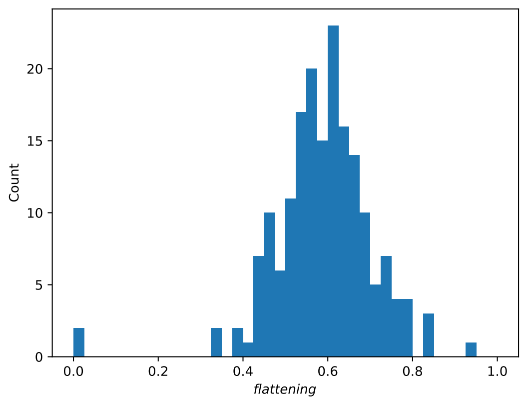


FIGURE 3.3: Example plot of all the minimum and maximum for every simulation. It is important to note, that the flatness and N_{corr} are from the same system but not the same point of view. Therefore, there are 180 results illustrated in this plot.

Here, we again want to look at the distribution of the flatness and N_{corr} this time their minimum and maximum



(A) Distribution of N_{corr}



(B) Distribution of the flatness

FIGURE 3.4: Example plot of the distribution of minimum flatness and maximum N_{corr}

Now we want to find the one point of view from which the simulated host galaxy is the closest to Centaurus A. For that we calculate the ratio of N_{corr} and the flatness from each POV and then pick the highest. with that we make sure to have the highest possible N_{corr} and the lowest possible flatness from the same perspective. We again plot the result as above.

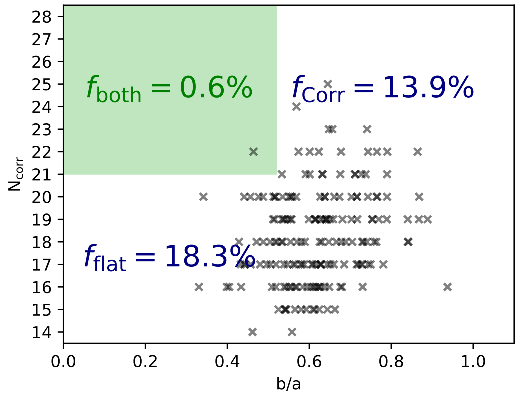
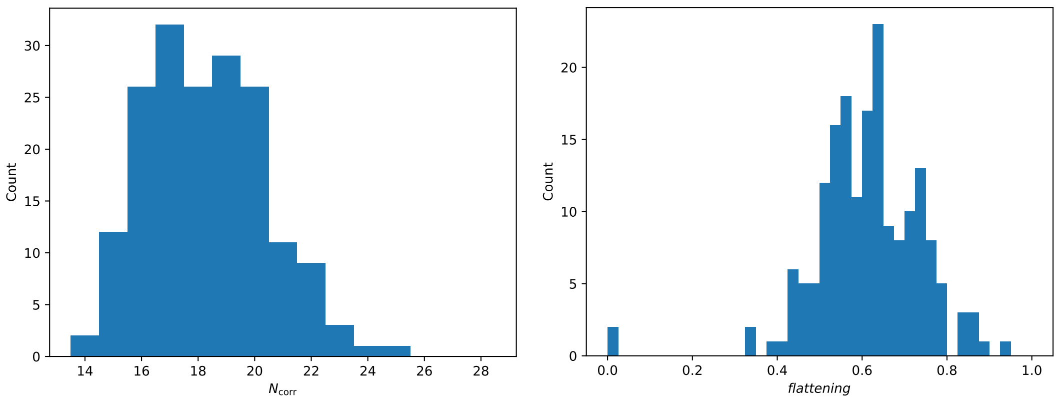


FIGURE 3.5: Example plot of the highest possible N_{corr} and lowest possible flatness from the same POV for each simulation.

we want to look at the distribution of the optimal N_{corr} and flatness as well.



(A) Distribution of N_{corr}

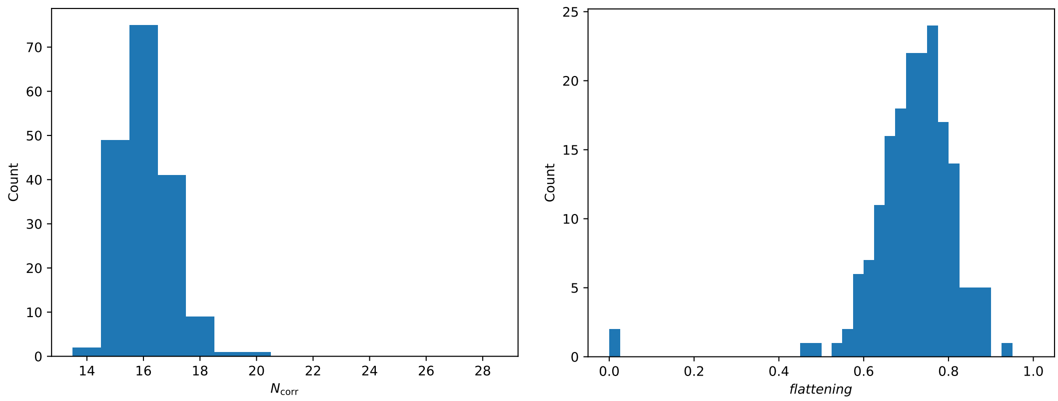
(B) Distribution of the flatness

FIGURE 3.6: Example plot of the distribution of minimum flatness and maximum N_{corr}

At the end we also calculate the average value of every calculated flatness and N_{corr} by

$$Mean = \frac{1}{(n_{Rotation} \cdot n_{Simulations})} \sum_i f_i \text{ or } N_{corr,i} \tag{3.10}$$

and plot their distribution.



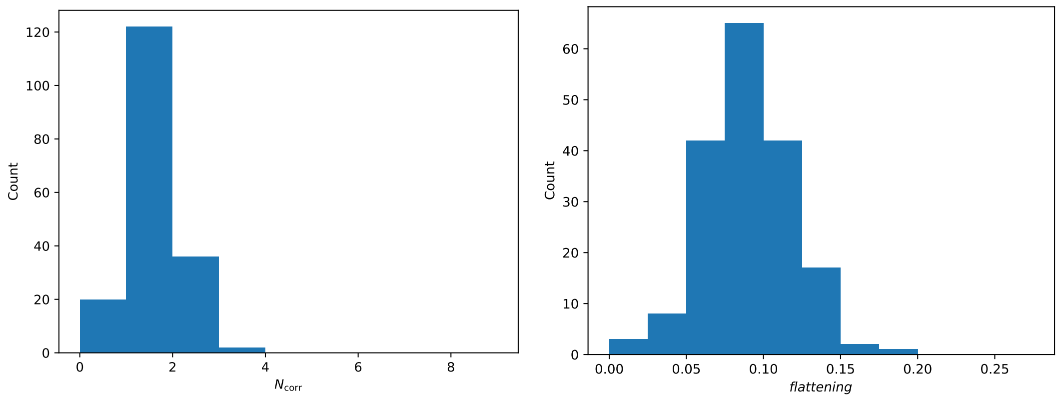
(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 3.7: Example plot of the distribution of the average values of flatness and maximum N_{corr} for each simulated system

we repeat this procedure, only after calculating the standard deviation of all the values for each simulation using the numpy function

```
sd = numpy.std(List)
```

and then plot the result



(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 3.8: Example plot of the distribution of the standard deviation of every value for each simulated system

finally, we plot the calculated two dimensional flatness b/a together with the three dimensional flatness c/a calculated as described above in Chapter 3.3.1.

we then repeat everything described in this chapter for all 180 Simulations with 10, 100, 1000 and 10000 rotations.

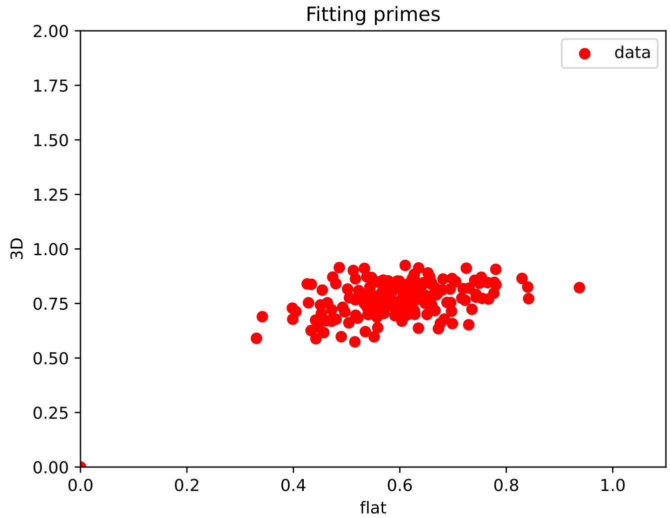


FIGURE 3.9: Example plot of 2D flatness on the x-axis and the 3D flatness on the y-axis

3.4.1 random system

We create as described in Chapter 2.3 a random System and repeat every step for this system as well. We only use 100 rotations for the randomly created system. The goal of this practise is to make sure our results are not randomly generated as the results for this system will be.

Chapter 4

Results

In this chapter we show every Plot produced as described in the previous chapter. Every plot is shown in the following order, first the results for the 180 randomly created Systems then the 180 Simulations rotated 10, 100, 1000 and 10000 times.

