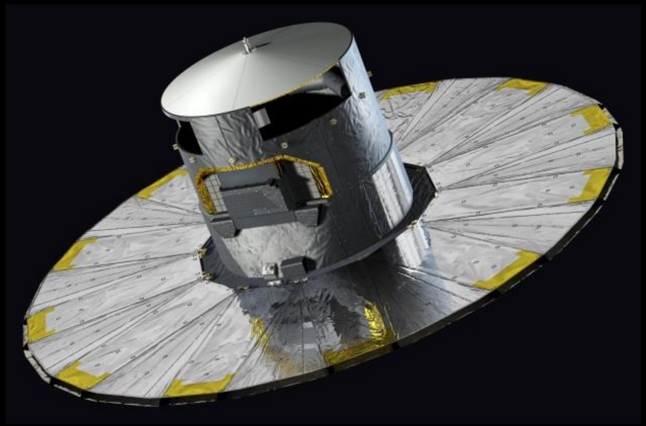
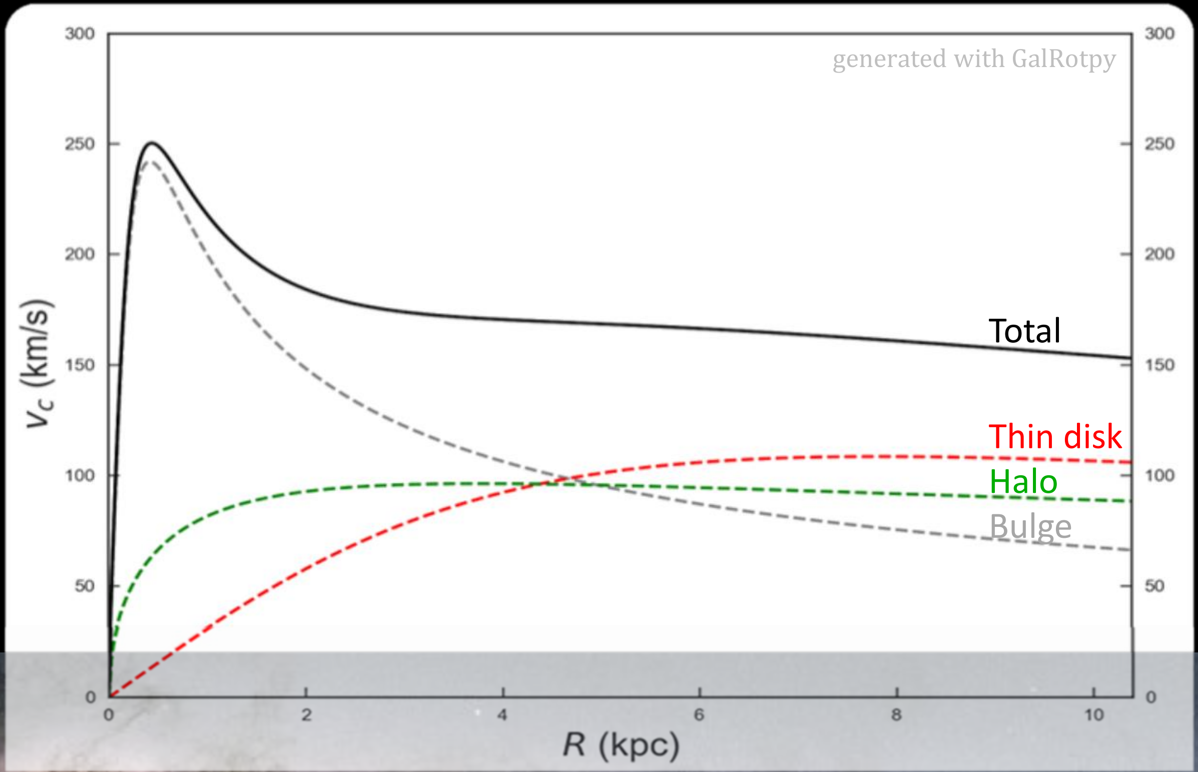