4.1 Every calculated Value

First we show every calculated value for N_{corr} over every calculated value for flatness from the same POV. The x-axis shows b/a, while the y-axis shows N_{corr}. The upper left corner shows how many of the snapshots show a system as flat or flatter as Cen A and with an N_{corr} as high or higher than Cen A, while the lower left corner shows the snapshots flat or flatter than Cen A and the upper right corner shows the amount of the snapshots having a minimum N_{corr} of 21.

random System

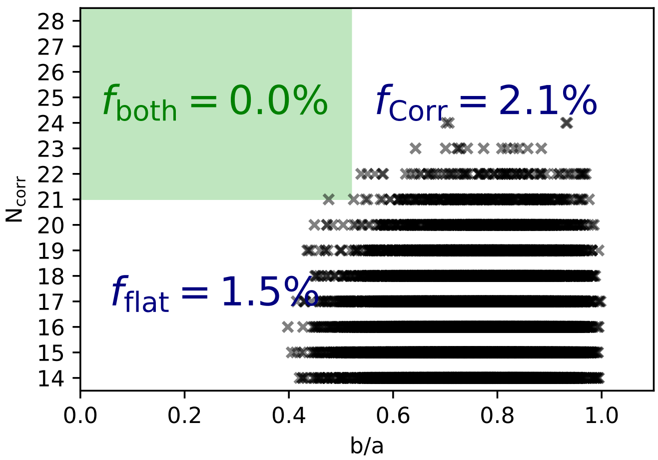


FIGURE 4.1: Every result calculated for the 180 randomly created systems with 100 rotations. both results were from the same POV

10 rotations

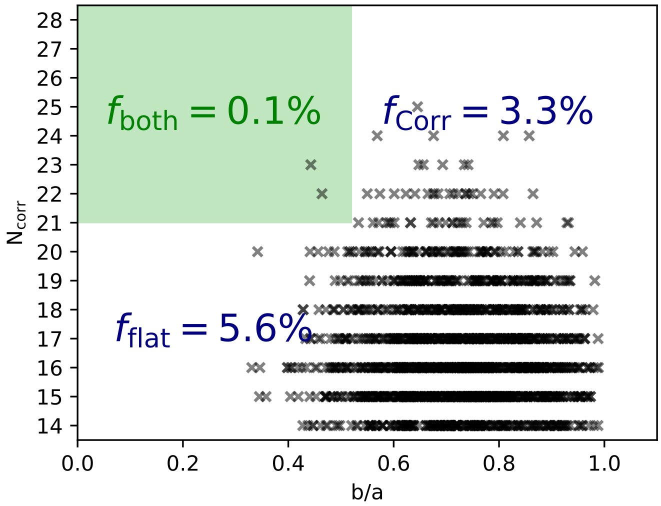


FIGURE 4.2: Every result calculated for the 180 simulations with 10 rotations. both results were from the same POV

100 rotations

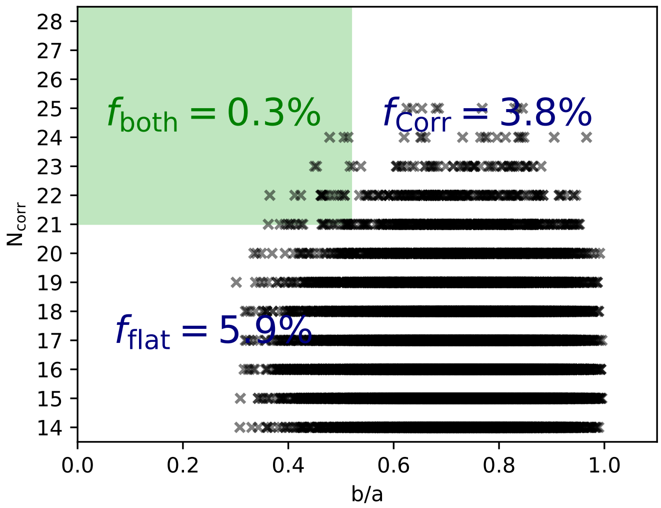


FIGURE 4.3: Every result calculated for the 180 simulations with 100 rotations. both results were from the same POV

1000 rotations

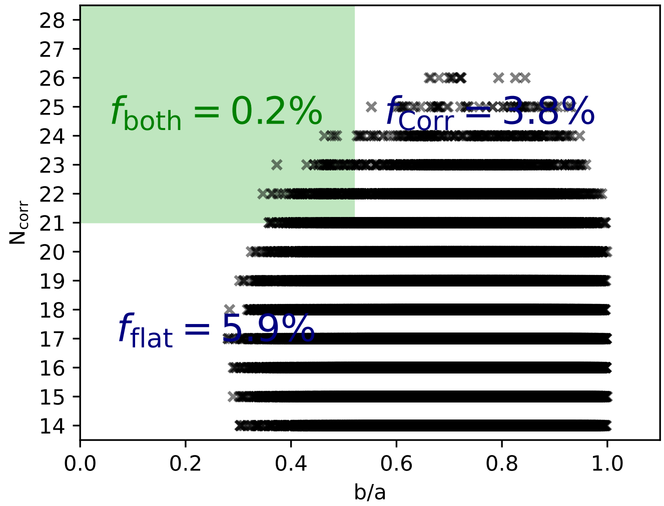


FIGURE 4.4: Every result calculated for the 180 simulations with 1000 rotations. both results were from the same POV

10000 rotations

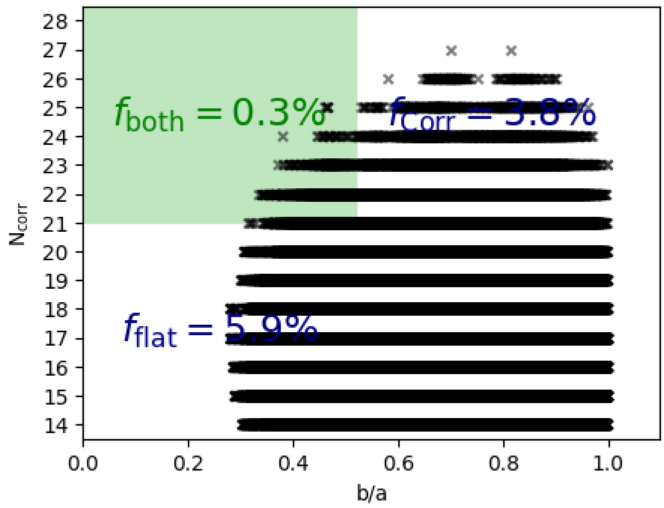
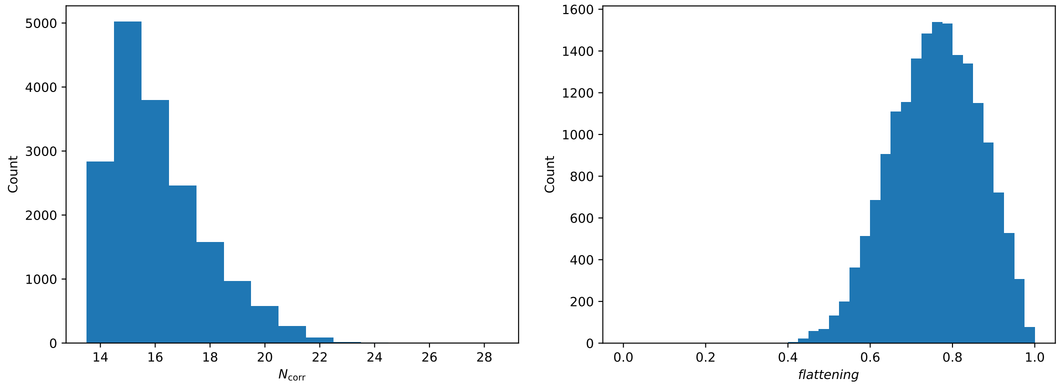


FIGURE 4.5: Every result calculated for the 180 simulations with 10000 rotations. both results were from the same POV

4.2 Distribution of all the calculated values

The following plots are the number of snapshots distributed over the calculated values.

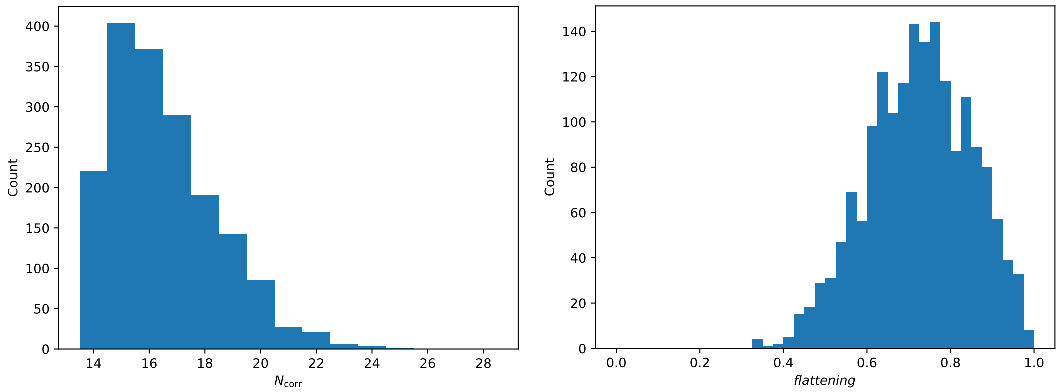
random system



(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.6: Histogram of the distribution of the calculated values of the 180 randomly created systems rotated 100 times

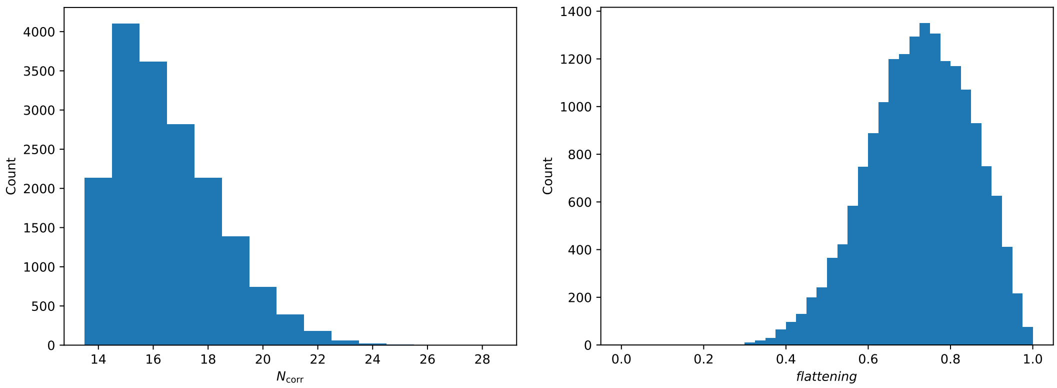
10 rotations



(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.7: Histogram of the distribution of the calculated values of the 180 simulated systems rotated 10 times

100 rotations

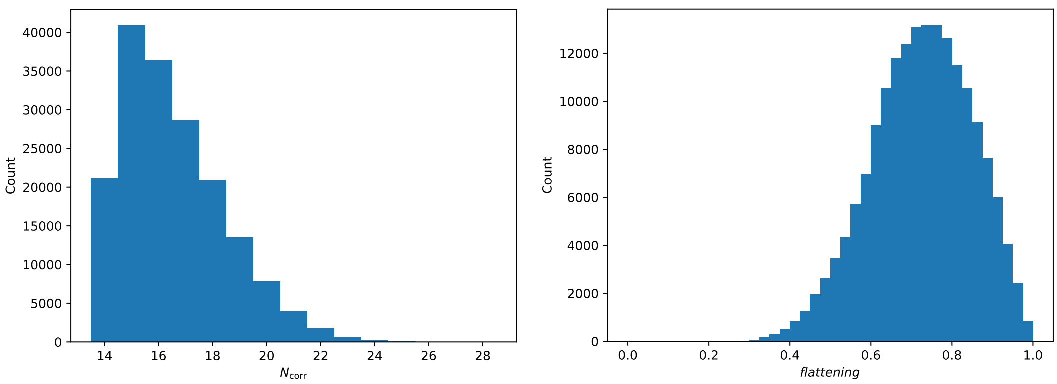


(A) Distribution of N_{corr}

(B) Distribution of the flatness

FIGURE 4.8: Histogram of the distribution of the calculated values of the 180 simulated systems rotated 100 times

1000 rotations

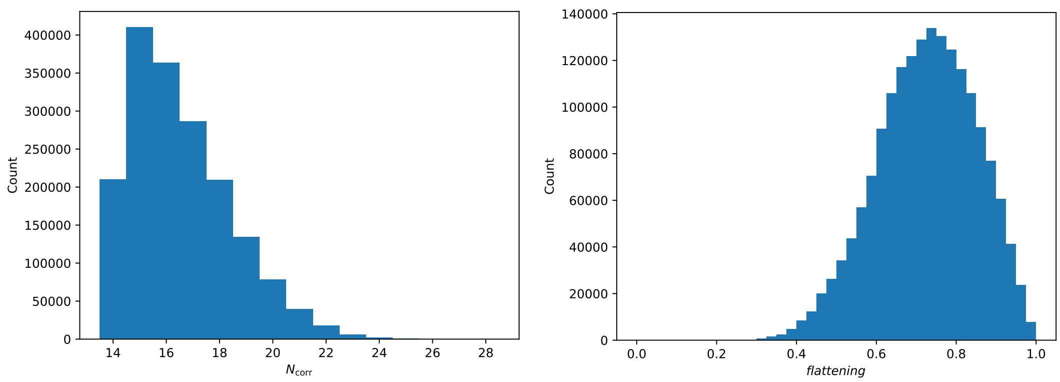


(A) Distribution of N_{corr}

(B) Distribution of the flatness

FIGURE 4.9: Histogram of the distribution of the calculated values of the 180 simulated systems rotated 1000 times

10000 rotations



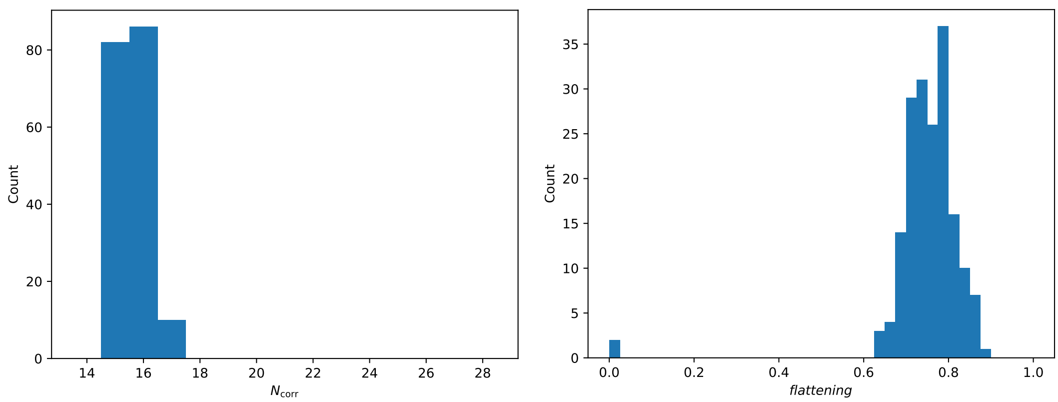
(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.10: Histogram of the distribution of the calculated values of the 180 simulated systems rotated 10000 times

4.3 average value

the following plots are the average value of all the calculated values for each of the 180 systems.

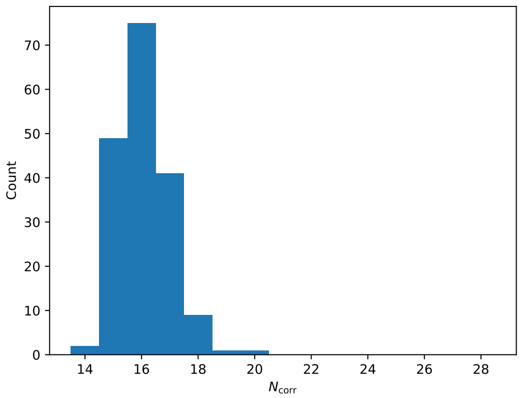
random system



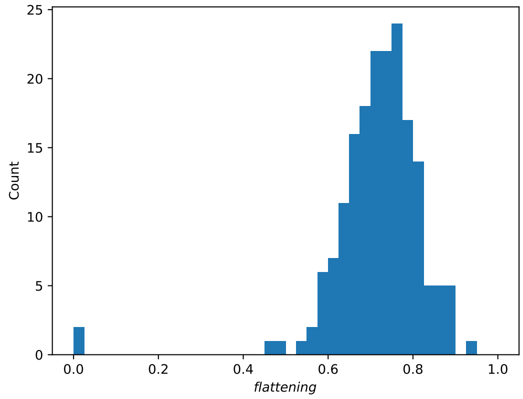
(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.11: Histogram of the distribution of the calculated average of the 180 randomly created systems rotated 100 times

10 rotations



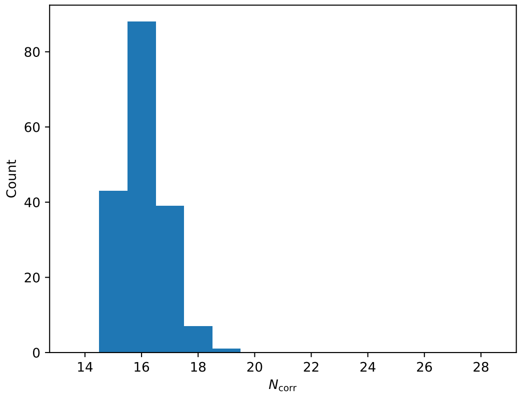
(A) Distribution of N_{corr}



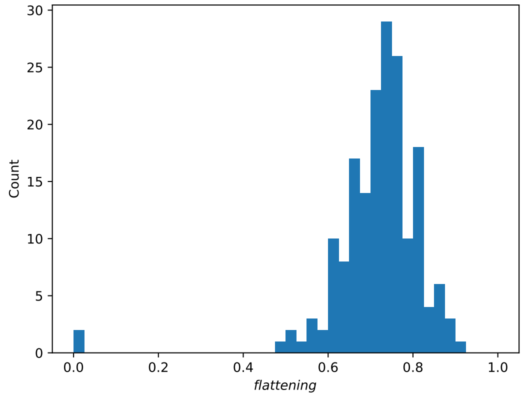
(B) Distribution of the flatness

FIGURE 4.12: Histogram of the distribution of the calculated average of the 180 simulated created systems rotated 10 times

100 rotations



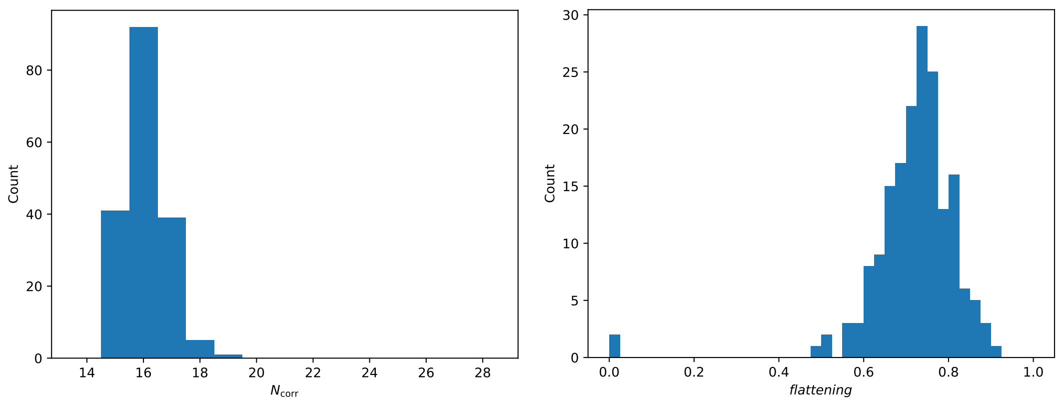
(A) Distribution of N_{corr}



(B) Distribution of the flatness

FIGURE 4.13: Histogram of the distribution of the calculated average of the 180 simulated created systems rotated 100 times