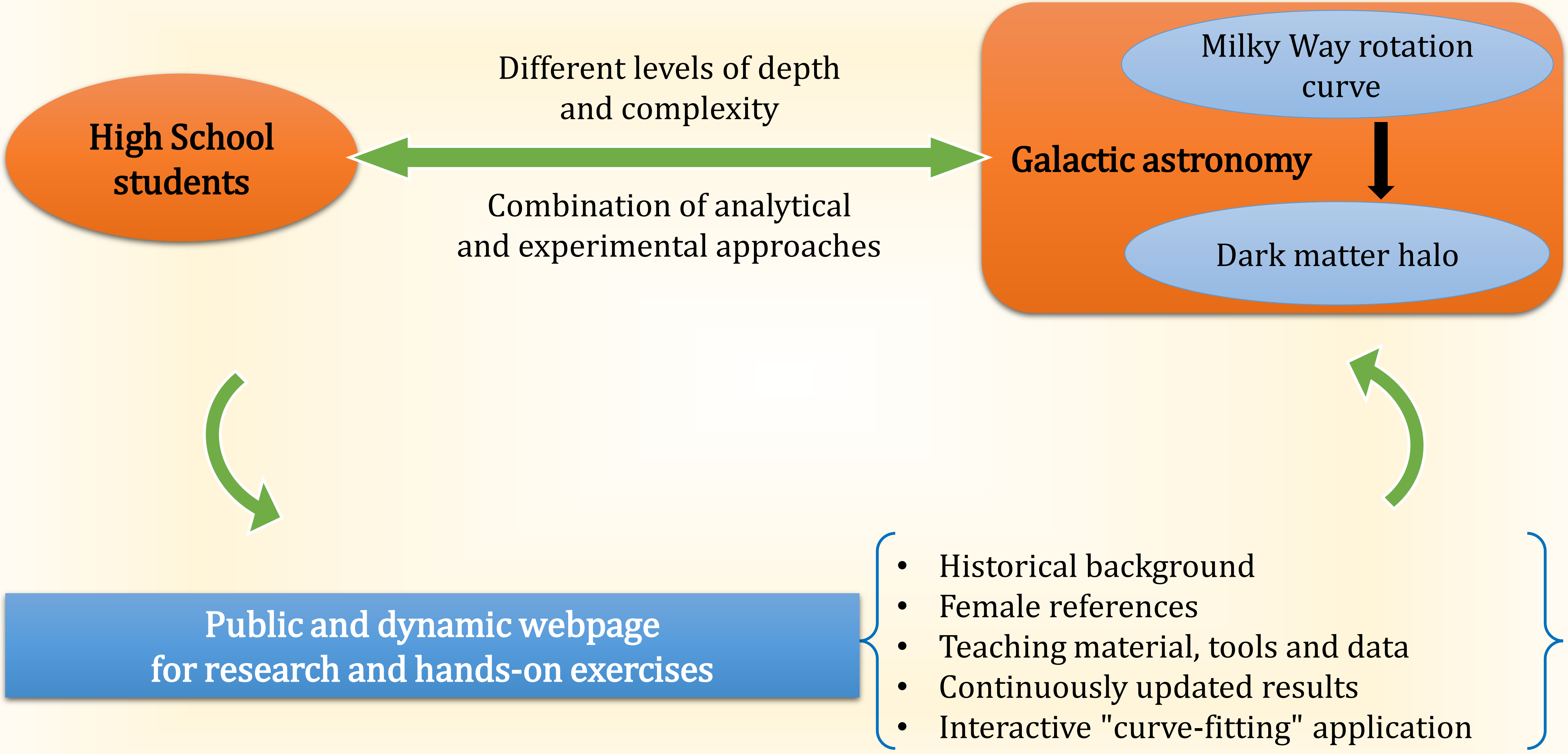
Disseminating the rotation curve of our Galaxy and its implication on the Dark Matter content

Ardèvol, J.[1] ; Antoja, T.[1] ; Figueras, F.[1] ; Aguilar, L.[2] ; Ling, J.F.[3] ; Raga, F.[1] ; Monguió, M.[1] ; et al.

[1] ICCUB , [2] UNAM, [3] USC

Abstract: We present a scheme for a flexible and adaptable activity aimed to introduce High School students to the concept of rotation curves applied to the Milky Way and the constraints it provides to the Dark Matter halo of our own Galaxy. The scheme can be adjusted to different levels of depth and complexity by combining several options: 1) input variables to work with, 2) methodology and tools applied, 3) tracers used to describe the rotation curve and 4) posterior analysis of results and overall approach. We want to include a gender perspective and motivate girls by offering female references as well, both classical and contemporary, such as Vera Rubin or Henrietta S. Leavitt as well as many other names from the exhibition 'AstrónomAs'. Besides, we aim to promote teamwork by implementing a dynamic webpage collecting the historical background, teaching material, current rotation curves and student results, together with active discussions. Moreover, it may include some public interactive application to try to fit as close as possible different data sets, which could allow users to explore the highly-degenerated parameter space of Galactic components (e.g., the disk, the bulge or the Dark Matter halo) and their masses.




High School students
Different levels of depth and complexity
Combination of analytical and experimental approaches
Galactic astronomy
Milky Way rotation curve
Dark matter halo
Public and dynamic webpage for research and hands-on exercises
Historical background
Female references
Teaching material, tools and data
Continuously updated results
Interactive "curve-fitting" application

Scientific learning

Acquire knowledge on gravitational effects of **dark matter**

Apply **simple models** to understand observables

Learn about **Galaxy morphology**

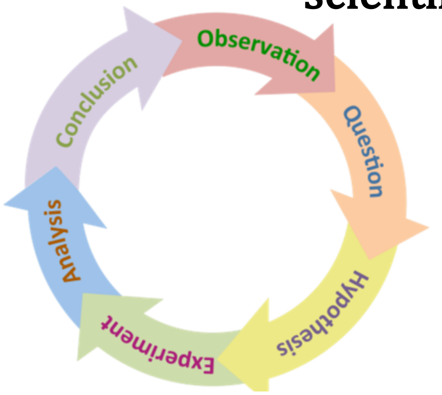
Understand **stars** as building blocks of the Galaxy