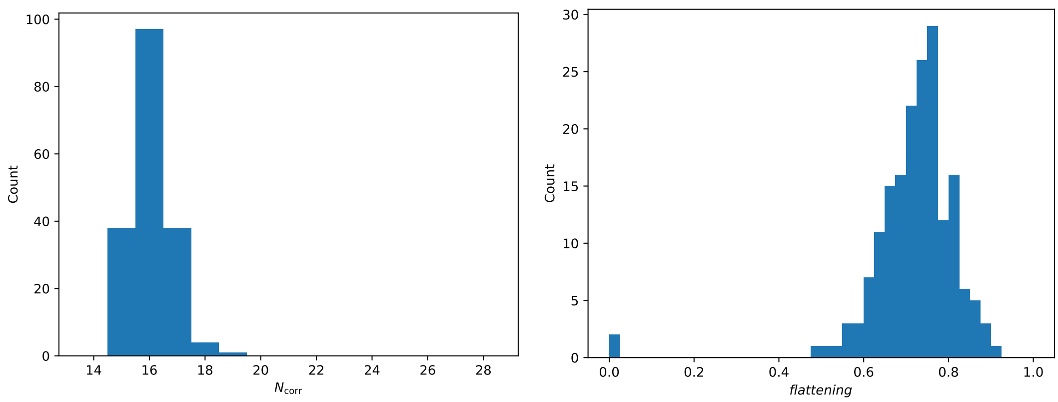
1000 rotations



(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.14: Histogram of the distribution of the calculated average of the 180 simulated created systems rotated 1000 times

10000 rotations



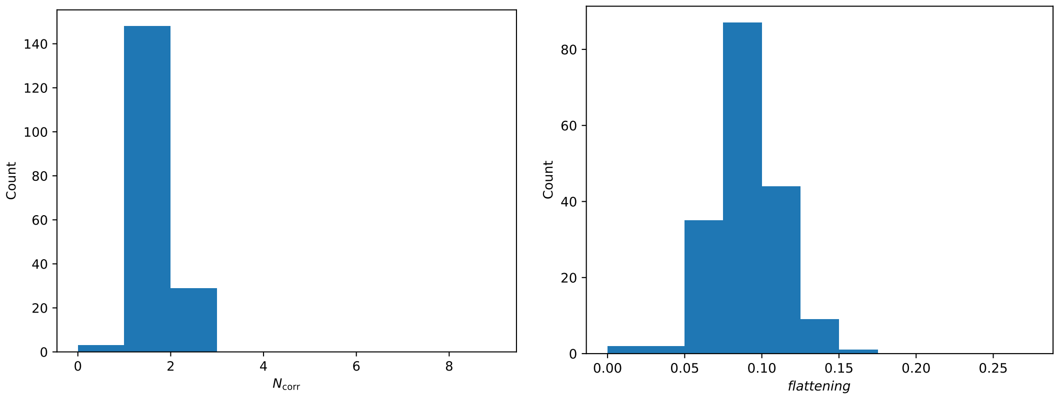
(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.15: Histogram of the distribution of the calculated average of the 180 simulated created systems rotated 10000 times

4.4 standard deviation

After we calculate the standard deviation of the values for every system we plot the distribution just as before.

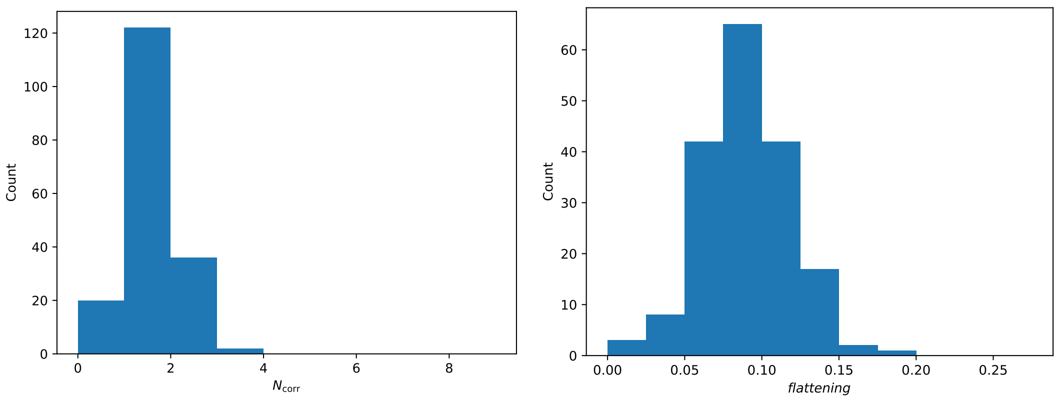
random system



(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.16: Histogram of the distribution of the calculated standard deviation of the 180 randomly created systems rotated 100 times

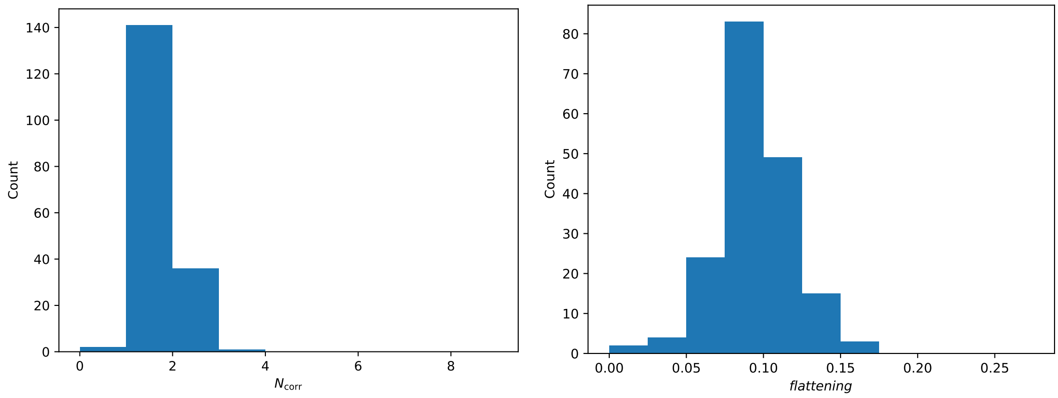
10 rotations



(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.17: Histogram of the distribution of the calculated standard deviation of the 180 simulated systems rotated 10 times

100 rotations

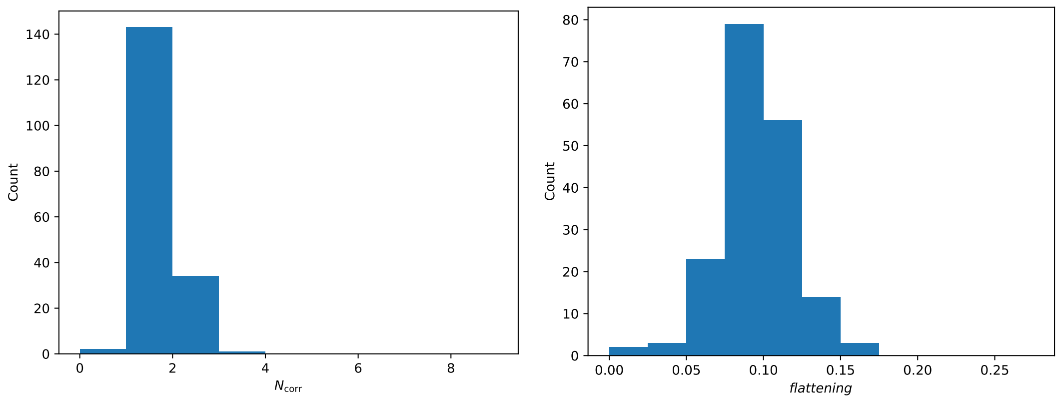


(A) Distribution of N_{corr}

(B) Distribution of the flatness

FIGURE 4.18: Histogram of the distribution of the calculated standard deviation of the 180 simulated systems rotated 100 times

1000 rotations

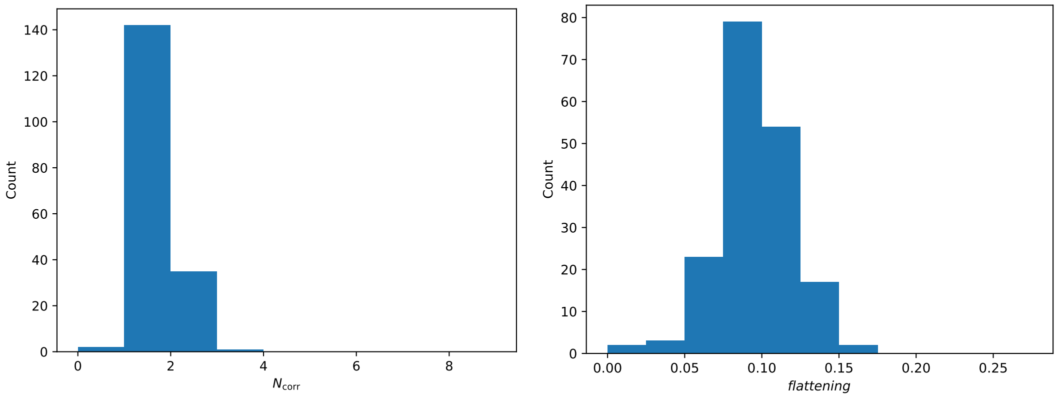


(A) Distribution of N_{corr}

(B) Distribution of the flatness

FIGURE 4.19: Histogram of the distribution of the calculated standard deviation of the 180 simulated systems rotated 1000 times

10000 rotations



(A) Distribution of N_{corr}

(B) Distribution of the flatness

FIGURE 4.20: Histogram of the distribution of the calculated standard deviation of the 180 simulated systems rotated 10000 times

4.5 plotting the extremes

for every system we found the minimum flatness and the maximum N_{corr} and plot the 180 values like described in Chapter 3. the values however, are not from the same point of view.

random System

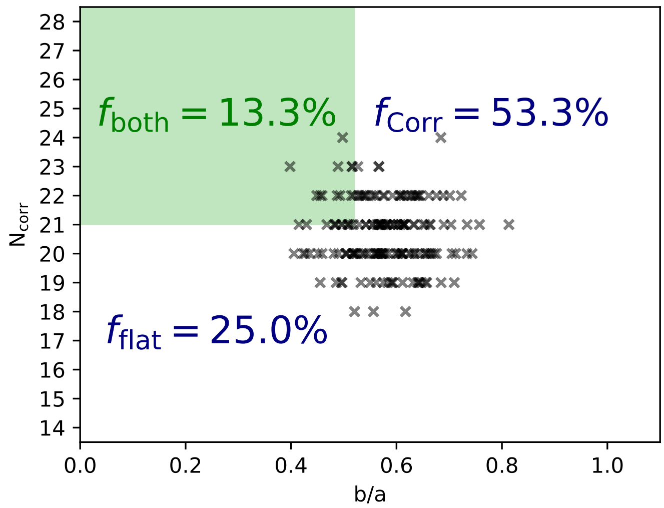


FIGURE 4.21: calculated extremes for the 180 randomly created systems with 100 rotations. the results are not from the same POV

10 rotations

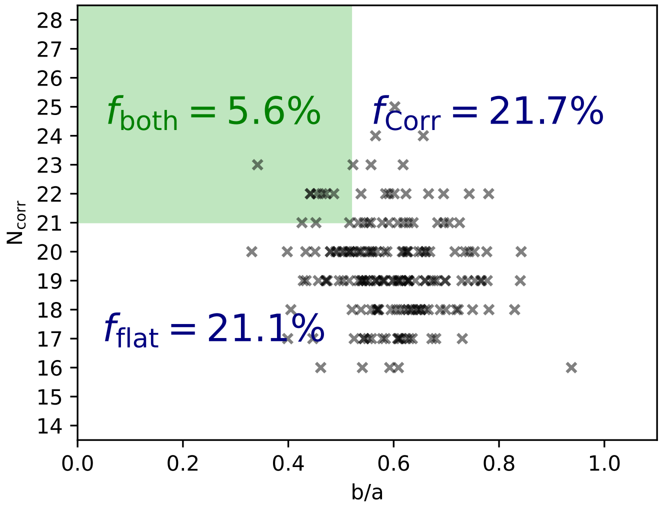


FIGURE 4.22: calculated extremes for the 180 simulated systems with 10 rotations. the results are not from the same POV

100 rotations

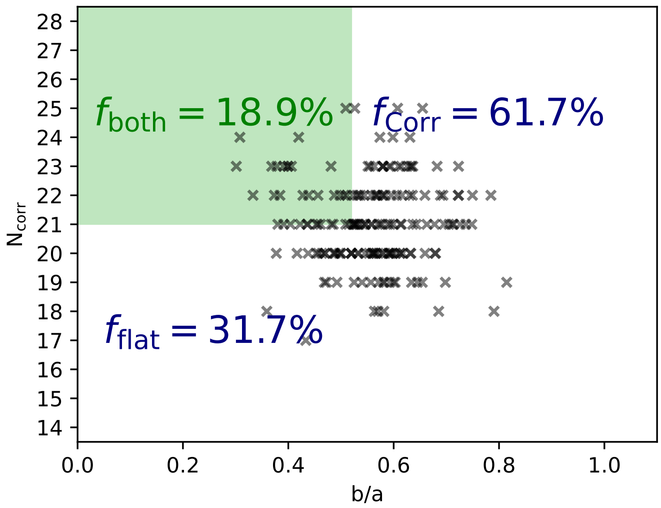


FIGURE 4.23: calculated extremes for the 180 simulated systems with 100 rotations. the results are not from the same POV

1000 rotations

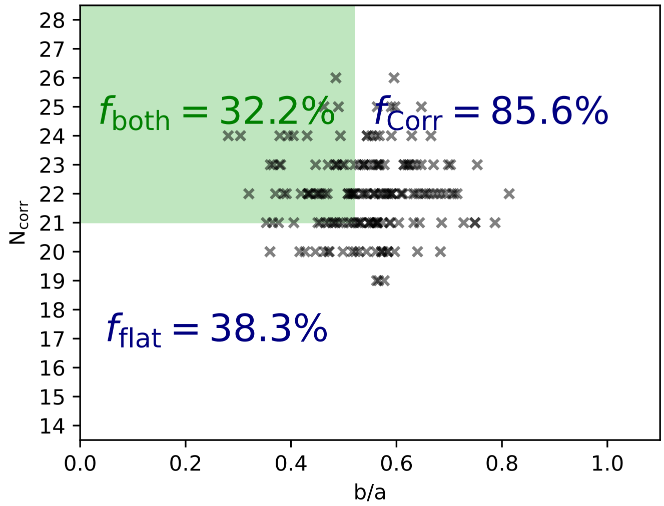


FIGURE 4.24: calculated extremes for the 180 simulated systems with 1000 rotations. the results are not from the same POV

10000 rotations

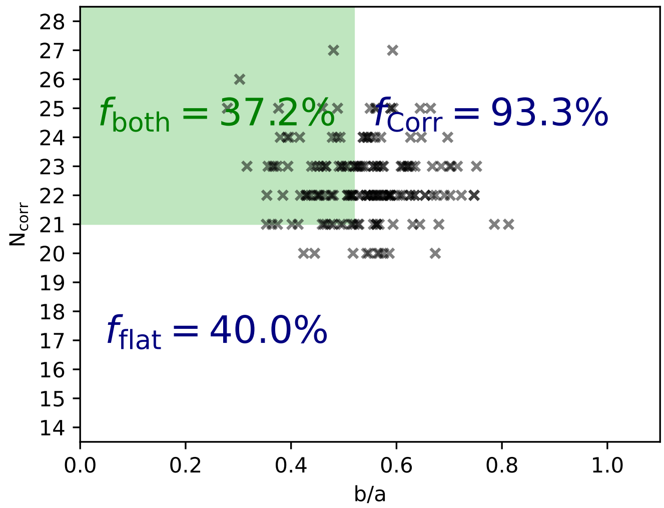
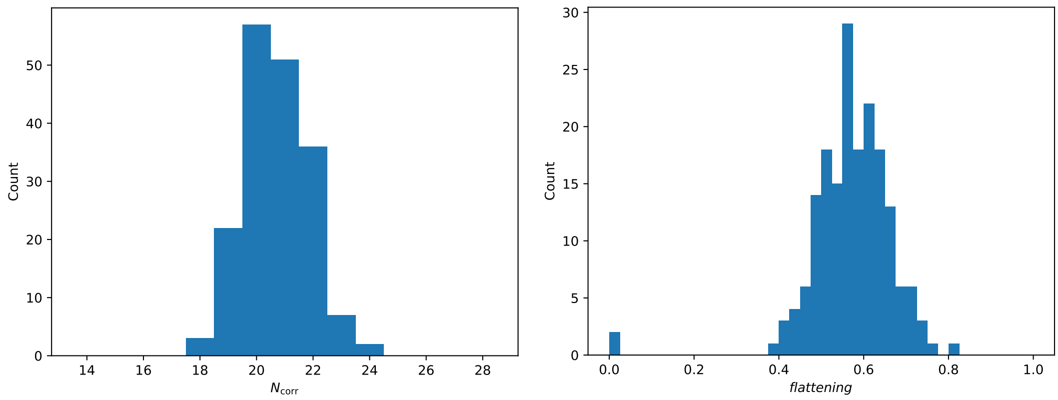


FIGURE 4.25: calculated extremes for the 180 simulated systems with 10000 rotations. the results are not from the same POV

4.6 Distribution of the extremes

Now we look at how the extremes for flatness and N_{corr} is distributed over all systems and rotations.