Take-home message

Methodology and experience

Discover the **Gaia space mission**

Become familiar with the **scientific method**



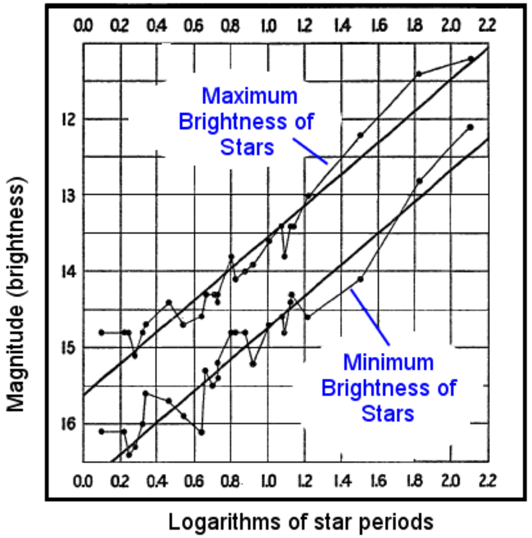
Stimulate **teamwork** and cooperation

Learn about **new tools**

A tribute to our pioneering female astronomers

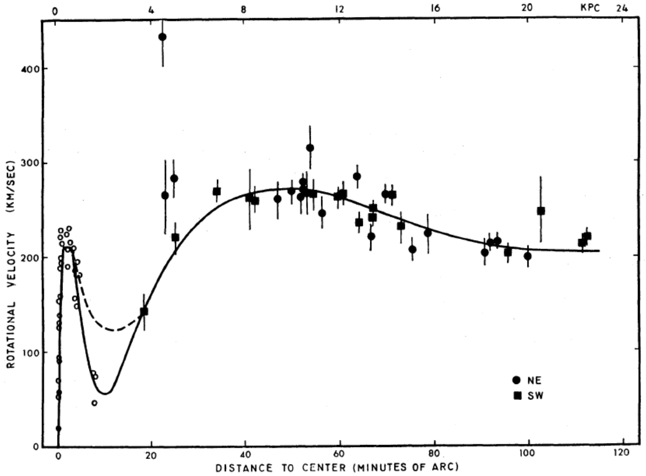
Henrietta Leavitt (USA, 1868-1921)
<u>The distance scale of the Universe</u>

She discovered the relation between the luminosity and the period of Cepheid variable stars.



Vera Rubin (USA, 1928-2020)
<u>Rotation curves, dark matter</u>

She measured the rotation curve of spiral galaxies leading to the realisation that most of their mass might be dark and resides in haloes.

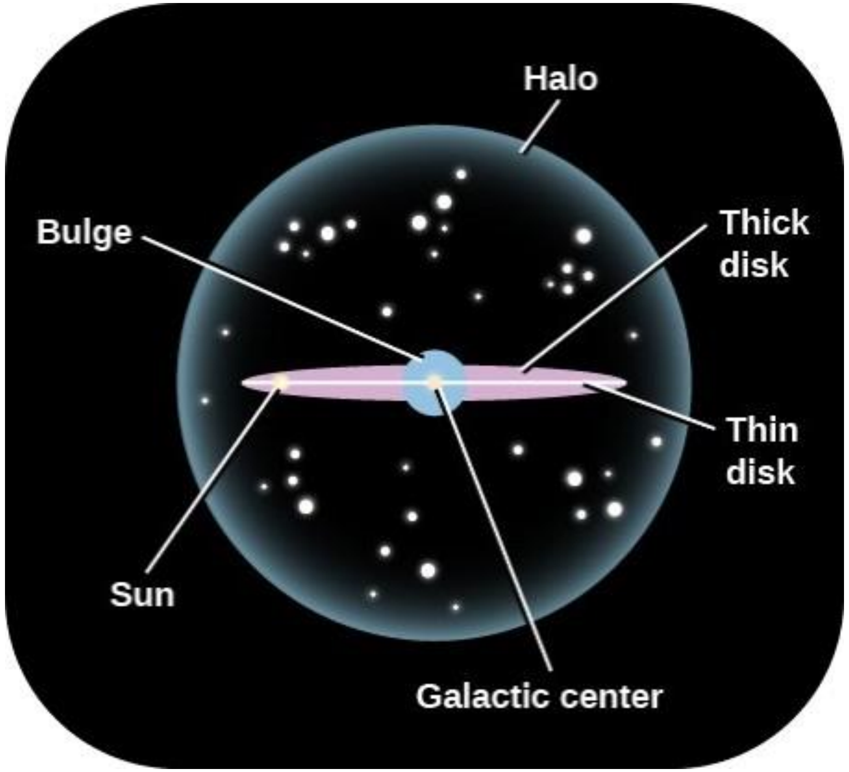


Analytical	Empirical

From gravitational force to the mass model of the Galaxy:

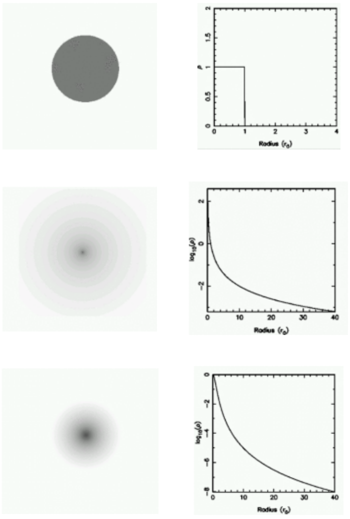
- Galactic components
- Density profiles

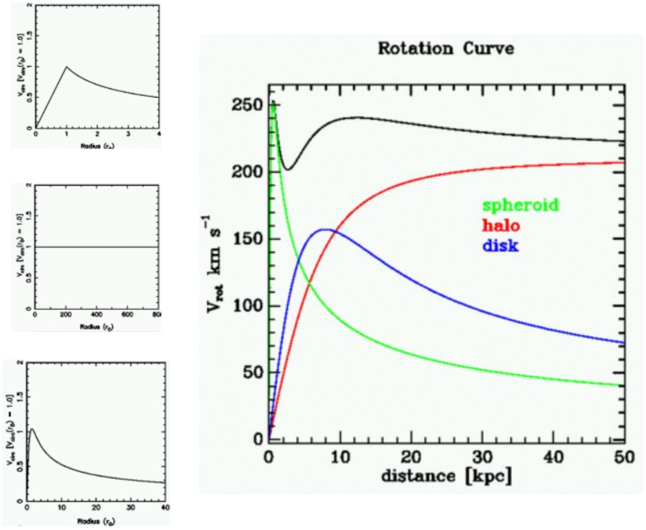
} Derivation of the modelled rotation curve



Select the density distribution	Derive and combine circular velocities

- Point source
- Uniform sphere
- Isotherm
- …
- Disk-like
- Plummer model





PYNBODY (Python 3.5): **Radial density profiles** making profiles of all kinds.	PYNBODY (Python 3.5): **Plotting the rotation curve** combining different densities and masses

https://www.coursehero.com/study-guides/astronomy/the-architecture-of-the-galaxy/

https://www.astro.utu.fi/~cflynn/galdyn/lecture4.html

Analytical	Empirical

From gravitational force to the mass model of the Galaxy:

In galaxies, there are typically 10^9 to 10^{11} stars gravitationally interacting

Newton law: the gravitational interaction among them is

$$\mathbf{F}(\mathbf{r}) = -\frac{GM\mathbf{e}_\mathbf{r}}{r^2}$$

Strategies to approach the problem:

a) stars –as point masses– in a computer simulation
b) stars considered to have a smooth distribution in space

Two useful theorems (from Newton):

1. A body inside a spherical shell of matter experiences no net gravitational force from the shell.
2. A body outside a closed spherical shell experiences the same gravitational force as if all the matter in the shell were concentrated at a point at its center.

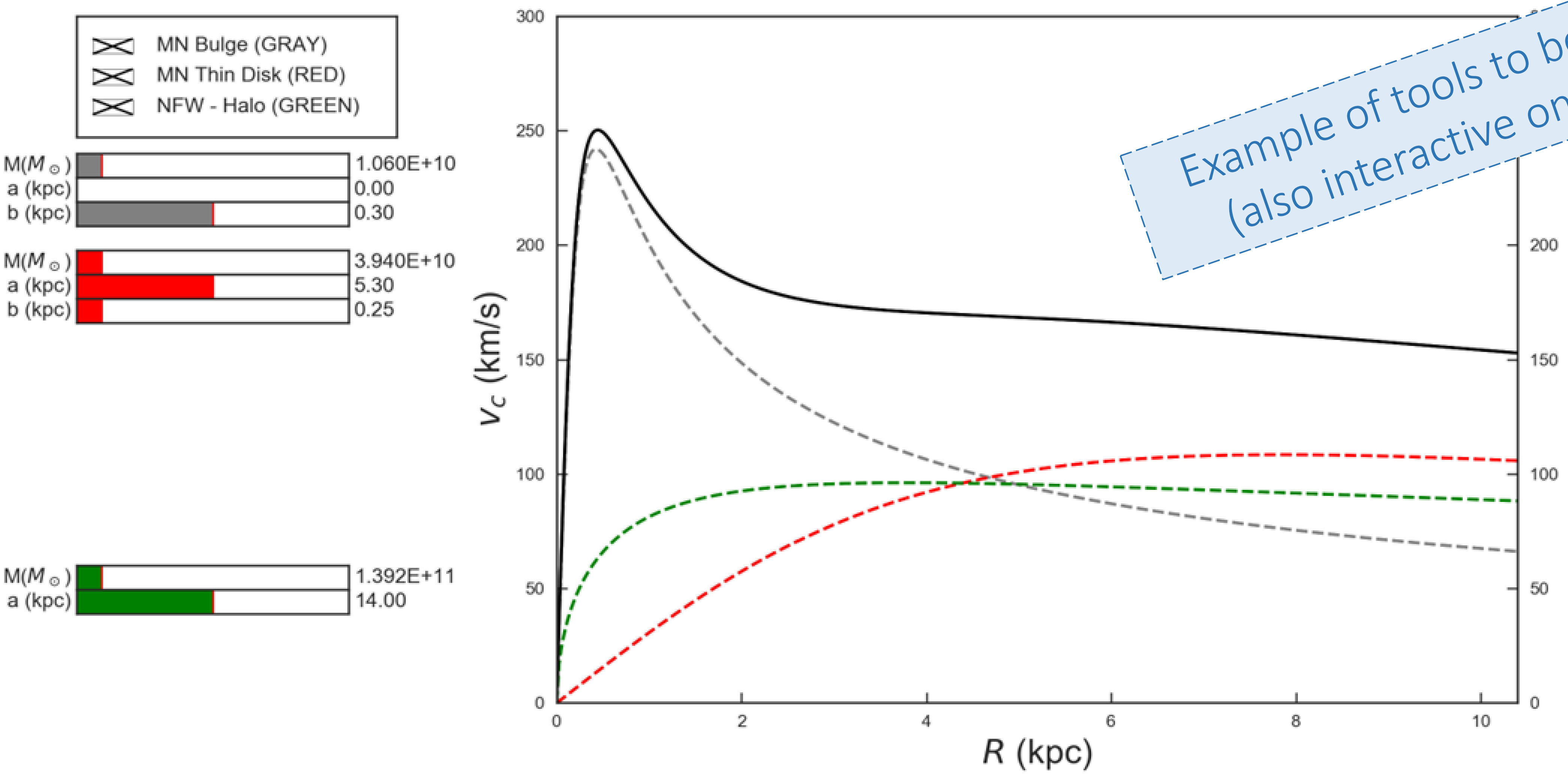
A test particle in a a circular orbit at radius r would have the **circular speed**:

$$F(r) = v_{circ}{}^2(r)/r$$

Example of educational content on web

https://www.astro.utu.fi/~cflynn/galdyn/lecture3.html

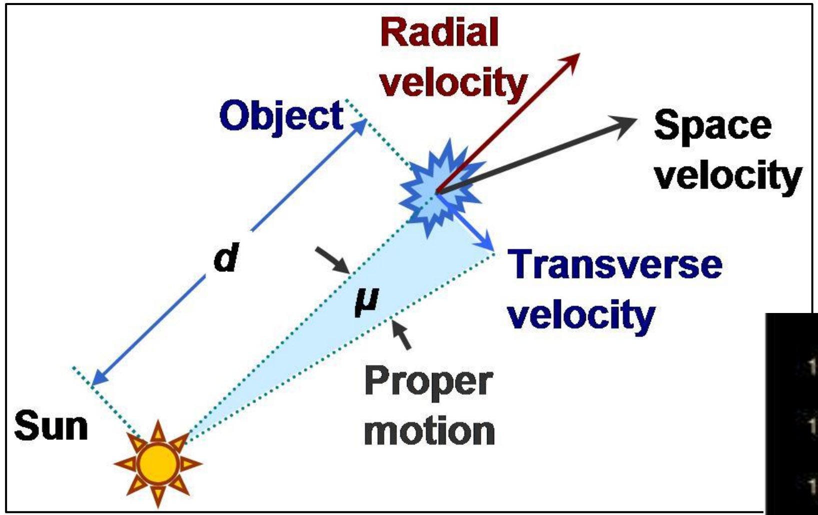
Analytical	Empirical



Example of tools to be used (also interactive on web)

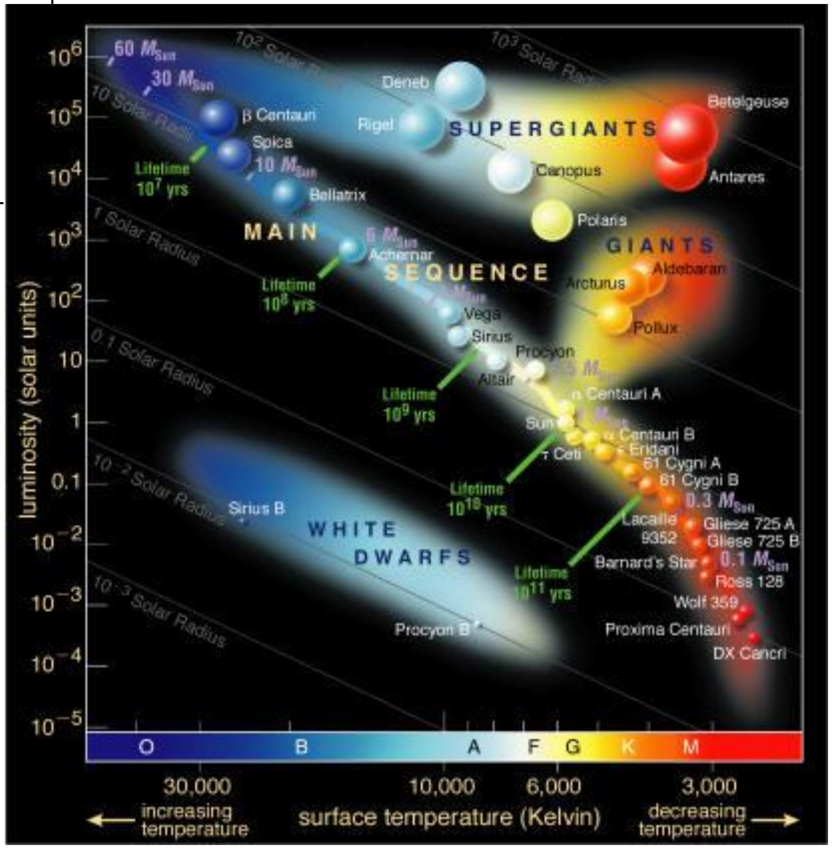
Generic modelled rotation curve generated by [GalRotpy](https://arxiv.org/pdf/1705.01665.pdf)
(https://arxiv.org/pdf/1705.01665.pdf)