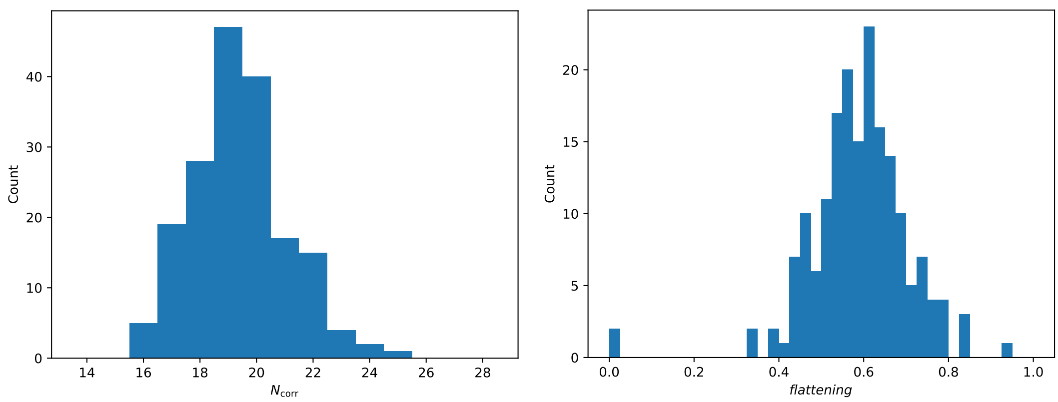
random system



(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.26: Histogram of the distribution of the minimum flatness and maximum N_{corr} of the 180 randomly created systems rotated 100 times

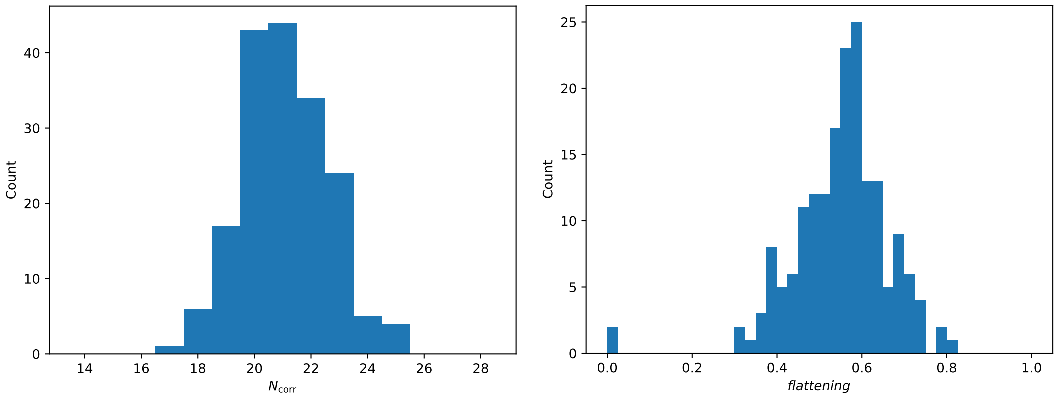
10 rotations



(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.27: Histogram of the distribution of the minimum flatness and maximum N_{corr} of the 180 simulated systems rotated 10 times

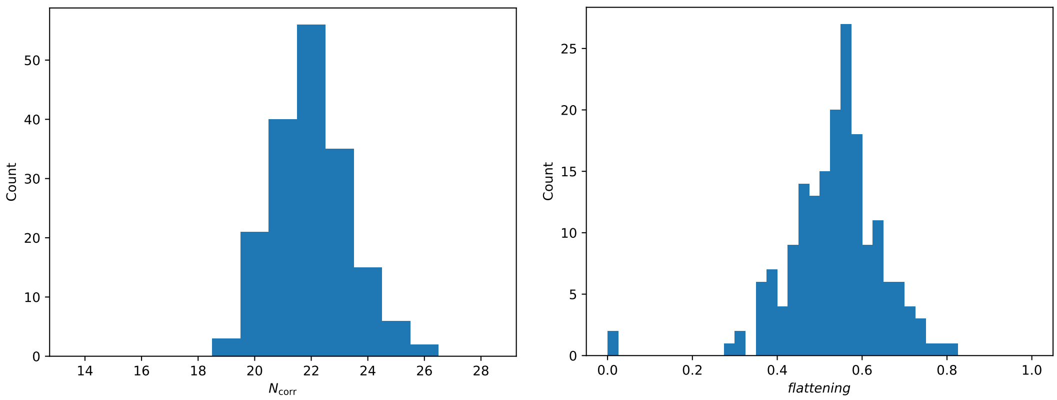
100 rotations



(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.28: Histogram of the distribution of the minimum flatness and maximum N_{corr} of the 180 simulated systems rotated 100 times

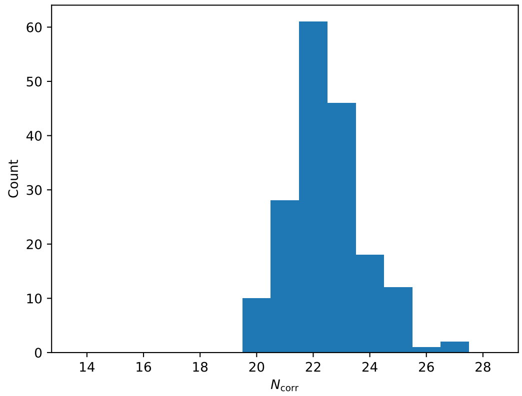
1000 rotations



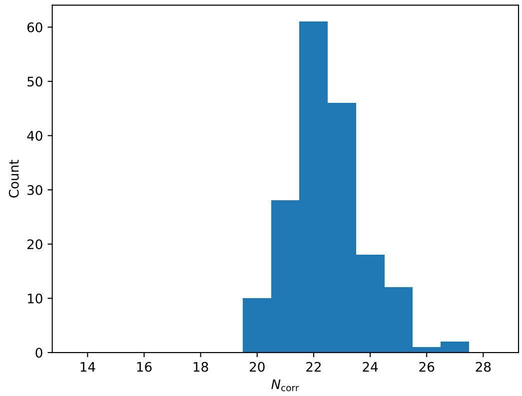
(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.29: Histogram of the distribution of the minimum flatness and maximum N_{corr} of the 180 simulated systems rotated 1000 times

10000 rotations



(A) Distribution of N_{corr}



(B) Distribution of the flatness

FIGURE 4.30: Histogram of the distribution of the minimum flatness and maximum N_{corr} of the 180 simulated systems rotated 10000 times

4.7 optimal pairing

The following plots all show the 180 most optimal pairing of N_{corr} and flatness from the same point of view. the determination of these pairs is explained in Chapter 3.

random System

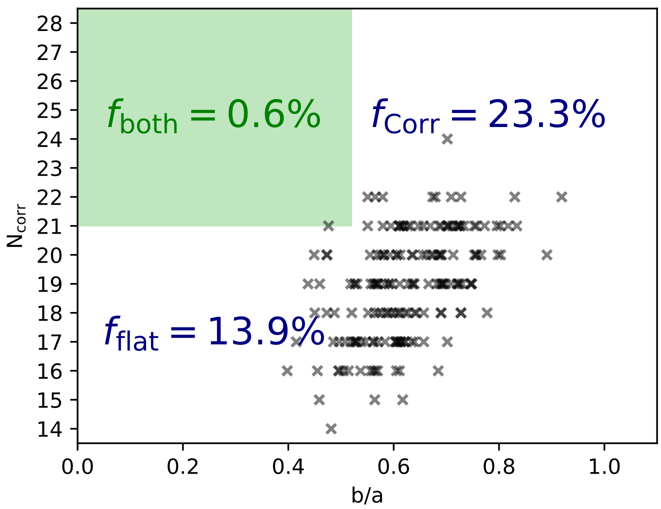


FIGURE 4.31: calculated optimal pairs for the 180 randomly created systems with 100 rotations.

10 rotations

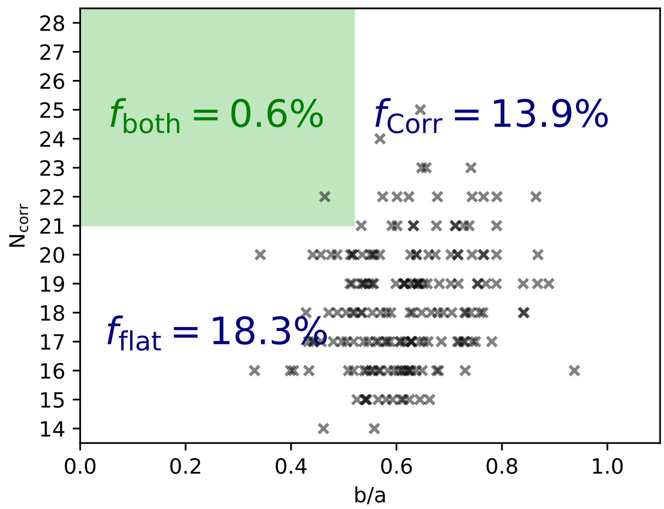


FIGURE 4.32: calculated optimal pairs for the 180 simulated systems with 10 rotations.

100 rotations

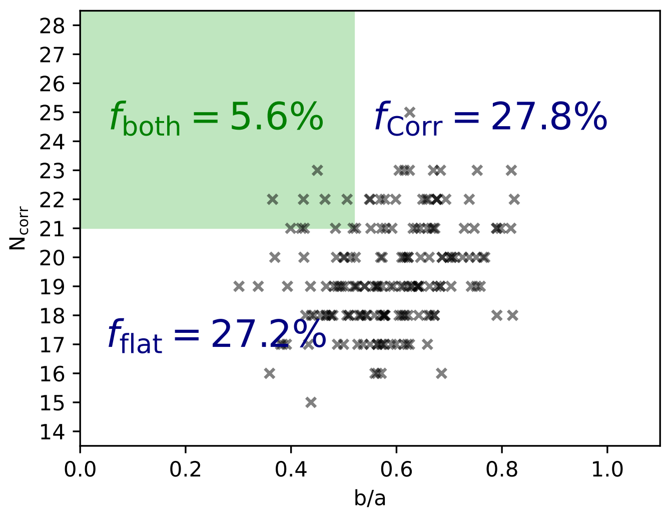


FIGURE 4.33: calculated optimal pairs for the 180 simulated systems with 100 rotations.

1000 rotations

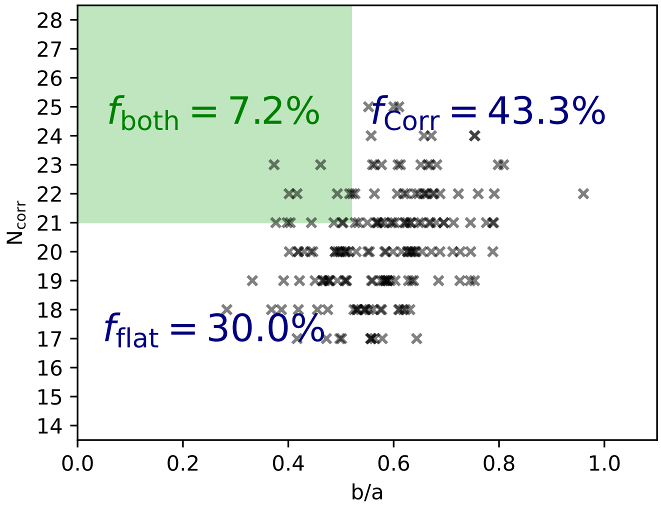


FIGURE 4.34: calculated optimal pairs for the 180 simulated systems with 1000 rotations.

10000 rotations

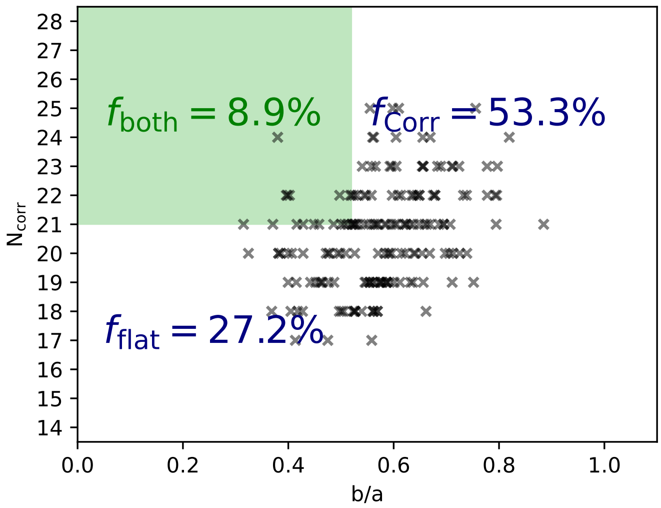
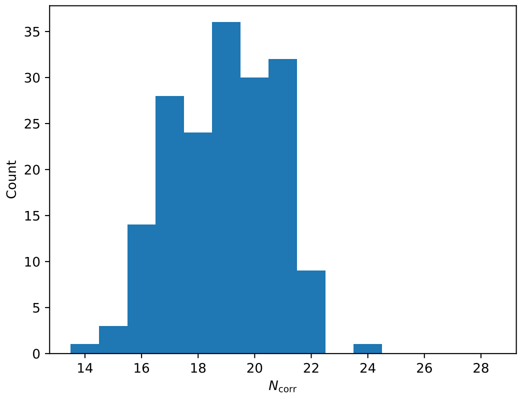


FIGURE 4.35: calculated optimal pairs for the 180 simulated systems with 10000 rotations.

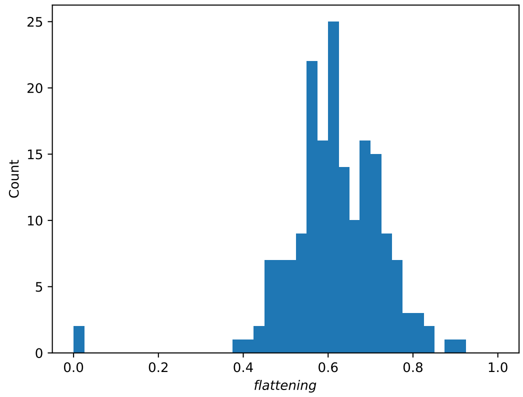
4.8 Distribution of the optimal pairing

Now we look how the values of the optimal pairing is distributed.

random system



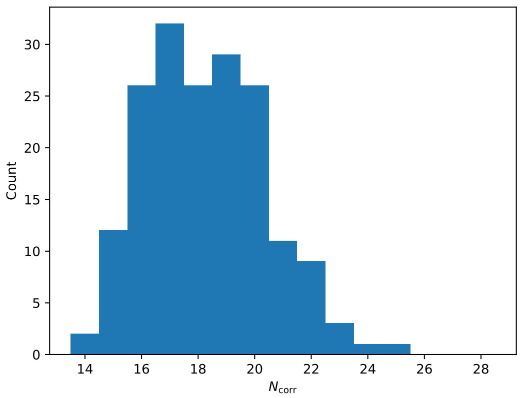
(A) Distribution of N_{corr}



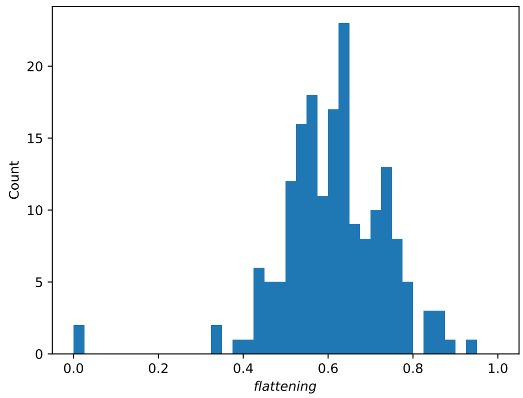
(B) Distribution of the flatness

FIGURE 4.36: Histogram of the distribution of the optimal flatness and maximum N_{corr} of the 180 randomly created systems rotated 100 times

10 rotations



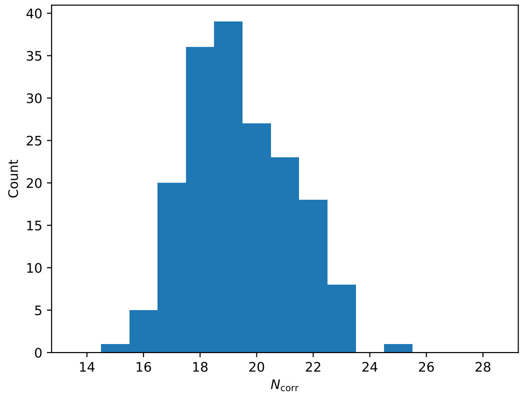
(A) Distribution of N_{corr}



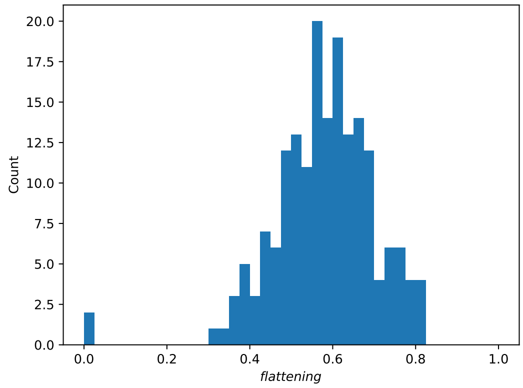
(B) Distribution of the flatness

FIGURE 4.37: Histogram of the distribution of the optimal flatness and maximum N_{corr} of the 180 simulated systems rotated 10 times

100 rotations



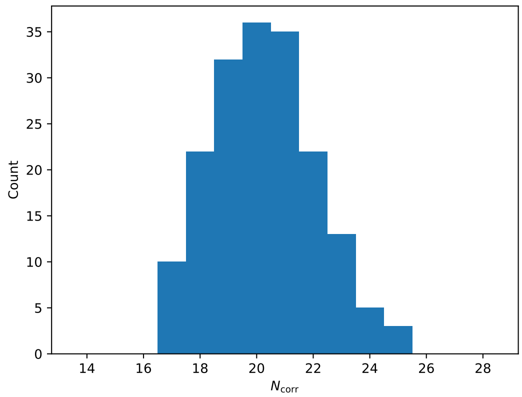
(A) Distribution of N_{corr}



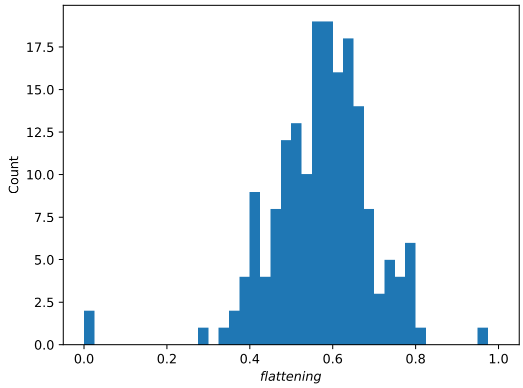
(B) Distribution of the flatness

FIGURE 4.38: Histogram of the distribution of the optimal flatness and maximum N_{corr} of the 180 simulated systems rotated 100 times

1000 rotations



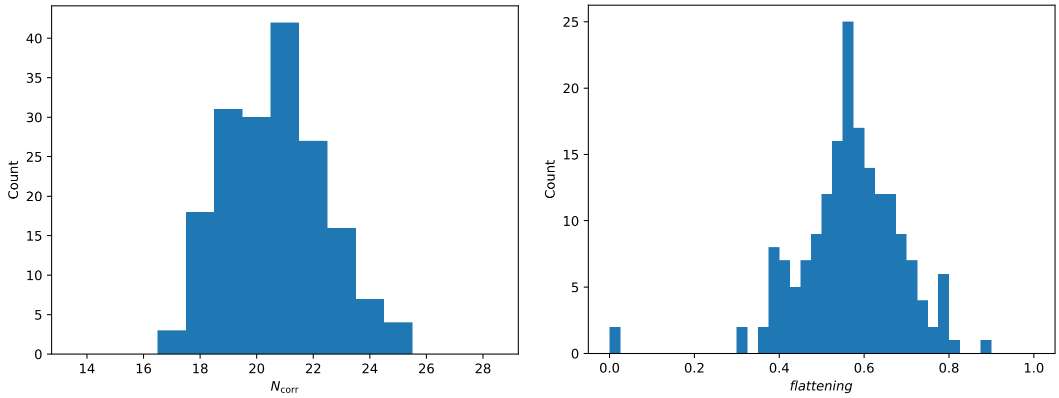
(A) Distribution of N_{corr}



(B) Distribution of the flatness

FIGURE 4.39: Histogram of the distribution of the optimal flatness and maximum N_{corr} of the 180 simulated systems rotated 1000 times