Analytical	Empirical



Brews Ohare;
https://commons.wikimedia.org/wiki/File:Proper_motion.JPG

https://www.universetoday.com/39974/hertzsprung-russell-diagram/



Working with Gaia data

What can we see? What do we need?

Astrometry:

- Concept of stellar distances in astronomy

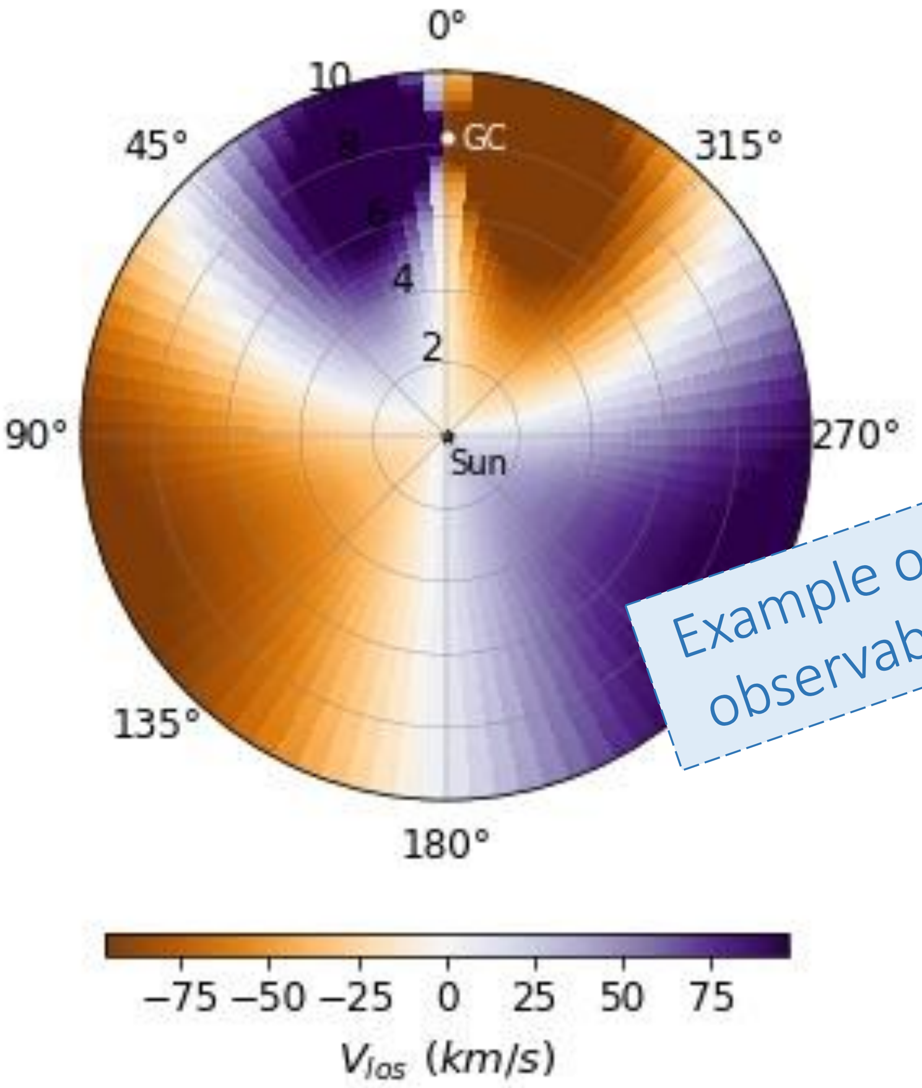
Kinematics for tracing the dynamics of the system:

- Velocities from the Sun and from the Galactic Centre

Stellar physics:

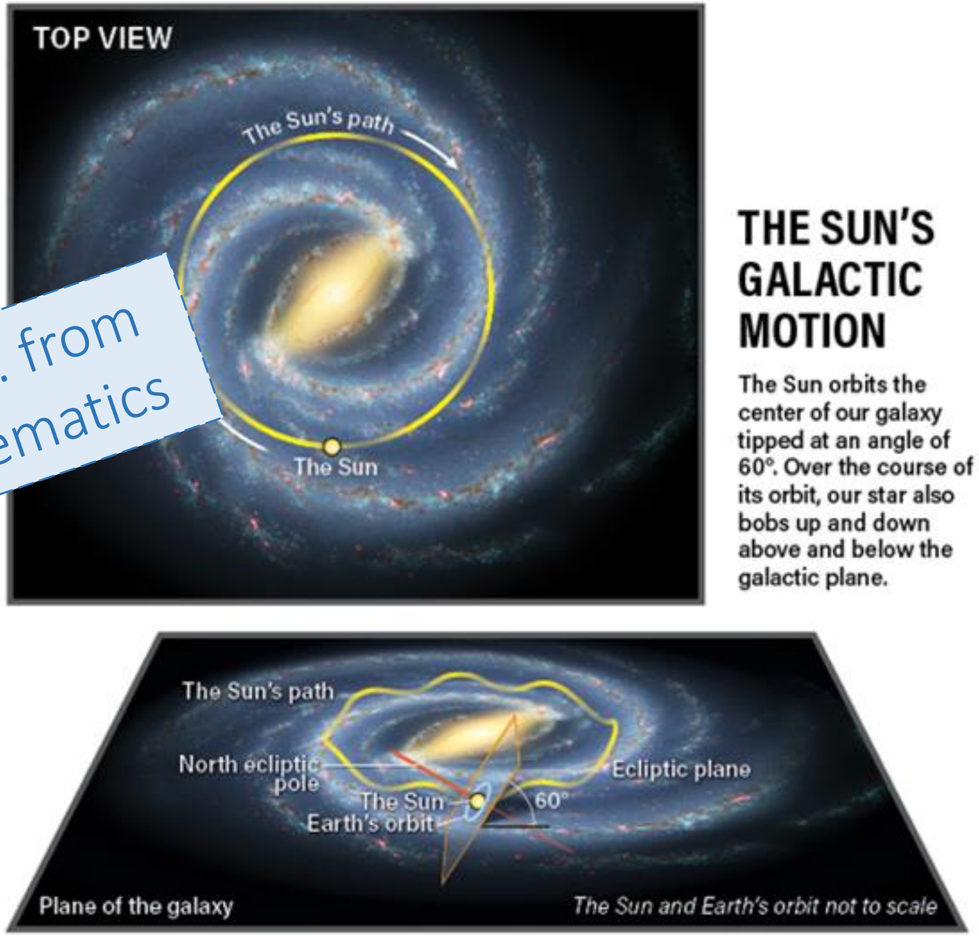
- Different stellar tracers (Cepheids, Red Giants, OB stars...)

Analytical	Empirical



Line-of-sight velocities observed from the Sun for a toy model with circular orbits and a flat rotation curve.

Example of material: from observables to kinematics



Roen Kelly; https://astronomy.com/magazine/ask-astro/2020/07/in-which-direction-does-the-sun-move-through-the-milky-way

Analytical	Empirical

Input data available on web:

Prepared data files with Galactic positions and velocities ready to directly obtain the rotation curve

Query to the data archive (proper motions, radial velocity and parallax) + use of **public codes** to derive Galactic velocities and distances

What do we measure? How do we use it?

- Examples of optimal use of available data: "looking to the anticenter, no transformation is needed"
- Range of application and limitations
- Work in the space of the observables: Can we use directly what we observe?

Analytical	Empirical

Take home message: the clear connection between both approaches

Making use of GalRotpy, the rotation curve will be fitted to the observed velocities

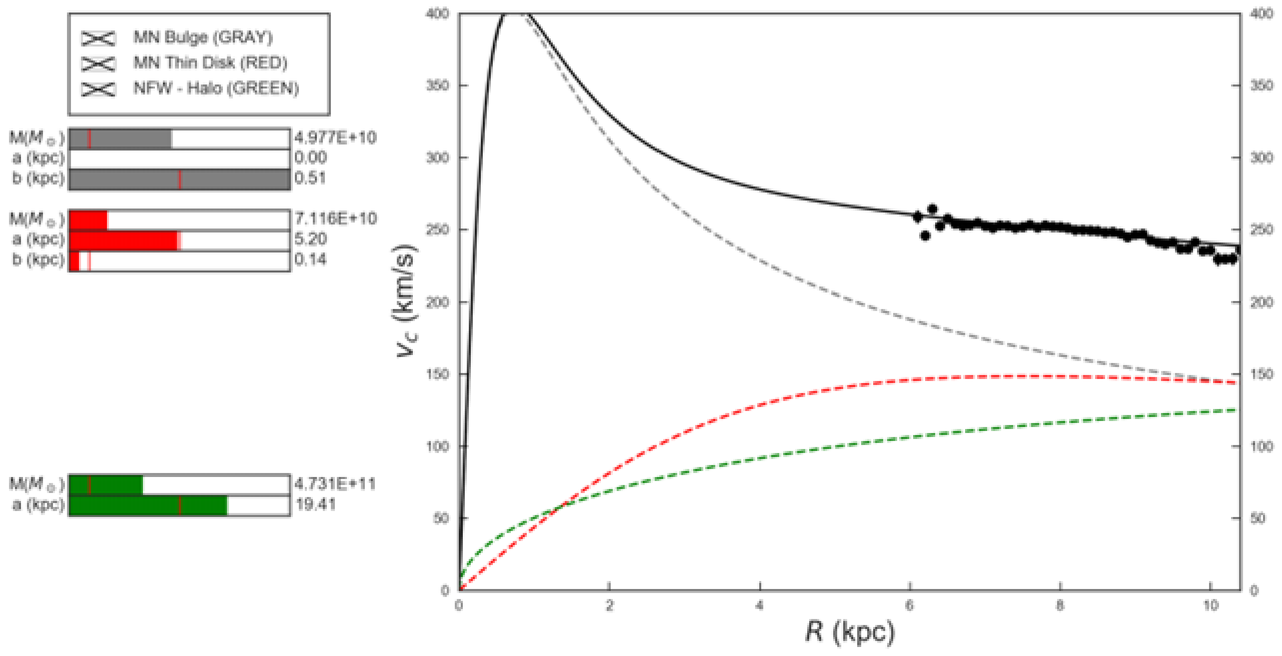
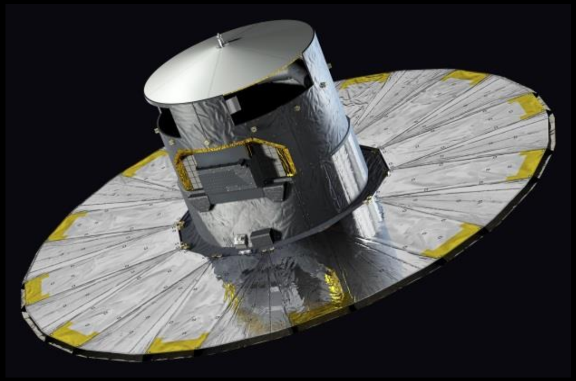


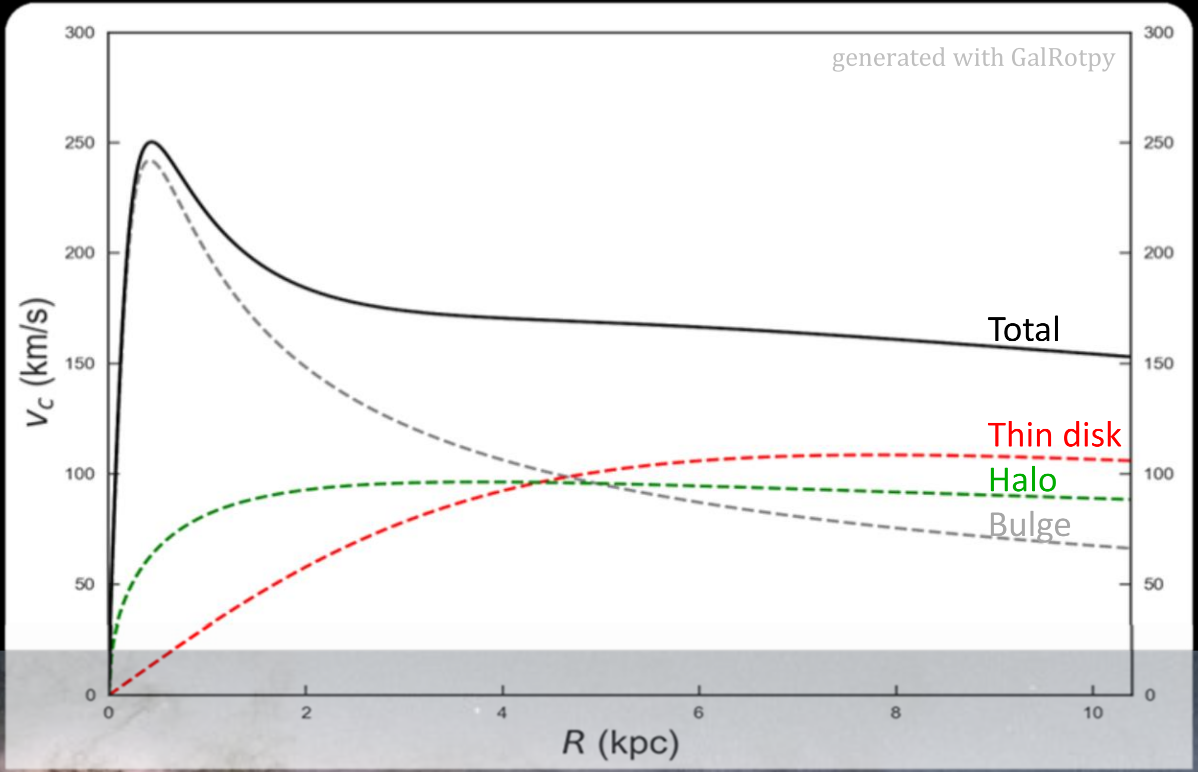
Figure 5.1: Fitting with halo. Figure generated by GalRotpy

Results and conclusions for students:

- Learn that scientific method needs fitting data with models to check them
- Analyse results in comparison with previous work (dynamical webpage)

Thank you





generated with GalRotpy
Total
Thin disk
Halo
Bulge
v_c (km/s)
R (kpc)
0
50
100
150
200
250
300
0
2
4
6
8
10