10000 rotations



(A) Distribution of N_{corr} (B) Distribution of the flatness

FIGURE 4.40: Histogram of the distribution of the optimal flatness and maximum N_{corr} of the 180 simulated systems rotated 10000 times

4.9 3D flatness to 2D flatness

The following plots all show the calculated 3D flatness over 2D flatness. the values are the ones of the same system, therefore giving us a total of 180 values.

random System

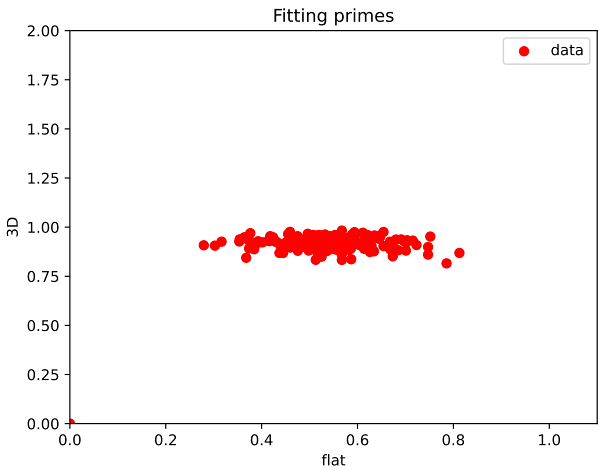


FIGURE 4.41: calculated 3D flatness over 2D flatness for the 180 randomly created systems with 100 rotations

10 rotations

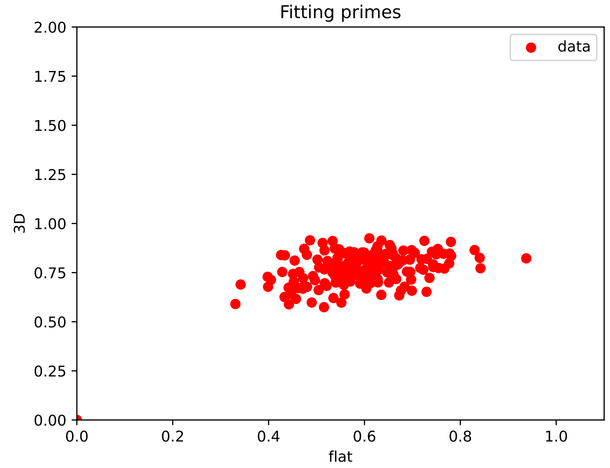


FIGURE 4.42: calculated 3D flatness over 2D flatness for the 180 simulated systems with 10 rotations

100 rotations

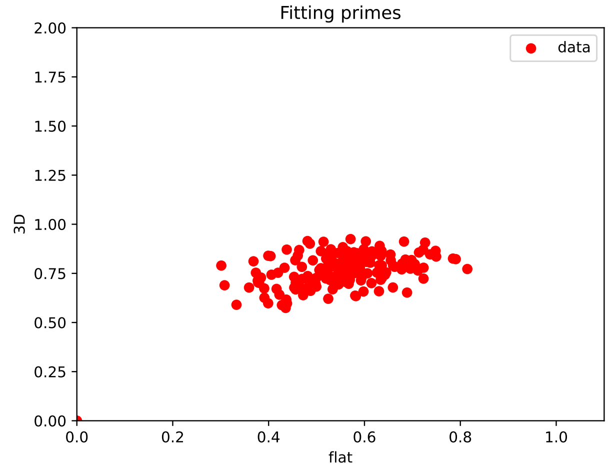


FIGURE 4.43: calculated 3D flatness over 2D flatness for the 180 simulated systems with 100 rotations

1000 rotations

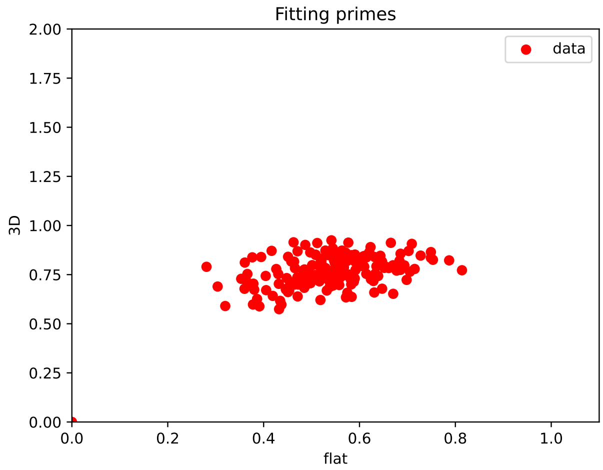


FIGURE 4.44: calculated 3D flatness over 2D flatness for the 180 simulated systems with 1000 rotations

10000 rotations

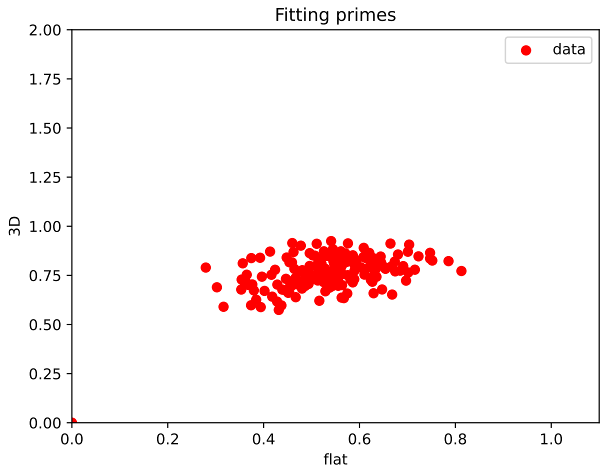


FIGURE 4.45: calculated 3D flatness over 2D flatness for the 180 simulated systems with 10000 rotations

Chapter 5

Evaluation

We evaluate the results in the same order as we executed the project. We start with the initiate idea of this thesis, what is the influence of the rotations on the results and what happens if we . From there, we came up with new ideas to understand our results better.

5.1 the initiate influence of the rotations

executing the python code for only 10 rotations, we receive the plot 4.2. This Plot is a first good result, since it shows a similar result to the references used for this thesis. [9] [10] [12]

0.1% of the snapshots, which means the results of the 180 systems from the different point of views, match the data from Cen A.

The flatness of the galaxies is always between 0.3 and 1. Looking at 4.7, you can see how the galaxies are distributed. most of them are somewhere between 0.6 and 0.8 with around 140 of the 1800 snapshots being around 0.75.

Chapter 6

Summary and Outlook

In this Chapter...

Declaration of Authorship

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbstständig verfasst und noch nicht für andere Prüfungen eingereicht habe.
Sämtliche Quellen einschließlich Internetquellen, die unverändert oder abgewandelt wiedergegeben werden, insbesondere Quellen für Texte, Grafike, Tabellen und Bilder, sind als solche kenntlich gemacht.
Mir ist bekannt, dass bei Verstößen gegen diese Grundsätze ein Verfahren wegen Täuschungsversuchs bzw. Täuschung eingeleitet wird.

Berlin,

Bibliography

1. Hannu, K. *FundamentalAstronomy* ISBN: 978-3-662-53044-3 (Springer, 2017).
2. Schneider, P. *Extragalactic Astronomy and Cosmology* ISBN: 978-3-642-54082-0 (Springer, 2015).
3. sciann13055. *Clustering Measurements of Active Galactic Nuclei* [Online; 19 December 2013]. 2014. https://www.eso.org/public/science/announcements/sciann13055/.
4. IllustrisTNGproject. *Project description* https://www.tng-project.org/about/. (2017).
5. Diemer, B. *cosmic web Images* http://www.benediktdiemer.com/visualization/images/. (2011).
6. Nolting, W. *Grundkurs Theoretische Physik* ISBN: 978-3-662-57583-3 (Springer, 2018).
7. Lifschitz. *Lehrbuch der theoretischen Physik* ISBN: 3-8171-1326-9 (Akademie-Verlag, 1973).
8. Müller, O., Rejkuba, M. & Jerjen, H. Tip of the red giant branch distances to the dwarf galaxies dw 1335-29 and dw 1340-30 in the Centaurus group. *Astronomy & Astrophysics* **815,** 1–10 (Jan. 2018).
9. A whirling plane of satellite galaxies around Centaurus A challenges cold dark matter cosmology. *al. Science* **359,** 534–537 (Feb. 2018).
10. The coherent motion of Cen A dwarf satellite galaxies remains a challenge for CDM cosmology. *science* **645,** 1–7 (Dec. 2021).
11. The spatial distribution of the MilkyWay and Andromeda satellite galaxies. *The astrophysical journal* **374,** 1125–1145 (Jan. 2007).
12. Pawlowski, M. S. The planes of satellite galaxies problem, suggested solutions, and open questions. *World Scientific Publishing Company* **33,** 496–503 (Feb. 2018).